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COMPOSITE REPAIR PERFORMANCE AT ELEVATED TEMPERATURES

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

Jim Souza
Pipe Wrap, LLC
Houston, Texas
jzouza@piperepair.net

Casey Whalen
Pipe Wrap, LLC
Houston, Texas
cwhalen@piperepair.net

ABSTRACT

For the better part of the past 20 years composite materials have been used to repair damaged piping and pressurized components in plants, refineries, and pipelines. The use of composite materials has been accompanied by comprehensive research programs focused on the development and assessment of using composite technology for restoring integrity to damaged piping and pressurized components. Of particular interest are composite repair standards such as ISO 24817 and ASME PCC-2 that provide technical guidance in how to properly design composite repair systems.

The vast body of research completed to date has involved assessments at ambient conditions; however, at the present time there is significant interest in evaluating the performance of composite repair materials at elevated temperatures. This paper is focused on the topic of high temperature composite repairs and addresses the critical role of utilizing temperature-based mechanical properties to establish a composite repair design. The backbone of this effort is the development of composite performance curves that correlate change in strength as a function of temperature. A discussion on supporting full-scale pressure test results are included, along with guidance for users in how to properly design composite repair systems for applications at elevated temperatures.

BACKGROUND

To provide the reader with background information on the use of composite materials, the authors have included documentation related to their recent history, information on the materials associated with the Atlas HT carbon-epoxy system, and a discussion on recent interests in using composite repairs at elevated temperatures.

Brief history of composite repair and research to date

The repair of pipelines and piping using composite materials has been widely accepted. The primary drivers behind the acceptance of this repair method have been composite manufacturers who have developed the repair systems and operators who have benefitted from their capabilities. The advantages in using composite materials for repairing damaged systems over conventional welded steel repairs include ease of installation, not welding, safety, ability to leave systems in service, and economics.

Accompanying the acceptance of composite materials have been extensive research efforts, primarily funded by the pipeline industry. Groups such as the Pipeline Research Council International, Inc., Gas Research Institute, oil and gas pipeline companies, and composite manufacturers have funded these programs. Research has been aimed at evaluating a wide range of anomalies including corrosion, dents, mechanical damage, defective seam and girth welds, and wrinkle bends. In these programs, more than 20 different systems have been evaluated. As a result, the industry's knowledge has advanced significantly.

Discussion on the Atlas CFE system

The Atlas HT system was developed by Pipe Wrap LLC to utilize the benefits of a high strength carbon fiber fabric with a proprietary high-temperature resistant, epoxy resin. The filler material and adhesive used on this system were also uniquely developed to address the needs of pipe rehabilitation at elevated temperatures.

The carbon fiber fabric developed by Pipe Wrap LLC is composed of bi-directional fibers. The tow count was determined for optimum hoop strength reinforcement around a pipe, while still supporting axial stiffness to resist axial tension and bending moments. A relatively thin weave was used to allow for easy handling and flexibility. This allows the fabric to intimately contact and conform to the pipe surface, thereby reducing the creation of inter-laminar voids during installation. Due to the conductive nature of carbon, a fiberglass weave is used as a first layer in the repair design as an isolation barrier. This eliminates any possibility of the carbon interfering with the cathodic protection systems. This thin layer of fiberglass is ignored in the design because the small amount of additional strength to the repair is insignificant.

The resin matrix used in the Atlas HT system is a multi-state curing system allowing for variable glass transition temperatures (T_g). This system requires an elevated step-wise temperature cure that can range up near 500°F (260°C) to achieve optimum mechanical properties. Because this particular system is a multi-state curing system, it allows one system to be cured at various temperatures to provide flexibility of matching the required temperature performance as determined by the repair scenario. With a T_g near 489°F (254°C), this matrix allows Atlas HT to be utilized at temperatures up to 420°F (216°C). As with most resins, strength and modulus decrease at elevated temperatures. Figure 1 illustrates a DMA analysis on the resin, which shows a gradual reduction in the loss and storage moduli with increasing temperature.

The filler material utilized as a load transfer mechanism was designed and developed to work in conjunction with the Atlas HT system. This paste utilizes unique additives to achieve a desired compression strength and modulus. The thermal properties show a similar T_g to the epoxy resin and a similar decrease in properties with increasing temperature. Compression coupons were created according to ASTM D695 and tested at various temperatures to determine change in material properties as a function of temperature. A general decrease in compressive strength is observed as temperature increases. With a value near 20 ksi (137 MPa) at room temperature, the compressive strength drops gradually to 13 ksi (89 MPa) near 392°C (200°C) as shown in Figure 2.

The adhesive was also formulated with additives to optimize properties for pipe repairs at high temperatures. An optimized level of adhesion between the filler material, adhesive and the composite resin is achieved due to the molecular design of each component. The lap shear strength of the adhesive was determined by performing a double lap shear sample using carbon-steel plates bonded together solely with the adhesive. Figure 3 shows the average load versus temperature test results. These samples were initially cured at 248°F (120°C), and eventually post-cured at 446°F (230°C). A maximum performance is observed near the cure temperature and gradually tapers off as the material approaches its T_g.

The components in this system, most notably the different polymer-based components, were all developed to create an optimum product designed for the specific purpose of composite repairs for reinforcing pipelines and piping operating at elevated temperatures. In this sense, the key elements to consider are the lap shear strength for the adhesive, compressive properties for the filler material and tensile strength and modulus characteristics for the composite wrap. While there are other properties that require consideration, these properties have the greatest influence on composite repair performance. Other considerations include environmental conditions, cyclic responses, and fatigue life.

Recent interest in high temperature applications

Although composites have been widely used for many years in plants and refineries as short term repairs of low pressure piping systems operating up to 450 ^{0}F (232 ^{0}C), there is an ever increasing interest in longer term repairs at these conditions. Encouraged by the long-term performance of composite repairs at ambient conditions, this interest has extended into the high-pressure pipeline systems operating between 140 ^{0}F - 300 ^{0}F (60 ^{0}C - 149 ^{0}C). As the interest of longer repair life increases for elevated temperature conditions, the composite repair systems must be properly designed and evaluated because polymer systems exhibit a gradual decrease in mechanical performance when exposed to increasing temperature conditions. An improperly designed system can fail either immediately or prematurely.

The composite design standards ASME PCC-2 and ISO 24817 have a temperature de-rate factor for elevated conditions that attempt to replicate the degradation versus exposure to increased temperature condition. This de-rate factor establishes the upper operating temperature limits for the composite system based on the resin's glass transition temperature (T_g). When exposed to temperatures approaching the T_g, most resins experience significant decreases in strength and modulus, resulting in a composite repair that no longer functions as designed.

Additional considerations should be given to, though rarely mentioned, the effects of temperature on the load transfer filler and the adhesive. It is very important to know how these two elements behave at elevated temperature to determine the longevity of a repair. Compressive properties of filler material may degrade resulting in early cracking and failure to properly transfer load to the composite. Likewise, adhesive bond strength may degrade at higher temperatures even though the temperature has not surpassed the glass transition temperature (T_g).

