Proceedings of the 2016 11th International Pipeline Conference
IPC2016
September 26-30, 2016, Calgary, Alberta, Canada

IPC2016-64311

REINFORCING LARGE DIAMETER ELBOWS USING COMPOSITE MATERIALS SUBJECTED TO EXTREME BENDING AND INTERNAL PRESSURE LOADING

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ABSTRACT

A study was conducted to evaluate the use of E-glass/epoxy composite materials for reinforcement of large-diameter elbows. Using a combination of sub-scale and full-scale testing, the study demonstrated that when properly designed and installed, composite materials can be used to reduce strain in reinforced elbows considering bending loads of up to 3.6 million ft-lbs (4.88 million N-m), cyclic pressures between 720 psi (4.96 MPa) and 1,440 psi (9.93 MPa), and burst testing. The stresses measured in the composite material were well below designated ASME PCC-2 design stresses for the composite materials. During testing, there was no evidence that previously applied bending loads reduced the overall burst pressure capacity of the composite-reinforced elbows. Finite element modeling was used to optimize the geometry of the composite reinforcement. The resulting design guidance from this study was used to provide direction for possible reinforcement of large-diameter elbows for in-service pipelines.

INTRODUCTION

This paper provides details on a study performed to evaluate the design and assessment of a composite reinforcement for 36-inch (900-mm) diameter 3D elbows. In conducting this study, full-scale destructive testing, sub-scale cold temperature testing, and numerical modeling using finite element analysis were used to validate the use of composite materials in this application. This paper provides results associated with the analysis and testing work that evaluated and validated the composite-reinforcement design.

Sections are provided with information on the aforementioned phases of work. The *Background* section provides some historical commentary on the use of composite materials in reinforcing high-pressure pipelines. Included is an *Analysis Methods and Results* section that provides an overview of the composite design optimization that was performed. The *Testing Methods and Results* section provides details on sub-scale and full-scale testing that was performed. These tests included composite coupon tests down to -40 °F (-40°C), tests to evaluate the effects of pressure during installation at anticipated ambient temperatures, testing to measure composite inter-layer strains, and full-scale testing that involved bending unreinforced and reinforced 36-inch (900-mm) diameter 3D 17° elbows prior to burst testing. The *Discussion* and *Closing Comments* sections provide information relating to the applicability of results to actual pipeline operation and insights associated with ensuring long-term performance of the composite reinforcement derived from previous experience.

BACKGROUND

Over the past decade the composite repair industry has benefitted with the development of industry standards such as ASME PCC-2 *Repair of Pressure Equipment and Piping* standard (Article 4.1, *Nonmetallic Composite Repair Systems: High-Risk Applications*). This standard provides guidance for the pipeline industry on how to properly design and qualify composite systems for repairing wall-loss corrosion damage in high-pressure pipelines. Not included in this standard (at the present time) are guidelines for explicitly designing composite systems to repair and reinforce features in high-pressure pipelines other than corrosion damage. Dating back to the mid-1990s, work has been conducted by numerous pipeline operators and repair companies to design composite-repair solutions to address issues such as the following[1]:

- Reinforcement of branch connections considering internal pressure, in-plane bending, and out-of-plane bending
- Repair of mechanical damage (dents with gouges) [8]
- Repair of plain dents, as well as dents interacting with ERW seam welds and girth welds [8]
- Reinforcement of wrinkle bends subjected to cyclic pressure and high-strain / low-cycle bending conditions [9]
- Reinforcement of vintage girth welds with 50% lack of penetration defects considering internal pressure, bending, and tension loads
- Reinforcement of crack-like features in pipes subjected to cyclic and burst pressures
- A study including full-scale testing to evaluate the use of composite materials for re-rating pipelines
- Design and assessment of a carbon-epoxy system used to reinforce offshore risers subjected to combined loads using finite element modeling and full-scale destructive testing [12-14]

The research programs in the above list served to provide valuable information and insights on the performance of composite repair technologies. The cumulative knowledge accumulated regarding the performance of composite repairs was important in completing the reported work and designing the system used in service.

[1] Only a partial list of the most pertinent studies has been provided.

In conducting these studies, a systematic method was developed for evaluating the performance of composite-repair systems considering diverse conditions. As can be noted from the preceding list, there is great variability in the types of studies that have been conducted, although each have contributed to the overall level of understanding.

The key to ensure that an appropriate design solution has been developed involves identifying the loading to be carried by the reinforcement and ensuring that stresses in the reinforced steel and composite material remain below designated design stresses. ASME PCC-2 has been a useful resource for providing industry (and this analysis) a methodology for establishing composite design stresses for long-term service.

Listed below are the specific steps used to evaluate the performance of composite systems for repairing and reinforcing pipelines.

1. Identify loading of the pipeline associated with the condition needing reinforcement. Examples include cyclic pressure for dents, bending and tension loads for vintage girth welds, and in-plane bending for welded branch connections.
2. Design the reinforcement necessary to provide the appropriate level of stiffness to the previously identified loading. Because of the diverse capabilities of composite systems in terms of their architecture (e.g., fiber orientation and thickness), matrix (resin) selection, and fiber type, this stage of the design process is extremely important. Provided below are several recommendations related to the design and optimization of the composite system.
    a. For reinforcement associated with axial tension and bending loads, fibers must be axially-oriented (relative to the axis of pipeline).
    b. The corollary to the preceding statement is also true: circumferentially-oriented fibers are necessary for loading associated with hoop stresses. This often includes the reinforcement of dents and corrosion.
    c. A legitimate starting point for determining composite thickness for any design is using the guidelines specified in ASME PCC-2 considering the highest permitted design pressure of the pipeline (i.e., 80% SMYS) assuming a corrosion depth of 80%. Although not all designs will require such a thick composite, it is best to utilize a thicker composite than actually required during the early stages of the design process.
    d. Finite element analysis modeling is an ideal means for quantifying the magnitude of reinforcement provided by competing composite technologies by considering variations in fiber type (i.e., elastic modulus), fiber orientation, length of reinforcement, and thickness of the reinforcement. Plots can be made to illustrate stress changes in the reinforced steel as functions of the selected variables. Limit-state analysis can also be performed by increasing the loading in question to a sufficient magnitude to cause failure in the reinforced steel; this requires elastic/plastic properties for the steel and a designated strain-to-failure condition for the composite materials.
    e. Once the design of the composite system has been selected and/or optimized, full-scale destructive testing should be conducted. The testing program should be designed to simulate actual pipeline field loading conditions, which often requires the use of large-capacity load frames. Additionally, strain gages should be used to measure strain in both the reinforced steel and composite materials. This includes installing strain gages within the reinforcing system itself to measure inter-layer strains, which can then be compared to allowable strains permitted in the composite by standards such as ASME PCC-2.
3. The last step in the design process involves documentation. This includes not only documenting all testing (sub-scale and full-scale) and analysis (finite element analysis modeling and hand calculations), but also integrating previous bodies of research that have contributed to the overall understanding of composite reinforcement for high-pressure pipelines.

