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ADVANCED TECHNIQUES FOR ESTABLISHING LONG-TERM PERFORMANCE OF COMPOSITE REPAIR SYSTEMS

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ABSTRACT

Although composite materials are used to repair and reinforce a variety of anomalies in high pressure transmission gas and liquid pipelines, there continues to be widespread debate regarding what constitutes a long-term composite repair. The United States regulations require that composite repairs must be able to permanently restore the serviceability of the repaired pipeline, while in contrast the Canadian regulations take a more prescriptive approach by integrating the ASME PCC-2 and ISO 24817 composite repair standards along with a requirement for establishing a 50-year design life.

In this paper the author provides a framework for what should be considered in qualifying a composite repair system for long-term performance by focusing on the critical technical aspects associated with a sound composite repair. The presentation includes a discussion on establishing an appropriate composite design stress using the existing standards, using full-scale testing to ensure that stresses in the repair do not exceed the designated composite design stresses, and guidance for operators in how to properly integrate their pipeline operating conditions to establish a design life. By implementing the recommendations presented in this paper, operators will be equipped with a resource for objectively evaluating the composite repair systems used to repair their pipeline systems.

INTRODUCTION

The design of composite repair systems for reinforcing high pressure steel pipelines is unique in that the design requires the designer to consider the behavior of both the composite system and the reinforced steel. In this regards the designer must not only understand how pipelines are designed and how composite materials respond to loading, he must see the design as a hybrid and understand the inter-dependent behavior of both the steel and the composite.

Over the past 20 years the author has evaluated more than 25 different composite repair systems manufactured by companies around the world. During this time period a significant body of research has been accumulated, much of it favorable in terms of developing technically-sound composite designs; however, on occasion the author has observed poor test results. The central aim of this paper is to provide the reader with a resource for evaluating whether or not a composite repair system meets the design requirements for reinforcing high pressure pipeline systems. This foundation for this paper is built on observations of what *has worked* and what *has not worked*.

An important observation made in reviewing the body of research data is that not all composite repair systems perform equally. This will be demonstrated by some of the results provided in this paper. Some of the items that will be highlighted in this paper address the need for composite repair systems to address the following subjects related to validating the long-term performance capabilities of a given repair system.
- Meeting the minimum industry standards including a design basis
- Performance-based testing
- Verification of design stresses
- Long-term performance (longevity and cyclic loading)
- Operating environments (water and temperature)
- Third party review
- Quality control

Any manufacturer of composite repair systems making installations on high pressure pipelines must demonstrate a working knowledge of the above areas. This includes recognizing system limitations and an unwillingness to extrapolate performance capabilities. An excellent example concerns material performance at elevated temperatures. It is not enough to know the glass transition temperature or heat distortion temperature for the resin used in a composite repair; physical destructive testing must be performed at temperature to demonstrate capabilities.

The sections that follow integrate the above list as part of the overall discussion on achieving long-term performance capabilities. The top performing composite repair systems in the world have demonstrated the ability to perform at a level to ensure that a long-term repair solution is provided. The *Background on Design of Repairs* provides information on the design basis per ASME PCC-2 and the importance of material qualification. The *Research Programs* section provides the reader with an overview of the extensive body of research that has been conducted, with a specific discussion on a long-term burial study and a program that evaluated the performance of composite repair systems used to reinforce dents.

BACKGROUND ON DESIGN OF REPAIRS

This section of the paper provides background concepts associated with designing a composite system for reinforcing damaged pipelines. Included are discussions on safety factors and material performance, as well as a review of stress/strain data to validate acceptable conditions in a composite system. Also included are results from previous testing programs that validated the designs of composite repair systems relative to the requirements of the composite repair standard, ASME PCC-2, *Repair of Pressure Equipment and Piping*, Part 4.

From a design standpoint, the operating pressures of gas and liquid transmission pipelines are based on the geometry of the selected pipe (diameter and wall thickness) and material properties (yield strength). Gas transmission pipelines, in particular, are assigned safety margins (design pressures) based on their proximity to buildings and people. Inherent in any discussion of the design of gas and liquid transmission pipelines is the concept of safety factors. When composite materials are used to repair high-pressure pipelines, their design must consider both the strain reduction in the reinforced steel, as well as considering stresses (or strains) in the composite material. Ideally, the composite must provide enough strain reduction in the steel to ensure that integrity is restored to the damaged sections of the pipeline; while at the same time possess sufficient stiffness to ensure that design stresses are not exceeded in the composite material that could potentially reduce its long-term performance.

The most fundamental technical issue associated with the design of a composite repair system centers on long-term performance. Because composite materials typically involve a polymer-based matrix (e.g., most often epoxy or urethane), the potential exists for time-dependent loss of strength. The key for the long-term performance of any composite repair system is based on the relationship between stresses in the composite at design conditions relative to failure strength of the composite material itself. While steel pipelines are typically designed with safety factors on ultimate tensile strength between 2 and 3, well-designed composite repair systems have safety factors relative to short-term failure strengths ranging from 7 to 10. These larger safety factors are to accommodate material degradation as a function of time and uncertainties associates with long-term performance.