DESIGN BASIS FOR COMPOSITE REPAIRS

A good design basis is central to the successful use of composite repair systems. The ASME PCC-2 and ISO 24817 standards have provided for industry a common platform for not only designing composite repair systems, but have provided a means for comparing competing composite technologies. This section of the paper provides details on designing a composite repair system, with a specific emphasis on designing for high temperature applications.

ASME PCC-2 Design methodology

For much of the period during which composite materials have been used to repair pipelines and piping, industry has been without a unified standard for evaluating the design of composite repair systems. Under the technical direction of 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 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 / Shore): 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 criteria.

Conventional ASME PCC-2 design at elevated temperatures using de-rating factors

Under Part 4.1 of the ASME PCC-2-2011 standard, there are several sections directly relevant to high temperature conditions. In section *3.4.2 Service Temperature Effects paragraph (a)*, upper boundary temperature limits are set for the repair system. A designated temperature constant is subtracted from either the glass transition temperature or the heat distortion temperature as shown in Table 1. T_m is the maximum temperature design limit of the repair system.

Paragraph (c) provides an equation to determine the temperature factor, f_T, which has maximum possible value of 1 (one). Equation 1 displays the equation for a temperature de-rate factor from ASME PCC-2-2011 (p. 143), specifically for temperatures in Celsius; T_d is defined as the design temperature of the repair system.

$$f_T = 6 \times 10^{-5} (T_m - T_d)^2 + 0.001 (T_m - T_d) + 0.7014 \quad \textbf{(1)}$$

Once calculated, the temperature factor is then used to determine allowable repair laminate strains as defined in PCC-2. Additionally, this equation takes into account stress induced by differences in thermal expansion between the repair and substrate. The symbols α_c and α_s represent the coefficient of thermal expansion (CTE) between the repair and substrate respectively. The value ε_{c0} is defined by PCC-2 as 0.25% for circumferential continuous loading (Equivalent to a 20-year design in ISO 24817-2006). ΔT is the absolute temperature change between installation and operating temperature. Equation 2 is the allowable repair laminate strains – circumferential (ASME PCC-2-2011 Part 4.1, pg. 145, Eq. 10a).

$$\epsilon_c = f_T \epsilon_{c0} - \Delta T (\alpha_s - \alpha_c) \quad (2)$$

Having determined the allowable repair strain, de-rated for higher temperatures, this value, ε_c, can be used in either the design method described in section *3.4.3.2 Underlying Substrate Yields* or *3.4.4 Repair Laminate Allowable Strains* to determine a minimum repair thickness. This design method, however, makes several assumptions on material performance. The only data used for the design material are room temperature strength values, CTE, and T_g or HDT. For the design case of a repair performed on a pipe operating at 248°F (120°C), the Atlas HT system would result in a temperature de-rate factor of 1.00 due to its relatively high T_g.

Alternatively, *3.4.5 Repair Laminate Allowable Stresses Determined by Performance Testing* can be used if performance testing, as outlined in *Article 4.1, Mandatory Appendix V*, was conducted at temperatures at or above the design temperature. If this test is performed at room temperature, the composite system is not qualified for higher temperature designs. If the test is performed at high temperatures, any repairs performed at lower temperatures are automatically over-designed.

Proposed methodology integrating actual material performance curves

For designs using high temperature materials, establishing a relation between ultimate tensile strength (UTS) and temperature can be an effective and more accurate methodology. First, use allowable strains to determine design life. UTS values need to be determined based on the design temperature. Establish a long-term stress value matching a 20-year design as defined by standards. Determine the relation between stain and long-term stress and set a maximum stress based on design life. By using this method, accurate designs can be calculated for the material depending only on the desired repair life. In this way, there are no assumptions regarding temperature effects on composite material performance. Rather, this method allows one to accurately design a composite repair based on tested material performance and desired design life. This approach accounting for degradation in material strength with increasing temperature is also consistent with the design methodology embodied in the ASME Boiler & Pressure Vessel Codes, where stress limits are established as a function of temperature.

In transmission pipelines, it is becoming more common for a 50-year design to be established. Additionally, in this design, a temperature of 248°F (120°C) was taken into consideration. The ISO 24817-2006 standard was used to project a 50-year design. This edition gives allowable strain values for 2, 10 and 20-year designs dependent on the operating class defined in section 6.2. A logarithmic extrapolation was used to project an acceptable "design allowable strain" for 50 years resulting in a value near 0.20% ~ 0.21%.

For design purposes, it was desirable to quantify the effects of temperature on the material properties, including UTS, of the Atlas HT composite system. Samples were tested at 81°F, 140°F, 176°F, 212°F, 248°F, and 284°F (27°C, 60°C, 80°C, 100°C, 120°C and 140°C) to establish an average UTS-temperature response curve. However, only data up to 212°C (100°C) was available for the initial design. This available data was used to estimate a conservative lower bound UTS of 142 ksi (979 MPa) at 248°F (120°C). This approach differs from the conventional ASME PCC-2 method in which a de-rating factor would be used. For this particular case, there would be no change in the design of 248°F (120°C) repair using the values obtained at 81°F (27°C) because the calculated temperature de-rate factor at this particular temperature is 1.00. As a result, a design using the ASME PCC-2 approach would result in a design based on an ultimate tensile strength near 205 ksi (1,413 MPa); a value that would result in an unconservative composite repair thickness.

A conservative estimated a long-term stress (s_{lt}) value of 56.8 ksi (392 MPa) was then determined as 40% of the UTS. Previous testing has shown this method to be very reliable, but conservative. At this point, several assumptions were made to create a 50-year design. Most notably, a s_{lt} of 56.8 ksi (392 MPa)corresponds with a 20-year repair when using a service factor (f_s) of 0.5, as stated in ISO 24817-2006 Table 9. With an s_{lt} and an ε_c design number for 20 years, and a targeted ε_c design for 50 years, two similar equations in the ASME PCC-2 standard (one using $E_c*\varepsilon_c$, the other f_s*s_{lt}) were matched to determine an s_{lt} value approximating a 50-year design. A value of 41.8 ksi (288 MPa) was selected, resulting in a 24-layer design. Results for this design are provided in Table 2.

TESTING EFFORTS

Testing is an essential element for evaluating composite repair systems; this includes sub-scale coupon tests and full-scale destructive testing. The motivation for testing is driven by the need to understand the complex interactions that occur between the different materials making up the repair system and their interaction with the reinforced steel substrate. Additionally, understanding the limit state (ultimate capacity) of a repair is necessary to ensure that at no point during operation of the reinforced system that the repair is subjected to unacceptable loads.

The subject matter of this paper is directed at the use of composite materials at elevated temperatures. The need for testing is even greater when evaluating the performance of composite materials subjected to high temperatures. Because most of the polymers used in conventional composite repair materials (i.e. epoxies and urethanes) are subject to temperature degradation, it is essential that the level of reinforcement be known as a function of temperature. The simplistic approach taken by the current Composite Standards to merely set operating temperature thresholds for design purposes is generally insufficient.

