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STRAIN-BASED DESIGN METHODS FOR COMPOSITE REPAIR SYSTEMS

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ABSTRACT

Composite materials are commonly used to repair corroded and mechanically-damaged pipelines. Most of these repairs are made on straight sections of pipe. However, from time to time repairs on complex geometries such as elbows, tees, and field bends are required. Conventional design methods for determining the amount of required composite materials are not conducive for these types of repairs. Over the past several years, the author has developed a methodology for assessing the level of reinforcement provided by composite materials to damaged pipelines using finite element methods. Instead of stress as the design basis metric, the method employs a strain-based design criteria that is ideally-suited for evaluating the level of reinforcement provided to non-standard pipe geometries. The finite element work has been validated using experimental methods that employed strain gages placed beneath the composite repair to quantify the level of reinforcement provided by the repair. This paper provides a detailed description of the strain-based design method along with appropriate design margins for both the reinforced steel and long-term performance of the composite materials.

INTRODUCTION

Traditional design methods for composite repair systems have relied on classical mechanics derived from strength of materials and compatibility relations. While these have served industry well, several noteworthy limitations exist in this approach. First, when composite materials reinforce steel pipelines they do so through a load transfer mechanism that involves increased compliance (i.e. loss of stiffness) in the steel as plasticity is induced with increasing loads such as internal pressure. As this transpires, the composite material takes on an increasing percentage of the load share. Traditional calculation methods based strictly on elastic behavior of the steel cannot accurately model this process. Secondly, if one is to argue the validity of using traditional analysis methods for straight sections of pipe, questions then arise regarding the use of the same design methods when considering the reinforcement of non-straight geometries such as elbow, tees, and wyes. Other factors, such as the inability of traditional design methods to fully-realize the capacity of the steel, are of note; however, the above two limitations are the most dominant.

Recognizing that these limitations exist, one must ask if a better analysis option exists. If one is to evaluate the design methodology employed by current composite manufacturers, it does not appear as if an alternative design method has been explored, or at least there is no published information on this particular subject. The solution to the present shortcoming resides in a subject area of engineering mechanics known as limit state design, and specifically one that is founded on a strain-based design process.

Observing the need for such a design methodology, this paper has been prepared based on recent experiences and several composite repair efforts that required the use of a strain-based design method. An overview of the strain-based limit state design process is provided, along with several examples from recent studies.

The organization of the paper is divided into the following section: the *Background* section provides an overview of limit state design methods, while the *Case Studies* section provides several examples of real-world studies evaluated using the proposed strain-based design method. Of particular note is a presentation on how a composite repair system was developed using the proposed design methodology. Also included is a *Discussion* section intended to provide the reader and the pipeline community with several basic considerations that should be made when using the strain-based design process.

STRAIN-BASED DESIGN METHODS

Although the repair of risers is considered a post-construction remediation activity as opposed to a design-type construction activity, the composite repair itself actually constitutes a design. This observation is due to design-type requirements associated with material selection and stress/strain limits imposed on both the reinforced steel and reinforcing composite material. When discussing reinforcement using composite materials, there are several points of significance. First, the limit state design can be used to determine the plastic collapse load of the reinforced structure. The issue of how much additional load is achieved by the addition of the composite material is addressed. Secondly, once the plastic collapse load is determined, a design load can be calculated using an appropriate design margin. Thirdly, both analysis and testing can be used to determine the maximum strain in the reinforced steel at both the design and plastic collapse loads. It is prudent to limit strain in the steel, although it is recognized that the contribution of the composite material will alter the maximum strains that would be permitted if no reinforcement were present. Lastly, because limit analysis is based on the use of elastic-plastic material properties for the steel, the analyst can extract that strain in the reinforcing composite material even after load has been transferred from the steel carrier structure. This is an important point as a purely elastic analysis will fail to account for the mechanics of the load transfer and underestimate the amount of load actually being carried by the composite material.

Both Division 2 and Division 3 of Section VIII of the ASME Boiler & Pressure Vessel Codes describe and specify the use of limit state methods for demonstrating adequacy of design [4]. Technical details are provided in Appendix 6 of Division 2 regarding the use of limit state design methods experimentally and how to calculate the design load based on measurements captured during pressure testing.

The largest body of research and development of limit state design methods has been funded by ASME through sponsored work by the Task Group on Characterization of the Plastic Behavior of Structures of the Pressure Vessel Research Committee (PVRC) of the Welding Research Council (WRC). WRC Bulletin 254 [5] contains three documents that contain an exhaustive body of research associated with limit analysis. One of the significant contributions from this WRC study to the present work on composite reinforcement is the method for determining the plastic collapse pressure using the *Twice-Elastic Slope Pressure*. This procedure permits determination of the plastic collapse load using pressure deflection data from either an analytical or experimental source. The application for this study is that the plastic collapse for any given load can be determined using the same methodology that involves incrementally increasing the load until a point of unbounded displacements occurs.

In terms of applying finite element methods to limit state design, WRC Bulletin 464 by Kalnins [6] provides specific guidance in using modern finite element codes. Details including required model input and interpretation of results are discussed.

