Recent Advances in Evaluating Composite Repair Technology Used to Repair Transmission Pipelines

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ABSTRACT

For the better part of the past 20 years, composite materials have been used to repair high pressure transmission pipelines. Initial efforts focused on repairing corrosion; however, as confidence in composite repair technology improved the pipeline industry showed greater interest in expanding its usage to repair other anomalies. The repair of dents and mechanical damage was evaluated through research efforts and the results showed significant promise. The reinforcement of other features such as wrinkle bends, branch connections, and corrosion in bends have also been evaluated.

In this paper the author provides results and insights associated with several extensive research programs currently being sponsored by the pipeline industry and numerous composite repair manufacturers. The ongoing focus of these efforts has been to demonstrate to industry the capabilities that composite repair systems have to provide long-term reinforcement to damaged pipelines.

INTRODUCTION

From their inception as a means for reinforcing pipelines, composite materials have been continually evaluated through testing and analysis. Some of this work has been conducted as part of industry-wide research programs, while much of it has been part of individual studies sponsored by the composite manufacturers themselves. Unlike carbon steel where grade (i.e. yield strength) is the fundamental material characteristic used for pipeline design, composite materials have several material characteristics for design that control their constitutive properties, namely fiber selection and orientation. Resin selection also plays an important role, especially with regards to material performance in different environments.

The primary purpose of this paper is to provide the pipeline industry with a broad-brush overview of the recent advances in the composite-repair world over the past five years. It is possible to develop more than ten papers on a wide range of subjects; however, the author has opted to limit discussions to the following subjects:

1. Industry standardization though ASME PCC-2 and ISO 24817
2. Evaluating long-term performance of composite materials
3. Repair of pipeline anomalies including plain dents, mechanical damage, and dents in seam/girth welds
4. Use of composite materials in reinforcing pipes subjected to bending loads

The sections that follow provide detailed discussions on the above subjects.

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 several engineers, namely Dr. Simon Frost, 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 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 degradation 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 both the composite 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).

LONG-TERM PERFORMANCE

Unlike steel where material properties are not time-dependant (at room temperature), composite materials can creep; 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).

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 12 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)

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. Figure 1 is a schematic showing the machining required for the test samples, while Figure 2 shows 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 3.

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 4 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 4:

- 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 5 is a schematic showing the basic layout for the test samples and Figure 6 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.

BENDING REINFORCEMENT

Most composite repair systems have been used to reinforce corrosion and dents in transmission and distribution pipeline systems; however, a study was conducted with co-funding from the U.S. Minerals Management to evaluate the use of composite materials in reinforcing corroded offshore risers. Additional funding was provided from four composite manufacturers that resulted in a Joint Industry Project (JIP).

The program incorporated 8.625-inch x 0.406-inch, Grade X46 pipe test samples that were prepared with simulated corrosion by machining. The geometry of the corrosion was 50 percent of the pipe's nominal wall, 24 inches in length, and axisymmetric (i.e. extended circumferentially all the way around the pipe). The program destructively tested a total of 12 separate samples with three being repaired by each of the four manufacturers. The tests included a burst test (increasing pressure to failure), a tension-to-failure test (pressure held constant with increasing axial tension loads to failure), and a four-point bend test (pressure and tension held constant with increasing bending loads) for each of the repair systems. Figure 7 shows a schematic of the four point bend set-up.

The four-team JIP was formed to assess the current state of the art of composite repair technology. Each repair system was evaluated considering a combination of pressure, tension, and bending loads. To maintain anonymity, each company's product was assigned a letter reference designation as noted below.

Product A – this system uses an E-glass fiber system in a water-activated urethane matrix.
Product B – this system uses an E-glass fiber system in a water-activated urethane matrix.
Product C – this system uses a carbon fiber system in an epoxy matrix.
Product D – this system uses an E-glass fiber system in an epoxy matrix.

