Proceedings of IPC2012
9th International Pipeline Conference
September 24 – 28, 2012, Calgary, Alberta, Canada

IPC2012-90573

DEVELOPMENT AND EVALUATION OF A STEEL-COMPOSITE HYBRID COMPOSITE REPAIR SYSTEM

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

Carl Brooks
Western Specialties
Avon, New York
cbrooks@westernspecialtiesllc.com

ABSTRACT

Composite materials are widely recognized as a resource for repairing damaged pipelines. The fibers in conventional composite repair systems typically incorporate E-glass and carbon materials. To provide greater levels of reinforcement a system was developed that incorporates steel half shells and an E-glass composite repair system. In comparison with other competing composite technologies, the hybrid system has a significant capacity to reduce strain in corroded pipeline to a level that has not been seen previously. Specifically, the hybrid system was used to reinforce a pipe sample having 75% corrosion subjected to cyclic pressure at 36% SMYS. This sample cycled 767,816 times before a leak failure developed. Furthermore, recent testing has demonstrated that the hybrid system actually places the pipeline in compression during installation. This paper will provide results on a series of specifically-designed tests to evaluate the performance of the hybrid system and the implications in relation to the service of actual pipelines.

INTRODUCTION

The purpose of this paper is to provide information on a testing program conducted to evaluate the ComposiSleeve™ system in repairing and reinforcing damaged high pressure transmission pipelines. This repair system is a hybrid design that integrates steel half-shells combined with a water-activated urethane E-glass composite.

The approach used to evaluate the repair system is based on full-scale experimentation, where defects were machined into test samples. The performance of the system was evaluated by means of destructive testing. Much of this work is based on previous studies conducted by SES for the pipeline industry in evaluating competing composite repair technologies. Having access to data associated with these prior studies permits a direct comparison of the repair system with other composite repair technologies. Of particular interest is the level of reinforcement provided by the repair system to the damaged region of the pipe. Composite technologies that are most effective are those systems that are able to successfully reduce strain in the damaged region (i.e. corrosion and dents) to acceptable levels. As will be presented in this report, the repair system is effective in reducing strain in the corroded region of a pipeline significantly below industry norms. In turn, the 767,816 cycles to failure measured for the pressure cycle fatigue sample is greater than any composite repair system tested to date.

This paper has been organized to provide the reader with a brief background on the repair system, including a descriptive schematic of the system. A detailed discussion on the test program, including results, is presented. The primary means for evaluating the repair system is its ability to provide reinforcement to a simulated 75% deep corrosion machined defect installed in a 12.75-inch x 0.375-inch, Grade X42 pipe sample. Sections of this paper include Background (with details on the repair of corrosion), Testing Methods and Results, Additional Testing: Methods and Results, Discussion, and Closing Comments.

BACKGROUND

The ComposiSleeve™ system (hereafter referred to as the *hybrid steel-composite repair*) is a hybrid design that integrates steel half-shells combined with an E-glass composite having a water-activated urethane resin system. Unlike conventional composite repair systems that utilize fibers (i.e. typically E-glass and carbon as the primary means for reinforcement), the repair system relies on the stiffness of steel and adhesive bonding between the outer surface of the pipe and inner surface of the steel half shell. Most of the composite repair systems currently on the market are either in compliance or seeking compliance with standards such as ASME PCC-2, *Repair of Pressure Equipment and Piping, Part 4, Nonmetallic and Bonded Repairs*. These standards were written primarily for wet wrap systems involving the use of either saturation in the field or pre-impregnated resins. Systems involving either pre-cured coils or half shell designs are not explicitly addressed in the current standards. As a result, any evaluation of these systems must rely on assessments via full-scale testing performance and not rely explicitly on calculations to determine the minimum required reinforcing thickness.

Provided in Figure 1 is a schematic diagram showing the components of the hybrid steel-composite repair system. The variables of interest include selection of the load transfer material, thickness of the steel, selection of the bonding adhesive between the pipe and steel sleeves, and thickness of the E-glass composite material.

At the present time there is no single published methodology that can be used to determine the minimum required thickness for a composite-based reinforcing sleeve such as the hybrid steel-composite repair system; however, as a minimum, the following should be considered from a performance standpoint.

- Stresses must be reduced in the damaged section of pipe to an acceptable level.
- Stresses in the reinforcing materials of the hybrid steel-composite repair (steel, composite, and adhesive) must not exceed design stresses.
- The repair must be able to withstand both static and cyclic pressure loading.
- Long-term performance is an essential variable of interest in qualifying repair systems.

A calculator was developed that could be used to determine the thickness of the overwrapping E-glass composite material. Typically, the hybrid steel-composite repair half shell thicknesses have not been less than 0.25 inches. In comparison to the relative low stiffness of the composite material, this thickness of the steel has been adequate for all testing completed to date (i.e. steel pipe thicknesses of 0.375 inches). Screenshots for the calculator are presented in Figure 2 and Figure 3, along with the appropriate equations. The essential elements of this calculator include the following:

- Properties of the base pipe material including diameter, wall thickness, and grade.
- Dimensions of the corrosion.
- Aspects of the repair including length and adhesive lap shear strength.
- Safety factors, especially with regards to the bonding adhesive.

The calculated required thickness of the composite material is based on the assumption that the **composite material** and the **bonding adhesive** are the two structural components that reinforce the damaged section of pipe, and resist that opposing force caused by the internal pressure. For conservatism, it is assumed that these two structural members resist a force caused by the product of the internal pressure and projected area of the corrosion. In other words, if the steel associated with the corroded region of the pipe were removed, the composite and bonding adhesive would be responsible for resisting the entire resulting force associated with the projected opening of the corrosion defect. While this condition would never exist, this approach provides a conservative mechanics-based reference point on which to make calculations.

Note the following input data in Figure 2.

- Pipe: 12.75-inch x 0.375-inch, Grade X42
- Corrosion geometry: 8 inches long x 6 inches wide
- Adhesive shear strength: 2,000 psi
- Composite tensile strength: 20,000 psi (long-term design strength)
- Length of repair: 18 inches
- Adhesive service factor: 0.2 (safety factor of 5)
- Composite service factor: 0.5 (safety factor of 2 on long-term strength)

The design factors that contribute to the strength of the reinforcing system include the shear strength of the adhesive, tensile strength of the composite material, composite thickness, and the length of the repair. Assuming that material selection is not an option, the composite thickness and length of repair are the two critical variables.