The sections that follow provide information on tests that were conducted on the Atlas CFE composite repair system at elevated temperatures using sub-scale and full scale testing.

Sub-scale testing to achieve performance curves

Coupon tests are useful for determining the strength and stiffness (i.e. elastic modulus) of composite materials. These material properties are necessary for designing repair systems as they dictate the required thickness levels. When considering the use of composite materials at elevated temperatures, material data is even more important. As the authors will present, an ideal means for designing a composite repair system for elevated temperature applications is to integrate design strength as a function of temperature.

Two types of sub-scale tests are used to design the composite repair. The short-term tensile test is used to quantify tensile strength (and modulus, if so desired) as a function of temperature. To establish, or validate, the long-term performance of the composite repair design, creep testing is used. In creep testing coupons involving elevated temperatures are subjected to varying loads as a function of time.

Short-term tensile testing Flat panels using the Atlas CFE system were fabricated. From these panels test coupons were taken and tested as a function of temperature. Testing was conducted in accordance with ASTM D3039.The key in this round of testing was to measure tensile strength as a function of temperature.

Provided in Table 3 is a summary of short-term tensile strengths as a function of temperature. As observed in the list, the maximum tensile strength occurred at room temperature at 229 ksi (1,579 MPa). The minimum tensile strength occurred at 212° F (100°C) at 169 ksi (1,165 MPa), not considering the failure in the grip. Figure 4 is a plot of the tabulated data showing tensile strength as a function of temperature. Also included in this figure is an equation correlating strength as a function of temperature. Curves fits of this type are useful for design purposes as they can be used to account for reductions in material strength with increasing temperature.

Creep testing This paper does not include any specific creep test data; however, creep testing is useful for establishing long-term performance characteristics of composite materials. At the present time, the Atlas CFE system is undergoing a 10,000-hour test at 248° (120°C) conditions where 18 different coupon samples are subjected to different loads for designated periods of time up to 10,000 hours. At the end of the current study, a curve will be generated plotting tensile strength as a function of time. The ASTM D2992 document provides details on the technical aspects associated with this type of testing work.

Figures 5 and 6 are photographs of the Stress Engineering Services Inc. creep test facility. Figure 7 is a schematic showing the layout of the test facility. The set-up has two 10-station creep machines, permitting 20 samples to be tested at one time. Each station has a capacity of 3,000 lbs. The heating unit has a temperature range up to 248°F (121°C). The system has an automatic break-detection feature where temperatures and rupture time are recorded by a computer.

Full-scale pressure test

In addition to the sub-scale coupon tests, full-scale testing was conducted. This particular test involved the repair of a simulated 75% corrosion defect machined into a 12.75-inch by 0.375-inch, Grade X42 pipe sample (actual material properties were as follows: Yield Strength of 53.2 ksi (367 MPa) and UTS of 75.5 (520 MPa)). Figure 8 is a schematic showing the set-up for the test sample, including machining details.

Strain gage were installed on the test sample, along with thermocouples, prior to installation of the Atlas CFE composite material. Figure 9 shows a close-up of the strain gages installed in the machined region of the test sample. Also included in this figure (upper right hand side) is a photograph of the wall thickness measurements made after machining. After installation of the composite material, thickness of the repair was measured to be approximately 0.43 inches (10.9 mm). Figure 10 is a photograph of the composite repair after installation.

Prior to the application of internal pressure, the test sample was filled with heat transfer oil. This medium was selected as the target test temperature was 248°F (120°C), a temperature that precluded the use of water due to the potential formation of steam in the sample. Figure 11 is a photograph of the sample in the test pit with insulation and induction heating coils. During pressure testing, internal pressure, strain and temperature were monitored at a rate of 1 scan per second.

Figure 12 shows a plot of hoop strain as a function of internal pressure at 248°F (120°C). Pressure holds of 5 minutes were made at 1,778 psi (12.3 MPa, 72% SMYS, where SMYS is the Specified Minimum Yield Strength of the pipe material) and 2,470 psi (17 MPa, 100% SMYS). Gage #1 was located in the middle of the simulated corrosion region and measured hoop strains of 1,832 με (microstrain) and 2,572 με at the 72% and 100% SMYS pressure levels, respectively (note: 10,000 με corresponds to 1% strain). Also included in Figure 8 are hoop strains measured on the base pipe.

Typically, internal pressure in reinforced pipe samples is increased to failure; however, due to safety concerns a maximum pressure of 3,765 psi (26 MPa) was applied. Prior tests on similar pipe material resulted in burst pressures of approximately 4,100 psi. As observed in Figure 12, by the point the maximum pressure of 3,765 psi (26 MPa) was reached strain in the main body of the pipe sample were exceeding strain levels beneath the repair in the simulated corrosion region.

Results for a second test are included in this paper, although this particular test was not part of the current high temperature study. A similar test was conducted using the same sample reinforced with the Atlas CFE system; however, no elevated temperatures were involved.

Hoop strain results for this test are plotted in Figure 13. As observed, during pressurization to the design pressure of 72% SMYS (1,778 psi), the maximum strain measured in the reinforced corroded region was 2,259 με. In comparison, the hoop strain for the high temperature at the same pressure level was 1,832 με. It should be noted that the thickness of the high temperature repair was 0.43 inches, while the thickness of the room temperature test was 0.28 inches.

NUMERICAL MODELING

While the vast majority of work associated with the composite reinforcement of pressurized piping and pipelines has involved experimental investigations, some numerical modeling work has been conducted. It is the author's observations that the role of numerical modeling in optimizing composite reinforcement will play a larger role in the design of future repairs. In terms of information available in the open literature, a body of work completed by Alexander et al presented at OMAE 2008 provides findings from a study involving the design and optimization of a carbon-epoxy system using finite element analysis (FEA) and full-scale destructive testing.

Using the same composite repair optimization approach, a recent study evaluated the reinforcement of pipe fittings using E-glass epoxy composite materials. This work involved optimization of the composite design using elastic-plastic FEA, in conjunction with full-scale testing. The optimization involved variations in composite thickness and fiber orientation. Experimental strain measurements beneath the composite reinforcement in the reinforced steel were correlated with finite element analysis results. Several figures are included from this recent analysis work and are listed below:

- Figure 14: Finite element model showing composite reinforcement
- Figure 15: Architecture of two different competing composite reinforcement configurations
- Figure 16: FEA model contour plots showing pressures required to induce yielding

The work as shown in these figures is a good representation of the type of numerical modeling that can be conducted to study the ability of composite materials to reinforce damaged piping and pipelines. Of particular interest is the magnitude of reinforcement provided by the composite material to the reinforced steel. The calculated stresses in the composite material should be compared to allowable design stresses based on the governing composite repair codes. The stresses (and strains) in the reinforced steel should be carefully evaluated to ensure that the repair achieves the intended design conditions, including cyclic service, if applicable.

As the subject matter of this paper is the use of composite materials at elevated temperatures, it is appropriate to provide a few comments regarding numerical modeling. The most fundamental composite material property used in FEA modeling is elastic modulus. The modulus, along with thickness of the composite, governs the magnitude of provided reinforcement. When modeling elevated temperature applications, it is critically important that the effects of temperature on the elastic modulus be included.