Test Program Details

Three samples were prepared to test each composite repair system (e.g. four systems required 12 total samples). After the pipe samples were fabricated, the composite repair manufacturers were invited to install their repair systems on the three prepared test samples, which were then destructively tested. These three samples included:

1. Pressure only test – sample destructively tested by increasing internal pressure to failure.
2. Pressure-tension test – sample destructively tested by increasing axial tension to failure while holding internal pressure constant (2,887 psi).
3. Pressure-tension test – sample destructively tested by increasing bending load to induce gross plastic deformation while holding internal pressure (2,887 psi) and axial tension (145 kips) constant.

As shown in Figure 8 strain gages were installed in three regions on each test sample: (1) on the steel in the corroded region beneath the composite repair, (2) on the base pipe away from the repaired region, and (3) on the outside surface of the composite material. The strain gage results were used to evaluate the level of reinforcement provided by the different composite repair systems.

Test Program Results

Over a five week period, tests were performed on one set of unrepaired samples and four different composite repair systems. Results are presented for the four repair systems and the unrepaired sample in the sections that follow. Considering all phases of testing, data were recorded for a total of 159 strain gages. However, presentation of results is limited to gages located beneath the repairs in order to demonstrate the level of reinforcement provided by each of the repair systems.

It should be noted that results for Product B are not included. The manufacturer of this repair requested that their results not be included after sub-standard performance resulted due to uncured adhesives.

Detailed results are only presented for the pressure-tension-bending test[1]; however, limited results for the other two test efforts are provided below.

<u>Pressure Test Results</u>

The failure pressures for the four repaired <u>burst samples</u> are listed below. All failures listed below in the composite-repaired samples occurred outside of the reinforced regions.

- Unrepaired – 3,694 psi
- Product A – 6,921 psi

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[1] Interested readers are encouraged to read the original paper having a detailed discussion on the test program and associated results. Alexander, C.R., *Evaluating the Use of Composite Materials in Reinforcing Offshore Risers Using Full-scale Testing Methods*, Paper No. IOPF2007-104, Proceedings of the ASME International Offshore Pipeline Forum, October 23-24, 2007, Houston, Texas.

- Product B – data not reported
- Product C – 7,502 psi
- Product D – 7,641 psi

Pressure-tension Test Results

The following tension failure data were recorded for the pressures-tension samples.

- Unrepaired sample – 317 kips
- Product A – 492 kips
- Product B – data not reported
- Product C – 562 kips
- Product D – 579 kips

Pressure-tension-bending Test Results

Prior to starting the testing phase of work, this particular test was recognized as the most likely challenge of the three test configurations. It not only combined constant pressure (2,887 psi) and constant axial tension (145 kips), it integrated bending loads that would induce significant axial strains in both the corroded steel and composite material. Unlike the pressure-tension tests where the primary focus was on the interfacial adhesive bond, this phase of testing integrated the needs for adequate bond strength. The repair was also required to have sufficient strength and stiffness in the composite to reinforce the corroded steel.

Results for the pressure-tension-bending test are provided in Figure 10. There are several noteworthy observations in reviewing the plotted data.