In his text, Walters [7] provides in-depth discussions on addressing interactions between a steel liner and reinforcing composite material. Elements of this document were foundational in the development of the finite element modeling effort used in this study. Additionally, this reference provided insights as to the acceptability and necessity that plasticity in the reinforced steel be permitted to engage the composite materials, with the caveat that strains must be limited in both the steel liner and reinforcing composite material to ensure that adequate safety margins are present.

A final comment concerns the strain limit imposed on the composite material. The *ASME 2006 Design Factor Guidelines for High-Pressure Composite Hydrogen Tanks* document [3] provides recommended design factors relative to short-term mechanical strength data. These values are provided relative to a short-term burst pressure for long-term stress rupture based on a fixed 15-year design life for fully wrapped and hoop wrapped composite tanks with metal liners. The recommended margins are based on the proven experience with existing standards for composite reinforced tanks.

DESIGNING A COMPOSITE REPAIR SYSTEM

To assist the reader with understanding various facets of the strain-based design process, it is a worthwhile exercise to explore how one might develop a composite repair system using this methodology. In this regard, the objective in developing a composite repair system would be to design a system to repair a damaged pipeline section incorporating loading requirements, material selection, and installation techniques. This also includes identifying and technically addressing the variables required to develop the composite repair system. In a general sense, the design requirements would be to develop a composite system that repairs corroded or damaged pipelines and ensures that the strains in the steel remain below an acceptable level. This must include combined loads such as pressure, tension, and bending loads.

Figure 1 presents the steps involved in the design process. This process involves both design efforts as well as identification of design limits to which the calculated stresses and strains can be compared. Included in **Figure 1** are details initiating at the preliminary design phase through completion of the final design verified using finite element analysis and prototype testing.

The sections that follow provide details on the design requirements for an optimized composite repair system. Also included are discussions on the development of a method for determining the allowable design stress and strain values. Finally, the proposed composite architecture and geometry for the optimized system are prescribed.

Design Requirements

In order to develop an optimized repair system, it is first necessary to identify what is required of the design. Provided below are two levels of design requirements. The *Primary Requirements* are those that govern the structural design of the composite repair. They effectively determine the composite architecture and geometric options of the repair. The next group, *Secondary Requirements*, is important in terms of how the repair functions and performs in situ. Once the Primary Requirements are satisfied, the design can proceed to optimization by addressing the Secondary requirements.

Primary Requirements Listed below are the primary design requirements.

1. Design must prevent bulging of the corroded pipe section due to excessive circumferential strains during pressurization. This can be achieved by placing circumferentially-oriented fibers close to the corroded region.
2. The repair must provide sufficient reinforcement so that strains induced during bending do not exceed a specified design strain. One option is to perform a limit state design that includes all loads (pressure, tension, and bending) and change only one load type (e.g. bending) while holding the other two constant. If the calculated collapse load is greater than the required design load then a sufficient level of reinforcement exists.
3. Design must be of sufficient length to maintain integrity of the interface bond between the repair and steel. It should be noted that from a mechanics standpoint, this is the least critical of the three provided primary requirements.

Secondary Requirements Listed below are the secondary design requirements.

4. Ease of installation
5. Economic viability
6. Quality control and design to ensure structural integrity during installation
7. Impact resistance
8. Does not cause corrosion or form a galvanic cell, but actually acts as a coating

Method for Determining Allowable Design States

From a design methods standpoint, determining allowable strain (and stress) levels in the materials of choice is critical. In a conventional design employing carbon steel as the construction material (e.g. a typical gas or liquid pipeline), the allowable stresses are specifically defined in ASME B31.8 or B31.4 as percentages of the material's yield strength [1, 2]. However, the integration of composite materials introduces another level of complexity to the design process. One of the challenges in developing a repair system that possesses adequate strength and stiffness to reinforce a given pipe damaged section involves determining the acceptable stress and strain conditions in the steel and reinforcing composite materials. It is clear that the design of the repair must take into account these allowable conditions, especially with regards to geometry and architecture of the composite materials. Fundamentally, there is a balance between having enough material to ensure that strains in the steel are minimized, but at the same time not installing an excessive amount of composite reinforcing materials. In other words, an optimum design is one that has enough material to meet the design requirements and ensure that strains in the reinforced steel are maintained below an acceptable threshold, but not has more composite material than is required. Having a thorough understanding of the mechanics of the problem, along with the integration of available industry-accepted allowable conditions, is the key to achieve a successful design.

The two keys to achieving an optimum design relative to allowable conditions in the steel and composite materials are found in the following:

- Determining the maximum acceptable strain in the steel (or other reinforced material) subject to applicable pressure, tension, and bending loads
- Defining the maximum allowable stress in the composite reinforcing material

Limit analysis methods were used to determine acceptable design conditions, but also to optimize a carbon-epoxy repair system.