Although elastic modulus data has not been included in this paper, the trends observed in Figure 4 for tensile strength demonstrates the reduction in strength with increasing temperature. A similar trend would be expected for the elastic modulus. In addition to the elastic modulus, numerical models should consider temperature-dependent properties of the filler (i.e. load transfer) materials when appropriate; such as cases involving severe corrosion or reinforcing dents.

DISCUSSION

This paper has provided information on a series of tests conducted to evaluate the performance of a carbon-epoxy repair system evaluated at elevated temperatures. Although the design basis is in large part based on the requirements set forth in ASME PCC-2, the design for elevated temperatures is based on performance of the composite material as a function of temperature.

As conveyed in this paper, conducting a combination of sub-scale coupon tests, in conjunction with full-scale destructive tests, is essential for engineers to understand the limit state capacity of a given repair at elevated temperatures. Because the results included in this paper are part of an ongoing study, the authors are not able to present the design story in its entirety; however, the use of appropriate safety factors to account for strength degradation at elevated temperatures have been used in the original design. It is appropriate to utilize reduced safety factors as knowledge increases on the performance of the composite material.

Strain measurements in the corroded region of the short-term burst test are certainly within the acceptable range for competing technologies. As a point of reference, the average hoop strain at 72% SMYS for the three participating carbon composite repair systems in an industry study sponsored by the Pipeline Research Council International, Inc. (PRCI) was 2,524 με (at ambient temperatures), which is greater than the hoop strain of 1,832 με measured for the Atlas CFE system at 120°C by approximately 40%.

With a design of 24 layers, the short-term burst test was conducted and performed better than expected. At 72% SMYS, the resultant strain was measured as 1,832 με (0.183%). This value was below the targeted 0.20% and indicates a slightly overdesigned repair. Using a less conservative linear extrapolation, shown previously in Figure 4, an average UTS near 170 ksi (1,172 MPa) can be calculated. Table 4 represents a more accurate design, integrating a UTS of 170 ksi (1,172 MPa). Using this value, a 24-layer design predicts 0.18% strain, which is validated by the short-term burst test. To more closely match our estimated 50-year design condition (strain near 0.205%), 20 layers of Atlas HT material would have sufficed using 43 ksi (296 MPa) as the 50-year s_{lt}. It should be noted that the 20-year design s_{lt} is still 40% of the UTS, in this case 68 ksi (468 MPa).

CLOSING COMMENTS

The paper has presented findings from a recent study evaluating the performance of a carbon-epoxy composite repair systems used to repair a corroded pipe sample subjected to internal pressure at elevated temperature conditions. The ASME PCC-2 and ISO 24817 composite repair standards were used in part to determine the required thickness of the repair. Ultimate actual tensile strength values based on cub-scale coupon tests near the target temperature were used to predict a more accurate repair. A comprehensive test program involving a combination of short-term coupon tests, long-term creep tests, and full-scale pressure tests are used to validate the design.

The program addressed in this study is a model for the approach that should be utilized by operators seeking to use composite materials outside their conventional design envelope. Although the focus of this particular study was on performance at elevated temperatures, other "non-conventional" conditions that should be studied include operating with cyclic pressures, subsea applications, and combined loading conditions including pressure, tension, and bending. The concept "when in doubt, test to failure" is the best means for ensuring a proper design and implementation of a given composite repair system for long-term use is achieved.

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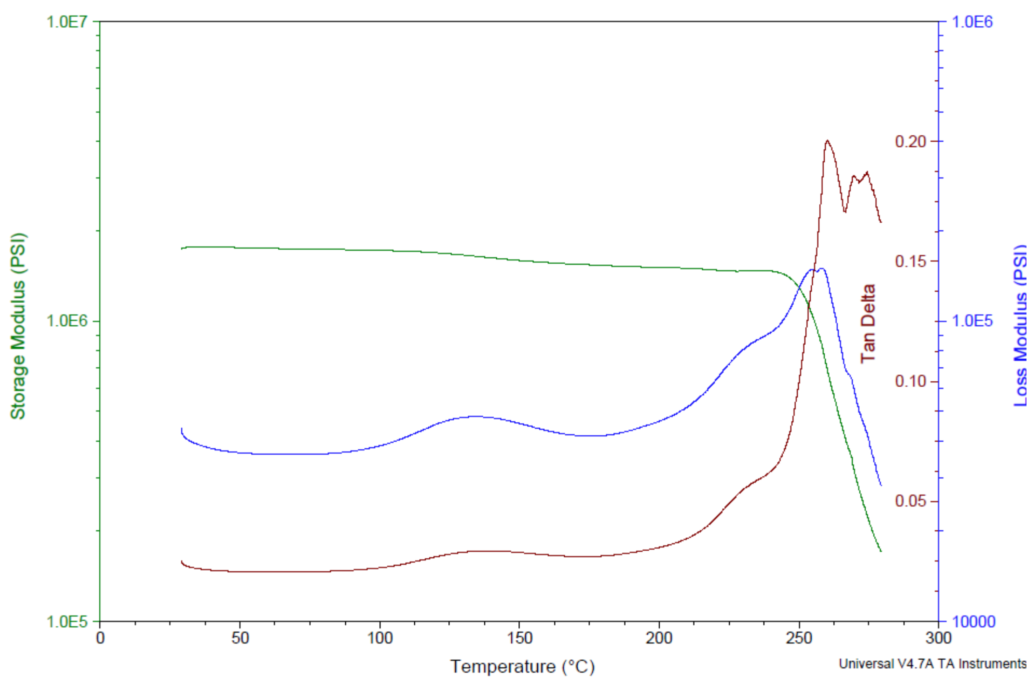

