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DEVELOPMENT OF INDUSTRY STANDARDS FOR COMPOSITE REPAIR SYSTEMS

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ABSTRACT

A significant amount of work has transpired over the past several years in generating consensus-based standards that include ASME PCC-2 and ISO 24817 for developing composite repair systems. The intent in developing these standards has been to provide industry with guidelines for designing composite repair systems to ensure that damaged pipelines and piping systems are safely and properly reinforced. With the numerous composite repair systems currently available to pipeline operators, the importance of evaluating the capabilities of each system cannot be overstated. The fundamental design variables available to manufacturers are stiffness, strength, and thickness of the composite. A properly-designed repair system ensures that strains in the reinforced steel and reinforcing composite material do not reach unacceptable levels. This paper provides a basic overview of the design philosophy embedded into the current design codes, as well as presenting results associated with several specific studies that were conducted to evaluate composite repair performance.

INTRODUCTION

Provided below are the Scope and Applicability sections from Part 4 (*Nonmetallic and Bonded Repairs*) of the 2008 edition of the ASME PCC-2 standard

> **1.1 Scope** This Article provides the requirements for the repair of pipework and pipelines using a qualified Repair System. The Repair System is defined as the combination of the following elements for which qualification testing has been completed.
> (a) substrate (pipe)
> (b) surface preparation
> (c) composite material (repair laminate)
> (d) filler material
> (e) adhesive
> (f) application method
> (g) curing protocol
>
> The composite materials allowed for the Repair System include, but are not limited to, glass, aramid, or carbon fiber reinforcement in a thermoset polymer (e.g. polyester, polyurethane, phenolic, vinyl ester, or epoxy) matrix. Fibers shall be continuous.
>
> **1.2 Applicability** This Article addresses the repair of pipework and pipelines originally designed in accordance with a variety of pipe standards, including ASME B31.1/B31.3/B31.4/B31.8, and ISO 15649 and 13623.

The *Applicability* section goes onto state that the Code covers situations involving damage that include internal and external corrosion, external damage such as dents, gouges, and cracks, as well as manufacturing defects. The repair of leaks is also permitted, although for high pressure transmission pipelines this repair option is unacceptable at the present time based on the authors' opinion and current standards. Because the focus of this article is repairing high pressure gas and liquid transmission pipelines, there is no discussion on the repair of leaking pipes.

The function of the Codes is design and within ASME PCC-2 there are three basic approaches for determining the minimum required thickness for a particular composite material in repairing corrosion and are listed below.

- Section 3.4.3 Pipe Allowable Stress
- Section 3.4.4 Repair Laminate Allowable Strains
- Section 3.4.5 Repair Laminate Allowable Stresses Determined by Performance Testing

The contents of this paper should not be used as a substitute for actually consulting and utilizing the composite repair design codes (i.e. ASME PCC-2 and ISO 24817). These design codes provide details that deal with specific issues when using composite materials in repairing and reinforcing damaged pipelines that should not be ignored.

The sections that follow provide details on the background of the current industry standards. A detailed discussion is also provided on determining the appropriate composite thickness using options available in the ASME PCC-2 standard. Lastly, two case studies are provided demonstrating how composite materials can effectively repair damaged pipelines.

INDUSTRY STANDARDS

For much of the time period during which composite materials have been used to repair pipelines, industry has been without a unified standard for evaluating the design of composite repair systems. Under the technical leadership of technical leaders from around the world, several industry standards were developed that include ASME PCC-2 and ISO 24817 (hereafter referred to as the *Composite Standards*). Interested readers are encouraged to consult these standards for specific details; however, listed below are some of the more noteworthy contributions these standards are providing to the pipeline industry.

- The Composite Standards provide a unifying set of design equations based on strength of materials. Using these equations, a manufacturer can design a repair system so that a minimum laminate thickness is applied for a given defect. The standards dictate that for more severe defects greater reinforcement from the composite material is required.
- The most fundamental characteristic of the composite material is the strength of the composite itself. The Composite Standards

specify minimum tensile strength for the material of choice based on maximum acceptable stress or strain levels.

- Long-term performance of the composite material is central to the design of the repair systems based on the requirements set forth in the Composite Standards. To account for long-term performance safety factors are imposed on the composite material that essentially require a thicker repair laminate than if no degradation was assumed..
- One of the most important features of the Composite Standards is the organization and listing of ASTM tests required for material qualification of the composite (i.e. matrix and fibers), filler materials, and adhesive. Listed below are several of the ASTM tests listed in ASME PCC-2 (note that there are also equivalent ISO material qualification tests not listed here).
    - Tensile Strength: ASTM D 3039
    - Hardness (Barcol or Shore hardness): ASTM D 2583
    - Coefficient of thermal expansion: ASTM E 831
    - Glass transition temperature: ASTM D 831, ASTM E 1640, ASTM E 6604
    - Adhesion strength: ASTM D 3165
    - Long term strength (optional): ASTM D 2922
    - Cathodic disbondment: ASTM-G 8

With the development of standards for composite repairs, industry can evaluate the performance of competing repair systems based on a set of known conditions. It is anticipated that the Composite Standards will either be accepted in-part or in-whole by the transmission pipeline design codes such as ASME B31.4 (liquid) and ASME B31.8 (gas).