In order to perform a limit analysis, a numerical method is required. Conventional limit analysis employs finite element analysis (FEA) using an elastic-plastic material model. FEA is ideally-suited for evaluating the level of reinforcement provided by a composite material to a given steel structure. Provided below are several of the more salient points to consider:

- When performing an analysis, FEA permits both the steel and the composite to be modeled independently. When loads are applied to a reinforced structure, the finite element model calculates the level of load distribution imparted to both the base material (typically steel), as well as the reinforcing composite material.
- During post-processing, stress and strain can be extracted from the FEA model. This is an essential part of the design process as one must consider the strain limitations for both the reinforced material and composite separately. For example, if strains in a reinforced pipe steel section are acceptable, but if strain in the composite material are loaded beyond the design strain limit, the level of reinforcement is not acceptable.
- FEA also offers the added advantage of being able to evaluate composite reinforcement of complex geometries such as tees, wyes, valves, and elbows. There are few analytic closed-form equations available for evaluating the level of reinforcement associated with these pipe geometries.
- It is possible to evaluate the effects of multiple loading combinations on the composite reinforced structure. Most of the research that has been done to date on pipeline composite reinforcement has focused on the restoration of hoop strength; however, there are scenarios where the effects of loads such as tension and bending must be considered. A Case Study will follow that shows how combined loads there involved in a study involving both finite element analysis and full-scale testing.

In addition to using FEA to determine strain, it is possible to using experimental methods. Finite element methods tends to be a more common means for conducting limit analyses; however, full-scale testing can be a powerful resource for determining how much reinforcement is provided by a composite overwrap. Additionally, although full-scale testing can be expensive, it offers to engineers the ability to confirm analytical work. With a properly designed test program, one can verify select analysis models. Once the confirmation takes place, the FEA models can be used with confidence to evaluate the performance of a range of variables and loading scenarios. Some would argue that in the absence of experimental verification, reduced confidence in the analysis findings will result. This in turn requires the use of larger design margins.

Strain Limitations for the Repaired Steel Section

One of the primary purposes when performing any structural repair is reduction of loads carried by the reinforced member. In providing reinforcement, the primary load path is no longer carried solely by the original member, but loads are also carried by the addition of the composite reinforcement. Strain is the best mechanics-based quantity to assess the distribution of load between the primary load carrying component (i.e. steel riser pipe) and the repair system (i.e. composite).

With the addition of the composite material, it is expected that local strain levels in the repaired pipeline will be reduced. Under normal operating conditions, limitations are imposed on stress, typically as percentages of the material yield strength. Limit analysis methods permit the assessment of a structure to take into account some level of plasticity to achieve greater use of the steel's capacity, but also some level of plasticity is needed to transfer a portion of the total load from the steel to the composite material.

The fundamental question is this – *when a structure is reinforced with a composite material what is an acceptable level of strain in the steel at design conditions?* The best method for demonstrating how this works is using an example. **Figure 2** and **Figure 3** show the results from a FEA model that was used to calculate the level of reinforcement provided to a 8.625-inch x 0.406-inch, Grade X42 pipe with 50% corrosion. The FEA model incorporated loads that included an internal pressure of 2,887 psi, an axial tension of 145 kips, and a bending load was incrementally increased to the point where thru-wall plasticity was induced in the pipe.

What is plotted in **Figure 2** are strains in the steel beneath the carbon-epoxy reinforcement. The elastic-plastic collapse bending load was calculated to be approximately 33.5 kip-ft (for the four-point bending configuration, the bending moment is calculated as the product of bending load and the moment arm of 35 inches). Using a design margin of 2.0, the design load is 16.8 kips. On this figure a triangular region is highlighted. This is the region of acceptability in terms of permissible design loads and strains. The top line of the triangle is established by the design margin, while the right side of the triangle is set based on a slope that is two times that load-deflection curve from the FEA model (this curve is known as the *double elastic slope curve*). Therefore, to answer the question regarding acceptable strain limits one can see from the presented problem that the strain limit for the steel is 0.2 percent at design load conditions. If strain are allowed to exceed this limit, the potential for generating permanent, unacceptable levels of plastic deformation in the steel is present.

Strain Limitations for the Composite Material

In addition to determining acceptable strain limits for the reinforced material, it is essential that strain limits be imposed for the composite material. ASME commissioned the Hydrogen Project Team and Becht Engineering Co., Inc. with the task of developing guidelines for design factors in fabricating high-pressure composite hydrogen tanks. The result of the effort produced ASME STP/PT-005, *Design Factor Guidelines for High-Pressure Composite Hydrogen Tanks* [3]. This report provides recommended design factors relative to short-term burst pressure and interim margins for long-term stress rupture based on a fixed 15-year design life for fully wrapped and hoop wrapped composite tanks with metal liners. Part of this effort included a review of the design margins between burst and the maximum allowable working pressures for tanks fabricated using composite materials. The majority of international design codes have a design margin of 2 for hoop wrapped tanks, and an average value on the order of 2.5 for fully wrapped tanks [3]. Additionally, design guidelines are provided relative to the stress limit as reflected in the following text from this document.

> The rules should permit specification of a required design life. However, to do so requires development of a design methodology that considers stress rupture for composite tanks. Until such a design methodology is developed, it is recommended that the fixed 15-year life and a 0.4 stress ratio for hoop wrapped tanks be used (STP/PTY-005, page 11).