As observed in Figure 3, the resulting composite thickness is 0.142 inches. If the shear strength of the adhesive, $\mathbf{t}_{adh}$, is varied, the following composite thickness, t_c, values are calculated:

- $\mathbf{t}_{adh}$ = 2,375 psi t_c = 0.010 inches
- $\mathbf{t}_{adh}$ = 2,000 psi t_c = 0.142 inches (default configuration)
- $\mathbf{t}_{adh}$ = 1,000 psi t_c = 0.492 inches
- $\mathbf{t}_{adh}$ = 500 psi t_c = 0.668 inches
- $\mathbf{t}_{adh}$ = 100 psi t_c = 0.808 inches

What is interesting to note in the above calculations is the significant contribution that the adhesive makes to the overall strength of the reinforcement. As noted, when the shear strength is assumed to be 2,375 psi, the need for composite reinforcement is practically non-existent. Of the three burst tests that were conducted, the test sample with no composite reinforcement did indeed demonstrate that that the adhesive-only case had adequate strength to resist the corrosion bulging and pipe expansion associated with the burst test.

TESTING TO ADDRESS REPAIR OF CORROSION

Full-scale testing was performed to evaluate the performance of the hybrid steel-composite repair system in repairing a corroded pipeline. While analytical calculations are useful for sizing the components within a system, it is essential that performance testing be conducted to validate the overall capabilities of a given composite reinforcement system. What is lacking in the calculations is the inter-dependent relationship that exists between the components in the system. For example, the load transfer material serves to ensure that load generated by the bulging corrosion is transferred into the composite fiber material. A filler material lacking the required rigidity will fail to engage the composite material, resulting in an excessive accumulation of strain in the reinforced steel material beneath the reinforcement. The end result in having a deficient filler material is a highly-loaded corrosion region that is susceptible to premature failure in the form of leaking, especially in the presence of cyclic pressure loading.

The sections of this paper that follow provide specific details associated with the testing methods and results used to evaluate the performance of the hybrid steel-composite repair system in reinforcing a corroded pipeline.

Testing Methods

Two types of testing were conducted. The first involved samples repaired to evaluate the increase in burst strength (i.e. limit state) of a corroded pipe section, while an additional test samples was prepared to evaluate the effects of cyclic pressure on the performance of the hybrid steel-composite repair.

The variable of interest in this study was the thickness of the E-glass water-activated urethane. An additional sample was also fabricated to determine what would happen if no composite materials were installed on the outside of the repair. The pipe test samples included a 12.75-inch x 0.375-inch, Grade X42 pipe with a corrosion region having a depth of 75% installed by machining. Figure 4 shows the schematic for this test sample. Strain gages were installed in the machined corrosion region, on the base pipe, and outside of the repair, as shown in Figure 5.

As stated previously, three types of tests were conducted, with details for the burst sample configurations listed below. The pressure cycle fatigue sample involved the *steel plus 18 wraps* configuration.

- Sample #1: Steel only
- Sample #2: Steel plus 18 wraps
- Sample #3: Steel plus 8 wraps

Figures 6 through 10 provide a series of photographs showing actual measurements made after the machining was completed. The target machining depth was 75%, although as can be seen from these photographs, the machining depth averages ranged from 74% to 78% of the pipe's nominal wall thickness. After machining, end caps were welded to each sample. The samples were sandblasted to a near white metal finish (NACE 2) prior to installation of the repair system.

In addition to the corrosion tests, results are also presented for a test designed to address the performance of the system in repairing leaks. Results are also provided for measurements taken during installation of the sleeve that actually quantified the level of compression measured during installation.

Test Results

Results are presented in this section of the paper detailing the measurements and final performance data associated with both the burst and pressure cycle fatigue tests. In addition to the actual performance data (i.e. burst pressure and number of cycles to failure), data were also generated from the strain gage measurements in the corroded steel region beneath repair. The strain measurements are a fundamental means for evaluating the ability of a repair system to reinforce a damaged section of pipe. With Stress Engineering Services, Inc. having performed corrosion repair tests on more than 15 different systems over the past 5 years, it is possible to evaluate the relative performance of a particular system to industry norms. A comparison of this type will be provided for the hybrid steel-composite repair system.

Burst Tests

The three burst tests were performed to determine the limit state capacity for each repair configuration. The recorded burst pressures for the three different repair configurations.

- Sample #1 (Steel only): P_{burst} = 3,995 psi
- Sample #2 (Steel plus 18 wraps): P_{burst} = 4,389 psi
- Sample #3 (Steel plus 8 wraps): P_{burst} = 4,374 psi

Figure 11 provides photographs of the three burst tests. Note that the failures occurred in the repaired region for all three samples; however, the failures occurred at pressure levels that would be expected for a perfect, undamaged pipe.

For the 12.75-inch x 0.375-inch, Grade X42 pipe, which has a minimum tensile strength of 60,000 psi, the estimated burst pressure is 3,529 psi. Even the minimum burst pressure of 3,995 psi (Sample #1 with steel only) is 113% of this value; while the maximum burst pressure associated with Sample #2 (i.e. 4,389 psi) is 124% of this value.

Of the three burst tests that were conducted, Sample #1 provides a significant contribution to the overall study because prior to testing, one of the questions to be addressed in the current scope was to identify the level of reinforcement provide by a repair configuration having only the adhesive bonding the steel half shell to the outer pipe surface. While Samples #2 and #3 demonstrate that the composite material provides additional reinforcement, Sample #1 shows that the adhesive by itself generates a robust level of reinforcement.

While the burst pressures are essential for understanding the limit state performance of a given repair, equally if not more important, is measuring the level of strain beneath the repair. For a repair system to work properly, it must ensure that strain levels in the damaged section of pipe (i.e. corrosion in this particular study) are minimized. There is no current limitation on strain in the reinforced section specified by any of the current design codes such as ASME PCC-2; however, it is possible to quantify acceptable strain levels by considering performance of the repair in testing. Burst testing is one means of establishing performance, although a better means for quantifying the capability of a repair system for corrosion and dents is via pressure cycle fatigue testing. The section that follows, *Pressure Cycle Fatigue Tests*, provides details on the pressure cycle fatigue test that was conducted on the hybrid steel-composite repair system.