DETERMINING COMPOSITE REPAIR THICKNESS

The sections that follow provide specific details on the above referenced ASME PCC-2 sections and their unique design approaches. An example problem is also provided to demonstrate the level of conservatism associated with each calculation method and the benefits in designing a performance-based system as detailed in Section 3.4.5, even though additional efforts and costs are associated in qualifying a given composite system to this level. Due to limited space in this article, all calculations assume structural contribution of the remaining corroded steel, although the option for not including this contribution is an alternative provided by the Codes that results in a greater required minimum composite thickness.

The following ASME PCC-2 nomenclature (i.e. variable descriptions) is used in the calculations that follow.

D	External pipe diameter (inches)
E_c	Tensile modulus for the composite laminate in the circumferential direction (psi)
E_s	Tensile modulus for the pipe steel (psi)
f	Service factor (inverse of safety factor, provided in ASME PCC-2 Table 5)
P	Internal design pressure (psi)
P_s	Maximum Allowable Working Pressure (MAWP) for corroded pipe using B31G, etc.
s	Specified Minimum Yield Strength (SMYS) for pipe (psi)
s_{lt}	95% lower confidence limit of the long-term composite strength via testing (psi)
t	Nominal wall thickness of pipe (inches)
t_{min}	Minimum repair thickness of composite (inches)
t_s	Minimum remaining wall thickness of pipe (inches)
ε_c	Allowable circumferential strain

Laminate Thickness Based on Pipe Allowable Stress (ASME PCC-2 Section 3.4.3)

The first design option that is provided in ASME PCC-2 is the most conservative of the three options presented in this article. Equation 3 from ASME PCC-2 is used to calculate the minimum required thickness considering hoop stresses based on internal pressure. Note that by including the P_s term credit is taken for strength associated with the remaining steel.

$$t_{min} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c} \right) \cdot \left(P - P_s \right) \qquad \text{(ASME PCC-2 Equation 3)}$$

In reviewing Equation 1 is it clear that the relative stiffness values of the steel (E_s) and the composite (E_c) are integrated to calculate the minimum required thickness. The use of this equation assumes that the substrate (e.g. remaining reinforced pipe material) does not yield and remains elastic throughout operation.

Laminate Thickness Based on Allowable Strains (ASME PCC-2 Section 3.4.4)

The next design option that is available in PCC-2 is calculating the minimum composite thickness based on hoop strain due to internal pressure using Equation 6 from PCC-2. Also included in PCC-2 is Equation 5 that integrates the effects of internal pressure in the pipe at the time of the composite installation, although this equation is not presented in this article.

$$t_{min} = \frac{1}{\varepsilon_c E_c} \left(\frac{P D}{2} - s t_s \right) \qquad \text{(ASME PCC-2 Equation 6)}$$

In solving Equation 6 the designation of an allowable long-term strain, ε_c, is required. Table 4 from ASME PCC-2 specifies that for continuous (sustained) loading conditions the allowable long-term strain for the repair laminate is limited to 0.25%, while for rarely occurring loads it is 0.40%.

Laminate Thickness Based on Allowable Stresses Determined by Performance Testing (ASME PCC-2 Section 3.4.5)

The minimum required composite thickness using the ASME PCC-2 Section 3.4.5 method is based on performance testing of the composite material itself. This approach requires additional testing on the composite material beyond what is required for the other calculation methods, such as the 1,000 hour survival test as presented in Section V-2.1 in Appendix V of ASME PCC-2 based on the methods of ASTM D 1598. In this particular test internal pressure is applied to a test sample having a minimum diameter of 4 inches and a minimum thickness of 0.120 inches. The sample's internal pressure and composite laminate thickness are selected to maximize the long-term composite stress, s_{lt}, using the equation below.

$$s_{lt} = \frac{P_{test} D E_c}{2(E_c t_{min} + E_s t_s)} \qquad \text{(ASME PCC-2 Equation V-1)}$$

In this qualification test three identical test samples must be repaired and survive 1,000 hours of testing at the designated pressure level with no deterioration of the laminate in the form of cracking, delamination, or leaking. An alternative equation (V-2) is also provided in Appendix V for test samples where yielding of the substrate steel occurs.

Once the long-term composite design strength is established based on the 95% lower confidence limit, the minimum composite repair thickness is calculated using Equation 11 from ASME PCC-2. In reviewing this equation, the use of a service factor, *f*, is required. The service factors are basically the reciprocals of safety factors and are listed in Table 4 of ASME PCC-2. If one opts to establish long-term laminate strength using the 1,000 hour data, the service factor, *f*, is 0.5 (i.e. safety factor of 2.0 for the composite material's strength).

$$t_{min} = \left(\frac{P\,D}{2} - t_s s\right)\cdot\left(\frac{1}{f\,s_{lt}}\right) \qquad \text{(ASME PCC-2 Equation 11)}$$

Calculating Composite Thickness Using ASME PCC-2

Table 1 provides calculations associated with the reinforcement of a 12.75-inch x 0.375-inch, Grade X42 pipeline having 50% corrosion where the MAOP would require a de-rating from 1,778 psi to a MAWP of 1,000 psi in the absence of a repair solution. Presented are results for all three calculation methods discussed previously (i.e. pipe allowable stress, repair laminate allowable strains, and repair laminate allowable stresses determined by performance testing). It should be noted that the contribution of the remaining steel is considered in all provided calculations.

