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ADVANCED INSIGHTS ON COMPOSITE REPAIRS

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ABSTRACT

In response to inquiries from pipeline operators regarding the long-term performance of composite materials, manufacturers have performed additional tests to evaluate the performance of their composite repair systems. Insights were gained through these additional tests that demonstrated the long-term worthiness of the composite system. Of particular importance were two types of tests. The first involved the application of strain gages between layers of the composite repair system that was used to reinforce a corroded pipe test sample. As the sample was pressurized the strain gages permitted a comparison between the measured values and design stresses per the ASME PCC-2 design code. The second series of tests involved pressure cycling a 75% corroded sample to failure. In addition to the inter-layer strain measurements, the pressure cycling provides an important insight regarding the long-term performance of the composite repair.

This paper addresses how the ASME PCC-2 Code, along with additional well-designed tests, can be used to design a composite repair system to ensure that it adequately reinforces a given defect. As composite materials are being used to repair pipeline anomalies beyond the corrosion-only defects, it is essential that pipeline operators utilize a systematic approach for ensuring the long-term performance of composite repair systems.

INTRODUCTION

This paper provides an evaluation of the A+ Wrap by Pipe Wrap®, LLC (A+ Wrap) composite repair system. The purpose of this paper is to provide information relating to performance testing used to evaluate this particular composite repair system relative to the requirements set forth in the ASME PCC-2 standard, as well as additional tests the authors have identified as important. Of particular interest was completion of the ASME PCC-2 Article 4.1, Mandatory Appendix V Measurement of Performance Test Data Section V-2.1. This test is used to establish the long-term design stress for a composite repair.

The foundation of any effort to evaluate the performance a composite repair system is full-scale destructive testing. This paper provides a technical presentation on three specific aspects of the testing completed on the composite repair system including: (1) ASME PCC-2 qualification tests, (2) Inter-layer strain measurements, and (3) Pressure cycle testing. In addition to the full-scale testing results presented in this paper, material testing was performed. Table 1 lists the required material tests per ASME PCC-2. <u>The aim of this paper is to provide the reader when an understanding of what is required to qualify a composite repair system for repairing corrosion in pipelines.</u> The authors have concluded that using standards such as ASME PCC-2 and ISO 24817 are essential elements of this process, but that additional efforts are required to certify a system for long-term service. The sections that follow provide information on the *Testing Methods and Results*. Also included is a discussion on the similarities and differences between ASME PCC-2 and ISO 24817. A Closing Comments includes several concluding remarks.

TESTING METHODS AND RESULTS

The sections that following provide specific details on the testing efforts conducted on the composite repair system, including the tests required for qualification per the ASME PCC-2 standard. All pressure tests in this paper involve only internal pressure at ambient temperature conditions. No additional external loads are considered.

ASME PCC-2 Qualification Tests

Provided in this section of the paper are results associated with ASME PCC-2 qualification testing, specifically *Appendix II – Spool survival test* and *Appendix V – 1,000-hour tests to establish long-term strength*. The first test is used to verify that without a safety factor, the composite system can reinforce a corroded section of pipe to a pressure level equal to at least the yield pressure of the pipe, while the latter test is used to establish the design strength of the composite material.

<u>Appendix II – Spool survival test</u>

A spool survival burst test was performed on a test sample made from 12.75-inch x 0.375-inch, Grade X42 pipe having machined 75% corrosion. Figure 1 is a schematic diagram showing details on the corroded pipe sample and also includes a photograph of the strain gages installed in the corroded region. The repair thickness was set to a minimum value to meet the test requirements designated in ASME PCC-2. According to ASME PCC-2 Article 4.1, Appendix III, *Short-Term Pipe Spool Survival Test*, the thickness of the composite material is selected to confirm that the repair system can restore the integrity of the damaged region of pipe up to the yield strength of the pipe (using actual measured yield strength values). Details are provided within Appendix III of ASME PCC-2 that designates the maximum thickness of the composite material. Using the tensile strength of the composite material, the calculated thickness for the A+ Wrap material was 14 wraps, or 0.308 inches. The target pressure of 2,935 psi was calculated based on the yield pressure for the undamaged pipe. This reinforced sample withstood and exceeded this target pressure, bursting at 3,658 psi (124.6% of the minimum required target pressure); thus, qualifying the system according to the test specifications.