- Unlike the other tests, there is a unique pattern observed for the level of reinforcement provided by each of the respective repair systems. As expected, the carbon in Product C provides the greatest level of reinforcement because for any given bending load it had the lowest measured strain. For comparison purposes, consider the strain in the steel at a bending load of 40 kips (bending moment of 116.7 ft-lbs) for each of the repair systems:
    - Product A – 4,130 microstrain
    - Product B – data not reported
    - Product C – 2,150 microstrain
    - Product D – 3,022 microstrain
- In assessing the relative performance of the composite systems, the objective of the repair is to reduce the strain in the corroded steel during bend testing, as well as provide reinforcement in the circumferential and axial directions due to internal pressure and axial tension loads, respectively. As noted in Figure 10, at some point the strain gage results appear to stop changing with increasing load (where plotted lines trend vertical). It is at this point that gross plastic deformation, as recorded by the strain gages, occurs outside of the reinforced region and that deflection is occurring primarily in areas outside the composite reinforcement. The sooner this transformation takes place, the more effective the repair is in reinforcing the corroded region.
- Another option for assessing the relative performance of the composite repair systems is to determine the applied bending moment at a specified strain value. If the strain limit is designated as 0.20 percent, the following bending forces and moments are extracted. This method is a better assessment of the relative performance of the repair systems. It should be noted that the unreinforced sample did not include internal pressure during bend testing as failure would have occurred at a lower bending load. The values in parentheses correspond to bending moments in kip-ft.
    - Unrepaired sample – 30 kips (87.5 kip-feet)
    - Product A – 26 kips (75.8 kip-feet)

  - Product B – data not reported
  - Product C – 70 kips (204.2 kip-feet)
  - Product D – 40 kips (116.7 kip-feet)

Figure 9 is a photograph of the Product C repair in the load frame prior to bend testing. Table 1 includes the failure results for all three tests and all three composite repair systems. Included in this table are the design loads. The design margin for each respective system is the ratio between failure load and design load. As an example, consider the pressure-tension-bending loads for System C (carbon epoxy system). The failure bending load is listed as 204.2 kip-ft and the design load is 51 kip-ft. The ratio between these bending moments is 4.0, which is certainly exceeds acceptable margins for strain-based design methods that range between 1.5 and 2.

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

This paper has provided information on how composite materials are being used to repair a wide range of pipeline anomalies including corrosion, dents, and reinforcing pipes subject to bending loads. 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 – Summary of test results relative to design conditions (Pressure-tension-bend test program)

Loading Conditions	Design Load	Failure Loads				
		Unrepaired	Product A	Product B	Product C	Product D
Internal pressure	2,887 psi	3,694 psi	6,921 psi	N/A	7,592 psi	7,641 psi
Tension Load	145 kips	317 kips	492 kips	N/A	562 kips	579 kips
Bending Force (Moment)	17.5 kips (51 kip-feet)	30 kips (87.5 kip-feet)	26 kips (75.8 kip-feet)	N/A	69.9 kips (204.2 kip-feet)	40 kips (116.7 kip-feet)

Notes:

1. The unrepaired bending sample did not include internal pressure at the time of testing. The decision to run this test without internal pressure was based on safety concerns and recognizing the possibility for failure at relatively low bending loads due to large strains.
2. The ratio of average failure loads for the repaired samples to the unrepaired sample for the internal pressure and tension load samples are 2.0 and 1.72, respectively.
3. The unrepaired sample exhibited failure loads exceeding the specified Design Load for both the pressure and tension tests.