The sections that follow provide information related to the design of composite repair systems based on performance-based testing to establish design strength for the composite materials.

Testing to Validate Material Performance

A study completed by SES in 2010 on a composite repair system provides useful information related to establishing long-term design strength for a given composite system. As part of material-qualification testing required by ASME PCC-2, composite materials were applied on the outside surface of undamaged pipe samples that were held at a constant pressure level for 1,000 hours. Strain gages were used to measure strains in both the composite material and reinforced steel pipe. The stress levels to which the composite materials were subjected were used to establish the long-term design strength of the respective composite materials.

In addition to the 1,000-hour pressure hold, burst tests were conducted on three test samples reinforced with the composite repair system after the hold period was completed. Figure 1 plots data that

were collected during this study. Several important observations are made in reviewing these data:

- At the design pressure of 1,778 psi (72% SMYS) for this particular pipe material, the hoop strain was 900 microstrain (0.09%) in the unreinforced pipe sample.
- With the addition of 0.188 inch of Armor Plate® Pipe Wrap, the pressure in the reinforced sample at the equivalent strain level of 0.09% increased to 2,420 psi (this is actually equal to 100% SMYS for the base pipe – extremely significant observation I that the same strain is measured for the reinforced sample yet the pressure increased from 1,778 psi to 2,470 psi, or 643 psi). A comparison of the data intersections along the **dashed blue line** implies that, when a composite thickness of 0.188 inch is added to the 12-inch nominal diameter pipe, the design pressure increases from 1,778 psi to 2,420 psi (an increase of approximately 30%).
- Similarly, if the pressure level is held constant at 1,778 psi, strains in the reinforced test samples decrease from 0.09% to 0.067% (strain reduction of approximately 26%). This is noted from the data intersections along the horizontal **dashed green line** (cf. Figure 1).

It is possible to use composite materials to reduce strain in a reinforced pipe for a particular design pressure. A critical variable in this approach is the design stress of the composite material. As long as the stress in the composite material is kept below a designated level, the long-term performance[1] of the reinforcement is assured.

Validation of Design Stress

Another series of tests performed by SES for two composite manufacturers in 2011 involved installation and monitoring of strain gages on the composite material. Strain gages were installed within the composite repair system (i.e., on layers as they were installed around the pipe, identified as *inter-layer strains*) to measure strains within the repair during pressurization. This engineering technique reduces the guesswork associated with attempting to quantify actual stresses in the composite material during pressurization of the pipe. For composite materials (and for purposes of this discussion), stress is the product of strain and elastic modulus of the composite material. It is necessary to measure the elastic modulus via mechanical testing on composite coupons. Measuring inter-layer strain is essential to ensure that composite materials are not overstressed. Without these types of measurements, there is no assurance that repair materials are not overstressed (even at design conditions), which could lead to failure of the material.

Equally important, when composite reinforcement materials are overstressed their ability to provide the required reinforcement to damaged sections of pipe is reduced. When designing a composite repair system for long-term service, it is essential that the magnitude of stresses in the composite material not exceed a designated design level (i.e., long-term design stress). ASME PCC-2 provides a means for determining the long-term design stress based on using results from either 1,000 hour or 10,000 hour pressurized pipe samples (refer to the 1,000-hour test discussed in the preceding section). Until relatively recently, there has been no attempt to actually quantify

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[1] There is some debate as to what constitutes long-term. A 50-year design life is not uncommon when discussing composite repair design; however, careful consideration must also be made regarding the type of anomaly being repaired and the service conditions to which it is subjected (e.g. cyclic pressure).

hoop stresses in the composite material of a repair used to reinforce a corroded section of pipe at a designated pressure level.

SES conducted tests on two different composite repair systems, both of which used E-glass fibers. The objectives in testing were two-fold. The first was to determine the actual distribution of strain in the layers of the composite reinforcement, specifically, determining which layers carried the greatest percentage of the load. The second objective was to measure the maximum stress (strain) in the composite material for comparison to the ASME PCC-2 long-term design stress (determined by the 1,000-hour test for each of the tested systems).

Figure 2 and Figure 3 plot hoop stress in the composite materials at 72% SMYS for Systems #1 and #2, respectively, as a function of radial position. Table 1 presents a summary of data for both systems measured at 72% SMYS, along with a comparison of the measured stresses to the respective long-term design stresses.

As a point of reference, when these two systems were used to repair a 12.75-inch x 0.375-inch, Grade X42 pipe having 75% corrosion, the cycles to failure when pressure-cycled at a stress range of 36% SMYS (ΔP = 36% to 72% SMYS) were 140,164 and 259,537 cycles for System #1 and System #2, respectively. Also, both of these systems ensured that strains in the corroded region of the pipe were limited to approximately 0.3% when the test sample was pressurized to 72% SMYS.