<u>The spool survival test does not constitute a complete repair.</u> A minimum composite thickness is selected that does not include safety factors to account for issues such as long-term degradation. The fact that a composite material survives a stress level of this magnitude is an indication that the composite material has the strength to meet the minimum requirements of this particular section of the PCC-2 standard.

Appendix V – 1,000-hour tests to establish long-term strength

A critically-important part of any composite repair design involves establishing the long-term strength of the composite material. Because the intent in using composite materials to repair damaged pipelines is to establish long-term performance, it is essential that the design stress of the composite material itself be kept below an appropriate design stress.

Appendix V of Article 4.1 of ASME PCC-2 offers several options for establishing the long-term design strength using full-scale testing. The particular protocol that was selected is the *Survival Testing* as outlined in Section V-2.1 that is provided below:

> *Sections of pipe of minimum diameter 100 mm (4 in.) and minimum thickness of 3 mm (0.12in.) shall be used and the Repair System applied. A value of internal pressure shall be applied (defined by the Repair System supplier) and sustained for 1,000 hr. If any deterioration of the repair laminate in the form of cracking, delamination, or leaking occurs, the Repair System will have failed the test. Three identical tests shall be performed and repair qualification is only possible if all three tests survive.*

A single burst test was conducted prior to the 1,000-hour test program started, while 3 samples were held at a 1,000 hour hold period. A burst test is not a requirement according to ASME PCC-2, but is a worthy exercise to validate the resulting long-term strength of the composite material. The burst test also provided information regarding strain in the reinforced steel pipe as a function of pressure to ensure that a pressure would be selected for the 1,000-hour hold (i.e. would not cause a failure). Listed below are the specific steps involved in this testing program. Listed below are the steps associated with this phase of work.

1. Purchase 12.75-inch x 0.375-inch, Grade X42 pipe (enough to fabricate four (4) 6-ft test samples).
2. Fabricate the four (4) 6-ft test samples by installing end caps on each sample as shown in Figure 4.
3. Calculate the required composite thickness based on the calculations outlined in ASME PCC-2, Appendix V, Section V-2.1.
4. The following test sample configurations to be used in testing:
    a. Sample #1 – **burst test sample** including strain gages mounted on the steel beneath the reinforcement and on the outside surface of the composite (refer to details shown in Figure 4)
    b. Sample #2 – 1,000 hour test sample loaded at P_1
    c. Sample #3 – 1,000 hour test sample loaded at P_1
    d. Sample #4 – 1,000 hour test sample loaded at P_1
5. Apply the calculated composite thickness to the test samples (this was 0.220 inches for A+ Wrap).
6. Perform a burst test on Sample #1 by incrementally increasing the internal pressure in the sample to the point of burst. From the measured strain gage and pressure data the following information will be collected:
    a. Ultimate capacity of reinforced composite test sample.
    b. Actual strain in composite material based on measured strain gage results as a function of internal pressure (not a value postulated on assumed material responses).
    c. Validation of <u>internal pressure</u> for 1,000-hour test samples based on measured strains in composite material and comparison to the equations in Appendix V of PCC-2.
7. Determine the appropriate internal pressure. This pressure is to be applied to three (3) of the prepared 1,000 hour test samples (Samples #2 through #4).

The 1,000-hour burst sample failed at a pressure of 4,791 psi. A test pressure of 3,350 psi was selected for the 1,000 hour test. The three test samples were held at the designated pressure level for 1,069 hours from May 20, 2010 to July 1, 2010. A pressure relief valve was installed in the system to ensure that over-pressurization of the samples did not occur. Using Equation (V-2) from Appendix V generates a composite stress of 20,369 psi. Also noted in these calculations is the composite thickness (t_{repair} in V-2) of 0.220 inches. A thickness greater than this value results in a lower calculated long-term strength; however, reducing the composite thickness increases the calculated long-term strength. <u>The resulting long-term design strength, s_{lt}, was measured to be 20,369 psi.</u>

Full-Scale Burst and Cycle Tests

This section of the paper provides specific details on two experimental studies that were performed on the A+ Wrap system to validate the level of reinforcement provided to a corroded region of pipe. These tests are not explicitly defined in ASME PCC-2, but are useful for evaluating the overall performance of the A+ Wrap material.