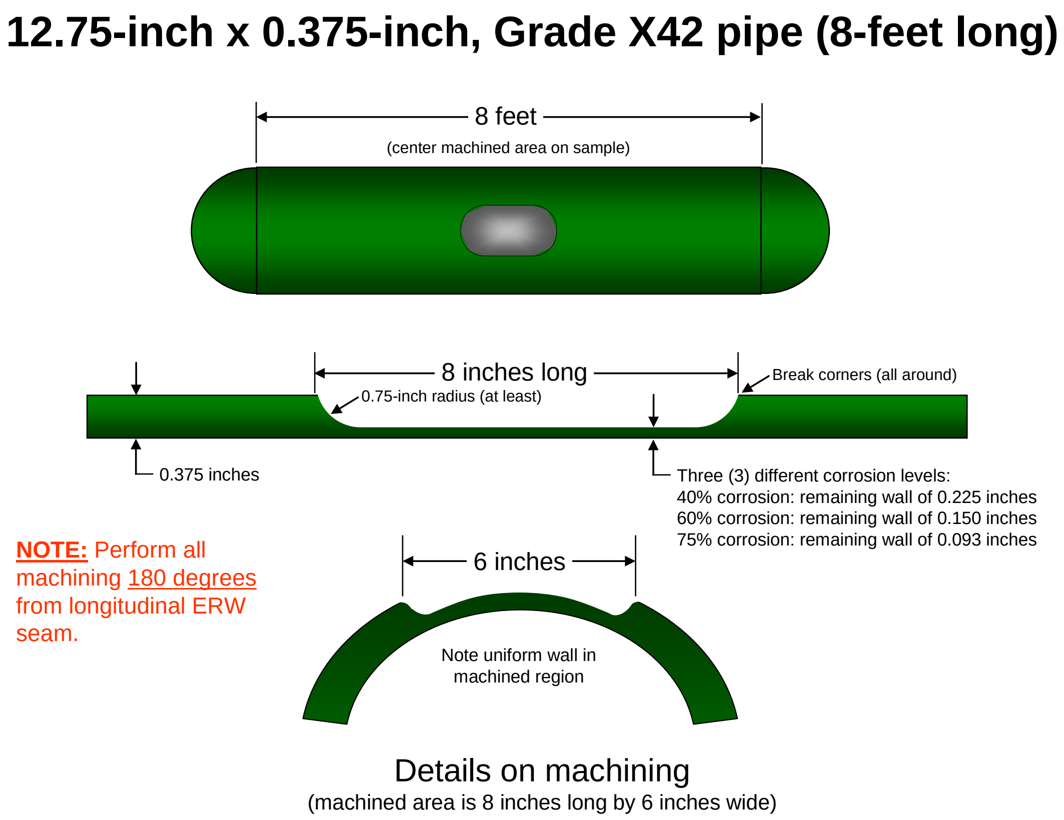


Figure 1 – Schematic of test samples for PRCI long-term study

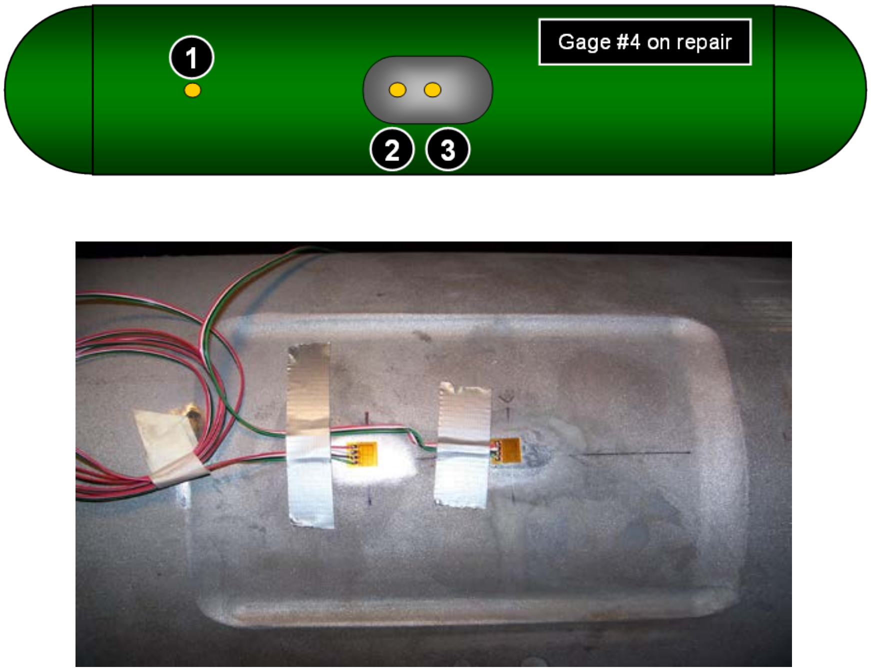