ANALYSIS METHODS AND RESULTS

After the loading conditions representative of those actually present in the elbows were identified, the analysis efforts focused on the development of an optimized composite-reinforcement system. The intent was to design a repair configuration that minimized stresses in the reinforced steel. Four models were constructed using the same overall composite thickness, but varied by evaluating different fiber orientations (i.e. hoop and axial). Due to time limitations associated with the project schedule and the need for rapidly developing a composite design, a single thickness of 1.0 inch (25 mm) was selected for assessment.

The Armor Plate® Pipe Wrap (APPW) is an E-glass / epoxy composite repair system. It was selected because of the large number and wide range of testing programs to which it has been subjected, including the reinforcement of wrinkle bends and branch connections that are of especially applicable to the current body of work. Further, the APPW system satisfies the requirements of the ASME PCC-2 standard, ensuring that the composite system meets the requirements of CSA Z662-11 Article 10.11.4.3. Because the composite repair installations were completed in Canada, it was necessary for the repair to meet the requirements of the CSA Z662 standard.

Based on prior experience regarding composite repair performance and options regarding fiber orientation, four combinations of the reinforcement were considered, involving specific lay-up combinations of circumferentially (C) and longitudinally (L) oriented fibers as listed below. The numbers listed correspond to the number of layers for that particular orientation (e.g., “3C” is three circumferentially-oriented layers). As noted, a total of 16 layers were selected for each combination; corresponding to a thickness of 1.0 inch (25 mm).

- Option 1: 3C | 1L | 3C | 1L | 3C | 1L | 3C | 1L
- Option 2: 16C
- Option 3: 16L
- Option 4: 2C | 2L | 2C | 2L | 2C | 2L | 2C | 2L

Figure 1 shows the configuration for the finite element model, including the addition of the composite materials, which extended 36 inches (900-mm) (i.e., one pipe diameter) on each side of the elbow. Symmetry boundary conditions were applied to this model to simulate plane strain conditions; however, the temperature was held constant at 116 °F (46.7 °C) while internal pressure was increased to determine the condition at which yielding occurred.

The ABAQUS general-purpose finite element software was used to complete the analysis. Both the composite and pipe / elbow steel materials were modeled using four-noded shell elements (i.e. type S4R). No effort was made to model potential disbondment between the composite and steel; however, extensive work by Alexander both analytically and experimentally have demonstrated that disbondment does not occur when composite materials are used to reinforce large sections of pipe (length of at least 3 pipe diameters) subjected to bending loads of sufficient magnitude to cause yielding in the base pipe material. A mesh density of sufficient magnitude was used to ensure that the finite element model captured the maximum stresses (and strains) in the model.

From a constitutive modeling standpoint, the composite material was modeled elastically, while the pipe material was modeled using elastic perfectly-plastic materials properties assuming a Grade X70 material (i.e. yield strength of 70 ksi (483 MPa)). The elastic modulii for APPW in the circumferential and longitudinal directions were modeled as 3.93 Msi (27.09 GPa) and 0.65 Msi (4.48 GPa), respectively. These are lower-bound 95% confidence level values based on sub-scale coupon tests. It should be noted that APPW is comprised of a multi-axis fiber system with a majority of the fibers running parallel to the primary direction of the cloth. Therefore, when APPW is installed circumferentially, most of the fibers are oriented circumferentially, although some fibers are oriented in the axial direction.[2]

Figure 2 includes four contour plots for each of the composite design configurations, illustrating the effects of composite reinforcement on the internal pressures required to cause yielding. Listed below are the internal pressures required to cause yielding in the elbow.

- Option 1: 3C | 1L (occurs 4X) P_{yield} = 2,370 psi (16.34 MPa)
- Option 2: 16C P_{yield} = 2,397 psi (16.53 MPa)
- Option 3: 16L P_{yield} = 1,800 psi (12.41 MPa)
- Option 4: 2C | 2L (occurs 4X) P_{yield} = 2,098 psi (14.47 MPa)

In reviewing the preceding results, it is observed that the circumferential-only configuration (Option 2) provides the greatest level of reinforcement, while the longitudinal-only configuration (Option 3) provides the least amount of reinforcement. These results were as expected because elevated circumferential stresses in elbows due to bending are typically associated ovality; the presence of circumferentially-oriented fibers minimizes ovality to ensure a reduced stress state in the elbow. Most importantly, these results demonstrate that it is possible to design a composite reinforcement that ensures that yielding in the elbow will not occur when the composite material is present. From a pipeline design standpoint, if a composite material can prevent yielding from occurring in the reinforced pipe, the likelihood for ductile overloading is reduced from the operating scenario.

Figure 3 is a graph showing von Mises stress in the steel pipe at 1,440 psi (9.93 MPa) and 116 °F (46.7 °C) with APPW reinforcement. The von Mises stress in the pipe with the Option 2 reinforcement is 45.6 ksi (314.4 MPa), while even Option 3 provides some reinforcement as indicated by the steel having a stress of 59.3 ksi (408.86 MPa). These results confirmed that the circumferential-only configuration associated with Option 2 provides the greatest level of reinforcement; therefore, it was selected as the design configuration to be used.

TESTING METHDOS AND RESULTS

In conjunction with the analysis and numerical modeling work, sub-scale and full-scale testing was conducted as part of the validation effort. Testing included the following: coupon testing to measure material property changes at cold temperatures, a study to address the effects of internal pressure during installation, and full-scale testing on 36-inch (900-mm) pipe that included bending, pressure to failure, and quantifying strain distribution within the composite reinforcement.

A significant body of testing work was completed to evaluate and validate the performance of the composite reinforcing technology; however, due to space limitations in this paper, limited results are provided that include the following:

- Cold-temperature coupon testing
- Full-scale bending and burst testing
- Inter-layer strain tests to measure strains in the composite to quantify stresses relative to the allowable design stress for the composite material per ASME PCC-2.

The sections that follow provide specific details on these test efforts.

Cold-Temperature Composite Testing

The ability of a composite system to reinforce a pipeline is directly proportional to the stiffness and strength of the material. It is widely recognized that composite material properties (i.e., elastic modulus and tensile strength) are reduced with increasing temperature; however, minimal testing has been completed to address the effects of cold temperatures. The primary concern at elevated temperatures is loss in strength as the glass transition temperature is reached; however, at cold temperature, no material degradation factor is available other than it generally being understood that there is a potential for brittle behavior.

Because of questions related to the above subject matter, a series of coupon-level tests was conducted to quantify the material properties of APPW at cold temperatures. Coupon-level testing was performed at temperatures down to -40 °F (-40 °C) on two of Armor Plate's epoxy resin systems including the MP (Multi-purpose) and ZED cold temperature systems. The MP system can be used with a wide-range of installation temperatures; however, the ZED system was specifically formulated for cold-weather conditions where proper curing of the MP resin would be difficult. Included in Figure 4 and Figure 5 are tensile strength and elastic modulus data plotted for the MP and ZED systems as functions of temperature, respectively. As noted, the magnitude for both of these values generally decreases with decreasing temperature. Included in Figure 6 are photographs showing the test set-up and typical coupon failures.