One of the most important observations in reviewing the data presented in Table 1 is the relatively large material strength design margins that exist for both systems, especially in relation to the short-term tensile strength. When comparing the measured stresses in System #1 and System #2, the ratios of mean tensile strength to maximum stress for the composite materials are 10.8 and 7.6, respectively. If the average stresses in the composite are considered based on the strain gage results, as opposed to the maximum stress reported in Table 1, the design margins are even larger. The significance of these design margins cannot be overstated. In order for a composite material to provide long-term reinforcement, it is essential that stresses in the composite material and reinforced steel be kept to a minimum.

RESEARCH PROGRAMS

A significant body of research and testing work has been conducted to evaluate the reinforcement of high-pressure gas and liquid transmission pipelines using composite materials. The sources of this work have been independent investigations funded by individual composite repair manufacturers and pipeline operators, as well as the Pipeline Research Council Institute, Inc. (PRCI).

The sections that follow provide details on both the independent investigations funded by pipeline operators and composite repair manufacturers, as well as five programs sponsored (or co-sponsored) by PRCI.

Independent Investigations

Pipeline operators and composite repair companies have determined that an effective approach to quantifying the benefits of using composite materials to reinforce pipeline components and anomalies includes full-scale destructive testing. These tests have demonstrated that the level of reinforcement provided by the composite material can be quantified by considering both the strain reduction in the

reinforced steel and the increase in stiffness associated with the combined properties of the steel and composite,

Although specific results are not included in this section of the paper, listed below are some of the independent investigations that have been conducted.
- Study to evaluate reinforcement of branch connections
- Reinforcement of wrinkle bends subjected to bending and tension loads
- Study to address the effects of elevated temperatures
- Reinforcement of pipe fittings including elbows and tees
- Study to address the effects of internal pressure during installation

PRCI Composite Studies

As mentioned previously, PRCI has been instrumental in funding numerous studies focused on evaluating the use of composite repair systems. These studies have helped the pipeline industry better understand the capabilities of composite repair technology in reinforcing a variety of anomalies. The brief write-up on PRCI programs presented here is not exhaustive and includes limited technical data; however, the intent is to communicate the range of studies that have been conducted focused on evaluating composite repair technology. While the focus of most studies has been on buried pipelines, the above ground use of composites is appropriate as long as the materials are protected from the environment and specifically, exposure to UV sunlight.

Listed below are all of the PRCI studies that have been conducted to evaluate the performance of composite repair systems. Details associated with the MATR-3-4 long-term and MATR-3-5 dent studies are included in this paper.
- MATR-3-3   State-of-the-art assessment
- MATR-3-4   Long-term buried pipe
- MATR-3-5   Dent repair
- MATR-3-6   Subsea repair
- MATR-3-7   Vintage girth weld
- MATR-3-9   Establishing MAOP using composites
- MATR-3-10   Composite repair guidelines
- NDE-2-3   NDE of composite repair

MATR-3-4: Long-term Repair of Corrosion. The program involved the burial of 12-inch nominal diameter pipe samples having machined corrosion and subjecting them to periodic cyclic pressures. After designated periods of time, pre-assigned groups of pipe samples were removed from burial and burst-tested. All of the manufacturers participated for at least three years, while five companies elected to participate for a 10-year period (the longer study is currently ongoing, while all samples have completed the 3-year testing program).

Prior to burial of the pipe samples, a series of baseline burst tests was conducted, designated as the "Year 0" burst tests. The results of these particular tests were important in establishing the optimum level of performance that could be expected from a given composite repair system. What was clear in studying the results from these tests is that not all composite repair systems perform equally. Subsequent to the first round of burst tests in 2008, it has become even clearer that some composite repair systems perform better than others. Of particular interest with the Year 0 burst tests was the level of strain

reduction in the machined corrosion regions provided by the different composite repair systems.

The results for all tested systems are provided in Table 2. Below are listed average measurements at pressure levels equal to 72% SMYS. Product L performed poorly (not due to it being a thinner repair) and the results provided below include the removal of this statistical outlier.
- All composite systems: 3,734 με (without Product L: 3,269 με)
- E-glass systems: 4,497 με (without Product L: 3,771 με)
- Carbon composite systems: 2,524 με

There are several important observations derived from the results of the MATR-3-4 study completed up to this point. The first is that at the present time there are commercially-available composite repair technologies that can provide long-term reinforcement to damaged pipelines. The second observation is that several of the systems had significant problems in reinforcing more severe corrosion damage, i.e., enough to warrant concern regarding their use on high-pressure gas and liquid transmission pipelines. The final observation—and probably most important for operators in the context of actually using composite repair systems—is that the ASME PCC-2 and ISO 24817 standards are an excellent means for qualifying composite repair systems. Operators are cautioned in using composite repair systems that do not meet at least the minimum requirements of these particular standards, especially with regards to establishing a long-term design stress used to calculate the required thickness for a composite repair.