Presented in this section of the report are the strain gage results measured during burst testing of the three different repair configurations. The presentation includes plotted data, as well as tabulated data measured at pressure levels equal to 72% and 100% SMYS (1,780 psi and 2,470 psi, respectively). Figure 12 plots hoop strain as a function of internal pressure. Results are included for the following data sets:

- Leading E-glass technology
- Base pipe (non-corroded section)
- Sample #1: Steel only
- Sample #2: Steel plus 18 wraps
- Sample #2: Steel plus 18 wraps (outside surface of repair)
- Sample #3: Steel plus 8 wraps
- Data point at 72% SMYS for Industry average for other competing E-glass systems[1]
- Data point at 100% SMYS for Industry average for other competing E-glass systems[1]

There are several observations made in viewing this plot; however, the most noteworthy point is the significant reduction in strain provided by the hybrid steel-composite repair system when compared to other E-glass technologies. The large number of fatigue cycles acquired during the pressure cycle test is testimony to the appreciable level of performance (i.e. strain reduction) provided by the hybrid steel-composite repair system.

Also included are the tabulated data shown in Figure 13. As observed at 72% SMYS the PRCI average for E-glass material was 4,497 $\mu\varepsilon$, (where $\mu\varepsilon$ is microstrain with 10,000 $\mu\varepsilon$ corresponding to 1% strain). For the hybrid steel-composite repair systems that were tested, the minimum measured strain data was 1,610 $\mu\varepsilon$ (steel + 8 wraps), while the maximum measured of the three data sets was 2,220 $\mu\varepsilon$. Results at the 100% SMYS pressure level demonstrated similar performance characteristics when compared to the PRCI data set, although the results for the hybrid steel-composite repair are not as non-linear as the data for the PRCI E-glass systems.

Cyclic Pressure Fatigue Tests

For the pressure cycle fatigue tests the 12.75-inch x 0.375-inch, Grade X42 pipe having 75% corrosion was cycled from 36% to 72% SMYS until a leak developed in the corroded region beneath the repair. The hybrid steel-composite repair system achieved 767,816 cycles before a leak failure developed in the repair. Of the 11 different repair configurations tested via pressure cycle fatigue to date, the hybrid steel-composite repair system achieved the greatest number of cycles to failure. Provided below are data for other test samples.

- 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 (Pipe #1): 212,888 cycles to failure
- Carbon system (Pipe #2): 256,344 cycles to failure
- Carbon system (Pipe #3): 202,903 cycles to failure
- E-glass system: 259,537 cycles to failure
- Carbon system (Pipe #4): 532,776 cycles (run out, no failure)
- ComposiSleeve™ system: 767,816 cycles to failure (MAX)

It should be noted that in order to achieve this number of cycles, the welds joining the end caps to the ComposiSleeve™ test sample had to be repaired multiple times. As with the burst tests, the pressure cycle

---

[1] These data acquired as part of the long-term testing program (MATR-3-4) being co-sponsored by the Pipeline Research Council International, Inc. and 13 other composite repair systems. For additional details consult www.compositerepairstudy.com.

fatigue tested integrated strain gages installed in the corroded region beneath the repair. The strain gages measured hoop and axial strains at designated cycle periods during testing. Figure 14 plots the maximum hoop strain and hoop strain range for Gage #1 located beneath the repair up to 100,000 cycles, while Figure 15 lists hoop and axial strains at designated cycle periods. The strain range is the difference between the maximum and minimum strains.

In viewing the strain data from Figure 14 and Figure 15 there are several important observations. Note that the data plotted in Figure 14 is for Gage #1 located beneath the repair.

- The maximum measured strain beneath the repair (i.e. Gage #1) increased from 1,756 με at start-up to 3,318 με at 100,000 cycles. This is approximately a 90% increase over the designated cycle period.
- Over the 100,000 cycle recording period there was actually a decrease in the Gage #1 hoop strain range from 914 με at start-up to 810 με at 100,000 cycles. This represents a strain reduction on the order of 12%.
- The strain range in the base considering the 36% SMYS pressure differential was 460 με. The average hoop strain range measured during the 100,000 cycle period was 811 με, a value that is approximately 76% more than the nominal base pipe.
- The DOE B-curve is provided below, where ΔS represents strain range in psi. If the maximum hoop strain of 914 με is considered, the corresponding design life is estimated to be 1,836,094 cycles. The actual fatigue failure data was 767,816 cycles. The likely explanation for the difference is rooted in the presence of a stress concentration factor (SCF) in the vicinity of the machined corrosion. A stress concentration of only 1.24 generates a cycle to failure condition of 776,000 cycles using the DOE B-curve (a value close to the actual fatigue life of 767,816 cycles). An SCF of this magnitude is completely consistent what could be expected for a machined corrosion region.

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

- It is clear from the significant number of cycles achieved during testing that the hybrid steel-composite repair system is uniquely effective in reducing strain in the reinforced region of the pipe. This statement is reinforced by the fact that the hybrid steel-composite repair system was able to increase the fatigue life beyond other composite-based systems (although one carbon data point at 532,776 cycles is a run out condition).
- To be useful from a design standpoint, the 767,816 cycles to failure must by adjusted to account for variations in fatigue data and to introduce an acceptable level of conservatism. In other words, even though the test ran for more than 750,000 cycles, it is not appropriate to assume that an actual repair can function for this many cycles. If a safety factor of 10 is employed, the number of design cycles for the hybrid steel-composite repair system is 76,781 cycles (i.e. 767,816 cycles / 10).
- From a high pressure gas pipeline standpoint pipeline applications standpoint, the 76,781 design cycles for a pressure range of 36% SMYS corresponds conservatively to a design condition of **21 years** for a *very aggressive* pressure cycle condition (3,683 cycles per year), **228 years** for a *moderately aggressive* pressure cycle condition (337 cycles per year), and **600 years** for a light pressure cycle condition (128 cycles per year). The data from Kiefner et al[2] in Figure 16 was used in generating the above service life values.

Leak Repair Testing

In addition to the burst and pressure cycle tests, repairs were made on two (2) test samples, using 12.75-inch x 0.375-inch, Grade X42 pipe material, with each having a 60% deep corrosion defect. One of these test samples had a thru-wall hole (Sample #1). Prior to burst testing, each test sample was subjected to 22,503 pressure cycles from 890 psi to 1,780 psi, or from 50% to 100% of the maximum operating pressure (MAOP). After the pressure cycles, the samples were subjected to a static burst test. Sample #1 developed a noticeable leak at approximately 4,000 psi of internal pressure. The maximum pressure reached was 4,163 psi. Sample #1 did not burst due to a leak that developed at the high pressure condition. The leak occurred in the repaired region. Sample #2 burst in the base pipe away from the repair where the maximum pressure applied to the sample was 4,033 psi. Figure 17 provides two photographs of the thru-wall defect test sample prior to repair.