Figure 2 – Strain gage locations and photograph of machined region

Figure 3 – Photographs from PRCI long-term study

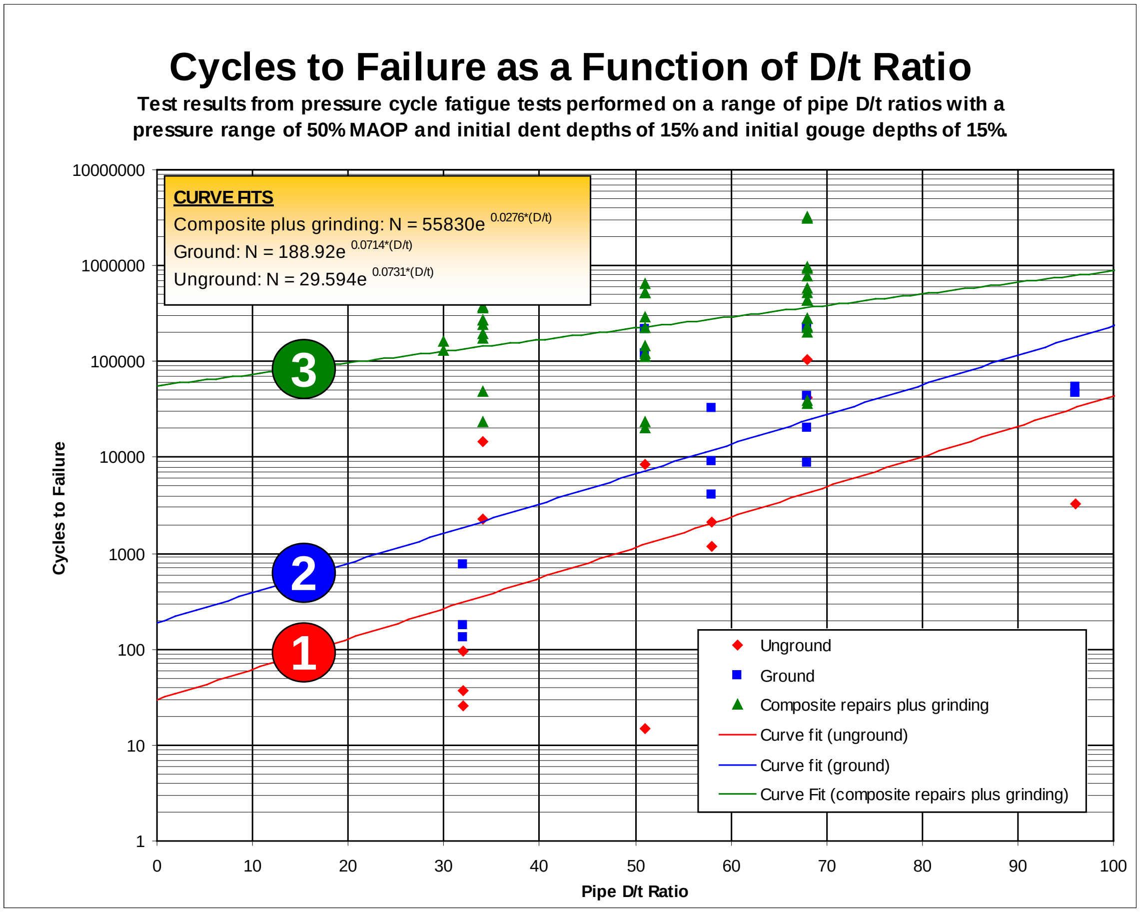