MATR-3-5: Repair of Dents. With the execution of the MATR-3-4 project, PRCI members were interested in evaluating the use of composite materials for reinforcing dents, including dents interacting with ERW seam and girth welds. The PRCI MATR-3-5 study, *Composite Repair of Mechanically-Damaged Pipes*, was co-funded by PRCI and eight composite repair companies that included the following:
- Two rigid coil systems (one E-glass and one steel)
- Four carbon systems
- Four E-glass systems
- One steel sleeve system

The purpose of this program was to determine whether composite materials can effectively repair dents in high-pressure pipelines subjected to cyclic pressure service. Much like its predecessor program, MATR-3-4, which evaluated the long-term performance of composite repair systems in repairing corrosion, this program included the participation of several composite repair manufacturers and one steel sleeve manufacturer, whose contributions included funding, materials, and personnel time for installation work.

The participating composite repair systems were used to repair specific dent configurations installed in 12.75-inch x 0.188-inch, Grade X42 pipe ERW material. The dent geometries included plain dents, dents in girth welds, and dents in seam welds. The dents were installed to a depth of 15% of the pipe's outer diameter (1.91 inches) using an NPS 4 end-cap indenter held in place while the pipe sample was pressurized to 72% SMYS, or 892 psi. After all aspects of the denting process were completed, strain gages were positioned near the dents, after which the composite repair systems were installed on the outside surface of the pipe at a pressure of 0 psi. Figure 4 is a schematic diagram showing the configuration for each pipe sample, while Figure 5 is a photograph showing the side profile of the dent.

Each manufacturer was responsible for its design and for performing installations. All repairs included a filler material, also known as the load transfer material, which was used to fill the dented region of the pipe before the composite material was installed. In this program, composite fiber materials included E-glass and carbon. One system utilized high-strength steel wound around the circumference of the pipe, and bonded with a resin. Matrix resins included two-part epoxies and water-activated urethanes in a pre-impregnated, or pre-cured, form. In this case, the binding component in the composite repair system was applied to the cloth and allowed to partially cure. This is sometimes referred to as a "pre-preg."

Each composite repair system was evaluated using a total of six dents, except one system that was only used to repair two plain dents. The six dents in each pipe sample were pressure cycled to failure or 250,000 cycles (whichever occurred first) at a pressure range of approximately 100 psi to 992 psi. These pressure values are referred to in this paper as having a range equal to 72% of the pressure imposing the specified minimum yield strength (SMYS) in the hoop direction, varying from 100 psi, or 8% SMYS to 992 psi, or 80% SMYS.

Of the 11 tested systems, six products used to repair plain dents were able to achieve the 250,000 cycle run-out condition as shown in Figure 6. Some samples ran for more than 250,000 cycles. One repair system was cycled beyond the run-out condition to determine the actual limit state of the pipe, which resulted in a fatigue failure of the ERW seam in the base pipe (outside of the repairs) at 358,470 cycles.

As seen in other composite repair studies, the effectiveness of a composite repair is directly proportional to the level of reinforcement that it provides to the damaged pipe material. In this particular study, those systems that were most effective were able to significantly reduce strains in the dented regions of the pipe samples. Table 3 lists strain ranges for each of the repair systems in reinforcing plain dents.

CLOSING COMMENTS

The paper was prepared to provide the pipeline industry with a resource for evaluating the design of composite repair technology based on numerous programs conducted for the pipeline industry. The resources included in this document represent a significant body of work completed over the past 20 years focused on understanding the mechanics and materials of composite repair technology. The insights gained in completing these studies have been used to establish the technical foundation for repairing a wide range of anomalies and features in high-pressure gas and liquid pipelines.

The foundation for using composite repair systems to reinforce high pressure pipelines is built on two cornerstones. The first is a good design basis, preferably in accordance with the ASME PPC-2 or ISO 24817 composite repair standards. The design integrates material properties for the system in question to establish the repair dimensions (i.e., thickness and length), as well as establishing the limitations for the repair considering factors such as operating temperature and cyclic pressure conditions. The second cornerstone is validation of the design itself via destructive testing. Because of the multiple components involved in every composite repair system (i.e., fiber, polymer matrix, and load transfer filler material), it is essential

that the interdependent behavior of the components be evaluated simultaneously. Some of the early composite repair research failed to take this interdependency into account.

This paper has provided the reader with an overall understanding on the composite repair technology's state of the art, while at the same time providing a detailed explanation of the design basis for modern composite repair technologies. As numerical modeling and testing techniques evolve, it is possible for optimized solutions to be developed for specific applications. In moving beyond conventional uses for repairing and reinforcing pipelines, such as the reinforcement of corrosion and dents, the foundational elements provided in this paper can be used to evaluate future applications.