Pipe Compression During Installation

In addition to the tests results provided in this paper, a series of measurements were made to measure stresses generated in the pipe beneath the hybrid steel-composite repair reinforcement. What makes this repair system unique is not only the fact that it employs steel as part of the reinforcement, but that the pipe is actually placed into compression during the process of installation. The same strain gages that were used to make measurements during testing during a recent project focused on reinforcement vintage girth welds were also used to measure strains during installation. Provided in Figure 18 is a schematic showing the geometry for girth weld sample used to measure compressive stress in the pipe beneath the reinforcement.

In the phase of testing two samples used for measurement, with three bi-axial strain gages placed on each sample that were used for monitoring the level of compression during installation. Refer to Figure 18 for locations of the gage relative to the girth weld position. Table 1 provides a summary of stresses measured during compression phase of testing. As noted in this table, a maximum compressive hoop stress of 43,860 psi with an average compressive stress on the order of 30,000 psi.

The test data presented previously in this paper have supported the concept that this particular reinforcing system has the ability to reduce strain in the base pipe. These particular measurements provide insight as to why the system has performed well. The ability of the system to actually place the pipe into compression partially explains the basis for the low strains measured in the 75% corrosion sample during pressurization. Additionally, the extremely long fatigue life achieved with the 75% corrosion sample (i.e. 767,816 cycles) is better understood in the context of a compressive stress field that reduces the mean cyclic stress, as well as introducing the possibility that the machined corroded region was at least partially in compression during the early stages of pressure cycling.

[2] Kiefner J. F. et al, *Estimating Fatigue Life for Pipeline Integrity Management*, Paper No. IPC04-0167, Presented at the International Pipeline Conference, Calgary, Canada, October 4 – 8, 2008.

DISCUSSION

This paper has provided details on testing conducted to evaluate the hybrid steel-composite repair pipeline repair system. The results demonstrate that this repair system can significantly reduce strain in corroded sections of pipe, the end results being the ability to restore pressure integrity and increase pressure cycle fatigue life.

One of the challenges concerning the ability of composite-based repair systems to repair damaged pipelines concerns long-term performance. This issue primarily relates to degradation of the polymer-based resins and adhesives that are central components in every composite repair system. One of the techniques commonly used in the composite repair industry is to use large safety factors (i.e. between 5 and 10) on design stresses relative to long-term adhesive lap shear and composite tensile strengths. This approach ensures that even in the presence of material degradation, stresses in the composite repair system do not reach unacceptable levels. Additionally, as long as the composite system possesses adequate strength and stiffness, the strain in the damaged sections of the pipeline will not reach unacceptable levels.

As observed in the detailed reports provided in the appendices, the hybrid steel-composite repair system can be specifically designed for reinforcing a wide range of pipeline anomalies. As demonstrated in this report, performance-based testing is the ideal means for evaluating the ability of the hybrid steel-composite repair system. The overall approach should, as a minimum, include identifying the pipeline anomaly, determining the required level of reinforcement, designing and installing the repair, and evaluating the overall performance of the repair system via full-scale destructive testing. Through monitoring strain gages beneath the repair during testing and identifying the ultimate capacity of the repair, it is possible to estimate how the repair will perform in actual service.

CLOSING COMMENTS

Composite materials are widely-accepted as a viable means for repairing damaged high pressure pipelines. The ComposiSleeve™ is a hybrid system that employs a bonding adhesive, two steel strong-back half shells, and a composite overwrap. Results provided in this paper demonstrate that this particular repair system significantly reduces strain in a damaged section of pipe, so that the integrity of even severely-corroded pipelines is restored to levels expected in an undamaged section of pipe. The hybrid steel-composite repair represents an engineered system that can be designed to meet the specific needs for repairing specific anomalies in a high pressure pipeline system.

REFERENCES

1. American Society of Mechanical Engineers, *ASME Post Construction SC-Repair & Testing, PCC-2, Repair Standard, Article 4.1, Non-metallic Composite Repair Systems for Pipelines and Pipework: High Risk Applications*, New York, New York, 2007 edition.
2. Report prepared by Stress Engineering Services, Inc. for LMC Industrial Contractors, Inc., *Evaluation of the CompsiSleeve™ Pipeline Repair System*, Houston, Texas, June 2011.

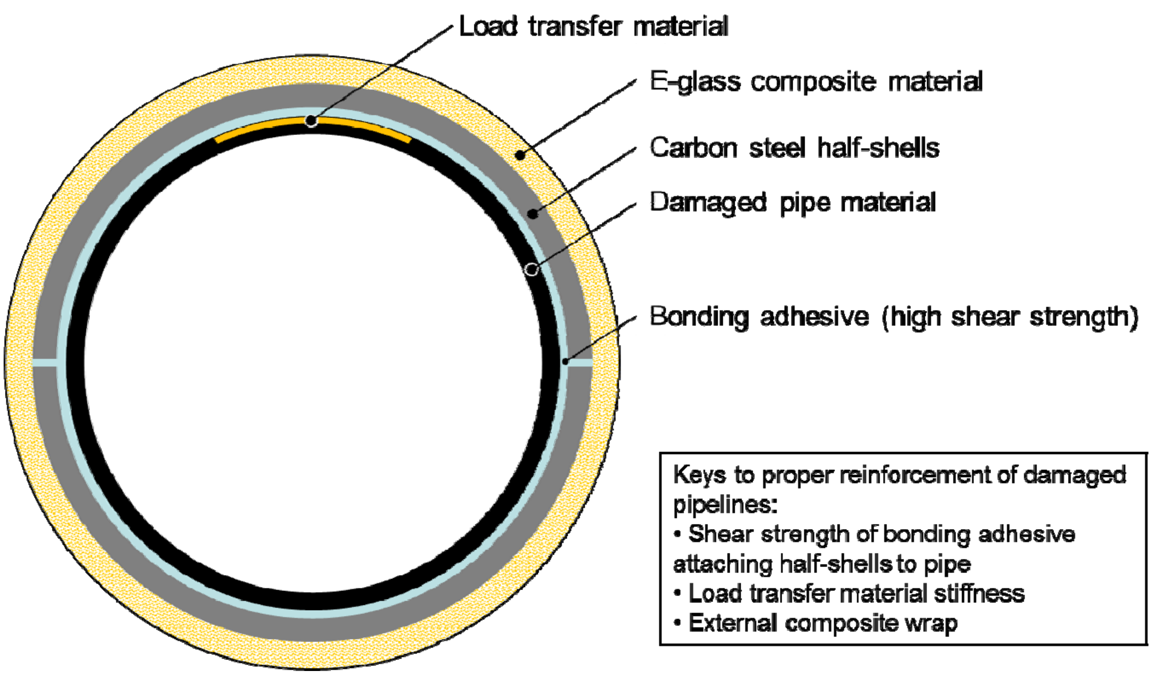

Figure 1 – Schematic diagram showing components of the ComposiSleeve™ system

Western Specialties Composite Thickness Calculator

This calculator is used to estimate composite material thickness. No consideration of the CompositSleeve steel "thickness" is considered (it is assumed that this material is sufficiently thick), although the adhesive bond strength is critical to the calculation process. Input values are as noted and include pipe dimensions, corrosion area, and material strengths.