- Burst test of 12.75-inch x 0.375-inch, Grade X42 pipe with 75% corrosion (including inter-layer strain measurements).
- Pressure cycle test of 12.75-inch x 0.375-inch, Grade X42 pipe with 75% corrosion from 890 psi to 1,780 psi until failure occurred (36% SMYS stress range)..

A 6-inch wide by 8-inch long corrosion section was machined in the pipe samples for both the burst and pressure cycle tests (cf. Figure 1). After machining was completed the samples were sandblasted to near white metal. Prior to applying the composite repair material, four strain gages were installed on each sample in the following regions.

- Gage #1: Gage installed on the base pipe
- Gage #2: Gage installed at center of the corrosion region
- Gage #3: Gage installed 2 inches from the center of the corrosion region
- Gage #4: Gage installed on the outside surface of the repair

The two strain gages installed in the corroded region (Gages #2 and #3) were required to quantify the level of reinforcement provided by the composite material. Stress Engineering has performed more than 60 burst tests on composite repair systems in the past several years using this test set-up. Additional strain gages were installed on the burst sample. Bi-axial strain gages were installed between the layers of the repair at every fourth layer and secured using epoxy. An additional bi-axial strain gage was installed on the outside surface of the base pipe away from the composite repair, centered between the end cap weld and the repair.

The strain gages monitored during these burst tests indicate whether or not a composite material is performing effectively. When performing properly, composite materials ensure that strains in the damaged section of pipe are restrained and maintained at an acceptable level. The designated level of acceptability is based on the performance requirements; however, for cyclic service it is recommended that strain ranges be less than 0.35 percent (70% of 0.5% strain, where the Specified Minimum Yield Strength is defined as the steel's stress at 0.5% total strain). All repair installation work was performed by the staff of Pipe Wrap, LLC. The sections below provide details on the burst and pressure cycle fatigue test results, respectively.

Figure 2 shows the installation of the composite repair on 75% corrosion burst test sample, while Figure 3 is a photograph of the same sample after pressurization. Note that the failure occurred outside of the repair.

Burst Test Results

The burst sample was pressurized to failure and failed at a pressure level of 4,440 psi. The failure occurred in the base pipe outside of the repair. **T**he strain gage results that were monitored during testing at a rate of 1 scan per second. The strain gage readings in the corroded region of the pipe beneath the repair are compared to the average strain readings from the PRCI long-term study, including the following observations.

- At MAOP (72% SMYS or 1,778 psi) the measured hoop strain was 2,976 microstrain[1]; the average strain for E-glass materials at this pressure level in the PRCI MATR-3-4 long-term study was 4,497 microstrain.
- At 100% SMYS (or 2,470 psi) the measured hoop strain was 6,472 microstrain; the average strain for E-glass materials at this pressure in the MATR-3-4 long-term study was 5,692 microstrain.

As noted previously, the failure in the test sample occurred outside of the repair. The repair involved 36 layers of A+ Wrap (0.76 inches thick). The significance in the failure having occurred outside of the repair is that these results indicate that the repair is at least as strong as the base pipe. Additionally, at the failure pressure the hoop strain in the reinforced corroded region was on the order of 2.5 percent, whereas the strains in the base pipe outside of the repair were in excess of 10 percent (based on the final measured circumference at the failure location of the pipe).

Figure 5 plots hoop stress as a function of layer. The hoop stress in the composite was calculated as the product hoop strain and the elastic modulus of 3.01 million psi. The strain gage installed on the filler material quit working when the internal pressure was 2,097 psi. At MAOP (72% SMYS), the difference in hoop strain between the bottom and top of the filler material was 407 microstrain, and the difference between underneath the filler and the 4th layer was 1,772 microstrain. At SMYS, the difference in hoop strain between underneath the filler material and the 4th layer was 3,736 microstrain. The hoop strain remained relatively constant through the composite (layers 4-28), but diminished toward the outer layer (layers 32 and 36). The average and maximum stresses measured in the composite material us the 72% SMYS design pressure (1,780 psi) were 3,940 psi and 4,806 psi, respectively.

Pressure Cycle Fatigue Test Results

In addition to the burst test, a pressure cycle fatigue test was completed. While the burst test is a good indication of the general reinforcement provided by the composite material, the pressure cycle fatigue test provides a strong indication about long-term performance of the repair. This is especially true when considering the results associated with a 75% corroded sample where there is strong potential for generating large strains in the corroded region of the pipe.