Along the same lines, ASTM D2992 for fiberglass pipe and fittings designates that the design be based on one-half (i.e. 0.5) the minimum expected fiber stress to rupture in 100,000 hours (95% confidence level), or the 50-year strength, whichever is less [8].

Worth reports results from a program assessing the effects of environmental exposure conditions on the performance of the Aquawrap® repair system, which is a water-activated polyurethane matrix with biaxial E-glass fibers [9]. This program involved a wide range of tests; however, the tests of greatest interest for the discussion at hand included assessing the degradation of tensile strength due to salt water soak exposure (10,000 hours), exposure to dry heat (140°F for 3,000 hours), and creep rupture tests (10,000 hours), The latter program was used as the basis for establishing the long-term strength of the Aquawrap® repair system considering an extrapolated 25-year projection that accounted for 52% of its initial (time zero) tensile strength.

CASE STUDIES

An effective method for demonstrating how to use a strain-based design method is through case studies. The three (3) following case studies are based on work performed previously in evaluating composite reinforcement of actual pipeline systems.

Repairing Corrosion

Armor Plate® Pipe Wrap (APPW) is an E-glass/epoxy composite repair system used to repair corroded and mechanically-damaged structures. APPW is installed in a wet condition on pipelines and the thickness of the repair is governed by the geometry of the corrosion (depth and length), as well as the pipe geometry and material grade. To determine the amount of APPW that is required to reinforce a given level of corrosion, the ArmorCALC™ calculation tool was developed.

The example problem that is provided is based on a range of corrosion levels (e.g. 25%, 50%, and 80% of the pipe's nominal wall thickness) in a 12.75-inch x 0.188-inch, Grade X52 pipe. The operating pressure for the pipe is 1,104 psi. **Figure 4** is a screenshot from ArmorCALC™ for a corrosion depth of 25% showing the required number of wraps is 4. This information was combined with a finite element model to generate the results plotted in **Figure 5**.

The following observations are made in viewing **Figure 5**.

- The lower bound collapse load (LBCL) is plotted as the **SOLID BLUE** line. As the corrosion depth increases the LBCL is reduced. The LBCL was calculated by the FEA models and corresponds to the loads at which the model would no longer converge. From a material standpoint this is load (pressure) at which gross plastic yielding occurs.
- The design pressure is calculated by multiplying the calculated LBCL by 0.6 (see below for discussion on design margin). The **SOLID RED** curve shows the calculated results.
- For corrosion levels in excess of 25%, one notes that the design pressures for the composite-reinforced results (**SOLID GREEN**) do not change and are not less than the operating pressure of 1,104 psi with increasing corrosion levels. The reason for this is that the failure in the finite element models occurred outside of the composite reinforced regions. In other words, if the appropriate amount of composite material is present failure will occur outside of the repair.

For those who perform limit analyses, there are typically discussions regarding what is an acceptable design margin. In a recent discussion with a pipeline operator, the author went through the following calculations to demonstrate that the design margin of 1.67 (inverse of 0.6) is acceptable based on traditional pipeline design standards. Consider the following calculations for Grade X52 pipe using the methods of ASME B31.8 Location Class 1 Division 2 (design factor of 0.72).

1. The minimum specified yield and ultimate strengths (UTS) for Grade X52 pipe per API 5L are 52 ksi and 66 ksi, respectively.
2. The minimum stress level at which the pipe will be expected to fail by burst is the UTS, or 66,000 psi.
3. The design stress at the operating pressure per ASME B31.8 Location Class 1 Division 2 is 0.72 times 52,000 psi, or 37.440 psi.
4. Using the above calculations, the ratio of the design stress to the UTS is 0.57 (37,440 psi divided by 66,000 psi).

The above discussion is important because although the use of limit analysis is a relatively new concept for pipeline design, the design margin of 0.6 is built into every pipeline. What is not considered in this discussion are limits on strain; however, as demonstrated in the previous discussion (cf. **Figure 2**), a properly-design composite reinforcement will ensure that strain in the reinforced steel are kept with acceptable limits.

Reinforcing Field Bends with Ovality

In pipeline operation, excessive levels of ovality in field bends will reduce their pressure integrity. A study was conducted to evaluate the level of reinforcement of field bends using Armor Plate® Pipe Wrap. As mentioned previously, APPW is an E-glass/epoxy composite repair and when installed around pipelines it has elastic modulii of approximately 2 X 10^6 psi and 1 X 10^6 psi in the circumferential and axial directions, respectively. The material properties for the composite material are important as they are used as input into the finite element models.

Figure 6 is a contour plot from one of the finite element models showing von Mises stresses in a field bend at design conditions. The geometry for the finite element models was based on measurements made in the field on actual fiend bends. By making actual measurements, greater representation of actual ovality levels was included in the study. Several models were constructed in order to capture the effects of factors such as the following.

- Increasing the overall thickness of the field bends
- Increasing the thickness at the intrados of the field bends
- Adding Armor Plate® Pipe Wrap as a composite reinforcement (0.50 inch thick wrap)

As discussed and presented previously, the finite element models were run with iterations continuing until convergence was no longer possible. Elastic-plastic material properties for the steel were used, and for the composite reinforcement model elements were included to account for APPW that included the appropriate material properties. The nominal properties for the pipeline in this study are 16-inch x 0.375-inch, Grade X52. Measurements in the field demonstrated that the thickness at the intrados was greater than nominal, while some thinning was observed at the extrados.