An extremely important observation in reviewing the calculated results provided in Table 1 is the reduction in the minimum required laminate repair thickness associated with the three calculation options. It is clear from this presentation that with the inclusion of the long-term data as required for using Equation (9), a less conservative composite thickness results due to the greater effort undertaken in determining the actual long-term strength.

CASE STUDIES

One of the consistent elements associated with the development and qualification of composite repair systems has been experimental evaluation. This evaluation has involved assessments at both the coupon and full-scale levels. Evaluating material performance at the coupon level is an effective means for determining the strength of the composite, while at the same time being less expensive than full-scale testing. The primary emphasis in the Codes up to this point in time has been in designing composite repair systems to reinforce corrosion; however, there is also an abundance of data demonstrating that composite materials can be used to reinforce wrinkle bends, elbows, field branch connections, dents, and others anomalies. Results from several prior studies have been presented in the previous articles associated with this series.

Two case studies are presented that deal specifically with the reinforcement of corrosion using composite materials. The first case study involves the repair of an 8-inch nominal diameter pipeline with 50% corrosion that was reinforced using a carbon-epoxy system. During testing strain gages monitored strain in the reinforced steel region and were used to demonstrate the level of reinforcement provided by the composite material. The second case study discusses results associated with a testing program used to evaluate the capacity for a carbon-epoxy system to reinforce 75% corrosion in a 12-inch nominal diameter pipeline subjected to cyclic pressures.

Case Study #1 – Burst Testing a Composite-reinforced Corroded Pipe

In 2006 a program was conducted for the U.S. Minerals Management Service to evaluate the use of composite material in repairing offshore risers. Part of this study involved repairing a burst test sample having 50% corrosion using a 0.60-inch thick carbon-epoxy system that included two pre-cured half-shells. Strain gages were installed in the corroded region of the 8.625-inch x 0.406-inch, Grade X46 pipe sample and monitored during pressurization to failure. Results from this test are provided in Figure 1. Included in this plot are a few annotations that designate the lower bound collapse load (5,975 psi) from which the design pressure (2,988 psi) is calculated. This design pressure exceeds the maximum allowable operating pressure of 2,887 psi of a non-corroded pipe. The results of this program demonstrated that the carbon repair was effective in reinforcing the corroded pipe and ensured that strains in the reinforced steel did not reach an unacceptable level. This study is classified as one based on strain-based design limits.

Case Study #2 – Pressure Cycle Testing a Composite-reinforced Corroded Pipe

Most of the experimental research associated with the composite repair of corroded pipelines has focused on burst tests. The general philosophy has been that in the absence of cyclic pressures during actual operation, there are few reasons to be concerned with qualifying composite repairs for cyclic conditions. One could argue that only liquid transmission pipelines need to be concerned about cyclic pressures. However, recent studies have indicated that for severe corrosion levels (on the order of 75%) there is a need to take a closer look at the ability of the composite to provide reinforcement. The case study presented herein was actually preceded by a series of tests using E-glass materials that evaluated the number of pressure cycles to failure in reinforcing 75% corrosion in a 12.75-inch x 0.375-inch, Grade X42 pipeline. Figure 2 is a schematic showing the geometry of the test sample used in this study, while Figure 3 shows the positioning of strain gages beneath each repair in the corroded region. The test samples were pressure cycled at a pressure range of 36% SMYS (i.e. 894 psi for this pipe).

Tests were performed on six different composite systems that included the following cycles to failure.

- E-glass system: 19,411 cycles to failure
- E-glass system: 32,848 cycles to failure
- E-glass system: 140,164 cycles to failure
- E-glass system: 165,127 cycles to failure
- E-glass system: 259,357 cycles to failure
- Carbon system: 532,776 cycles to failure

Minimal information is provided with the above data (e.g. no information provided on thickness, composite modulus, filler materials, fiber orientation, etc.). However, one can definitely conclude that all composite repair systems are not equal. The study on the carbon composite system having four different pipe samples was specifically conducted by a manufacturer to determine the optimum design conditions for reinforcing the severely corroded pipe. Figure 4 shows the strains recorded in the four carbon-reinforced test samples. What is noted in this plot is that the lowest recorded mean strains occur in Pipe #4, which also corresponds to the test sample that had the largest number of cycles to failure.

JOINT INDUSTRY TEST PROGRAMS

In addition to the critical role that industry standards, several industry-sponsored programs have been organized to demonstrate and evaluate how composite materials can be used to effectively restore integrity to damaged pipelines. The sections that follow provide details on two of these programs that include a study to evaluate the long-term performance of composite materials and a program to evaluate the use of composites in repairing dented pipelines.

Long-term Performance Study

Unlike steel where material properties are not time-dependant (at room temperature conditions), composite materials are subject to creep-rupture; meaning that their long-term strength is affected by exposure over time to sustained loads. Environmental effects such as exposure to moisture, elevated temperatures, coupled with acidic and alkaline soil conditions are additional concerns. With all of this, any design involving composite materials must make some consideration of long-term performance. One option is to ensure that stresses generated during operation do not exceed a specified percentage of the material's short-term failure strength. As an example, consider ASME STP-PT-005 2006 *Design Factor Guidelines for High-Pressure Composite Hydrogen Tanks* that specifies that for a 15-year design life the composite not be loaded beyond 40% of its short-term failure strength (based on the lower bound ASTM D2992 value) for carbon fiber materials.