Figure 4 – Fatigue test results for composite-repaired mechanical damage samples

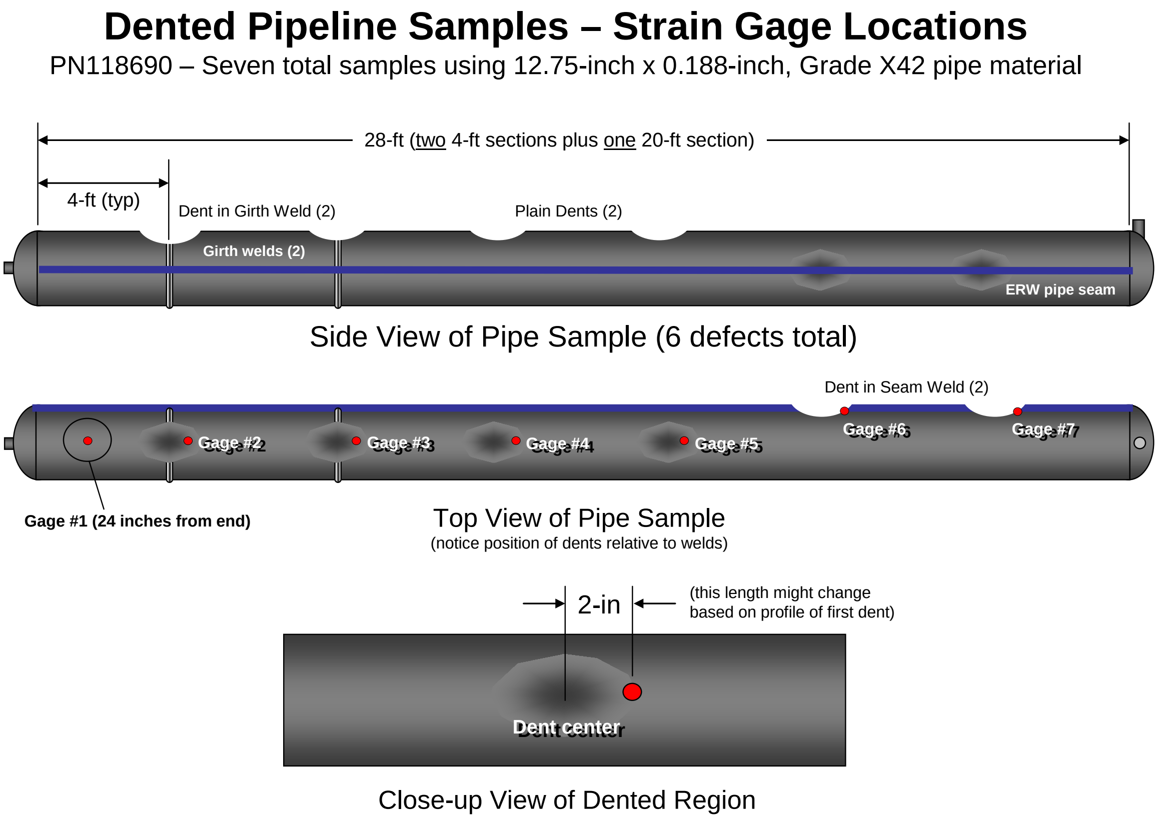
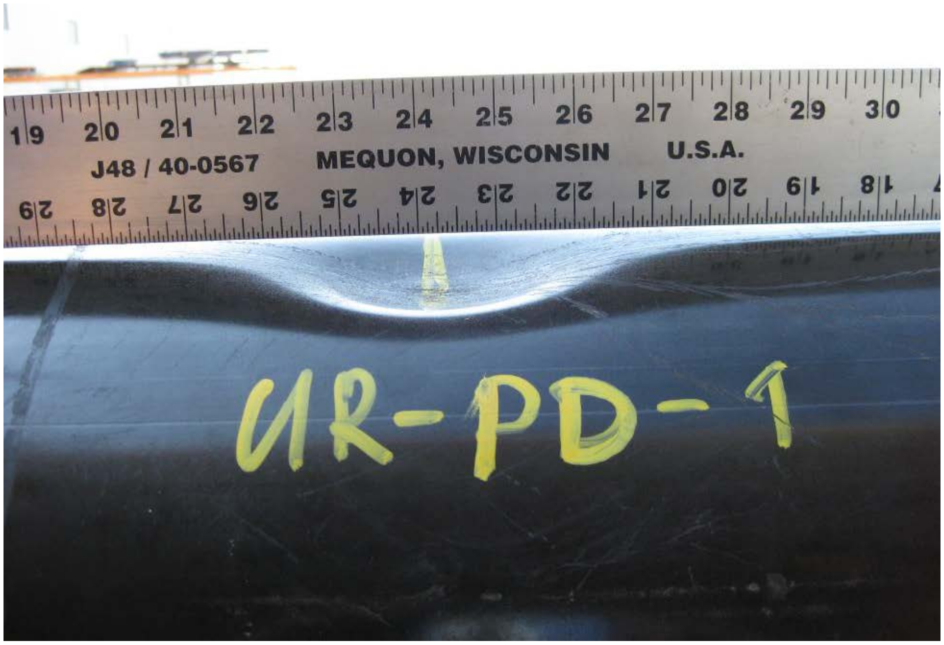