INPUT VALUES

Measured yield strength of steel pipe or mill certification:	$s_a := 43000\,psi$
Minimum Specified Yield Strength (SMYS) of steel pipe:	$S := 43000\,psi$
Measured ultimate tensile strength of steel pipe or mill certification:	$s_{UTS} := 76000\,psi$
Nominal wall thickness of test pipe:	$t_s := 0.375\,in$
Outside diameter of test pipe:	$D := 12.75\,in$
Long-term strength of composite material:	$s_{lt} := 20000\,psi$
Lap shear strength of the adhesive material:	$\tau_{adh} := 2000\,psi$
Length of repair:	$L_{repair} := 18 \cdot in$
Per layer thickness of composite::	$t_{layer} := 0.020\,in$
Length of corrosion:	$L_{corr} := 8 \cdot in$
Width of corrosion:	$w_{corr} := 6 \cdot in$
Service factor for composite material (ASME PCC-2 Table 5):	$f := 0.2$
Service factor for adhesive material	$f_{adh} := 0.2$

Figure 2 – Western Specialties Composite Thickness Calculator (1/2)

CALCULATED VALUES

The thickness of the composite is determined by considering the level of restraint provided by the steel sleeve and the required containment pressure.

SMYS pressure: $P := \frac{2 \cdot S \cdot t_s}{D}$ $\quad P = 2529 \cdot psi$

Predicted burst pressure of pipe based on UTS: $P_{burst} := \frac{2 \cdot s_{UTS} \cdot t_s}{D}$ $\quad P_{burst} = 4471 \cdot psi$

$$t_c := \frac{1}{2 \cdot f \cdot s_{lt}} \cdot \left[\frac{P \cdot L_{corr} \cdot w_{corr}}{L_{repair}} - \tau_{adh} \cdot f_{adh} \cdot \left(\frac{\pi}{2} \cdot D - w_{corr} \right) \right] \qquad t_c = 0.142 \cdot in$$

Number of wraps based on per layer thickness of composite: $N_w := \frac{t_c}{t_{layer}}$ $\quad N_w = 7 \cdot wraps$

Figure 3 – Western Specialties Composite Thickness Calculator (2/2)