What has not been included in the data plotted in Figure 4 and Figure 5 are the strain-to-failure measurements. Because of the concerns regarding the potential for brittle behavior, the issue of elongation was monitored closely. Listed below are the strain-to-failure (i.e., elongation) measurements recorded for the composite repair material at the four temperatures of interest.

- 70°F (21°C) 1.9%

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[2] The following material properties were measured for APPW (S – tensile strength; E – elastic modulus; ε – strain at failure):

- Circumferential: S = 67,006 psi E = 3.93 x 10^6 psi ε = 1.70% (S = 461.95 MPa, E = 27.09 GPa)
- Longitudinal: S = 6,950 psi E = 0.86 x 10^6 psi ε = 0.81% (S = 47.91 MPa, E = 5.93 GPa)

- 32°F (0°C) 2.2%
- 0°F (-18°C) 2.2%
- -40°F (-40°C) 2.4%

It is clear that both the MP and ZED resin systems performed well at cold temperatures, with no loss in tensile strength and reduction in elongation. Additionally, there is no loss in elastic modulus at colder temperatures. There is also no indication of brittle behavior at any of the tested temperatures, observed in the average strain to failure for ZED system test coupons at -40 °F (-40°C) was 2.4%.

Full-scale Testing

Conducting full-scale tests was an essential part of the overall validation program. The intent was to subject the composite reinforcement to loads beyond those expected in actual service to demonstrate the integrity of the composite materials and quantify the magnitude of reinforcement provided to the elbow. Full-scale testing has been the primary means for validating composite repair technology and was a major focus of the current study.

In addition to testing the elbows, testing was performed to quantify strains in the composite material. This particular test, referred to as the *Inter-layer Strain* (ILS) test, has been used previously to quantify strains (i.e., stresses) in the composite system at design conditions; ensuring that the stresses in the system are less than the ASME PCC-2 designated design stresses.

A total of four full-scale destructive tests were conducted, including testing elbows in the unreinforced and reinforced conditions. Listed below are the full-scale samples that were tested:

- Unreinforced elbow burst test
- Reinforced elbow burst test
  - Prior to reinforcement, the unreinforced elbow was subjected to OPEN and CLOSE bending at 1.8 million ft-lbs
  - After installation of APPW, this same elbow (tested previously in the unreinforced condition) was subjected to OPEN bending at 1.8 million ft-lbs (2.44 million N-m) and CLOSE bending at 3.6 million ft-lbs (4.88 million N-m) prior to the burst test
- Unreinforced straight-pipe burst test (for comparison with the ILS test results)
- Reinforced ILS straight-pipe burst test

The bending loads in testing were based on results from a global finite element model that integrated internal pressure and thermal loading. The model also included pipe-soil interaction. The pipeline system in question experiences minimal pressure cycling; however, to demonstrate the ability of the composite material to function in reinforcing the elbows it was subjected to cyclic pressure loading prior to the application of bending loads. Extensive research by Alexander et al has demonstrated that composite materials are able to withstand significant pressure cycling and still provide reinforcement to damaged pipe sections (i.e. pressure cycling up to 750,000 cycles in reinforcing 75% corrosion in 12.75-inch x 0.375-inch (323.85-mm x 9.52-mm) pipe with a pressure range equal to 72% SMYS) [4, 8, and 9].

During testing the unreinforced elbow sample care was taken to not introduce plastic strains in the elbow that would have prevented a direct comparison between the unreinforced and reinforced test samples. Strain gage measurements and the linear load-deflection response confirmed that no plastic deformation was introduced when testing the unreinforced sample.

The sections that follow provide specific details on the tests on the above four pipe samples that included combinations of bending and pressure loads.

Elbow Bend Testing

Bend testing was conducted on one of the two 36-inch (900-mm) diameter 3D 17° elbows. Testing was conducted in both the unreinforced and reinforced conditions. The same elbow was tested in these two configurations to ensure a direct comparison of results for the unreinforced and reinforced conditions. A second elbow was tested in the unreinforced condition, but was only subjected to a burst pressure test (i.e., no bend testing); serving as the reference case for the subsequent reinforced elbow burst test.

The following steps were performed in conducting tests on the **UNREINFORCED** sample.

- Pressurized sample to the 100% SMYS pressure of 1,790 psi (12.34 MPa). Held for 10 minutes.
- De-pressurized the sample to the design pressure of 1,440 psi (9.93 MPa). This pressure was held constant throughout the bend test.
- Applied a bending moment of 1.8 million ft-lbs (2.44 million N-m) (design conditions provided by AP Dynamics based on a global finite element model).
- Removed bending moment.
- Applied bending moment repeatedly to achieve a total of 3 bending cycles.
- Loads were applied to the elbow test sample to generate bending in the OPEN and CLOSE modes. The test sample was designed to permit rotation of the sample between these two phases of loading.
- Removed the applied bending load and reduced the internal pressure to 0 psi.

After testing was conducted on the sample in the unreinforced condition, the sample was reinforced with APPW. A total of 16 layers of the composite material were installed, resulting in a total composite thickness of 1.0 inch. The steps associated with this phase of testing are as follows:

- Composite materials installed with an internal pressure of 1,038 psi (7.16 MPa) held constant.
- Pressurized sample to the 100% SMYS pressure of 1,790 psi (12.34 MPa). Held for 10 minutes.
- De-pressurized the sample to the design pressure of 1,440 psi. This pressure was held constant throughout the bend test.
- Applied a bending moment of 1.8 million ft-lbs (2.44 million N-m) in the OPEN mode.
- Applied a bending moment of 3.6 million ft-lbs (4.88 million N-m) in the CLOSE mode.
- Applied bending moments repeatedly to achieve a total of 3 bending cycles in both the OPEN and CLOSE modes.
- Removed the applied bending load and reduced the internal pressure to 0 psi.
- Removed test sample from bending frame and moved for burst testing.

Figure 7 through Figure 9 provide photographs of the bending sample at various stages of testing. Of particular importance is the configuration of the test sample that permitted it to be loaded so that bending loads could be applied to open and close the elbow. As noted above, bending loads were applied to the test sample in the unreinforced condition before the composite material was applied.

Strain gages were installed on the test sample to measure hoop and axial strains. The strain of interest was measured by the gage located at the intrados of the bend. Table 1 provides hoop and axial strain measurements at the intrados of the elbow during bend testing, including the unreinforced and reinforced conditions in the OPEN and CLOSE modes. Using the bi-axial stress/strain relation, hoop and axial stresses were calculated using the strain measurements and are included in the table.

Several observations are made based on the data provided in Table 1.

- With bending moments up to 1,000 kip-ft (1.356 million N-m) in the CLOSE mode, the composite reinforcement reduces the magnitude of both hoop and axial stresses; in the OPEN mode, stress is reduced for the full range of applied bending moments.
- The presence of the composite reinforcement significantly reduces the stress changes that occur in the elbow with increasing bending loads.
- The OPEN mode generates larger hoop stresses at the intrados of the elbow.
- As expected, the CLOSE mode generates elevated compressive axial stresses at the intrados of the bend.