Using the same sample configuration as with the burst sample (both in terms of sample defect geometry and the A+ Wrap repair), the pressure cycle fatigue test was conducted. The repair involved 25 layers of A+ Wrap (0.50 inches thick). During testing the sample was pressure cycled from 890 to 1,780 psi (36 to 72% SMYS). Strain data were recorded using the same 4-gage configuration presented previously. Results from the pressure cycle test are presented in Figure 6. The data shown in this plot were recorded after 7,500 pressure cycles had been applied to the test sample. Figure 7 shows the cross-section of crack under the repair of the pressure cycle fatigue sample after testing had been completed. No crack existed in this machined corrosion region prior to testing. The crack initiation and propagation was the result of the cyclic pressure loading. Had the composite repair not been installed, the machined corrosion region would have failed on the first pressure cycle (previous testing of an unrepaired 75% corrosion sample failed at 1,574 psi)

Table 2 is provided to shows the maximum, minimum, range (i.e. delta = maximum – minimum), and mean strain values recorded at 7,500 cycles. These data are a summary of the results plotted in Figure 5. Note the following in relation to the specific strain gage results (cf. Figure 2 for gage locations):

- Gage #1: The strain range on the base pipe was 360 microstrain (stress of 10,800 psi)
- Gage #2: The strain range on the corroded pipe beneath the repair was 900 microstrain (stress of 27,000 psi)
- Gage #4: The strain range on the outside of the composite repair was 339 microstrain (an estimated stress of 1,000 psi assuming a composite modulus of 3.01 Msi)

A crack developed in the machined simulated corrosion region beneath the repair after **140,164 equivalent cycles** with a pressure range of 36% SMYS had been applied.

A summary of all pressure tests presented in this paper is provided in Table 3. Included in this table are data for the spool survival test, 1,000-hour burst test, and results for the burst and pressure cycle fatigue test samples where a 75% deep corrosion was repaired.

Comparison of ASME PCC-2 and ISO 24817

One of the questions that is often posed to composite manufacturers concerns the differences in the design and testing requirements designated in the two internationally-recognized composite repair standards, ASME PCC-2 Article 4.1 and ISO 24817. The intent of both of these documents is to provide for industry a common reference for properly designing composite repair systems for pressurized equipment.

The ASME PCC-2 2011 Article 4.1 and ISO 24817 documents are essentially equivalent in all major aspects of design, even though there are several subtle differences. For example, ISO 24817 presents more discrete design lives ranging from 2 to 20 years, while ASME PCC-2 2011 Article 4.1 only defines a 20 year design condition. The minimal differences between the two standards do not affect their equivalency for most repair applications. For most long-term applications the resulting composite repair designs will be the same, although ISO 24817 provides a wider range of options in terms of design life, thus providing greater flexibility with regards to performance life.

[1] Note that 10,000 microstrain corresponds to 1 percent strain. As a point of reference, per API 5L, *Specification for Line Pipe,* yield strength is defined at 0.5% strain (or 5,000 microstrain).

CLOSING COMMENTS

This paper has provided details on testing performed to evaluate the A+ Wrap composite repair system. The purpose of this paper is to present information relating to the performance of this composite repair system in relation to the criteria set forth in the ASME PCC-2, including the designation of long-term design strength and the minimum composite thickness. Of particular interest to operators is verifying that the repair system is properly-designed to ensure long-term service. Specifically, this involves calculating the required minimum composite thickness for repairing a particular corrosion defect. A+ Wrap is designed such that a safety factor of 4.1 is imposed on the lower bound short-term strength of 41,398 psi (or a safety factor of 5.1 on the mean short-term strength of 51,700 psi). When considering that the maximum stress in the composite material was measured to be 4,806 psi, a safety factor of 8.61 is calculated in relation to the lower bound short-term strength of 41,398 psi. As noted previously, these safety factors are greater than safety factors employed in other industry sectors using composite materials. This is necessary as pipelines are buried, are subjected to sustained pressure loads, and are often subject to harsh operating conditions.

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 Pipe Wrap, LLC, *ASME PCC-2 & ISO 24817 Certification Document for the A+ Wrap System*, Houston, Texas, June 2011.