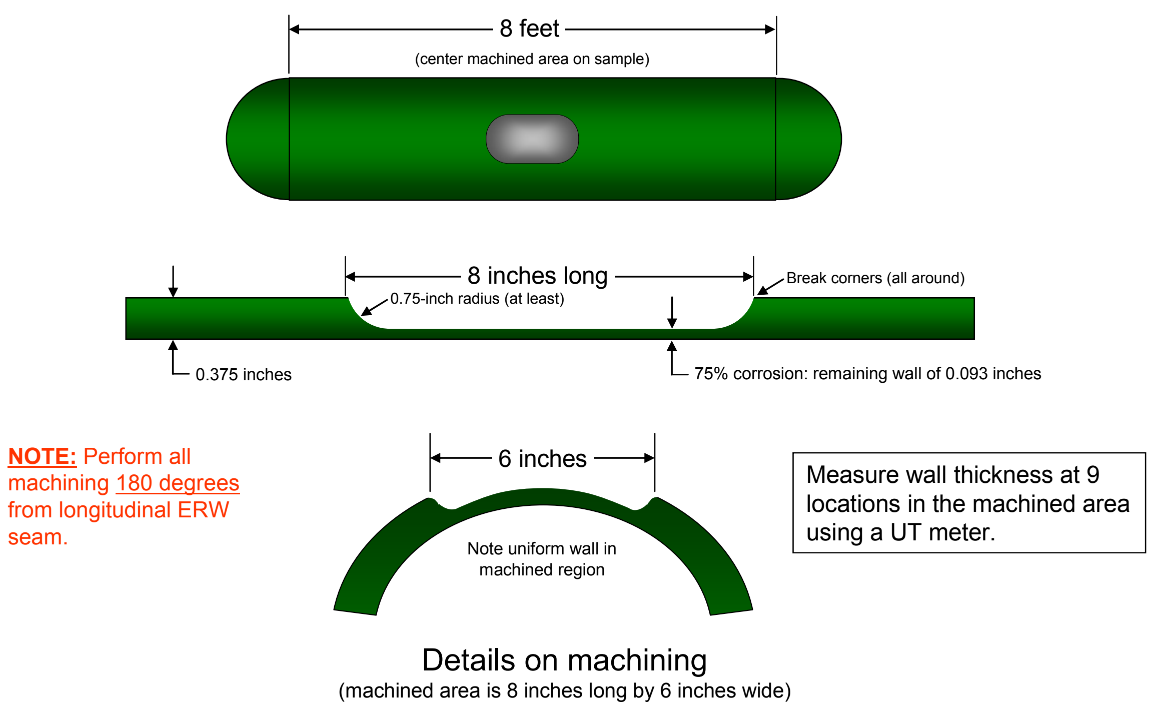

Figure 4 – Schematic of test sample with machined corrosion

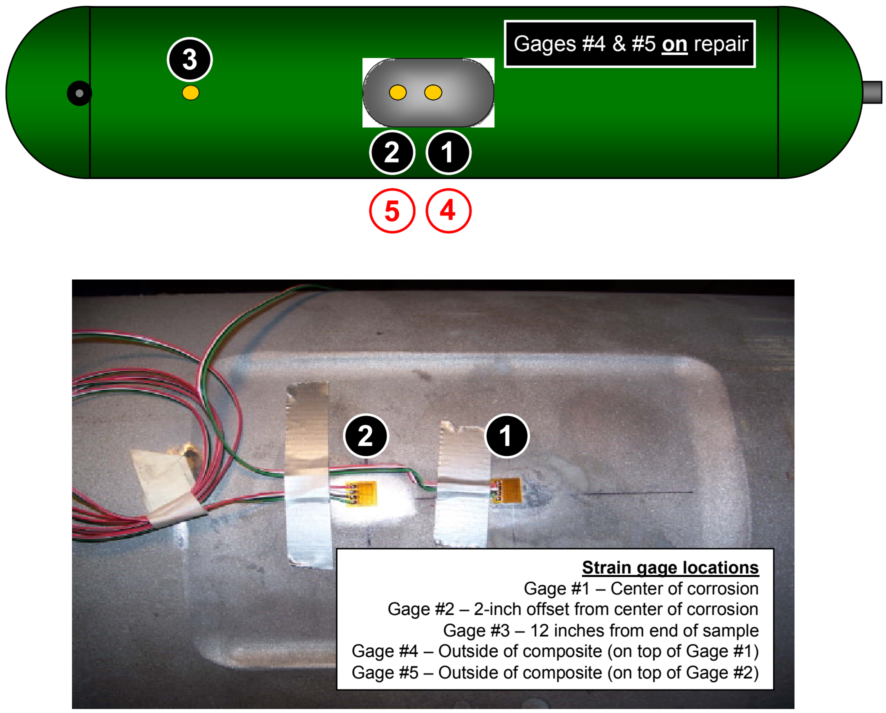

Figure 5 – Schematic showing location of strain gages on corrosion sample

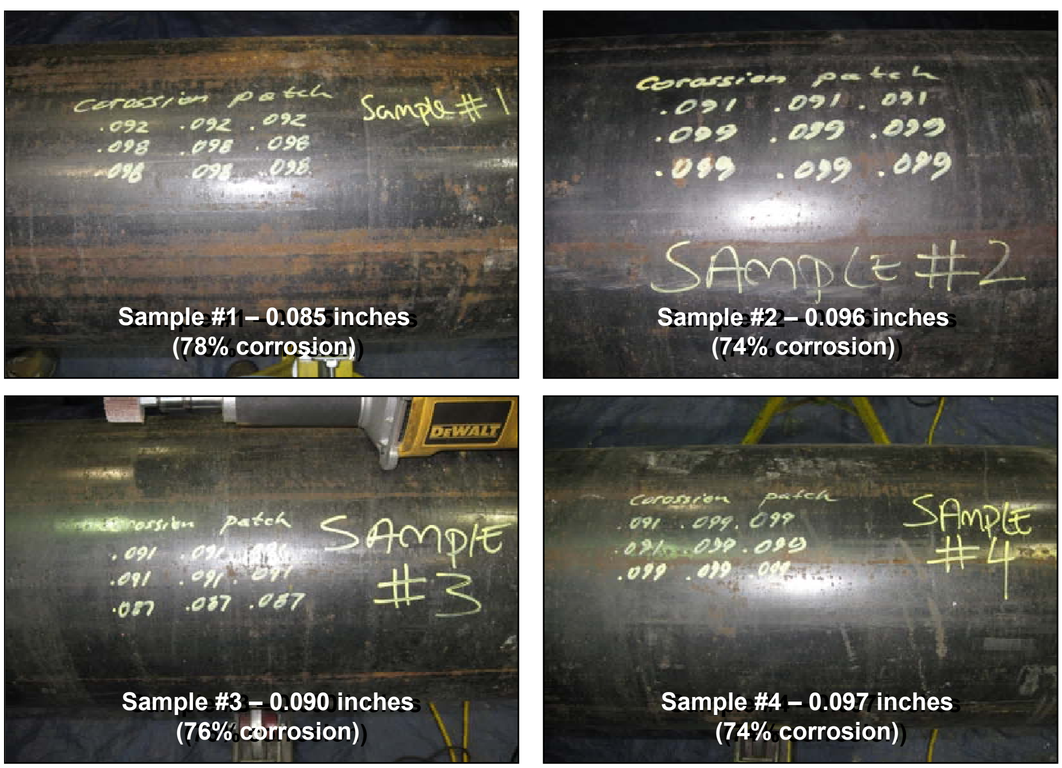

Figure 6– Photographs showing machined corrosion depths

Figure 7 – Photographs of test sample preparation efforts (Set #1)

Figure 8 – Photographs of test sample preparation efforts (Set #2)

Figure 9 – Photographs of test sample preparation efforts (Set #3)

Figure 10 – Photographs of test sample preparation efforts (Set #4)