Figure 7 is a bar chart showing the effects of factors discussed previously. The following increases in the collapse pressure (and design pressure) were calculated relative to the base case with a wall thickness of 0.375 inches. Note that the nominal thickness of the field bend is 0.375 inches.

- Increasing the overall thickness of the field bend to 0.420 inches increases the pressure capacity by 136 percent
- Increasing the thickness at the intrados of the field bend to 0.420 inches increases the pressure capacity by 112 percent
- Adding APPW with a thickness of 0.50 inches increases the pressure capacity by 178 percent

One of the important benefits in performing this study was the demonstration that the measured field bend geometries did not reduce the design pressure capacities below acceptable limits. Even the base case with a wall thickness of 0.375 inches had a design pressure of 1,500 psi, which was in excess of the 1,400 psi operating pressure of the pipeline.

Reinforcing Pipe with Combined Loads

As mentioned previously, one of the benefits in performing limit analysis methods is the ability to simultaneously consider the effects of combined loads. The case study presented in this section of the paper details work performed in evaluating the ability of a carbon-epoxy repair system developed by the author in reinforcing pipes subjected to internal pressure, tension, and bending loads.

The principal aim of this study was to design a composite system to repair offshore risers incorporating design requirements, material selection, and installation techniques. This also included identifying and technically addressing the variables required to develop the composite repair system. The design requirements for this effort was to develop a composite system that repairs corroded or damaged risers and ensures that the global load path stresses in the steel portion of the riser remain below an acceptable level. This must include combined pressure, tension, and bending loads [10].

Two methods were used to evaluate the performance of the carbon-epoxy composite repair system, hereafter referred to as the CRA system. The first was FEA where different lay-up conditions were assessed to optimize the design. The second method of evaluation included full-scale testing. In order to conduct these tests, components of the repair system were fabricated based on the optimized design developed as part of the analysis stage.

The sections that follow provide details on the analysis, fabrication, and testing efforts involved in this study.

Assessment Based on Finite Element Methods Once the calculations were completed using classical mechanics, a finite element model was developed to determine the following:

- Stress and strain in the composite material considering design load conditions
- Strain in the steel considering design load conditions
- Confirming that the 0.200 inch thick hoop-oriented fibers were sufficient for the required design conditions
- Assess the effects of different thicknesses of the axially-oriented fibers (important for evaluating bending load rigidity)

The discussions that follow provide details on the finite element models used in this study and address the following topics:

- Material properties
- Geometry and boundary conditions
- Loading
- Post-processing and extracting data from the models

For the composite material, properties are input in local coordinates of the element. For materials modeled isotropically such as the pipe steel, orientation is not important; however, when modeling composite materials orientation is critical. This is especially true when one considers that a primary advantage in using composite materials is the ability to directionally-control the material properties.

The listing of elastic properties for composite material in the finite element model associated with the *ELASTIC card is as follows:

$$E1,\ E2,\ \nu12\ ,\ G12,\ G23,\ \text{and}\ G13$$

where E is the elastic modulus, ν is Poisson's ratio, and G is the shear modulus (G12 and G13 represent the transverse shear modulii).. The directions "1" and "2" correspond to the specific direction of the fiber or cloth. For the uniaxial stitched carbon fabric modeled in this study, "1" corresponds to the direction of the fiber, while "2" designates the transverse direction that is primarily controlled by the epoxy resin. For the steel, a simple elastic-plastic model was used with yield and ultimate strength of 61 ksi and 74.6 ksi, respectively.

To assess performance of the repair subject to design loads, a finite element models was analyzed for the CRA system that included internal pressure (2,887 psi), axial tension (145,000 lbs), and a range of bending forces. A four point bend configuration was used in the finite element model, so to compute the applied bending moment the applied force is multiplied by 2.92 feet (i.e. 10,000 lbs corresponds to a bending moment of 29,200 ft-lbs). There are several noteworthy observations in reviewing the data plotted in **Figure 2** (presented previously) that are listed below.

- The data corresponding to the unrepaired condition (solid red curve) did not include pressure. This was to mimic the test program that did not include pressure during the bend test for the unrepaired case. If pressure had been applied, an excessively low bending capacity would have resulted for the corroded unrepaired case due to gross plastic yielding in the steel.

- The primary source of the design limits is based on the uncorroded base pipe data (green line). From this case the design load is calculated. As noted in the figure, the following data points are determined:
  - Plastic analysis collapse load of 33.6 kips.
  - Design load (bending force) of 16.8 kips (design margin of 2.0 on the collapse load) which also corresponds to a bending moment of 49.1 kip-ft.
  - At the design condition, the maximum permissible axial strain in the steel beneath the repair is 0.214 percent (corresponds to the intersection of the horizontal line designating the design load and the double elastic curve).