Elbow Burst Testing

After all phases of bending testing were completed, the reinforced elbow was burst tested. A second sample was also fabricated using another elbow to permit burst testing of an unreinforced elbow (no bending loads were applied to this second sample prior to burst testing). The following sections provide results for burst testing conducted on the unreinforced and reinforced elbows.

Burst Test of Unreinforced Elbow

During pressure testing, the reinforced elbow sample was pressurized to the following pressures and held for 10 minutes at each level.

- 1,038 psi (7.16 MPa) (58% SMYS, as a point of reference, this was the composite installation pressure)
- 1,440 psi (9.93 MPa) (80% SMYS, design pressure)
- 1,611 psi (11.11 MPa) ((90% SMYS)
- 1,790 psi (12.34 MPa) (100% SMYS)

The unreinforced sample failed at a pressure of 2,952 psi (20.35 MPa). The failure occurred at the intrados of the bend as a longitudinally-oriented fracture in a ductile manner as shown in Figure 10. Strain gages were monitored during testing; results are presented and discussed in a subsequent section of this report.

Burst Test of Reinforced Elbow

A burst test was conducted on the reinforced elbow sample after it had been subjected to the bending tests as described previously. In addition to the pressure holds applied to the unreinforced sample, several additional load steps were applied to the reinforced sample that included the following.

- A 4 hour hydrotest at 1,790 psi (12.34 MPa).
- After hydrotesting, the sample was cycled between 720 psi (4.96 MPa) and 1,440 psi (9.93 MPa) to achieve a total of 10 pressure cycles.

As shown in Figure 11, the burst test failure of the reinforced elbow sample occurred outside the elbow and reinforcement in the base pipe, which had a wall thickness of 0.75 inch (19-mm). The failure pressure was 4,000 psi (27.58 MPa).

Comparison of Unreinforced / Reinforced Elbow Test Results

In addition to obtaining the burst pressures, the team measured hoop and axial strains on the intrados of the bend at various pressure levels. Table 2 provides the hoop and axial strain measurements and corresponding stresses as functions of internal pressure. Stresses at pressures exceeding 1,790 psi (100% SMYS) are not included because of the yielding of the pipe; once steel is loaded beyond the proportional limit[3], the linear relationship between stress and strain no longer exists. Of particular interest are hoop strains measured at the following pressure levels:

- At 1,440 psi (9.93 MPa): (80% SMYS, or MAOP):
  - Unreinforced: 2,512 με
  - Reinforced: 1,811 με
- At 1,790 psi (12.34 MPa): (100% SMYS):
  - Unreinforced: 3,104 με
  - Reinforced: 2,203 με
- At 2,400 psi (16.55 MPa): (134% SMYS)
  - Unreinforced: 7,576 με
  - Reinforced: 3,078 με

In reviewing the above data, as well as the results provided in Table 2, it is clear that the composite material reduces strain in the reinforced section of the elbow. This strain reduction is the primary reason that the composite materials were installed. At the design pressure of 1,440 psi, the reduction in hoop strain due to the composite reinforcement is greater than 25%.

Inter-layer Strain Testing

As mentioned previously, the ILS test is an effective means for validating the design stress of a composite repair system relative to the designated design stress from ASME PCC-2. For purposes of this test, a 36-inch x 0.500-inch (914.4-mm x 12.7-mm), Grade X70 pipe material was selected. The actual measured yield and tensile strengths were 88.1 ksi (607.43 MPa) and 98.1 ksi (676.38 MPa), respectively. Two tests were conducted as part of this effort that included pressure testing both reinforced and unreinforced samples. The reinforced sample was fitted with 16 layers of APPW, which corresponds to a composite thickness of 1.0 inch. This is the same thickness used to reinforce the elbow samples.

As with all phases of testing in this study, strain gages were installed on the pipe beneath the composite reinforcement. The ILS samples did not have any defects, anomalies, or components having stress concentration factors. The purpose of the test was to quantify the level of reinforcement provided by the composite in terms of strain reduction and increase in burst strength, as well as quantifying the stress in the composite material as a function of internal pressure. The unreinforced sample failed at a pressure of 2,966 psi (20.45 MPa), while the reinforce sample failed at a pressure of 3,623 psi

[3] Up to the "proportional limit" stress (σ) is proportional to strain (ε) based on Hooke's Law. The stress/strain graph is a straight line and the gradient (i.e., slope) is equal to the elastic modulus of the material (E = σ/ε).

(24.98 MPa) in the end cap. Had the end cap not failed, the burst pressure of the reinforced sample would have been greater. Table 3 provides a summary of the stress and strain results for the two ILS tests. As observed, at pressures exceeding 1,400 psi (9.93 MPa), the composite reinforcement reduces stresses in the reinforced steel. In Table 3, stresses exceeding 1,944 psi (13.4 MPa) (100% SMYS for this pipe material) are not included because of the yielding of the pipe. Of particular interest are hoop strains measured at the following pressure levels:

- At 1,750 psi (12.07 MPa): (90% SMYS):
  - Unreinforced: 1,796 με
  - Reinforced: 1,245 με
- At 1,944 psi (13.4 MPa): (100% SMYS):
  - Unreinforced: 1,991 με
  - Reinforced: 1,380 με
- At 2,400 psi (16.55 MPa): (134% SMYS):
  - Unreinforced: 2,457 με
  - Reinforced: 1,872 με

As with the elbow test samples, the composite materials effectively reduced strain in the reinforced steel. Even at the 90% SMYS pressure condition, the effect of the reinforcement is significant. Another objective in the ILS testing was to quantify the composite stress at design conditions (80% SMYS) to ensure that stresses in APPW did not exceed the design stress of 11,918 psi.[4] Plotted in Figure 12 is the composite hoop stress as a function of layer in the ILS reinforced sample. The hoop stress plotted in this figure was calculated using the strain gage measurements in conjunction with the elastic modulus of 4.4 Msi (30.34 GPa) for the APPW material. A maximum composite stress of 5,486 psi (37.82 MPa) was calculated, which is less than the composite design strength of 11,918 psi (82.17 MPa). Considering the data plotted in Figure 12, the average composite stress is more on the order of 3,000 psi (20.68 MPa).

The results of the ILS test demonstrate that stresses in the composite material are well below the design stress for APPW. Also, consistent with results for the elbow tests, the composite material is effective at reducing stress in the reinforced steel, and its presence ensures a significant increase in burst strength.

DISCUSSION

One of the challenges associated with evaluating the performance of composite-reinforced pipelines is the inter-dependent relationship between the steel pipe material and the composite system. The use of strain gages is extremely valuable for quantifying load transfer and measuring strains in the composite and reinforced steel, especially at design conditions. The results of this study are a model for the pipeline industry in how numerical modeling and full-scale testing can be used to evaluate the effectiveness of a composite reinforcement.