Figure 1 - DMA result on the Atlas HT system

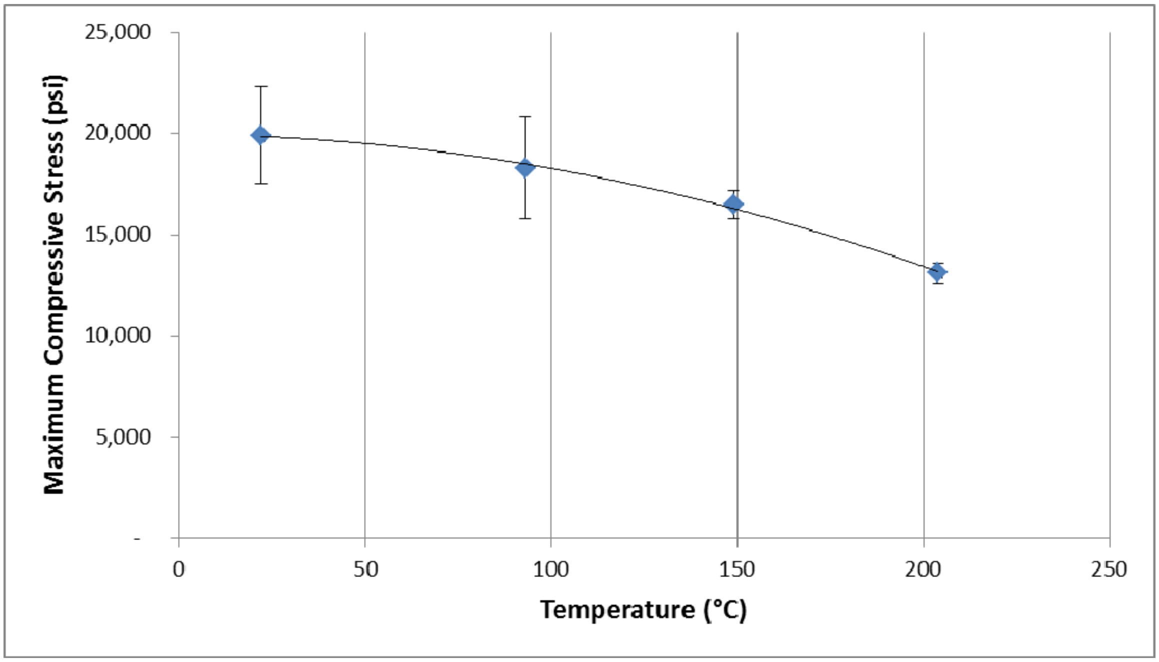

Figure 2 - Compressive strength results of HT filler (load transfer) material

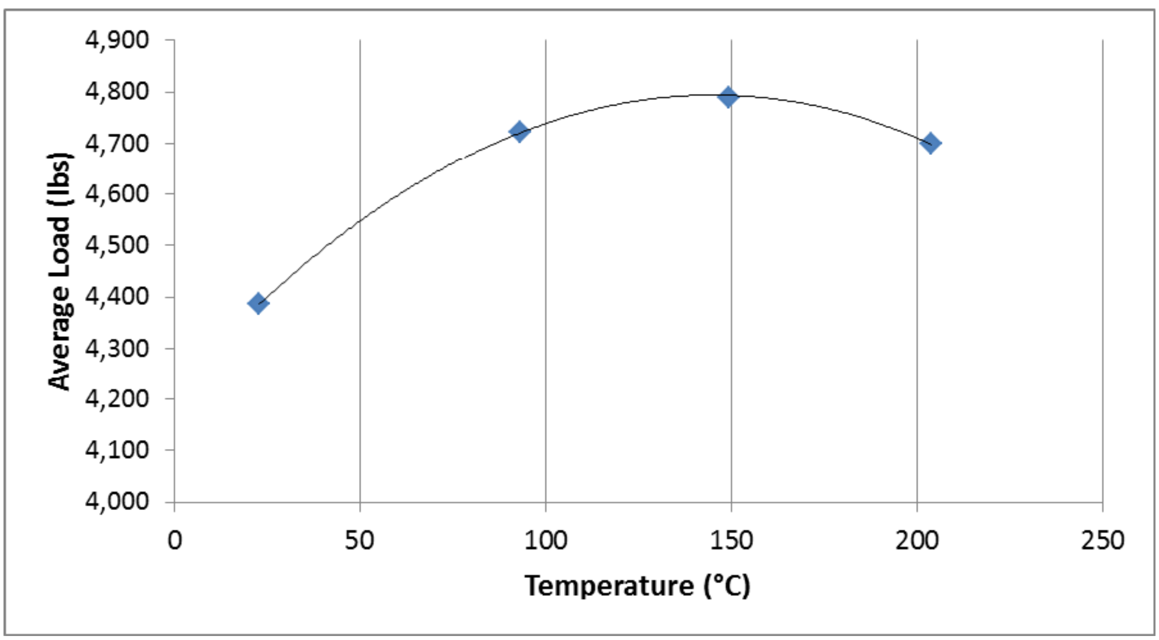

Figure 3 – Lap shear strength of adhesive

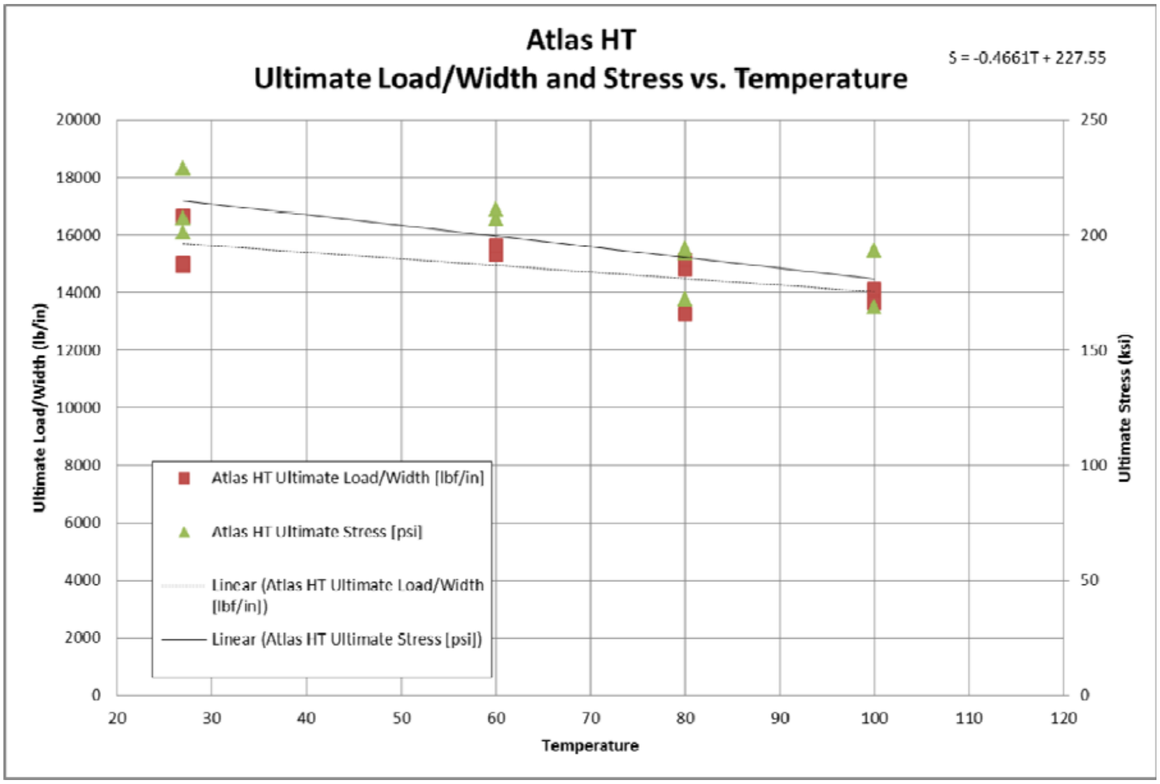

Figure 4 – Tensile strength as a function of temperature

Figure 5 – Photograph showing the creep test facility

Figure 6 – Close-up view of the creep test facility showing loading chamber