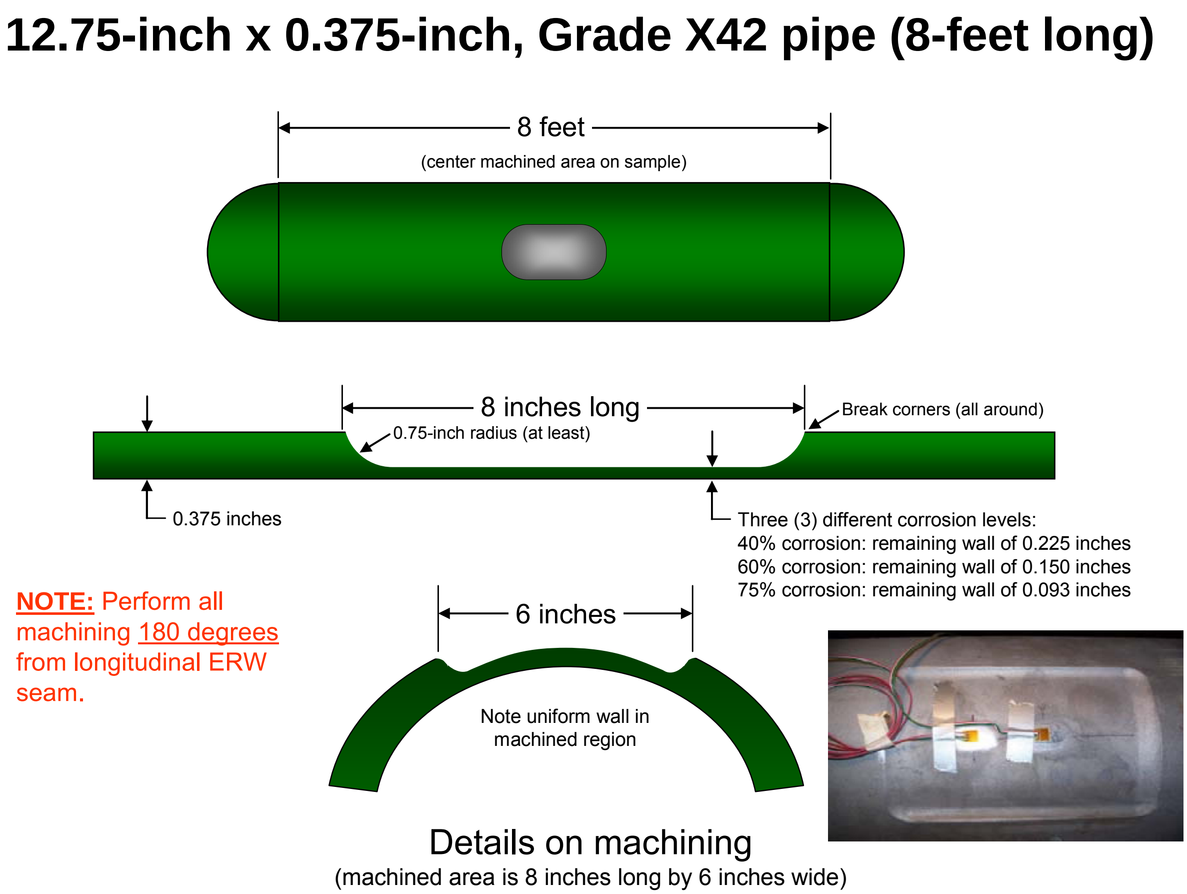

Figure 1 – Schematic diagram showing details on the corroded pipe sample
(75% corrosion sample used in all testing reported herein)