Figure 5 – Dent test sample layout with specified locations for strain gages



4. **Figure 6 – Side view of unrepaired plain dent after indentation with pressure**

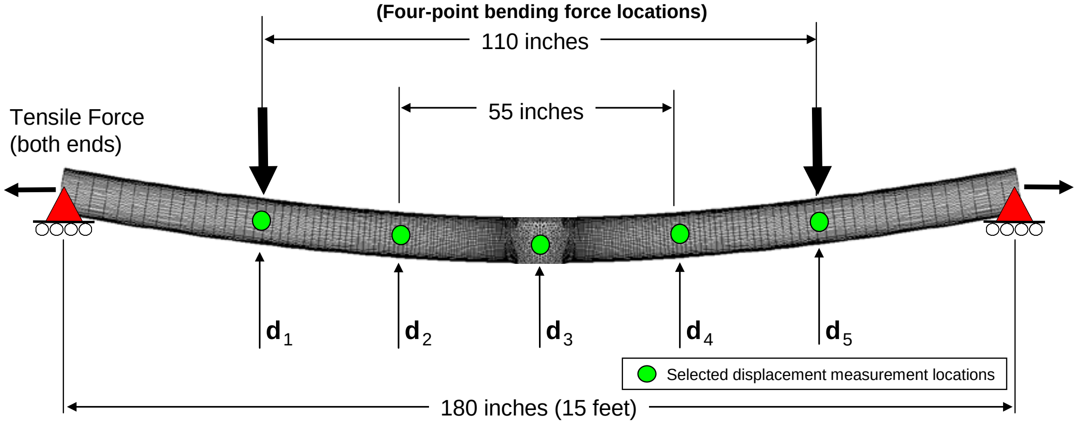


Figure 7 – Four point bending configuration for pressure-tension-bend testing