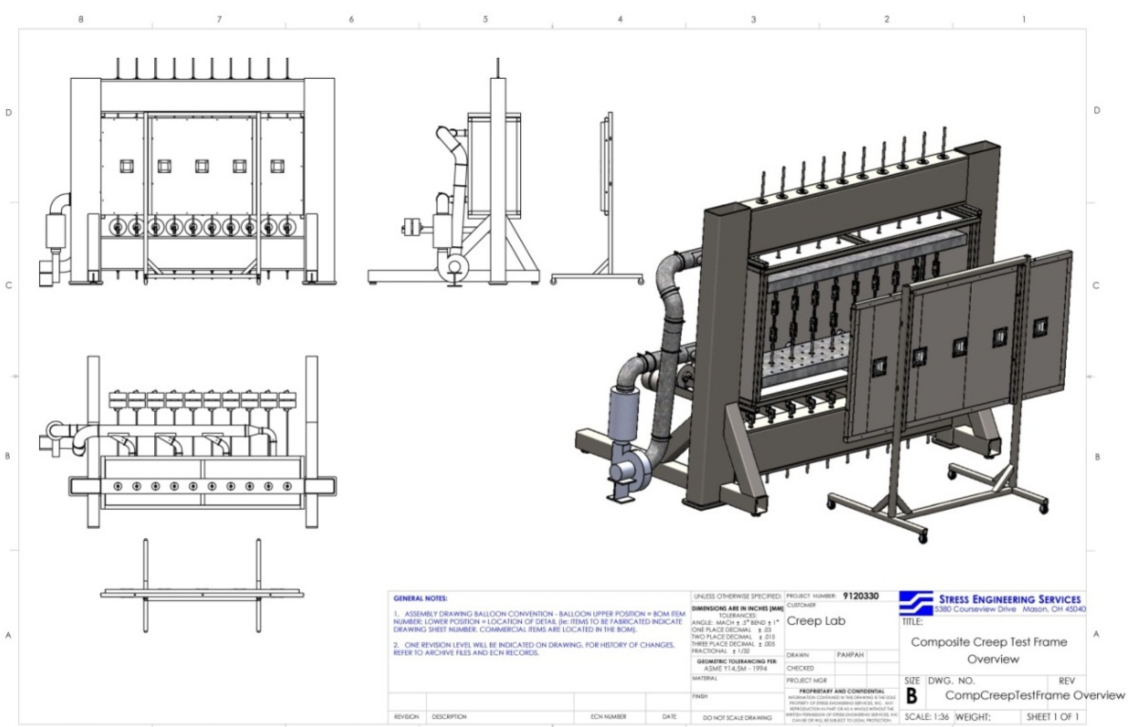

Figure 7 – Detailed drawings of the creep test facility

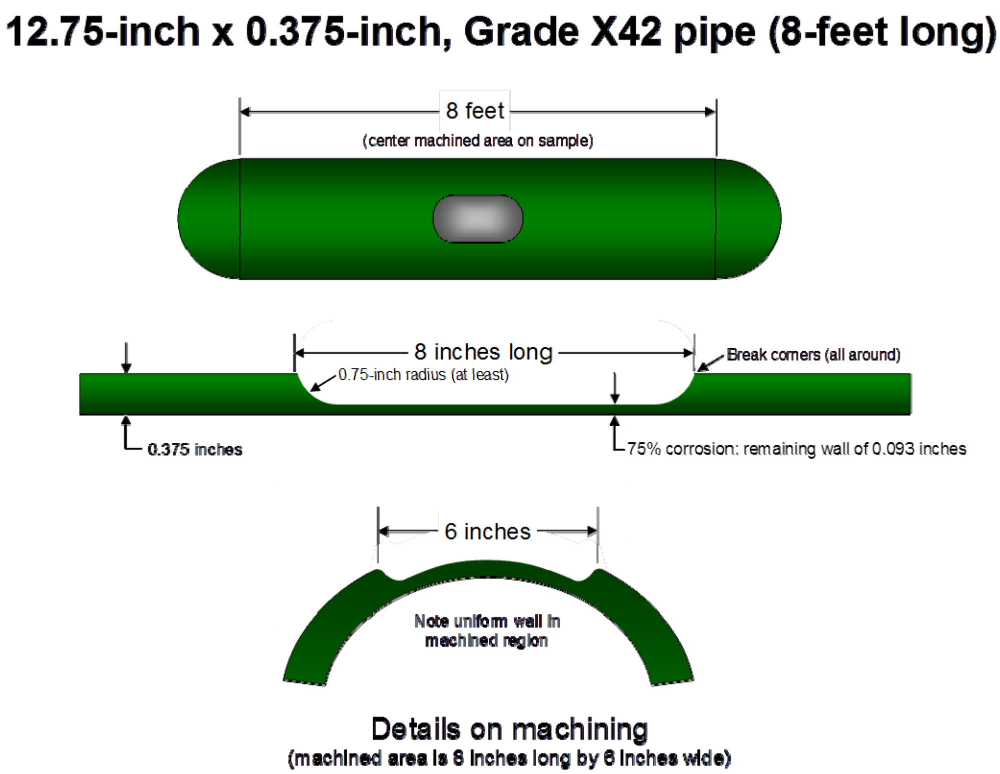

Figure 8 – Schematic diagram showing configuration for full-scale pipe sample

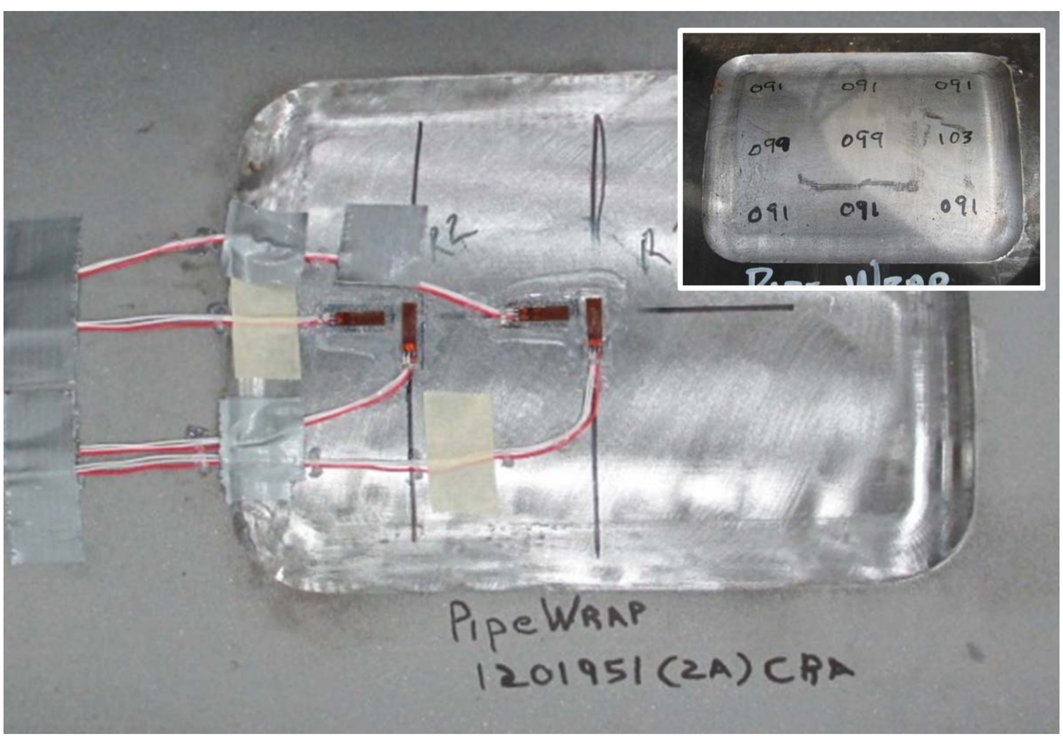

Figure 9 – Close-up view of the machined region of the pipe sample

Figure 10 – Photograph of composite repair after installation

Figure 11 – Photograph of sample in test pit with insulation and induction heating coils