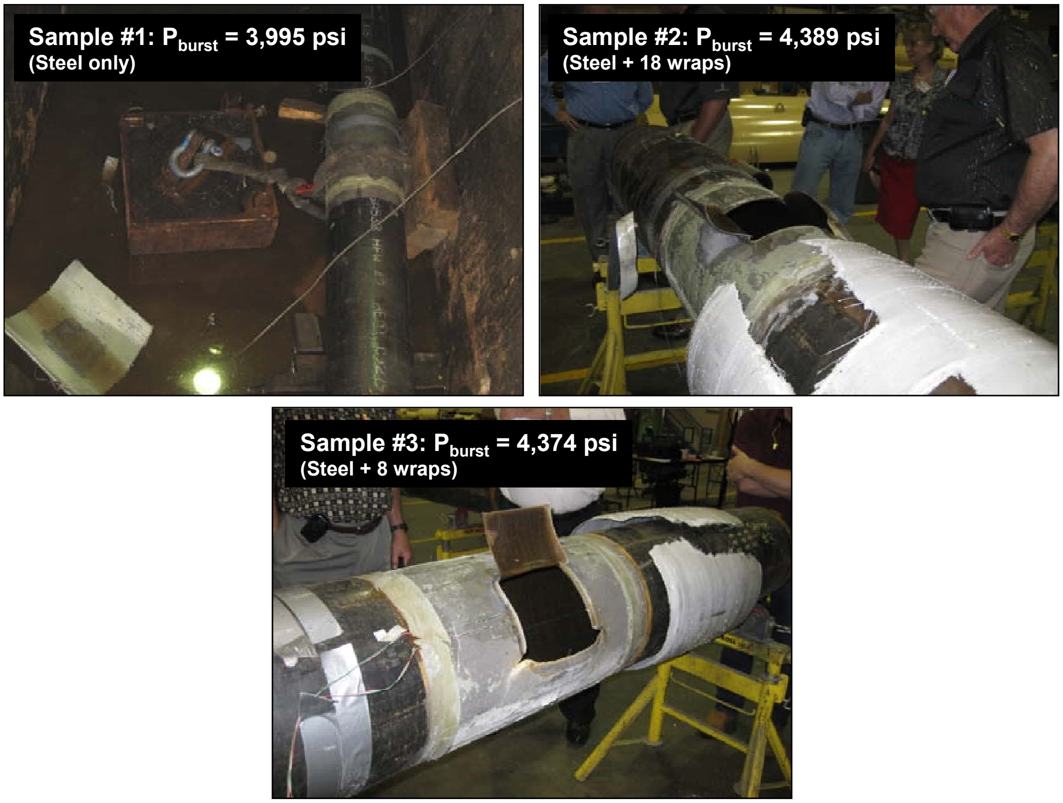

Figure 11 – Photographs of three burst tests

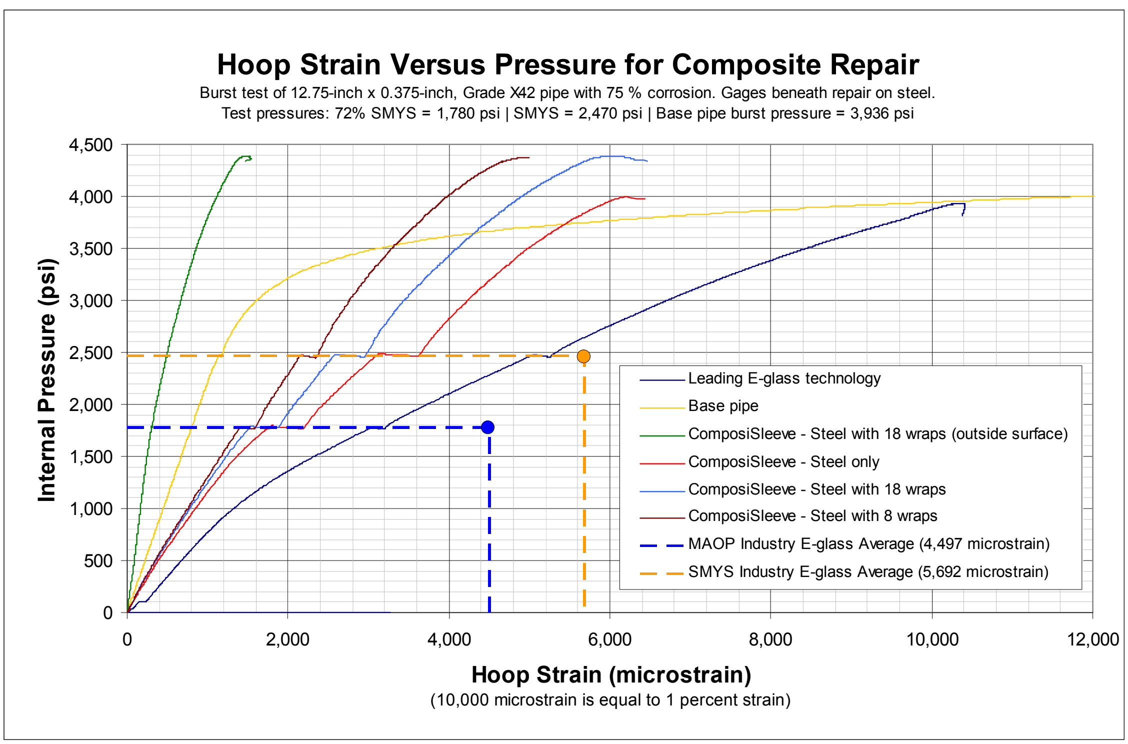

Figure 12 – Hoop strain measured as a function of internal pressure

- Strain at 72% SMYS (design pressure)
  - PRCI average: 4,497 με
  - Steel only: 2,220 με
  - Steel + 8 wraps: 1,610 με
  - Steel + 18 wraps: 1,910 με
- Strain at 100% SMYS (yield pressure)
  - PRCI average: 5,692 με
  - Steel only: 3,630 με
  - Steel + 8 wraps: 2,370 με
  - Steel + 18 wraps: 2,970 με

Data from PRCI Test Program

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

At both the design and yield pressures, the ComposiSleeve™ strain is <u>less than one-half of the industry average</u> for E-glass repair materials when considering the steel + 8 wraps configuration.