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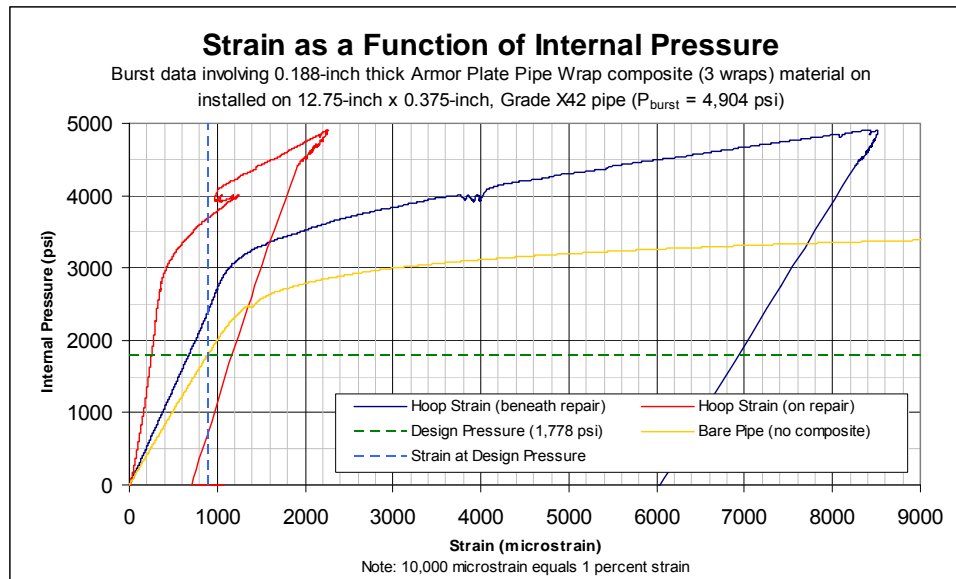
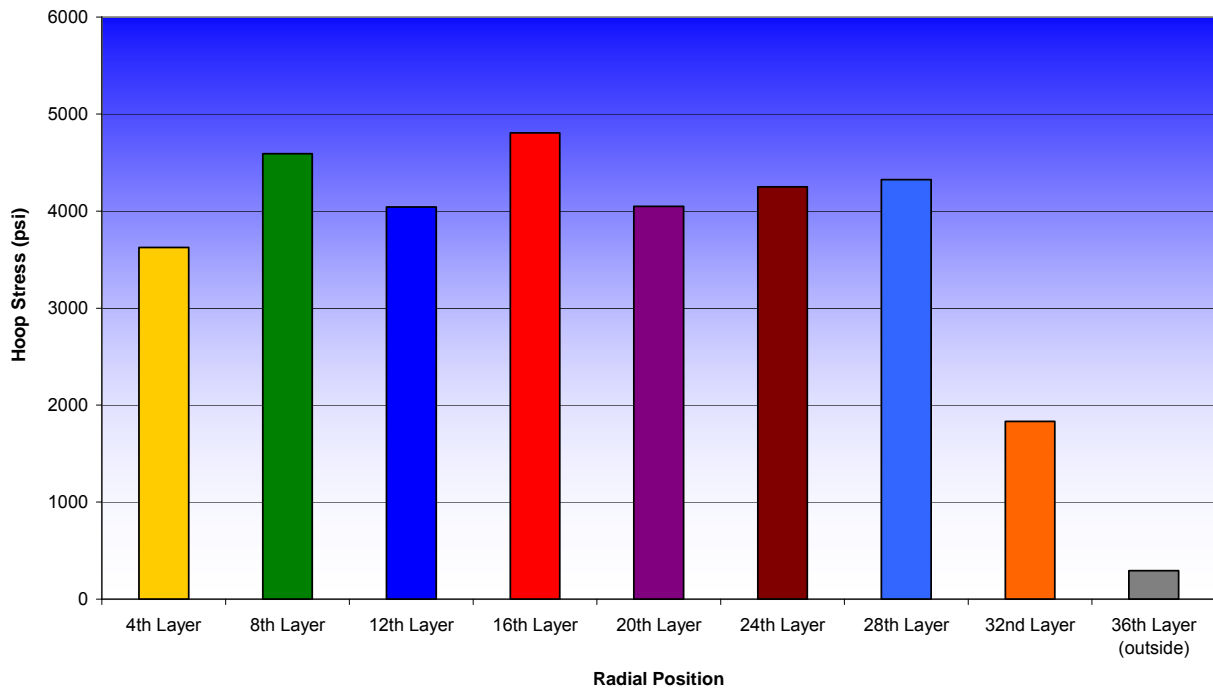**Figure 1: Strain measurements for composite-reinforced test samples**