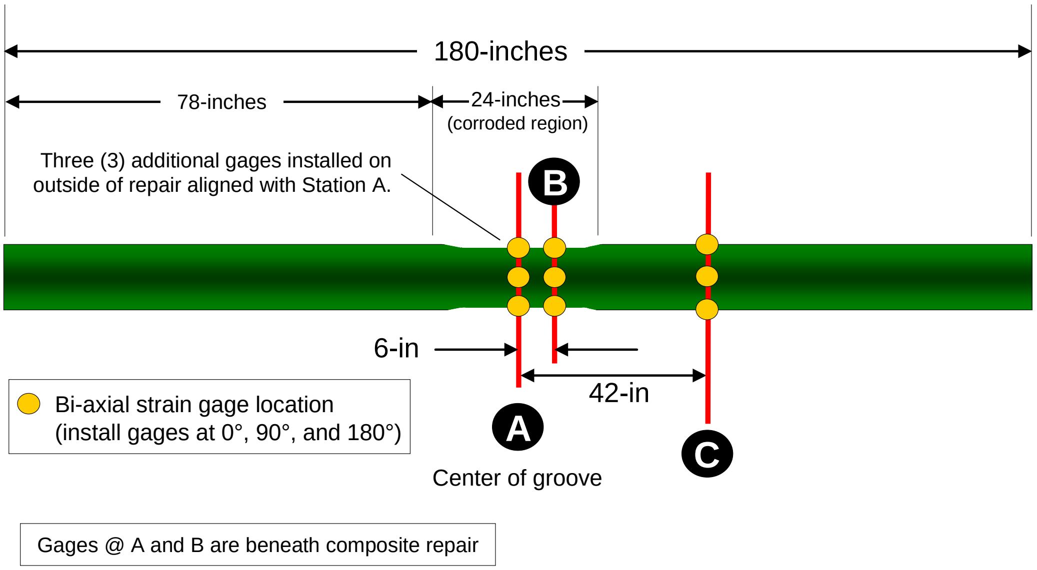


Figure 8 - Location of strain gages on the pressure-tension-bend samples

Figure 9 – Load frame used for pressure-tension-bend testing

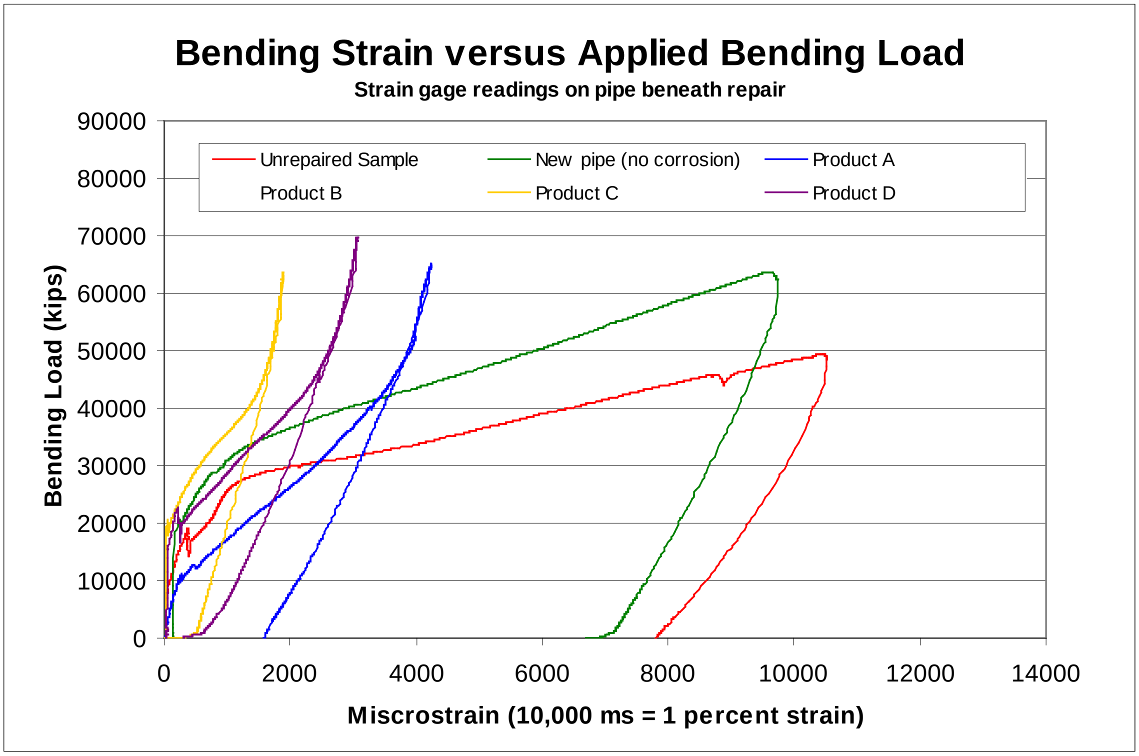


Figure 10 – Test results from pressure-tension-bending testing