Figure 13 – Tabulated hoop strain data acquired during pressure testing

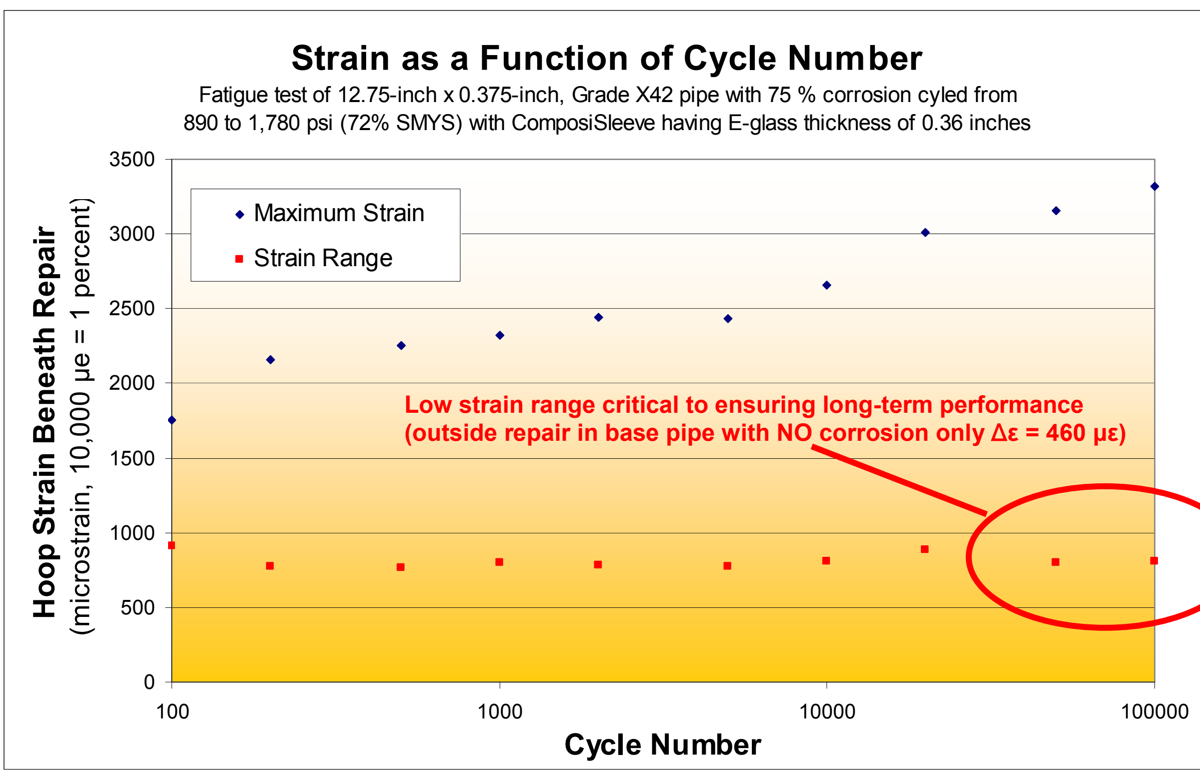

Figure 14 – Strain as a function of cycle number for 75% corroded sample

Cycle Count	Strain Type	H3	A3	H1	A1	H2	A2	H4	A4	H5	A5
		µe	µe	µe	µe	µe	µe	µe	µe	µe	µe
100	Maximum	756	220	1756	168	1664	369	117	24	59	21
	Minimum	9	-11	71	-63	65	21	-1	-10	-12	-24
	Range	383	104	914	53	864	195	58	7	24	-1
200	Maximum	754	214	2163	147	1963	403	118	11	52	4
	Minimum	319	68	1389	39	1250	247	28	-19	-5	-34
	Range	435	146	773	109	713	156	90	29	58	39
500	Maximum	753	222	2252	136	2024	403	115	1	47	-6
	Minimum	312	69	1485	30	1315	246	26	-28	-12	-43
	Range	441	152	768	106	709	157	89	29	59	37
1,000	Maximum	748	217	2319	112	2065	394	113	-10	40	433
	Minimum	300	67	1523	4	1330	232	22	-40	-18	-77
	Range	448	150	797	109	735	162	92	30	58	510
2,000	Maximum	748	219	2445	98	2160	397	125	-10	52	-9
	Minimum	315	68	1661	-13	1436	237	30	-42	-11	-51
	Range	433	151	784	111	723	160	95	32	62	41
5,000	Maximum	751	217	2432	77	2100	373	202	13	146	13
	Minimum	304	64	1660	-30	1388	220	73	-26	52	-38
	Range	447	154	773	106	711	153	129	38	94	52
10,000	Maximum	769	221	2653	84	2304	408	228	23	176	13
	Minimum	324	73	1849	-36	1562	236	108	-11	89	-34
	Range	444	149	805	119	742	171	120	33	88	46
20,000	Maximum	774	228	3010	35	2617	406	246	22	215	-13
	Minimum	320	72	2121	-125	1797	194	107	-14	110	-67
	Range	453	156	889	160	820	212	139	36	105	54
50,000	Maximum	777	227	3159	-54	2690	308	189	-72	167	-38
	Minimum	332	78	2358	-169	1950	143	29	-127	23	-141
	Range	445	149	801	115	740	165	160	55	145	103
100,000	Maximum	740	222	3318	-28	2818	319	158	-60	168	-8
	Minimum	281	51	2508	-139	2070	158	-6	-116	17	-118
	Range	459	171	810	111	748	161	164	56	150	111

Figure 15 – Hoop and axial strain listed as a function of cycle number
(refer Figure 4.2 for location of strain gages)

Percent SMYS	Very Aggressive	Aggressive	Moderate	Light
72	20	4	1	0
65	40	8	2	0
55	100	25	10	0
45	500	125	50	25
35	1000	250	100	50
25	2000	500	200	100
Total	3660	912	363	175
Single equivalent number of cycles with ∆P as noted				
72%	276	67	25	10
36%	3,683	889	337	128

Figure 16 – Service life based on pressure cycle range

S

Figure 17 – Photographs of test sample having a thru-wall defect

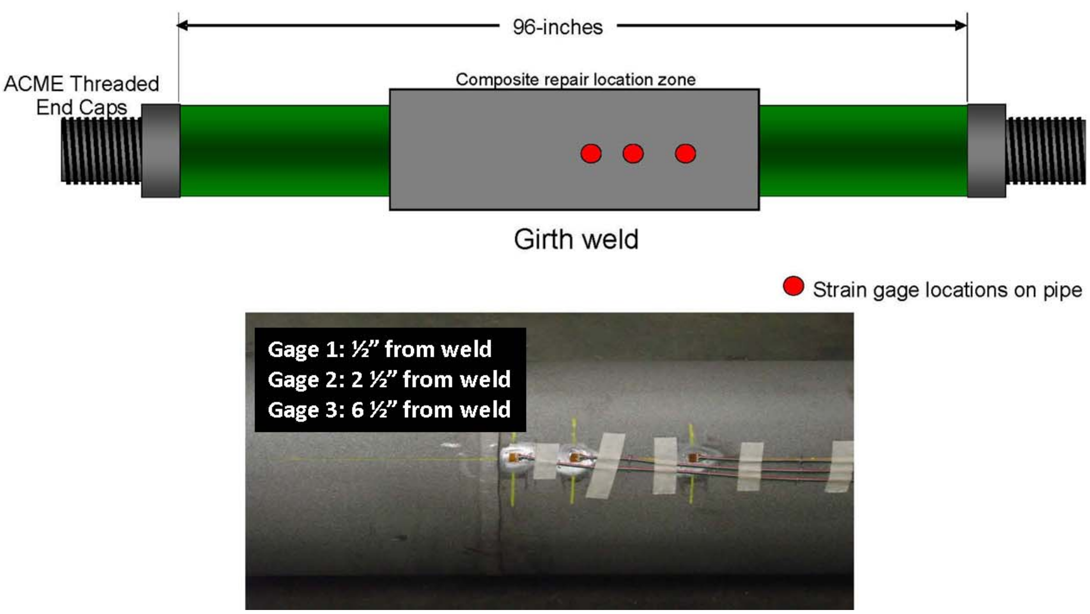

Figure 18 – Geometry for girth weld sample used to measure compressive stress

Table 1 – Summary of stresses measured during compression phase of testing

	Gage	ε Hoop (microstrain)	Hoop (stress)	Eq. Press	Avg Eq. Press
S1	1	-1114	-33,420	-980	-869 (psi)
	2	-1462	-43,860	-1,287	
	3	-385	-11,550	-339	
S2	1	-749	-22,470	-659	-798 (psi)
	2	-1230	-36,900	-1,082	
	3	-741	-22,230	-652	

The Equivalent Pressure (Eq. Pressure) is the internal pipe pressure that would have to be exceeded for hoop stresses in the pipe to go into tension. As a point of reference, 72% SMYS for the 12.75-inch x 0.188-inch, Grade X42 pipe is 890 psi.