In summary, the following design limits are imposed on the CRA system design:

- **Carbon/epoxy material** stress limit of **40,000 psi** (in accordance with the methods outlined in ASME STP/PT-005 Design Factor Guidelines for High Pressure Composite Hydrogen Tanks), which corresponds to a strain limit of **0.40 percent**.
- **Strain limit on corroded steel** beneath the reinforcement of **0.214 percent**
- The maximum permissible **bending load** (based on design conditions with a design margin of 2.0 on the collapse load) is **16.8 kips**

Fabrication and Installation Efforts Six (6) carbon half shells, each 60 inches long, were fabricated at Comptek Structural Composites, Inc.'s facility in Boulder, Colorado. The architecture of the half-shells uses an inner single layer of E-glass balanced weave cloth that is approximately 0.050 inches thick. On top of this inner layer the uniaxial carbon stitched fiber cloth of 0.400 inches was installed, which corresponds to a total of 20 layers. The half-shells were cured under a vacuum seal. The completed half shells were shipped to Stress Engineering Services, Inc. in Houston.

Prior to testing and installation of the repair system, three (3) steel pipe test samples were fabricated. The samples were fabricated using 8.625-inch x 0.406-inch, Grade X46 pipe. A 50 percent simulated corrosion circumferential groove spanning 24 inches in length was machined in each sample. The samples configurations were as follows:

- Burst sample with a length of 8 feet
- Tension sample with a length of 8 feet
- Bending sample with a length of 15 feet

Strain gages were installed on each of the above test samples with details provided in a following section of this paper.

The following steps were involved in the installation of the repairs. Figures are referenced that include photos for each step as appropriate.

1. Sandblast the surface of the pipe where the composite repair to be installed.
2. To repair the 24 inch long corroded section of pipe, the uniaxial stitched carbon cloth material was cut to length. Repairs were made by saturating the cloth with two part epoxy and wrapping the cloth around the pipe in the hoop direction. Two rows of material, each totaling 10 layers, were installed in the damaged region as shown in **Figures 7** to produce a total thickness of 0.200 inches.
3. Blue plastic stricter wrap material was applied over the outside surface of the hoop wrapped material. Perforation of the plastic wrap was done to permit the excess resin to extrude. The hoop wrapped material was permitted to cure overnight.
4. After the stricter wrap material was removed, the Spabond 340 two-part epoxy was mixed using a mixing gun. The mixed gray epoxy was hand applied using a slotted trowel with ¼-inch by ¼-inch square grooves as shown in **Figure 8**.
5. The carbon half shells were installed on the outside surface of the pipe. The 60-inch long half shells were centered axially on the corroded region. **Figure 9** shows the carbon half shells being installed on the 8-ft long tension sample.
6. Steel banding clamps were installed on the outside surface of the carbon half shells to restrain them during curing. To expedite the installation process, the banding clamps were left on the half shells beneath the outer hoop wrapped layers.
7. Once the carbon half shells were locked in place with the steel banding clamps, the outer hoop wrapped carbon material was installed. The same materials used previously for the inner corrosion hoop layers were used in this layer (uniaxial stitched carbon with an epoxy matrix); however, only 5 layers were installed resulting in a total thickness of 0.100 inches. Five rows of carbon material were installed that resulted in a small axial 1.5 inch gap between each of the layers. Stricter wrap material was installed on the outside surface of the hoop wraps.
8. The samples were permitted to cure overnight and the stricter wrap was removed the following morning. **Figure 10** shows the final repair including the carbon half shells and outer carbon hoop wrapped material.

Samples were permitted to cure for a full 24-hour period before testing was started. During the curing phase, the necessary cables and instrumentation were connected to the data acquisition system used to record data during testing.

Evaluation Based on Full-scale Testing Methods Biaxial (i.e. hoop and axial) strain gage rosettes were used in testing to determine the level of strain in the pipe steel and composite materials. The strains they measure provide information that determines if a composite repair system is functioning as designed. Strain gages were installed on three different stages including (1) prior to installation of the repair, (2) installed on the carbon half shells, and (3) on the surface of the hoop-wrapped carbon layers installed on the outside surface of the repairs.

Figure 11 is a schematic showing the location of the strain gages installed on the CRA system test samples. Note that six total gages are located on the outside of the repair. Three of these are on the outside surface of the pre-cured carbon shell, while three are placed on the outside surface of the carbon hoop material (this composite material placed over the carbon half shells to restrain them).

Presented in this section of the paper are detailed discussions on the strain gage results measured for samples repaired using the CRA system during the pressure, tension, and bending tests, respectively. A follow-up discussion provides comparison of results with those calculated for the system using finite element methods. Although three different tests were completed, for brevity results are only presented for the test involved pressure, tension, and bending.

Figure 12 is a schematic that shows the basic arrangement for the tension and bending loads applied to the sample. The load frame that had the ability to simultaneously apply tension and bending loads is shown in **Figure 13**. This frame has the capacity to generate 1 million lbs in tension and 750,000 ft-lbs.

Figure 14 plots axial strains measured during loading of the bending test sample. Note that during testing an internal pressure of 2,887 psi and an axial tension of 145 kips were included in addition to the bending load. Strain gages in this plot are the same as those presented previously for the pressure-only and pressure-tension test samples.