To address the long-term performance of composite materials in reinforcing corroded pipelines, a program is currently underway. The program is being co-sponsored by the Pipeline Research Council International and the 13 composite repair manufacturers that are listed below.

- 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 XHab (10 years)

This particular program is the first of its kind and involves 144 12.75-inch x 0.375-inch, Grade X42 test samples with machined corrosion (depths of 40, 60, and 75% of the pipe's nominal wall thickness). The samples are held at a constant pressure of 36% SMYS and cycled periodically from 36% to 72% SMYS (e.g. 900 annual cycles plus 4 blowdowns to 0 psi). At designated periods of time (1, 2, and 3 years) test samples will be removed from the ground and burst tested. Tests were also conducted on a set of 36 samples prior to burial to serve as a baseline data set. Four manufacturers (refer to list above) have also elected to leave test samples in the ground for 10 years and additional burst testing will be conducted at 5, 7.5, and 10 years. Additionally, strain gages were installed in the corroded regions beneath the repairs and are used to quantify the level of reinforcement provided by each composite repair system during the designated pressure cycle periods. The Year 0 burst tests were completed in December 2008 and the test samples that have been buried are currently under pressure during the first year of the study. Interested readers are encouraged to find additional details on the program's website at www.compositerepairstudy.com. Refer to Figures 2 and 3 that show the machining required for the test samples and a photograph showing the location of strain gages installed in the corroded region of each test sample. Several photographs showing the burial of the test sample are provided in Figure 5.

Repair of Pipeline Dents

Early work in evaluating the repair of dents containing gouges (i.e. mechanical damage) was sponsored by the Gas Research Institute (GRI) in evaluating the Clock Spring repair system. This program was started in 1994 and over the past 15 years the following systems have been evaluated in terms of their ability to reinforce mechanical damage using the same basic test matrix originally conducted by GRI.

- Armor Plate Pipe Wrap (Armor Plate, Inc.)
- Aquawrap (Air Logistics)
- Pipe Wrap A+ (Pipe Wrap, LLC)
- Black Diamond HP (Citadel Technologies)
- I-Wrap (EMS Group)

The essential elements of the mechanical damage test programs conducted in evaluating the above six repair systems involved the following elements.

- Pipe test samples were damaged by installing gouges that were 15% of the pipe's nominal wall thickness and dent depths that were 15% of the pipe's outside diameter.
- A 6-inch long flat bar was used to generate the dents, while the gouges were installed by machining (prior to denting) using a shape similar to a Charpy V-notch with a 0.002-inch radius notch.
- After the dents were installed, an internal pressure equal to 36% SMYS was applied to generate microcracking at the base of the gouge.
- For those samples repaired using composite materials, the gouges were removed by grinding. Either dye penetrant or magnetic particle inspection techniques were used to make sure that all of the cracks were removed.
- The composite repair materials were installed on the designated test samples. The thickness was based on the manufacturer's recommendations.
- The test samples were pressure cycled to failure using an equivalent pressure range equal to 36% SMYS.

Figure 6 plots the cycles to failure for test samples that include the three following defect configurations: (1) No repair, (2) Repaired by grinding, and (3) Repaired by grinding with composite materials. The following observations are made in reviewing the data plotted in Figure 6:

- Samples repaired by grinding had fatigue lives that were approximately 10 times those of *unrepaired dents and gouges*.
- Those defects that were repaired by grinding and composite materials had fatigue lives that were approximately 1,000 times those of *unrepaired dents and gouges*.

The predominant conclusion is that composite materials, when properly designed and applied, can significantly increase the fatigue life of unrepaired mechanical damage. A properly-designed composite system for repaired mechanical damage ensures that local strains in the dent are reduced so that alternating strains are maintained to a minimum level.

In addition to the previous studies on mechanical damage, a program is currently being sponsored by the Pipeline Research Council International, Inc. and six composite repair manufacturers (Armor Plate, Air Logistics, Citadel, Furmanite, Pipe Wrap A+, and WrapMaster). The program is evaluating the ability of composite materials to reinforce plain dents, dents in ERW seam welds, and dents in girth welds. Figure 7 is a schematic showing the basic layout for the test samples and Figure 8 is a photograph showing a side view of a plain dent. This program is currently underway; however, two of the six systems have been tested to run-out at 250,000+ cycles with no failures in any of the repaired dents.

ADDITIONAL INVESTIGATIONS

In addition to the test programs discussed in this paper, the author has been involved with other studies that have contributed additional levels of understanding to how composite materials can be used to reinforce piping and pipelines.

- Program to evaluate the reinforcement of wrinkle bends in pipelines. This particular program was funded by the El Paso Pipeline Group and involved a detailed investigation that evaluated how composite materials reduce local strain in wrinkle bends and provide structural reinforcement and extend fatigue lives. Strain gages were used to monitor strain beneath the composite repairs and all testing was destructive via pressure cycling to failure. This work was presented at the 2008 International Pipeline Conference in Calgary.
- Composite materials have been used successfully to reinforce complex geometries such as elbows and tees. Armor Plate, Inc. funded a program to evaluate the level of reinforcement provided by Armor Plate Pipe Wrap to 12.75-inch x 0.375-inch, Grade Y52 elbow and tee pipe fittings that had 50% corrosion simulated via machining. Strain gages showed that the composite material successfully reinforced the corroded regions of the repair and burst testing demonstrated that failures could be achieved outside of the corroded regions at pressures equal to a non-corroded test article.