From a design standpoint, it is clear that at design conditions stresses in the composite material are less than the ASME PCC-2 design stress of 11,918 psi (82.17 MPa) for the Armor Plate® Pipe Wrap system. Results from the ILS study indicate that the average stress in the composite was on the order of 3,000 psi (20.68 MPa). This is especially important from a long-term standpoint as the key from a design standpoint is to ensure that large safety factors are present in the composite material. Considering that the average tensile strength for the Armor Plate® Pipe Wrap ZED system at room temperature is 68.6 ksi (472.98 MPa), a safety factor on the order of 22 exists. Although one could argue that the current design is overly conservative, in view of the critical role these elbow reinforcements are serving, one could hardly argue against the robust design.

A question often posed regarding the use of composite materials used to reinforce pipe sections subjected to bending loads concerns the interfacial bond between the steel and inner layers of the composite material. Significant research that includes more than 25 full-scale bend tests has demonstrated that as long as the thickness of the composite (approximately 1.5 times the thickness of the steel) and length of the repair (at least three pipe diameters) are adequate there is no reason to be concerned about the development of disbondment. Significant work was conducted by Alexander both experimentally and analytically in addressing this issue that included including evaluating the effects of large areas of disbondment [14].

Another critical aspect of the current study is the complex nature of the combined load cases. The full-scale testing efforts applied bending moments on the order of 2 times those expected in service, yet when tested there appeared to be no degradation in performance. The extreme bending load of 3.6 million ft-lbs (4.88 million N-m) is two times that maximum bending design moment of 1.8 million ft-lbs (2.44 million N-m) associated with the pipeline design. This extreme value was selected to demonstrate the range of performance capabilities associated with the composite reinforcing technology. The mindset was that if the composite reinforcing system could withstand a bending that was two times design conditions and still reinforce the pipe during burst testing, engineers could proceed with confidence in its use.

Additionally, the strains measured in the reinforced steel were clearly reduced considering the presence of bending loads (opening and closing the elbow) and internal pressure. The composite reinforcement is effective at lowering the von Mises stress state to ensure that yielding does not occur at design conditions. The reduction of the hoop stress due to the presence of the composite materials reduces the stress state in the elbow.

Stresses are of primary concern for composite repairs because the long-term performance in PCC-2 is established based on 1,000-hr tests (and the design Equation 12). Confirming the long-term performance of the composite was critical in this study and correlating the measured results back to the ASME PCC-2 allowable stress was essential. As noted throughout this paper, this work is basically a limit state design that is at its core strain-based. Therefore, when evaluating the performance of the steel elbow it is appropriate to use strains.

A final comment is with regard to an aspect essential to the success of this study, that is, the use of elastic-plastic data to quantify the true benefits of the composite reinforcement via limit-state design. Although typically achieved using numerical modeling, limit-state design can also be accomplished using full-scale testing. The approach involves the loading of a structure into the plastic regime (i.e., well beyond the proportional limit) to determine the load at which unbounded displacements occur. Unbounded displacements

[4] The design strength of 11,918 psi (82.17 MPa) for Armor Plate Pipe® Wrap is based on 1,000-hour long-term testing completed as part of the ASME PCC-2 certification. This includes a safety factor of 2.0 on the long-term strength for the composite material.

occur in steel when gross plasticity develops and significant levels of displacement occur with minimal increases in loading.

CONCLUSIONS

This paper has provided a summary of results associated with a comprehensive study completed to quantify the benefits of installing composite materials on 36-inch (900-mm) elbows. There are three important conclusions associated with this study. First, a composite repair system was designed that was effective in reinforcing the elbow to ensure that the calculated design pressure exceeded 80% SMYS based on finite element modeling. Secondly, the experimental work confirmed that the 1inch thick, circumferentially-oriented composite reinforcement generated a design pressure of 1,800 psi (12.4 MPa), which is 25% greater than the MAOP of 1,440 psi (9.93 MPa). Finally, from a long-term design standpoint the average stress in the composite is approximately 25% of the ASME PCC-2 allowable design stress for the APPW composite repair system.

This body of work represents a comprehensive approach for not only designing a composite repair system to reinforce high pressure pipelines subjected to combined loading conditions, but an approach for integrating analysis and testing to validate the design. The approach is a model for other complex applications of composite repair technologies.

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Table 1: Strain measurements at intrados of elbow during bend testing

	Open Position							
	Unreinforced				Reinforced			
Bending Moment kip-ft (million N-m)	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
500 (0.67)	2,387	656	85.1 ksi (586.75 MPa)	45.2 ksi (311.64 MPa)	1,818	599	65.9 ksi (454.37 MPa)	37.7 ksi (259.93 MPa)
1000 (1.356)	2,472	1,169	93.1 ksi (641.91 MPa)	63.0 ksi (434.37 MPa)	1,787	998	68.8 ksi (474.36 MPa)	50.6 ksi (348.88 MPa)
1800 (2.44)	2,590	1,996	105.1 ksi (724.64 MPa)	91.4 ksi (630.18 MPa)	1,738	1,662	73.7 ksi (508.15 MPa)	72.0 ksi (496.43 MPa)
3600 (4.88)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

	Closed Position							
	Unreinforced				Reinforced			
Bending Moment kip-ft (million N-m)	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
500 (0.67)	2,243	-171	72.2 ksi (497.8 MPa)	16.5 ksi (113.76 MPa)	1,784	-45	58.7 ksi (404.72 MPa)	16.2 ksi (111.70 MPa)
1000 (1.356)	2,152	-657	64.5 ksi (444.71 MPa)	-0.4 ksi (-2.76 MPa)	1,820	-434	58.7 ksi (404.72 MPa)	3.7 ksi (25.51 MPa)
1800 (2.44)	2,010	-1,389	52.5 ksi (361.98 MPa)	-25.9 ksi (-178.58 MPa)	1,888	-1,037	59.2 ksi (408.17 MPa)	-15.5 ksi (-106.87 MPa)
3600 (4.88)	N/A	N/A	N/A	N/A	1,712	-2,484	49.1 ksi (338.53 MPa)	-65.0 ksi (-448.16 MPa)

Table 2: Stress and strain results for reinforced and unreinforced elbow burst tests

Unreinforced				
Internal Pressure	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
1,038 psi (7.16 MPa)	1,820	136	61.3 ksi (422.65 MPa)	22.5 ksi (155.13 MPa)
1,440 psi (9.93 MPa)	2,512	204	84.8 ksi (584.68 MPa)	31.6 ksi (217.88 MPa)
1,611 psi (11.11 MPa)	2,799	235	94.6 ksi (652.25 MPa)	35.4 ksi (244.08 MPa)
1,790 psi (12.34 MPa)	3,104	265	105.0 ksi (723.95 MPa)	39.4 ksi (271.65 MPa)
2,400 psi (16.55 MPa)	7,576	167		
2,800 psi (19.31 MPa)	4,059	69		
2,952 psi (20.35 MPa) (BURST)	4,163	183		
Reinforced				
Internal Pressure	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
1,038 psi(7.16 MPa)	1,364	173	46.7 ksi (321.99 MPa)	19.2 ksi (132.38 MPa)
1,440 psi (9.93 MPa)	1,811	249	62.2 ksi (428.86 MPa)	26.1 ksi (179.95 MPa)
1,611 psi (11.11 MPa)	1,998	283	68.7 ksi (473.67 MPa)	29.1 ksi (200.64 MPa)
1,790 psi (12.34 MPa)	2,203	320	75.8 ksi (522.63 MPa)	32.3 ksi (222.7 MPa)
2,400 psi (16.55 MPa)	3,078	420		
2,800 psi (19.31 MPa)	5,732	370		
3,200 psi (22.06 MPa)	8,960	430		
3,600 psi (24.82 MPa)	12,495	737		
4,000 psi (27.58 MPa) (BURST)	16,988	1,221		