Figure 2: Hoop Strain at 72% SMYS per radial position for System #1
(Hoop stress calculated as the product of measured strain and the composite's elastic modulus)
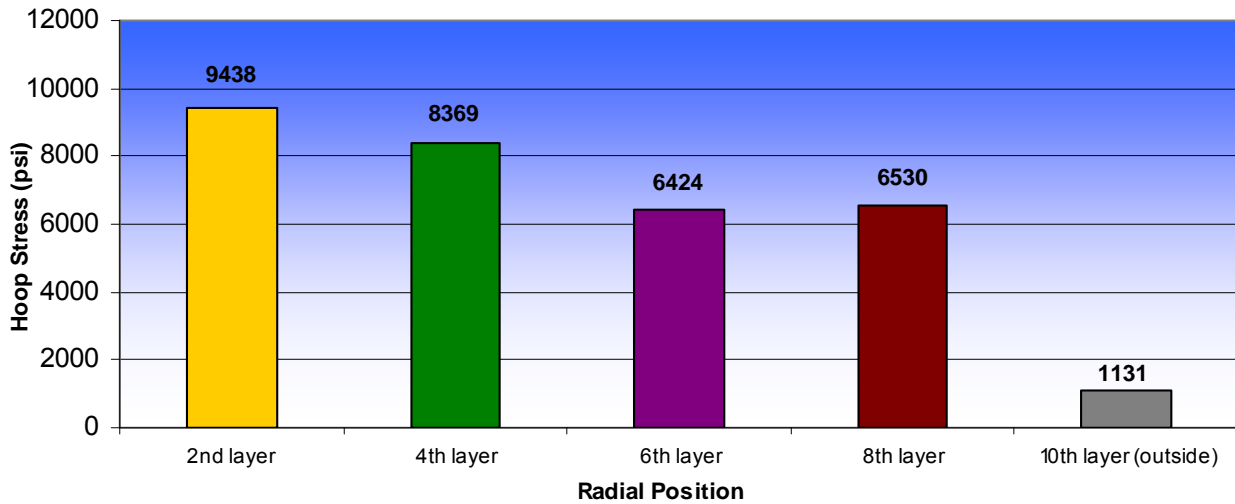