The following observations are made in viewing the results plotted in **Figure 14**. It should be noted that for the four-point bending configuration, the bending moment is calculated by multiplying the bending load by 35 inches (or 2.92 feet).

- At a bending load of approximately 20 kips all strain gages demonstrate deviation from the proportional limit (i.e. response is no longer elastic). This is consistent with hand calculations that show at a bending load of 25 kips yielding occurs in the 46 ksi yield strength pipe.
- As expected, the maximum strain occurs in the corroded region of the test sample beneath the repair (**BLUE** curve). At a bending load of 40 kips, the axial strain is measured to be 2,000 microstrain (0.20 percent).
- The strain in the carbon half shell (**GREEN** curve), although less than the strain in the reinforced steel, demonstrates that it is engaged with increasing bending loads.

Another important observation is that as the bending load is increased, the axial strains in the region of the reinforcement (i.e. everything except the **RED** curve) do not increase proportionally with increasing bending loads. The basis for this observation is that once a plastic hinge forms in the pipe (1.5 times the yield load, or approximately 65 kips), deformation initiates in the base pipe away from the composite repair. Additional loading only acts to plastically deform the pipe at the points of contact with the hydraulic cylinders and not transfer load into the reinforced region. This is a critically important observation as it indicates that the actual plastic collapse of the pipe will not occur in the repaired region, but rather outside the repair zone where local bending stresses are the greatest.

Figure 14 includes the strain gage data overlaid with the limit load parameters including the lower bound collapse load and the corresponding design load. Within the range of acceptable strain levels, the reinforcement provided by the CRA system is adequate. Because of the relatively low lower bound collapse load observed experimentally, all strains in the reinforced region of the sample are below the strains observed in the base pipe away from the reinforcement. This is important as it demonstrates that the reinforcement is functioning as intended and providing reinforcement to the corroded region of the test sample.

A final comment is warranted with regards to design requirements for the carbon material. Note that in both strain gages installed on the composite material the recorded strain levels never exceed 0.30 percent, a value less than the 0.40 percent allowable strain for the carbon material.

Comparing Analysis Findings with Test Results **Table 1** provides a comparison of results from both the analysis and testing efforts for the CRA system. The results are for strains in the reinforced region of the steel. In this table results are only presented for the burst and bending tests, as the tension to failure test was primarily an assessment of the shear strength of the adhesive bonding the carbon half shell to the steel pipe. What is important to note is that, in general, all measured strains are less than those calculated using finite element methods, including the results for both the design and limit load conditions. The exception to this observation is the strains recorded for the burst sample near the limit load of 5,700 psi (actual burst occurred at 6,517 psi).

DISCUSSION

Before providing closing remarks there are several points of discussion that need to be addressed. In order to use limit analysis methods, engineers must understand the potential modes of failure for a given structure. This is even more important when considering the effects of composite reinforcement. The present discussion is only valid if the failure mode is ductile static overload of the steel. No consideration is given for fatigue due to cyclic loading, and the strain-based design methodology is completely inappropriate for steel materials that do not exhibit ductility and are prone to brittle fracture.

Another comment is warranted when discussing the performance of composite materials. It is the author's experience that before undertaking sophisticated analysis efforts, manufacturers of composite repair system must first satisfy basic performance criteria such as material coupon testing to identify properties such as elastic modulus and tensile strength.

CONCLUSIONS

The intent of this paper was to introduce to the pipeline industry an alternate method for evaluating the level of reinforcement provided by composite materials to existing structures. It is recognized that some of the concepts introduced in this paper might be new to the reader.

The basic conclusion drawn for recent studies associated with strain-based limit state design involving composite reinforcement is that this method of design is ideally-suited for evaluating the level of reinforcement provided by composite materials. As shown with the study done using Armor Plate® Pipe Wrap to reinforce corroded pipes subjected to internal pressure, prior studies based primarily on elastic material response do not necessarily contradict the results of a strain-based design. When strain is used as the design metric, it is possible to more fully-utilize the strength that exists within both the composite and reinforced (e.g. steel) materials. The reward for the more rigorous efforts associated with performing a limit analysis is reducing what might be considered overly-conservative design margins.