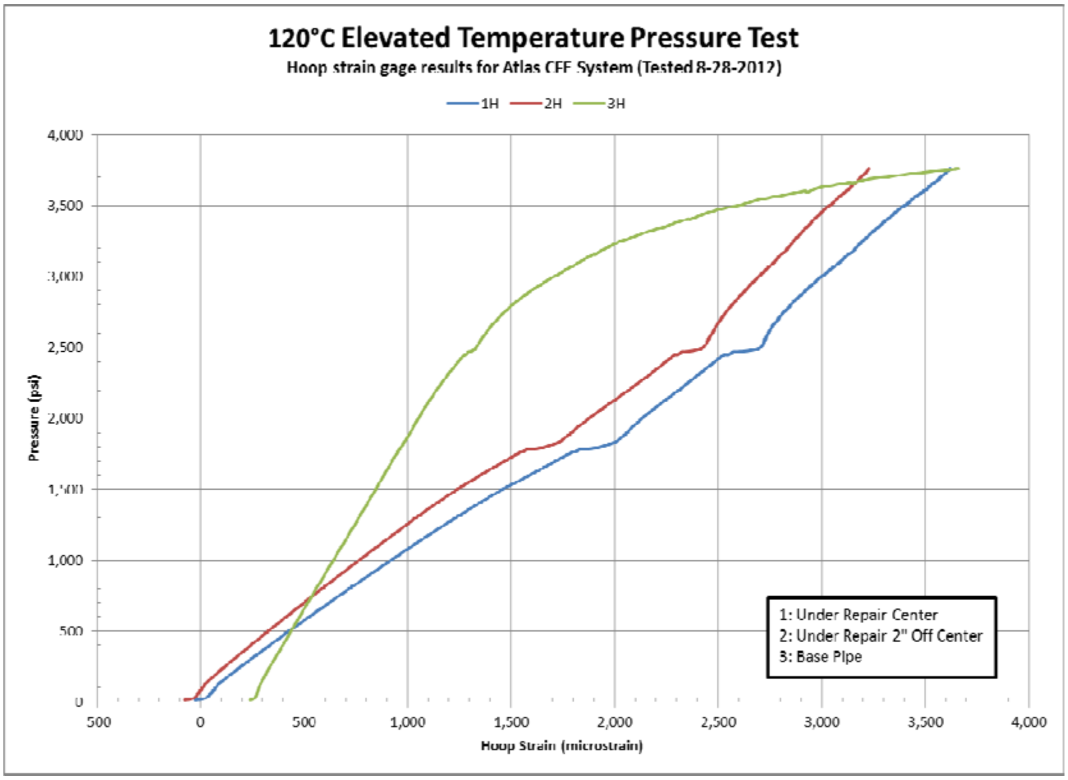

Figure 12 – Hoop strain as a function of internal pressure at 120°C

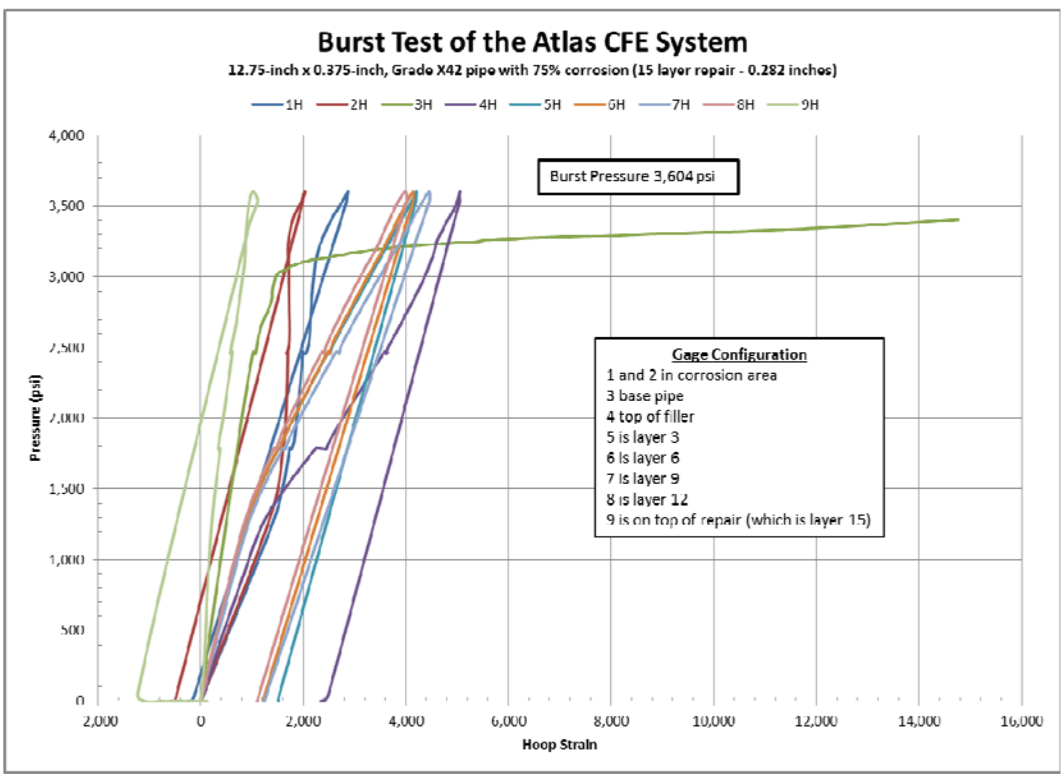

Figure 13 – Hoop strain as a function of internal pressure at 27°C

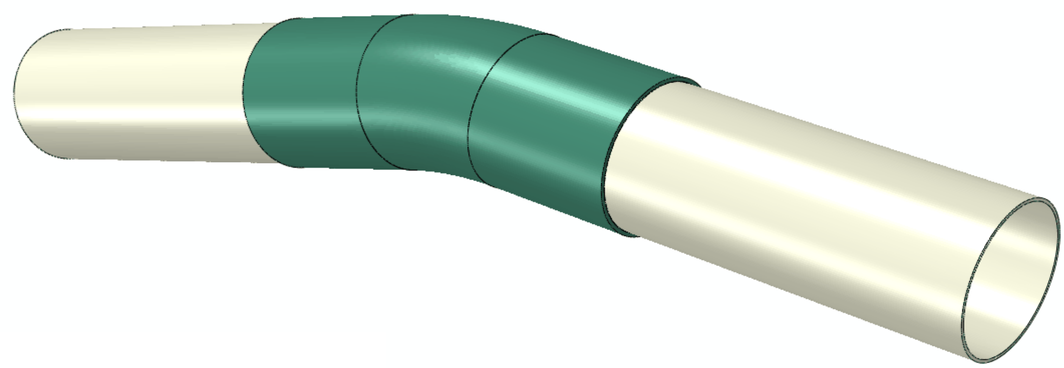

Figure 14 – **Finite element model showing composite reinforcement**

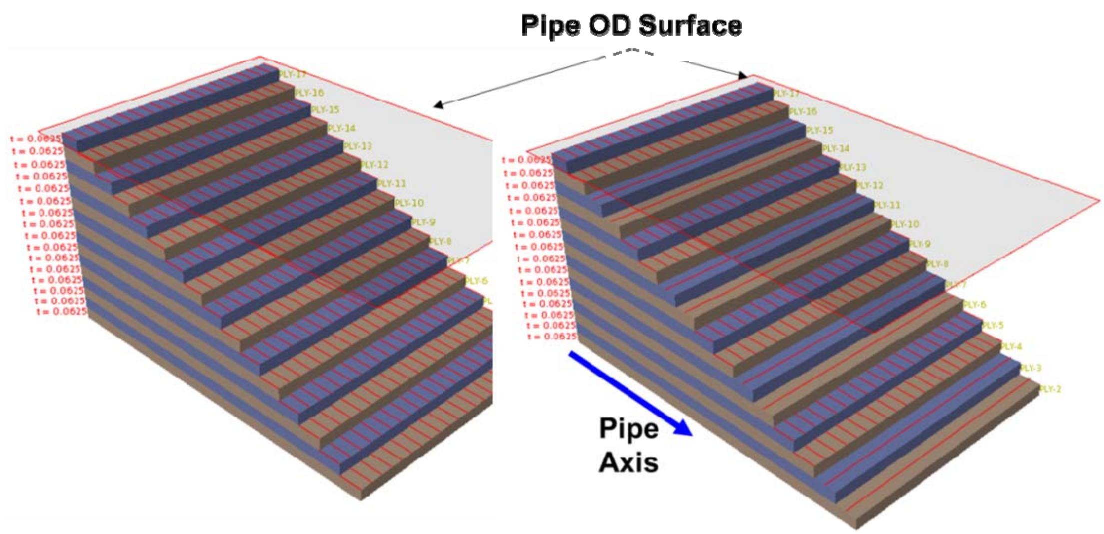

Figure 15 – **Architecture of two different competing composite reinforcement configurations**

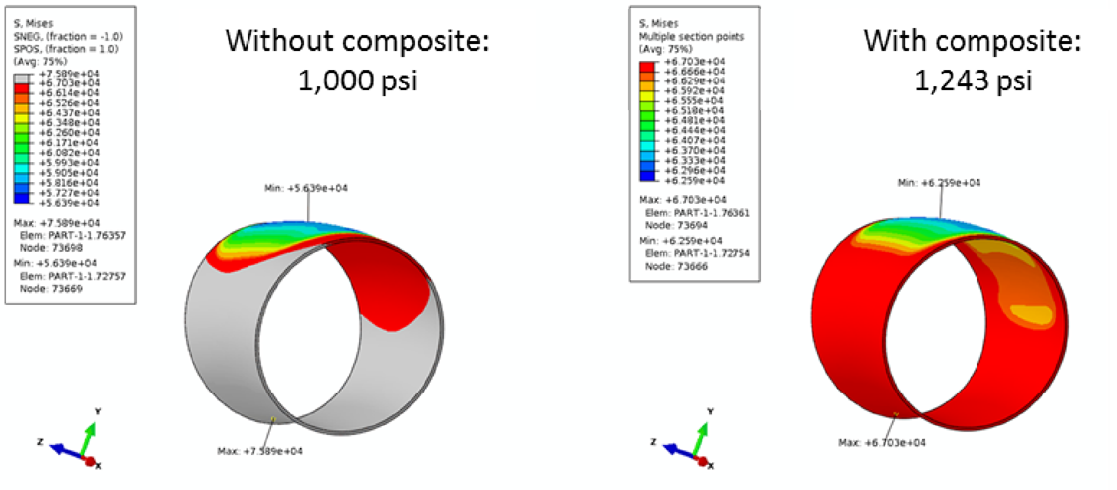

Figure 16 – FEA model contour plots showing pressures required to induce yielding
(Note that the presence of the composite increases the pressure at which yielding occurs)

Table 1 – Service Temperature Limits for Repair Systems
(ASME PCC-2 2011, pg. 143)

Property Measurement	Substrate Leaking, T_m	Substrate Not Leaking, T_m
T_g	T_g – 30°C (54°F)	T_g – 20°C (36°F)
HDT	HDT – 25°C (45°F)	HDT – 15°C (27°F)

Table 2 – Long-term strength projection; UTS of 142 ksi

Approx. s_{lt}	ε_c	Strain Based Equation resultant layers	Performance Equation resultant layers
56,800	0.25%	19.37	17.67
53,675	0.24%	20.50	18.69
50,550	0.23%	21.76	19.85