It is clear that additional testing programs will be conducted in the future to evaluate the repair of piping components and pipeline systems. While analysis techniques and numerical methods can provide insights into the performance of composite materials, destructive testing coupled with strain gage analysis is the ideal means for evaluating the ultimate reinforcing capacity of composite repair systems.

CLOSING COMMENTS

Composite materials continue to play an important role in repairing damaged pipelines. When properly designed and installed, they are able to restore the integrity of damaged pipelines back to their original integrity. The relatively recent development and application of composite repair standards such as ASME PCC-2 and ISO 24817 are contributing significantly to the proper design of the composite repair technologies. These standards will continue to develop as the pipeline industry requires that composite materials provide repair solutions for pipeline anomalies as part of their integrity management programs. Additionally, the development of industry-accepted standards has brought significant unity to a portion of the pipeline repair world where consensus was generally not the norm. The pipeline industry is being well-served through the development of these standards.

It is the author's perspective that composite materials have contributed significantly to the well-being of international pipeline systems. Composite materials provide the pipeline industry with a less expensive alternative to conventional repair options such as welded sleeves and cut-outs. It is expected that the evaluation of composite materials through testing and analysis will continue for many years to come based for at least two reasons. First, the pipeline industry is continuously establishing opportunities where composite materials can be used to reinforce deteriorated pipelines. Secondly, the manufacturers recognize the importance of developing new systems as composite material technology advances. Continued evaluation will only advance the accumulation of knowledge. The natural results will be a broader acceptance and confidence in the capabilities of composite repair systems by the pipeline industry.

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Table 1 – ASME PCC-2 Calculated Thickness Values

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

Notes (input variables used in above equations):

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

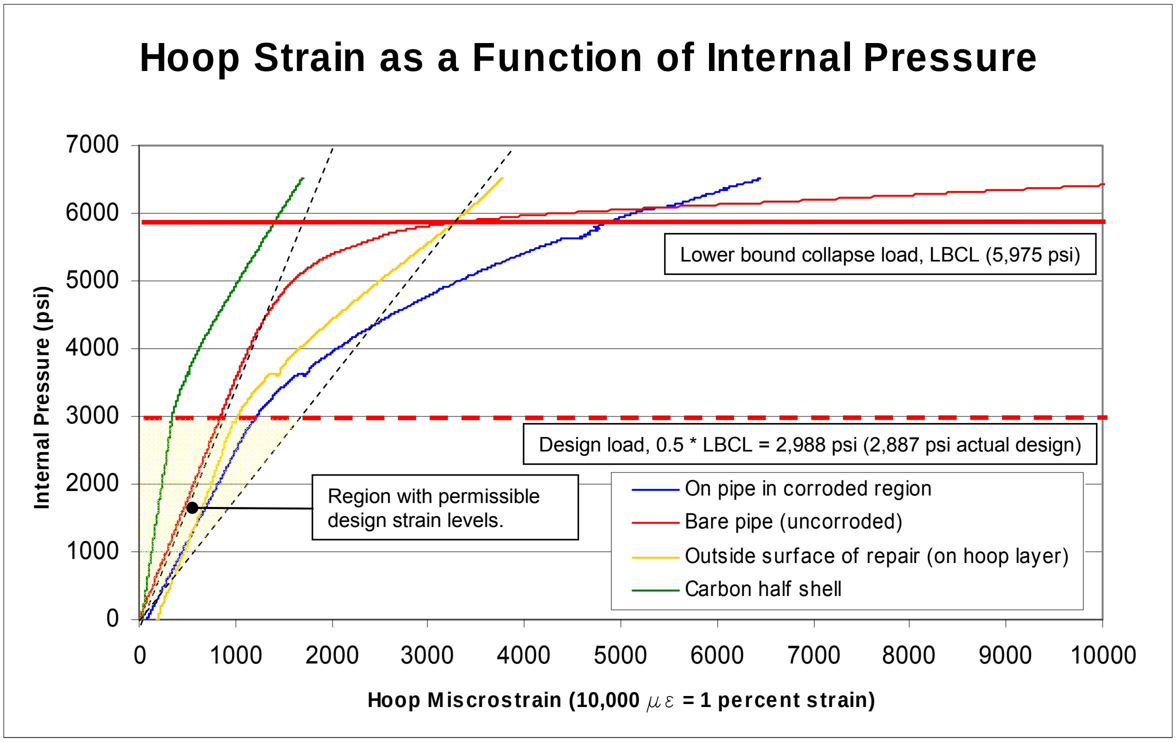

Figure 1 – Strains measured in composite reinforced corroded pipe sample
(8.625-in x 0.406-in, Grade X46 pipe with 50% corrosion)