Figure 3: Hoop Strain at 72% SMYS per radial position for System #2
(Hoop stress calculated as the product of measured strain and the composite's elastic modulus)
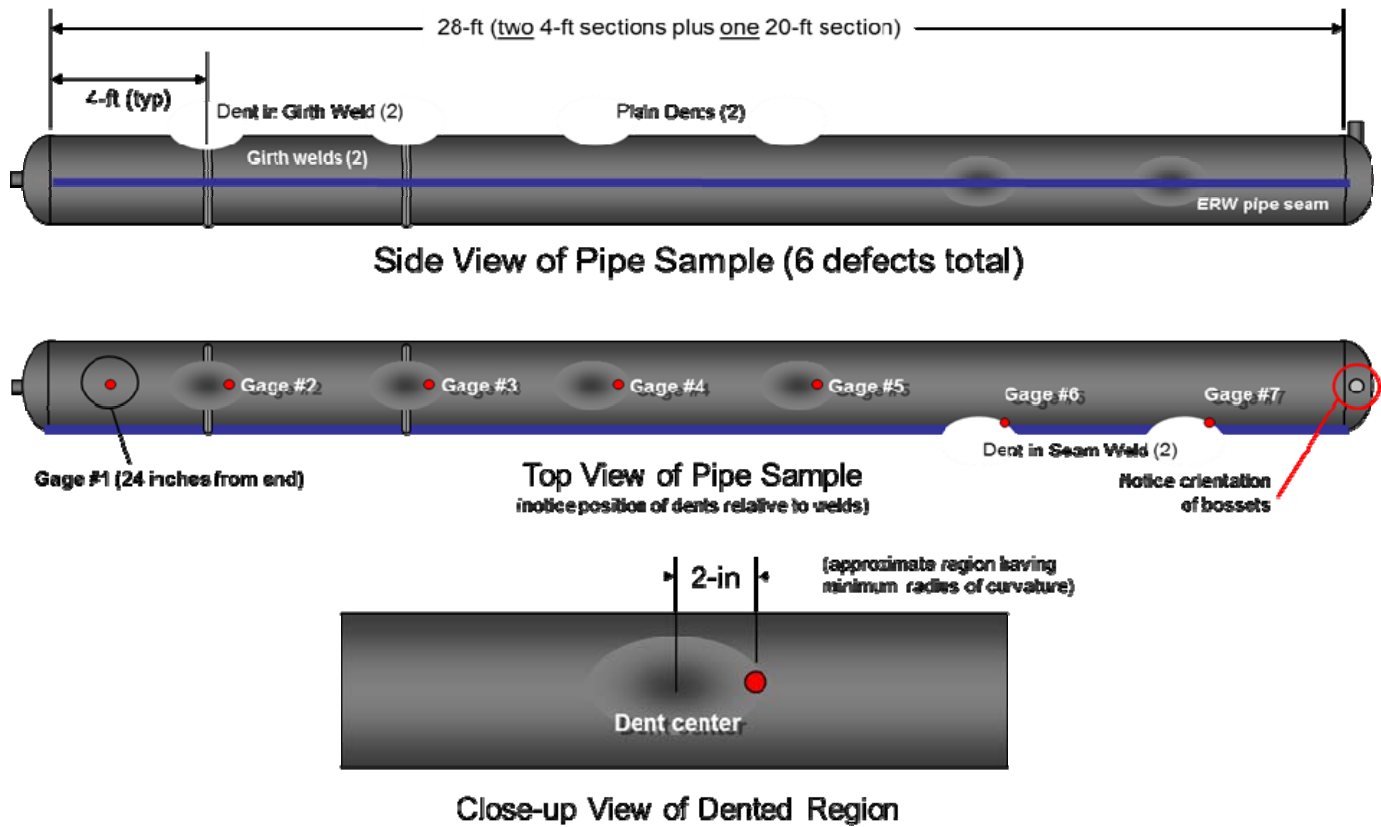
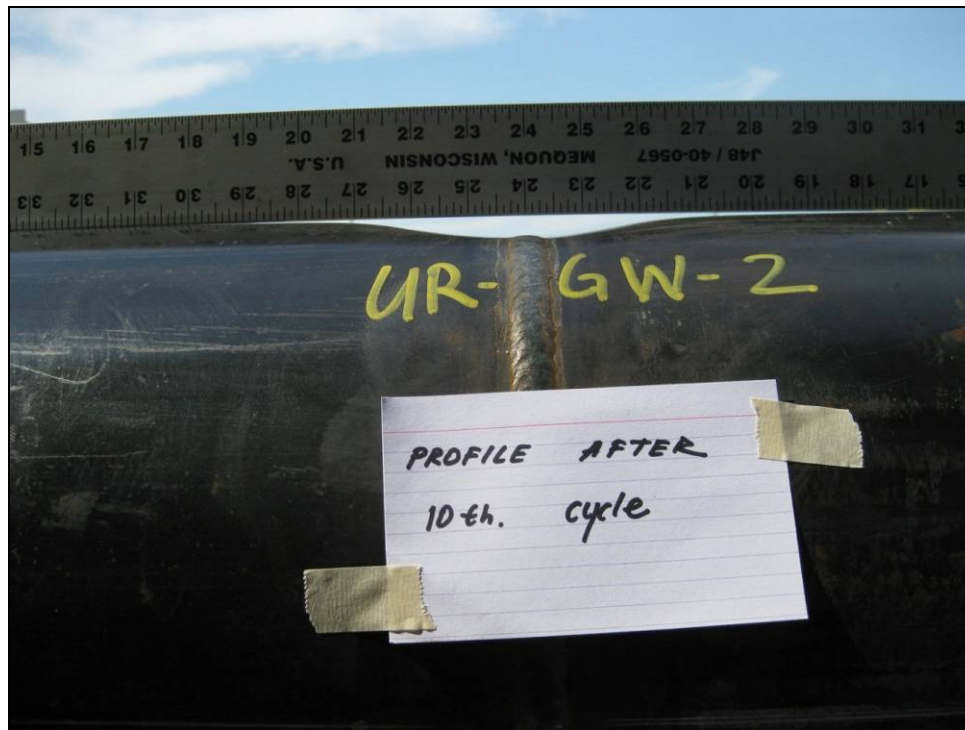**Figure 4: Dented pipeline samples including strain gage locations**