Figure 2 – Installation of composite repair on 75% corrosion burst test sample

Figure 3 – Photograph of failure in 75% corrosion burst test sample

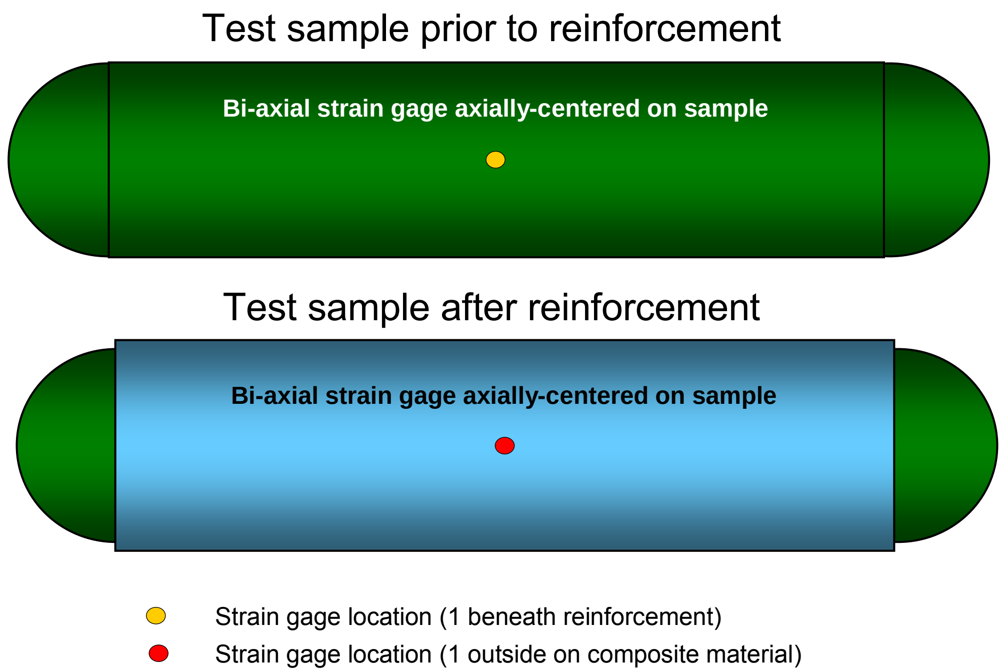

Figure 4 – Schematic of the ASME PCC-2 1,000 hour pressure test samples

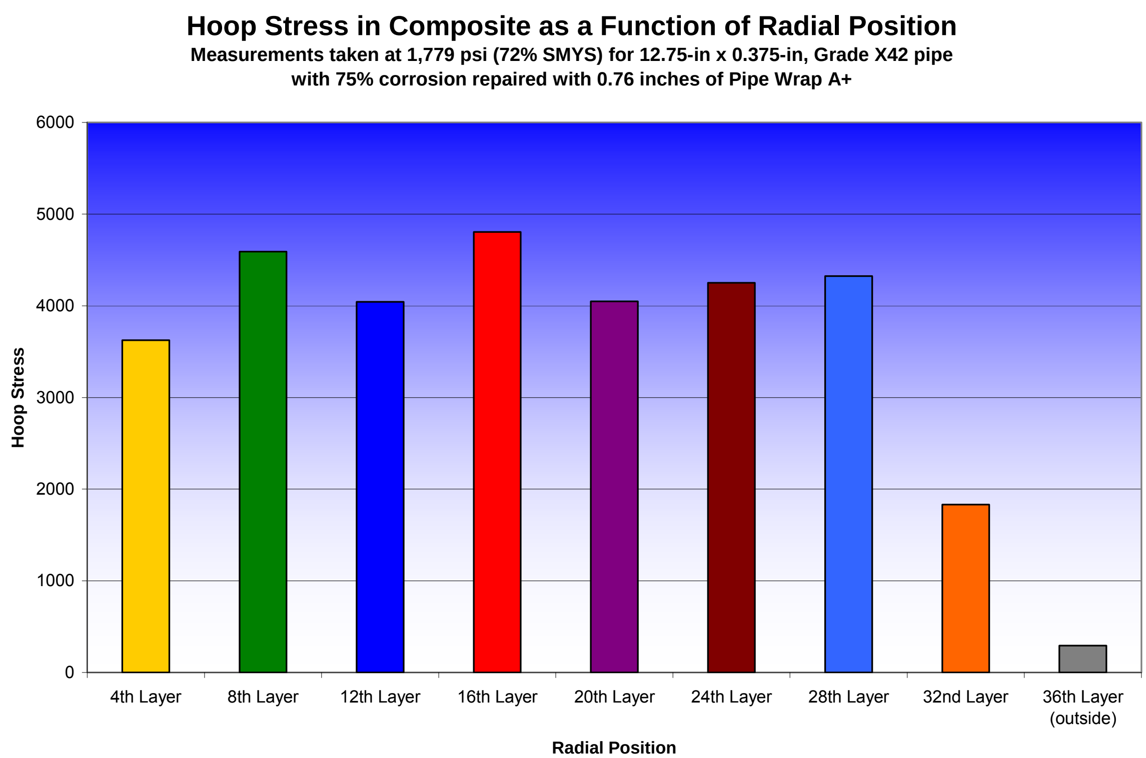

Figure 5 – Hoop Stress* in Composite as a Function of Radial Position
(Hoop stress calculated as the product hoop strain and the elastic modulus of 3.01 million psi)