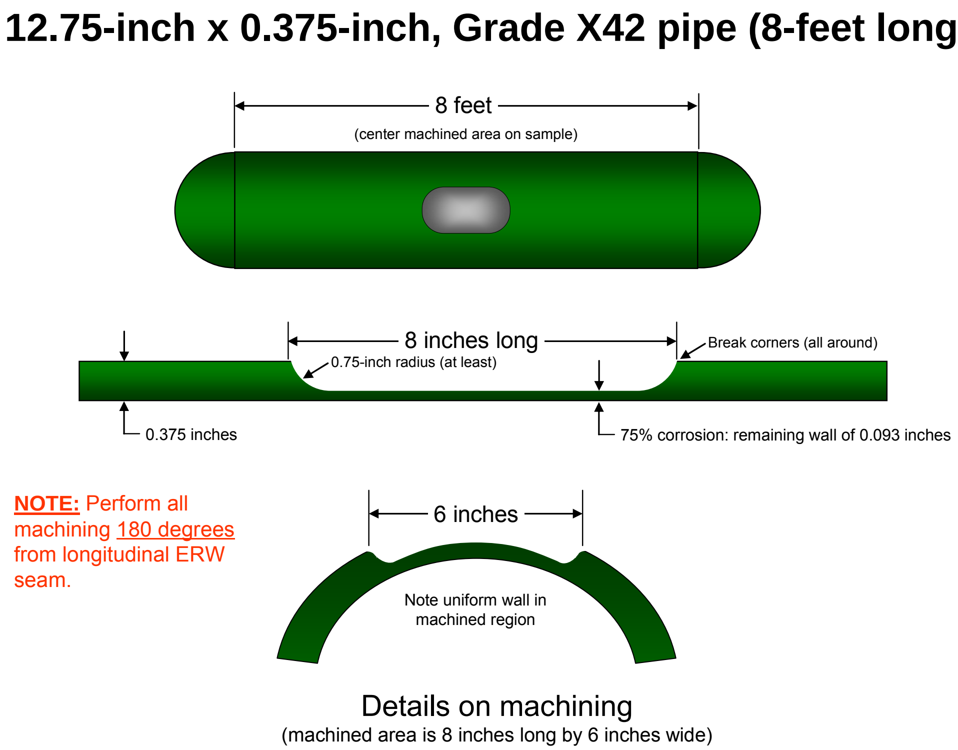

Figure 2 – Schematic diagram of composite repair pipe test sample

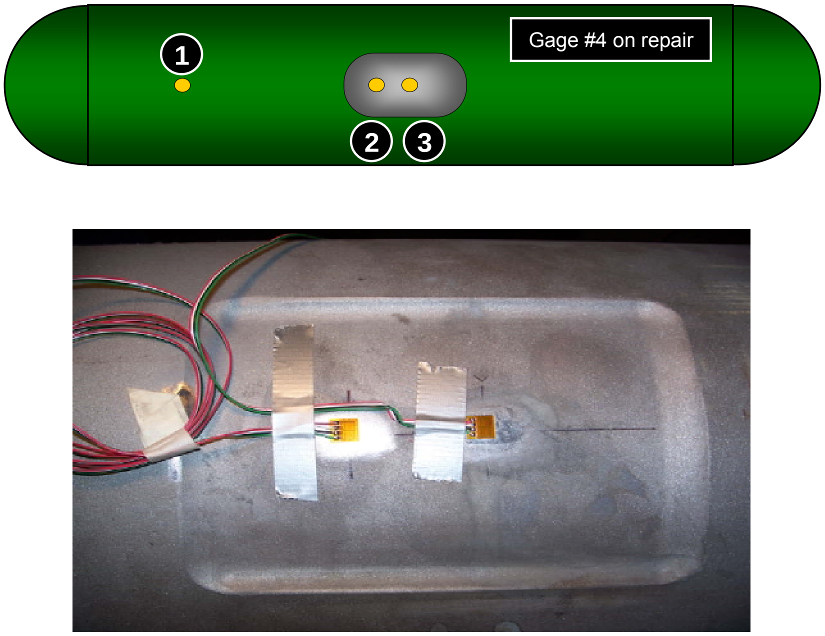

Figure 3 – Schematic showing location of strain gages of photo of machined region