Table 3: Stress and strain results for reinforced and unreinforced ILS burst tests

Unreinforced				
Internal Pressure	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
1,400 psi (9.65 MPa)	1,110	421	40.8 ksi (281.31 MPa)	24.9 ksi (171.68 MPa)
1,750 psi (12.07 MPa)	1,245	471	45.7 ksi (315.09 MPa)	27.8 ksi (191.68 MPa)
1,944 psi (13.4 MPa)	1,380	521	50.7 ksi (349.57 MPa)	30.8 ksi (212.36 MPa)
2,400 psi (16.55 MPa)	1,872	721		
2,800 psi (19.31 MPa)	2,343	926		
3,200 psi (22.06 MPa)	3,748	1,250		
3,600 psi (24.82 MPa)	6,129	1,699		
3,623 psi (24.98 MPa) (BURST)	6,275	1,728		
Reinforced				
Internal Pressure	Hoop Strain (με)	Axial Strain (με)	Hoop Stress	Axial Stress
1,400 psi (9.65 MPa)	1,077	260	38.1 ksi (262.69 MPa)	19.2 ksi (132.38 MPa)
1,750 psi (12.07 MPa)	1,796	458	63.7 ksi (439.20 MPa)	32.8 ksi (226.15 MPa)
1,944 psi (13.4 MPa)	1,991	512	70.7 ksi (487.46 MPa)	36.6 ksi (252.35 MPa)
2,400 psi (16.55 MPa)	2,457	640		
2,800 psi (19.31 MPa)	15,922	773		

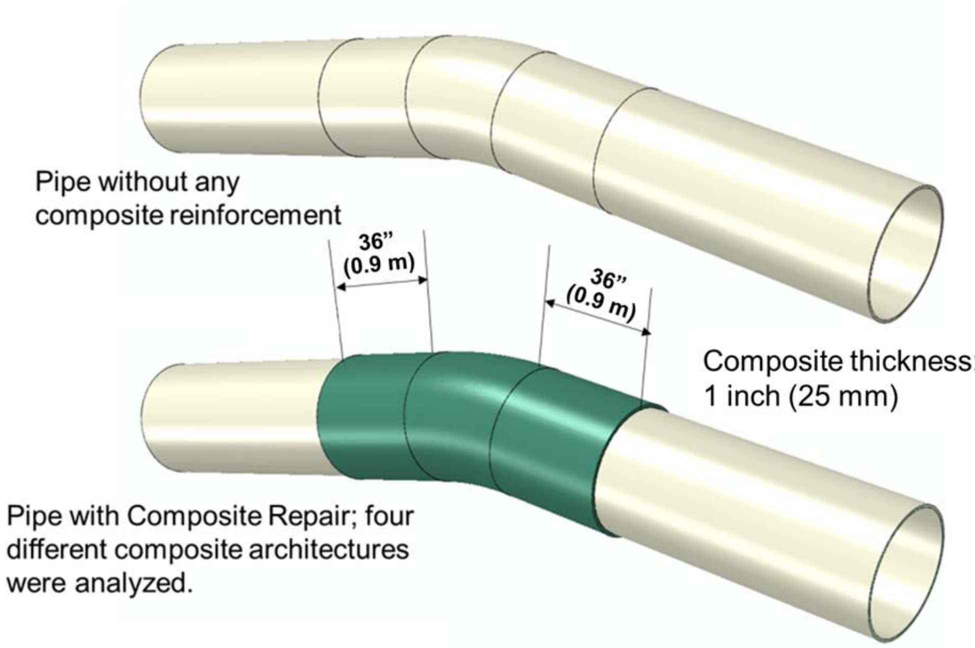

Figure 1: Finite element model showing composite reinforcing materials
(Note that 36 inches = 0.92 meters | 1.0 inch = 25.4 mm)

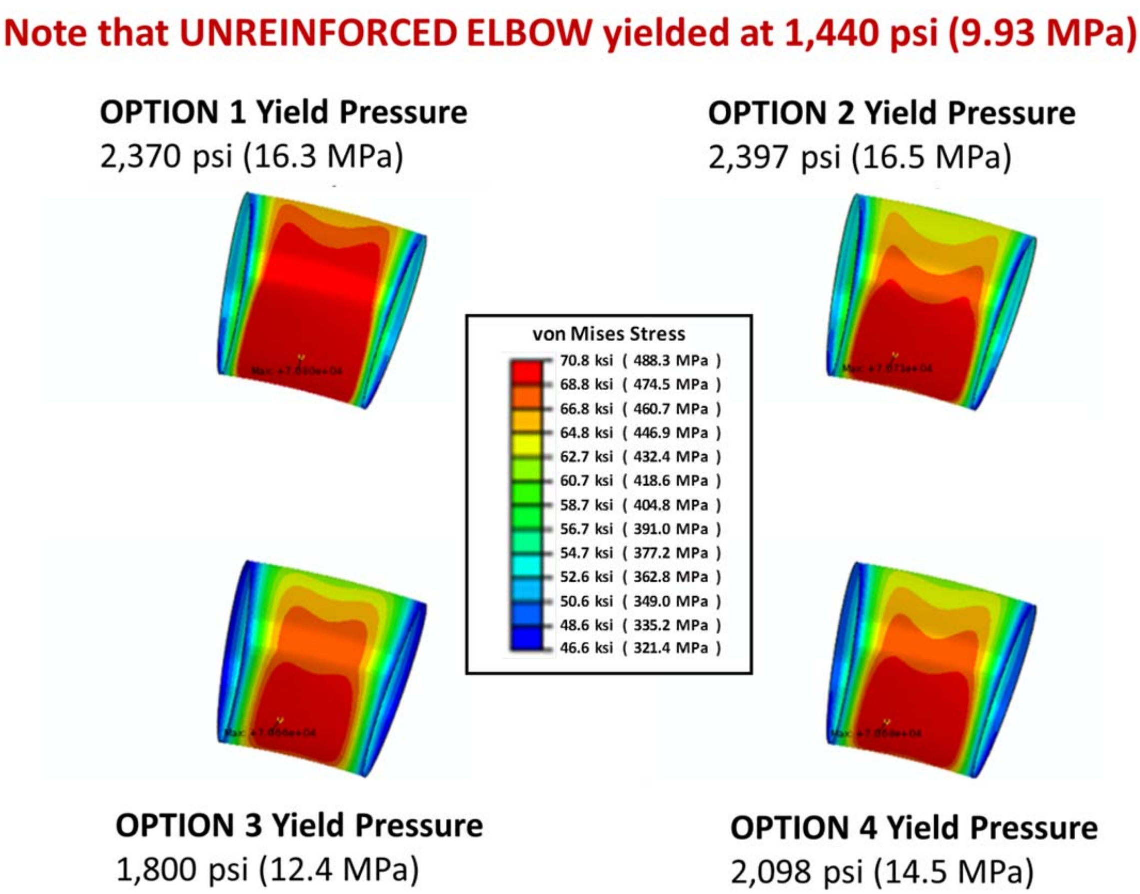

Figure 2: Effects of composite reinforcement on pressure required to cause yielding