Figure 5: Photograph showing side view of dent after 10 pressure cycles
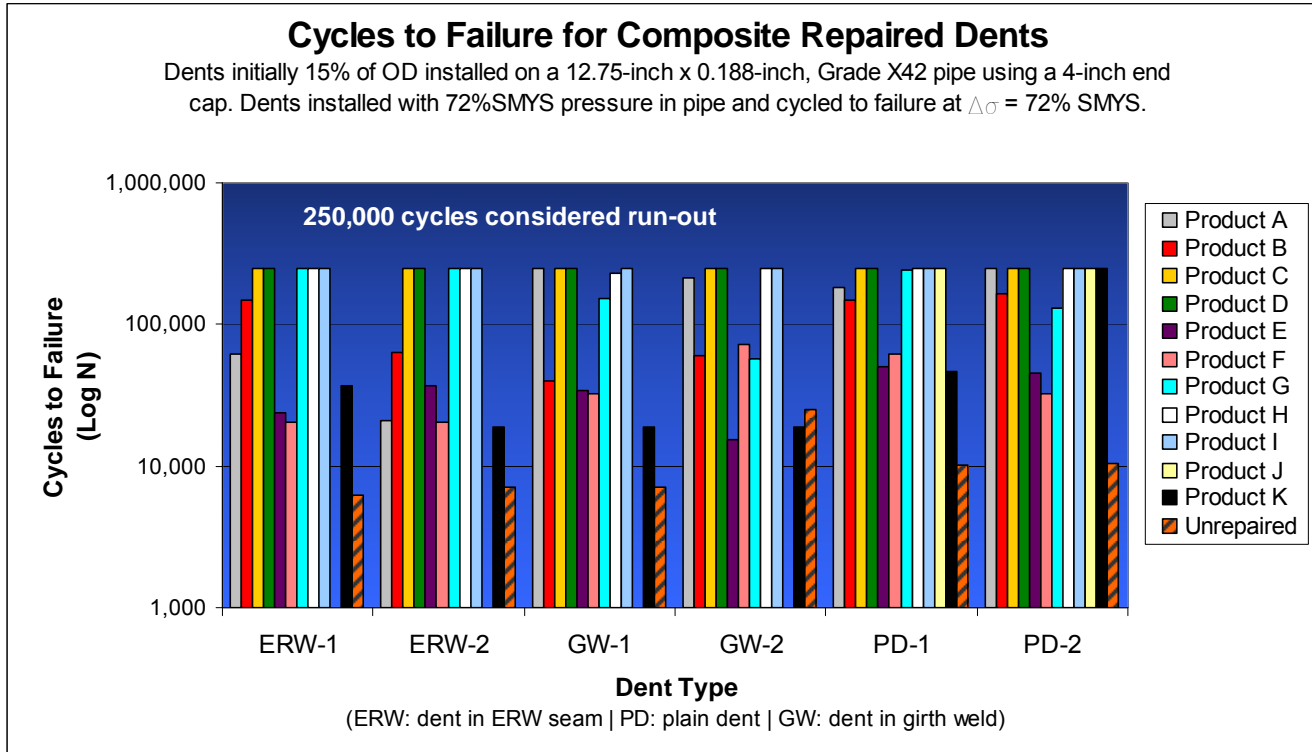
Cycles to Failure for Composite Repaired Dents

Dents initially 15% of OD installed on a 12.75-inch x 0.188-inch, Grade X42 pipe using a 4-inch end cap. Dents installed with 72%SMYS pressure in pipe and cycled to failure at $\Delta\sigma$ = 72% SMYS.

Figure 6: Pressure cycle fatigue data for MATR-3-5 study

Table 1: Comparison of Measured Stresses to PCC-2 Design Stresses

Stress Value	Calculation Variable	System #1 (t_{comp} = 0.76 inch)	System #2 (t_{comp} = 0.63 inch)
Mean Tensile Stress (based on short-term tensile testing)	A	51,700 psi	72,088 psi
Long-term Design Stress, S_{lt} (based on PCC-2 Appendix V testing)	B	20,369 psi	23,836 psi
Allowable Stress (based on short-term tensile testing)	C	10,184 psi	11,918 psi
Maximum Stress in Composite (based on measured strain values)	D	4,806 psi	9,438 psi
Maximum Measured Strain in Steel (75% corroded region)		2,976 µε	3,125 µε
Resulting Design Margins			
Mean Tensile Stress vs. Allowable Stress (A/C)		5.1	6.0
Mean Tensile Stress vs. Maximum Stress (A/D)		10.8	7.6
Usage Factor (percentage of allowable, D/C)		47%	79%

Note: 10,000 microstrain (µε) equals 1% strain.

Table 2: Results from MATR-3-4 Study – Long-term Repair of Corrosion

Measurements at MAOP (72% SMYS)			Measurements at 100% SMYS		
Minimum Hoop Strain	Maximum Hoop Strain	Average Hoop Strain	Minimum Hoop Strain	Maximum Hoop Strain	Average Hoop Strain
ALL composite repair systems					
1,829 µε	8,852 µε	3,734 µε	2,250 µε	8,852 µε [1]	4,905 µε
E-glass fiber composite repair systems ONLY					
2,667 µε	8,852 µε	4,497 µε	3,185 µε	8,852 µε [1]	5,692 µε
Carbon fiber composite repair systems ONLY					
1,829 µε	3,087 µε	2,524 µε	2,250 µε	4,106 µε	3,292 µε

Notes:
1. The maximum hoop strain measurement was actually higher as strain gage stopped working.
2. 10,000 µε corresponds to 1% strain.

Table 3: Results from MATR-3-5 Study – Repair of Dents
Plain dent hoop strain gage measurements (Δε at ΔP = 72% SMYS)

Product	Hoop Strain (microstrain)			Plain Dent Experimental $N_{average}$
	Plain Dent #1	Plain Dent #2	Average	
A	1,753	1,990	1,872	215,271
B	1,748	1,894	1,821	157,351
C	950	1,148	1,049	250,000
D	596	549	573	250,000
E	2,176	2,477	2,327	47,661
F	1,544	1,814	1,679	47,299
G	901	1,018	960	186,452
H	586	860	723	250,000
I	689	726	708	250,000
Unrepaired	4,396	4,678	4,537	10,249