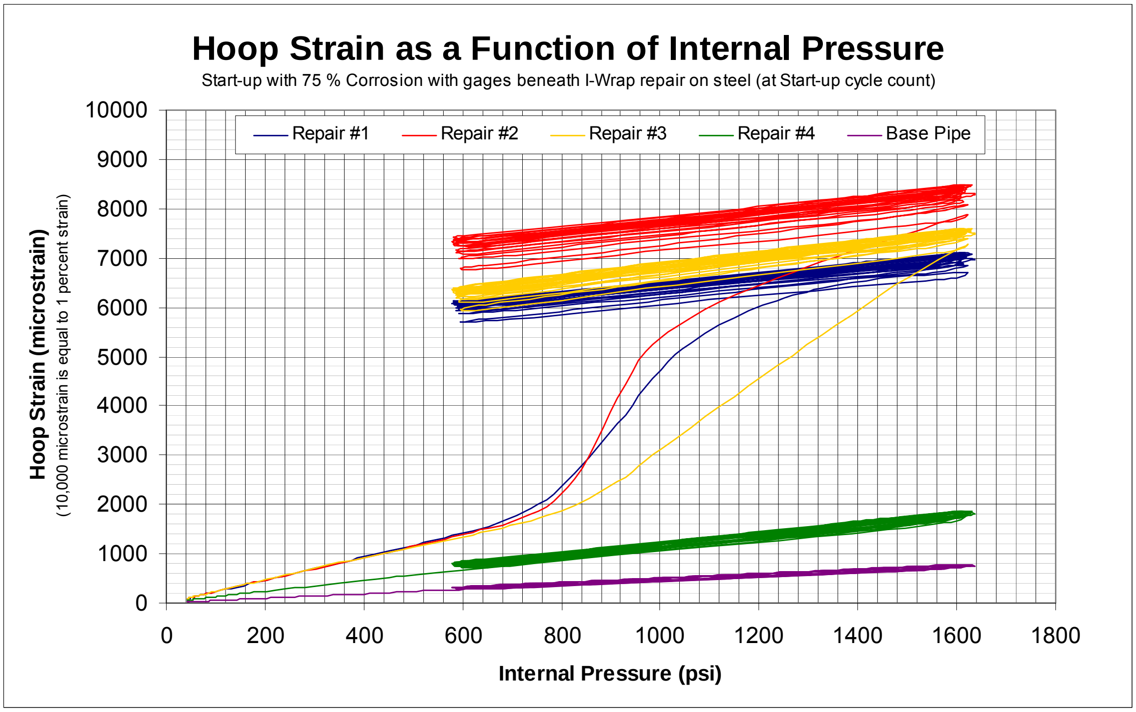

Figure 4 – Measured strain range in 75% corroded test sample
(test sample cycled at ΔP = 36% SMYS, data plotted at start-up)