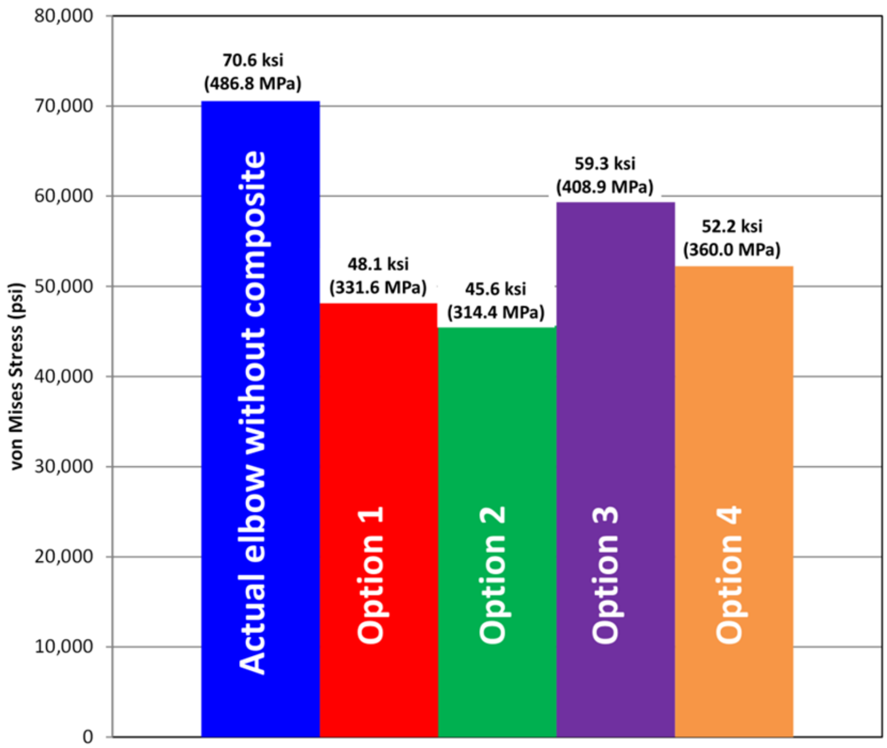

Figure 3: von Mises stress in pipe at 1,440 psi (80% SMYS) with composite reinforcement
Option 1: 3C / 1L (occurs 4X) | **Option 2:** 16C | **Option 3:** 16L | **Option 4:** 2C | 2L (occurs 4X)

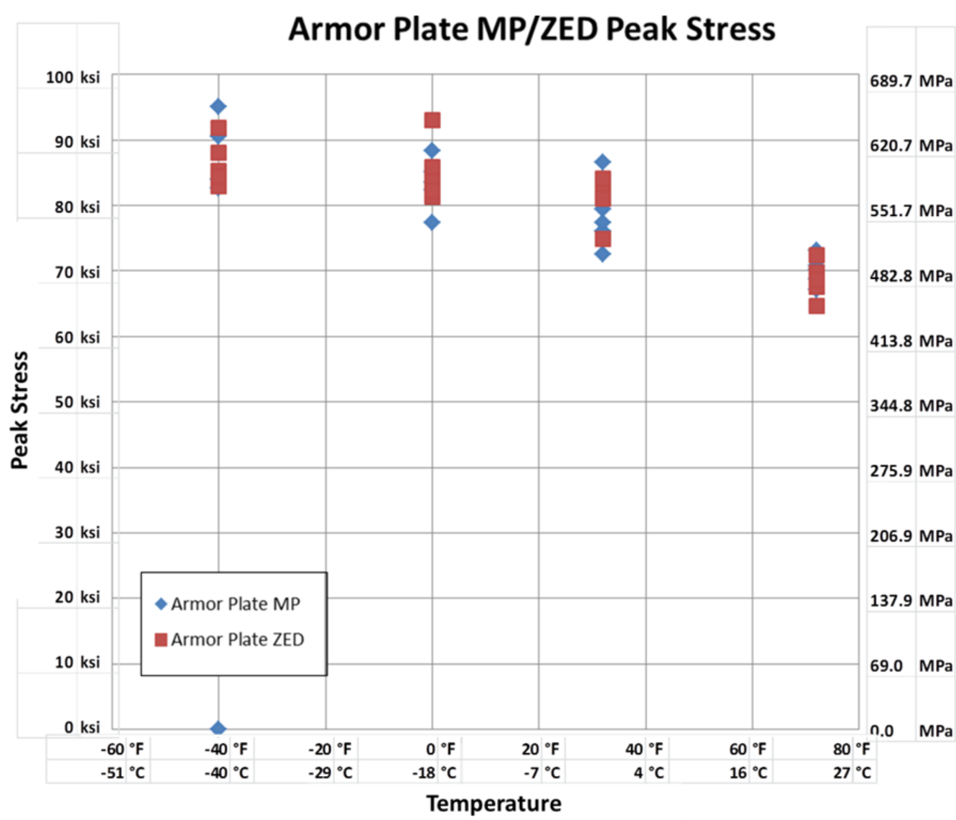

Figure 4: APPW tensile strength as a function of temperature (two resin systems)