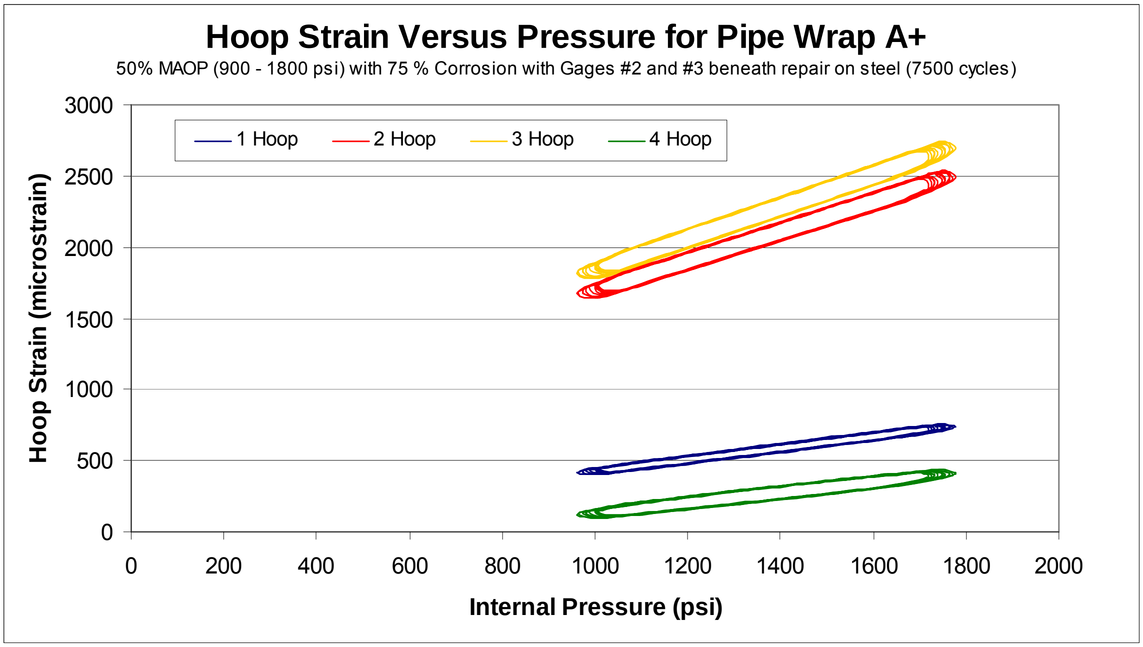

Figure 6 – Strain measurements during pressure cycling 75% corrosion sample
(Gage #1 on base pipe outside of repair | Gages #2 and #3 in corroded region beneath repair | Gage #4 on repair)