Figure 5 – Photographs from PRCI long-term study

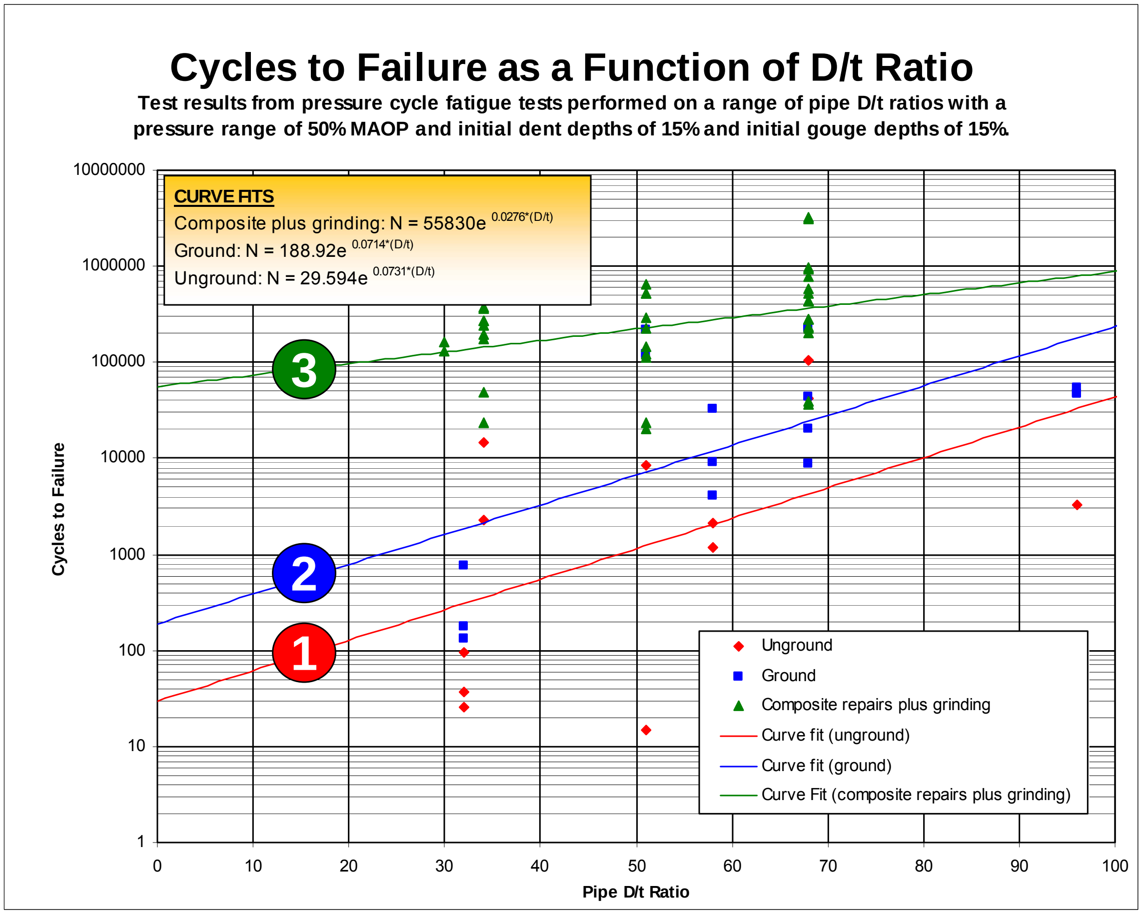

Figure 6 – Fatigue test results for composite-repaired mechanical damage samples

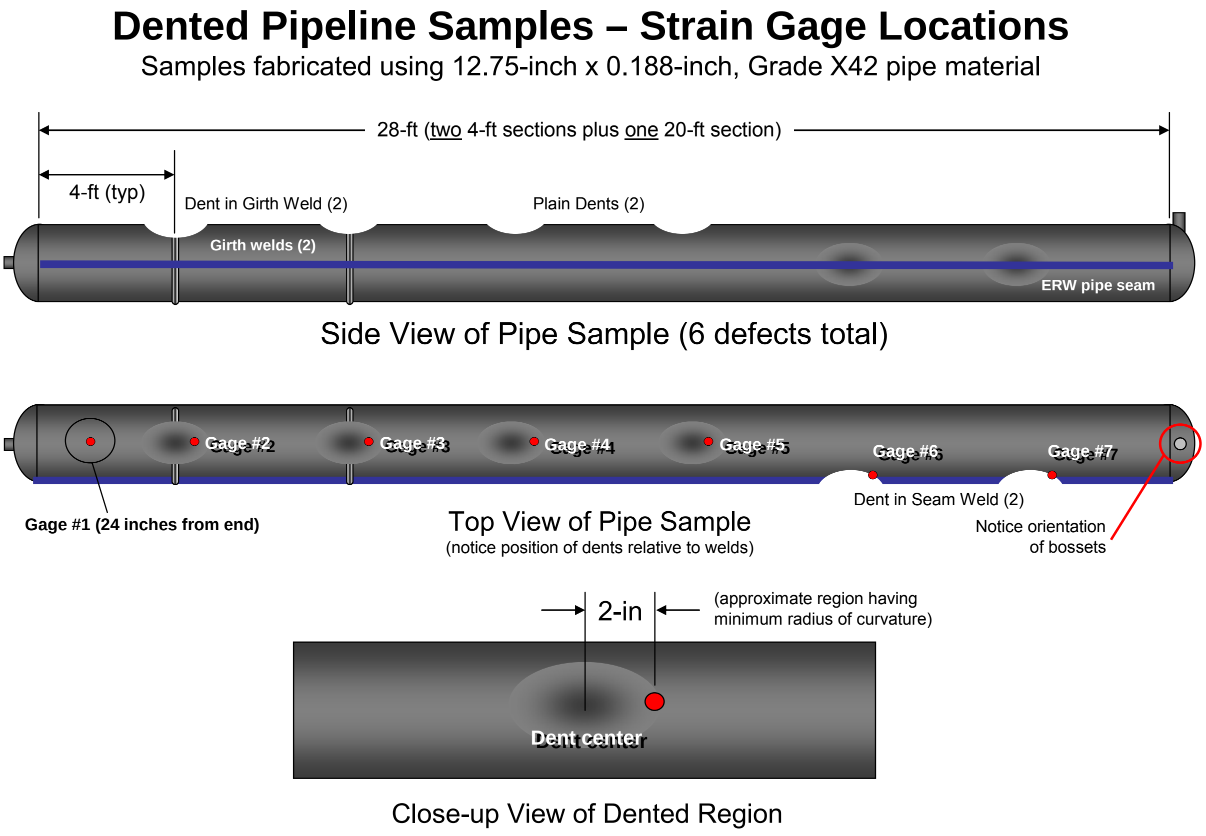

Figure 7 – Dent test sample layout with specified locations for strain gages

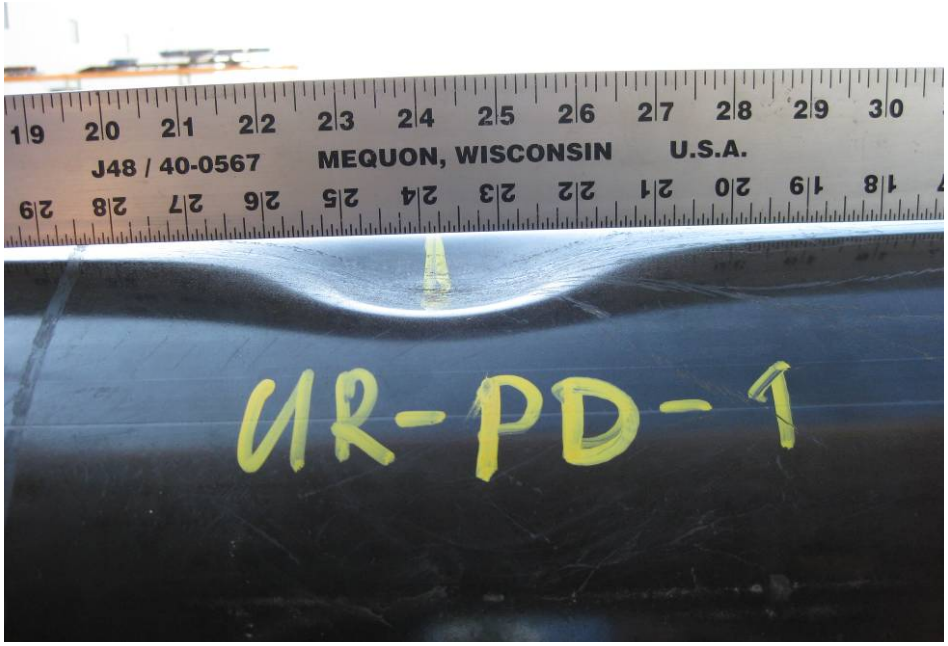

Figure 8 – Side view of unrepaired plain dent after indentation with pressure