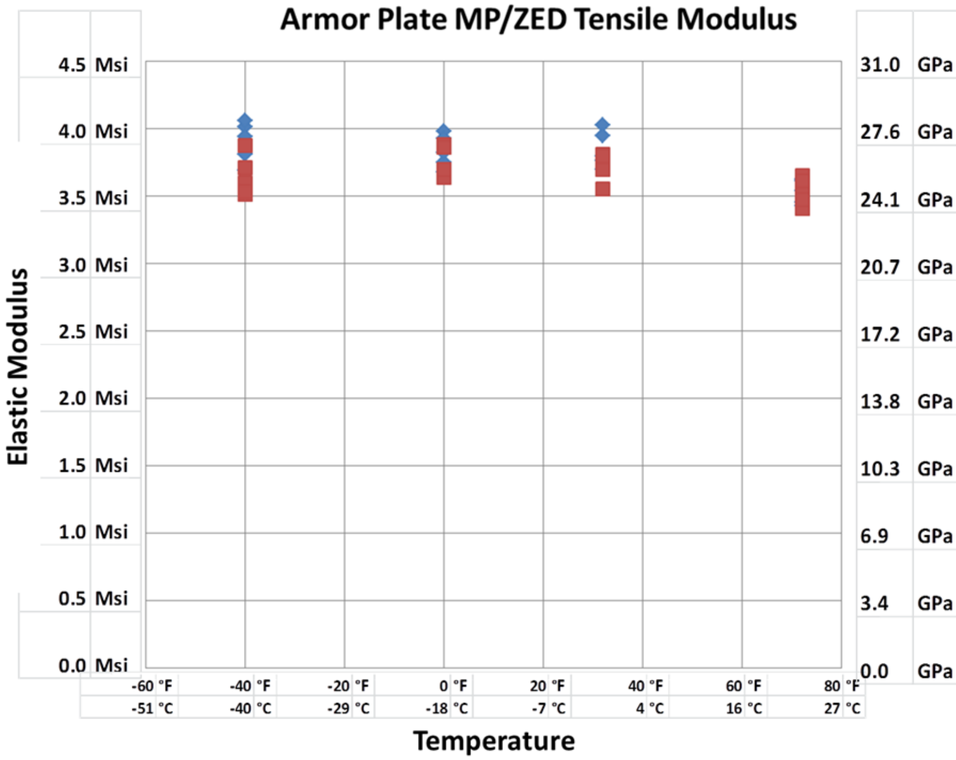

Figure 5: APPW elastic modulus as a function of temperature (two resin systems)

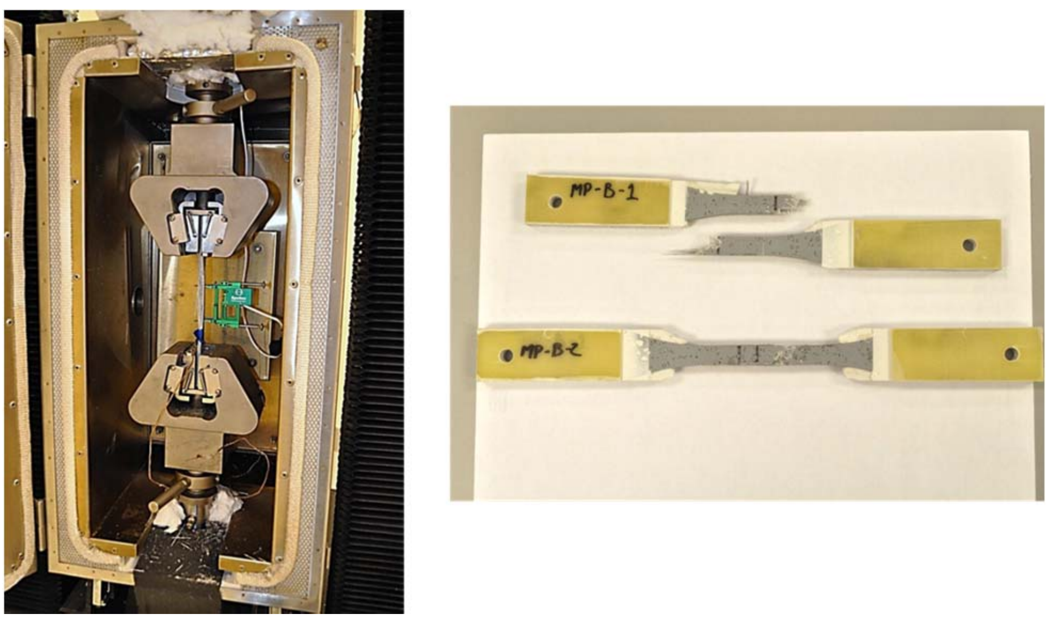

Figure 6: Photographs showing the test set-up and typical coupon failures

Figure 7: Unreinforced sample on bending beam in CLOSE mode

Figure 8: Close-up view of unreinforced sample on bending beam in OPEN mode

Figure 9: Aerial view of reinforced sample in bending load frame

Figure 10: Burst test failure of unreinforced elbow sample

Figure 11: Burst test failure of reinforced elbow sample

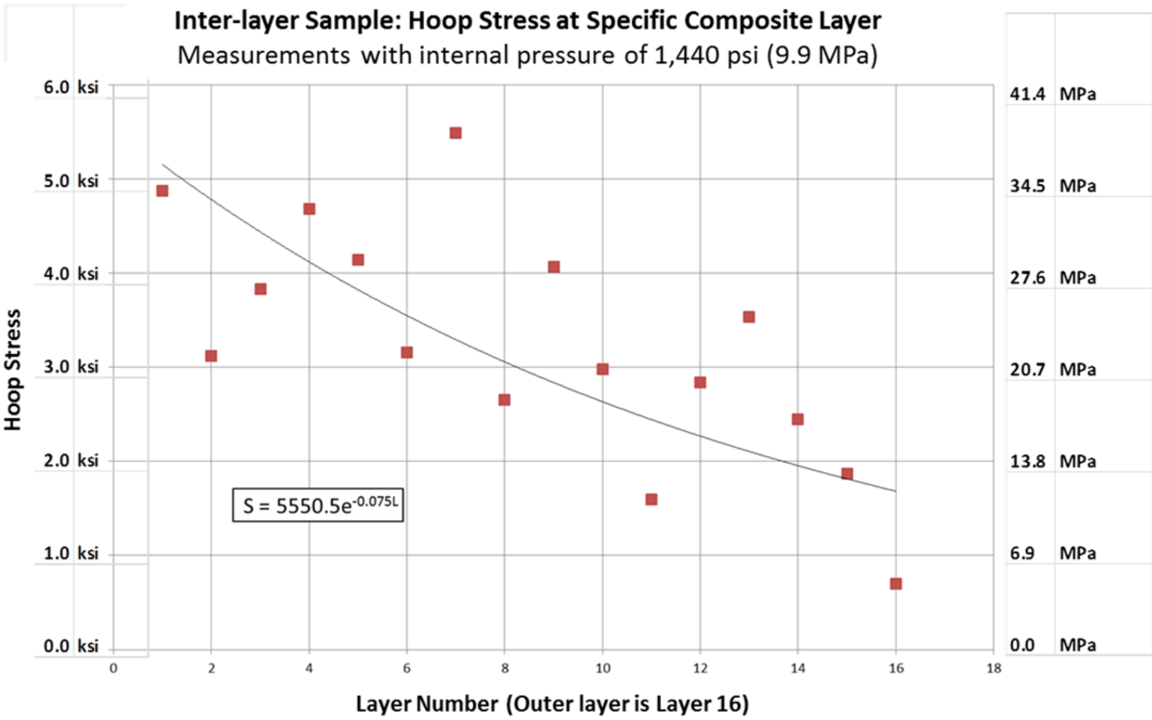

Figure 12: Composite hoop stress as a function of layer in ILS reinforced sample
(Equation provided above relates Hoop Stress (S) to Layer Number (L), units of ksi)