47,424	0.22%	23.20	21.16
44,299	0.21%	24.83	22.65
41,800	0.202%	26.32	24.00
41,174	0.20%	26.72	24.37
38,049	0.19%	28.91	26.37

Table 3 – Summary of short-term tensile strength as a function of temperature

Temperature (°C)	Sample	Max Crosshead Disp. [in]	Ultimate Load [lbf]	Ultimate Load/Width [lbf/in]	Ultimate Stress [psi]
27	A-A1	0.549	16653	16653	229
	A-B1	0.564	14885	14929	207
	A-B2	0.479	14951	15011	201
60	A-D2*	0.342	10788	11933	155
	A-C4	0.444	13850	15320	207
	A-A7	0.548	15081	15644	211
80	A-D1	0.543	14780	14810	192
	A-C6	0.494	12906	15131	194
	A-C7	0.355	11322	13257	172
100	A-C3*	0.378	9363	9633	125
	A-D6	0.577	13396	13656	169
	A-D7	0.464	14125	14125	193

*Indicates Grip Failure

Table 4 – Modified Long Term Strength Projection; UTS of 170 ksi

Approx. s_{lt}	ε_c	Strain Based Equation resultant layers	Performance Equation resultant layers
68,000	0.25%	19.37	14.76
64,259	0.24%	20.50	15.62
60,517	0.23%	21.76	16.58
56,776	0.22%	23.20	17.67
53,034	0.21%	24.83	18.92
51,163	0.205%	25.74	19.61
49,293	0.20%	26.72	20.36
45,551	0.19%	28.91	22.03
43,007	0.1832%	30.62	23.33
41,810	0.18%	31.50	24.00
38,068	0.17%	34.60	26.36