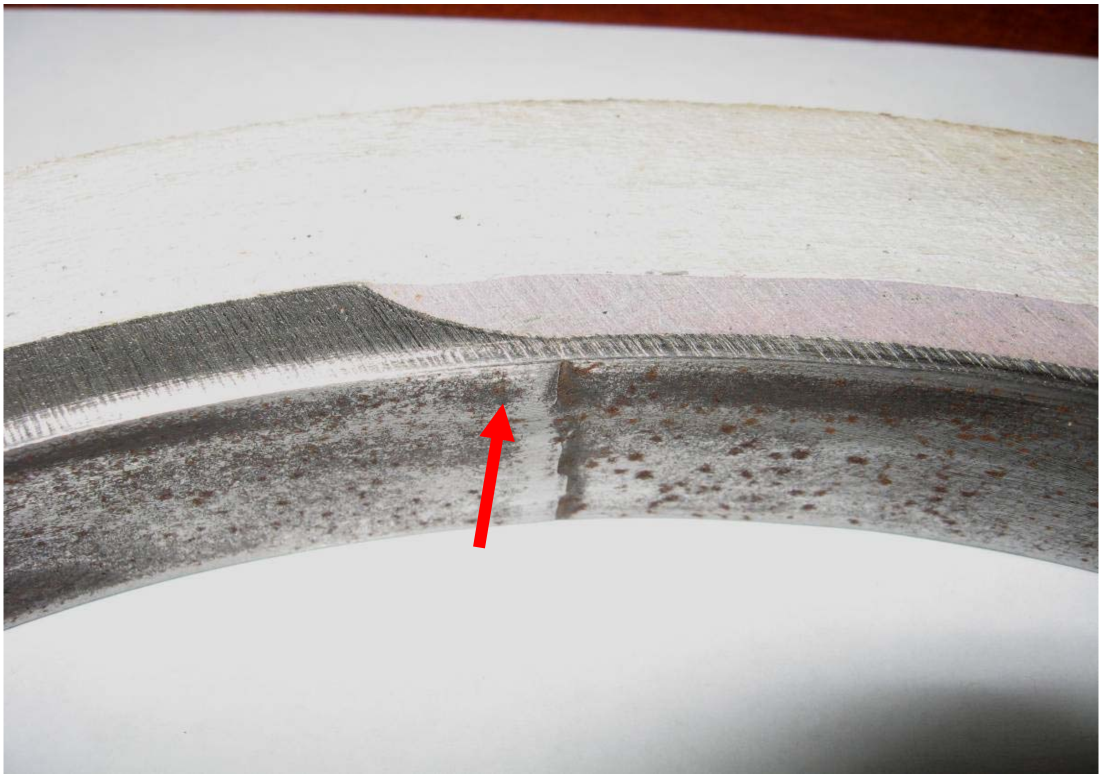

Figure 7 – Cross-section of crack under repair
(**RED** arrow shows location of longitudinally-oriented crack on inside surface of pipe ring)

Table 1 – Material Test Results for ASME PCC-2

Test Number (Table B2)	Status	Description of Test	Test Results
1	Required	Tensile strength	**Circumferential Orientation** Mean Values: S = 51,700 psi E = 3.01 x 10^6 psi ε = 1.72 percent Lower Bound Values (95% conf.): S = 41,398 psi E =2.8 x 10^6 psi ε = 1.48 percent **Longitudinal Orientation** Mean Values: S = 19,876 psi Lower Bound Values (95% conf.): S = 15,349 psi
2	Optional	In Plane Shear Modulus	Avg G = 185,400 psi
3	Required	Thickness per ply	.021 inches thick per layer
4	Required	Shore D Hardness	72-76
5	Required	Coefficient of Thermal Expansion	5.08-7.6 x 10^{-6} per °F (Axial)
6	Optional	Glass Transition Temperature	Tg = 149°F (65°C)
7	Required	Heat distortion temperature	N/A
8	Required	Adhesive shear strength (composite bond to steel)	1,487 psi (Average of 23 samples)
12	Required	Appendix III Spool Survival Test	3,658 psi (2,935 psi req'd test pressure)
13	Optional	Appendix V (1,000 hour test)	***Long-term design strength*** s_{lt} = 20,369 psi (based on three (3) 1,000 hour tests)
14	Optional	Cathodic disbondment	**Diameter value:** Epoxy only 7.3 mmr Epoxy / Pipe Wrap 4.3 mmr (ASTM G95-87)

Table 2 – Strain gage measurements made during pressure cycling

Strain Gage Results at 7,500 cycles (ΔP = 900 to 1,800 psi)								
	Hoop #1	**Axial #1**	**Hoop #2**	**Axial #2**	**Hoop #3**	**Axial #3**	**Hoop #4**	**Axial #4**
Max	761	219	2544	633	2745	496	435	441
Min	401	117	1644	414	1784	340	97	163
Delta	**360**	102	**900**	219	961	157	**339**	278
Mean	**576**	167	**2080**	520	2251	416	**267**	302

Table 3 – Summary of Pipe Sample Pressure Test Results

Sample Type	Failure Description	Notes
Spool survival test (ASME PCC-2, Article 4.1, Appendix II)	Failure at 3,685 psi	Failure in repair (as expected); exceeded the required pressure of 2,935 psi.
1,000 hour (ASME PCC-2, Article 4.1, Appendix V)	Burst at 4,791 psi	Composite-reinforced steel pipe. Three non-burst samples were held at 3,350 psi for 1,000 hours.
75% Corrosion Burst Test	Burst at 4,440 psi	Failure outside of repair (Fig. 3).
75% Corrosion Fatigue Test	Leak at 140,164 cycles	Failed by leak (ΔP = 36% SMYS, 890 – 1,780 psi).