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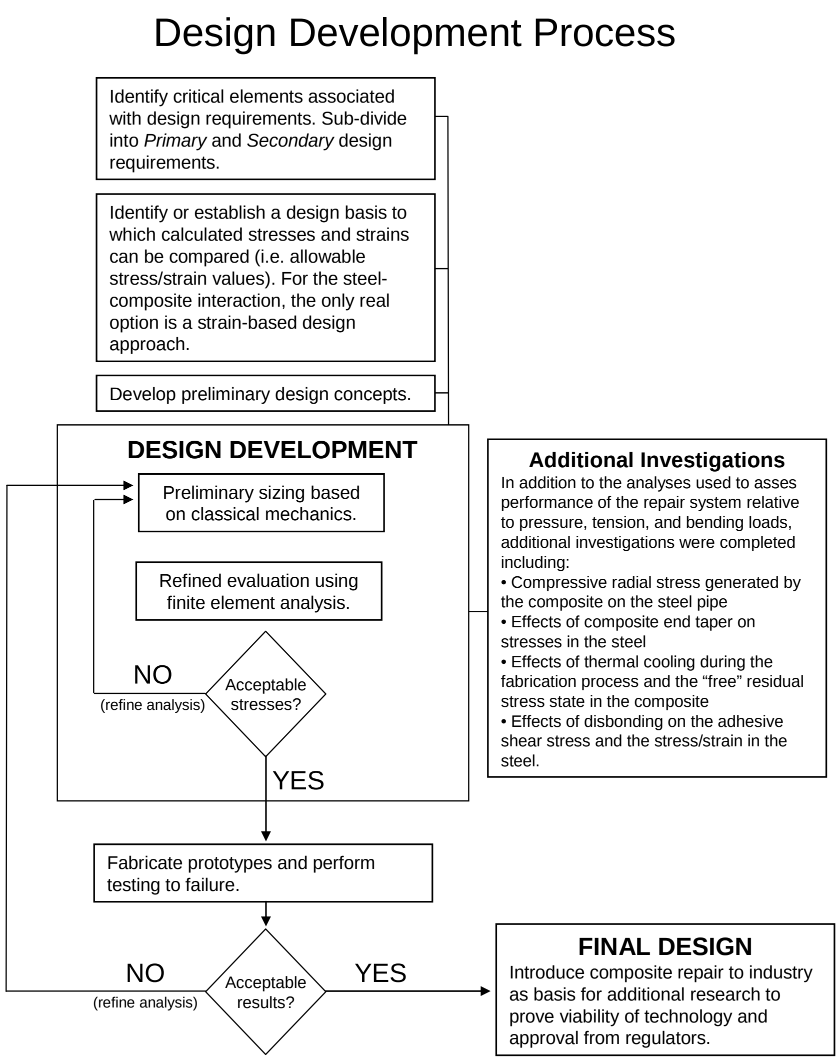

Figure 1 – Steps involved in the optimization process

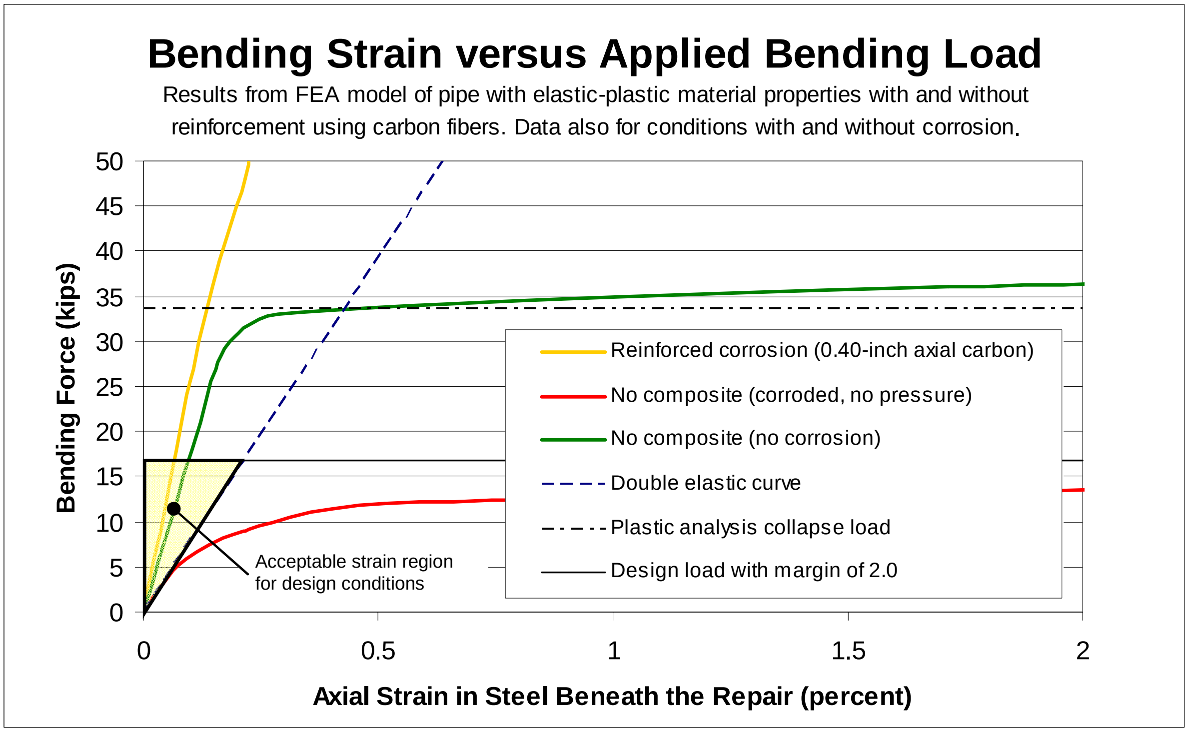

Figure 2 – Bending force versus axial strain in pipe
(carbon repair with 0.200-inch thick hoop | 0.400-inch axial | 0.100-inch layers)

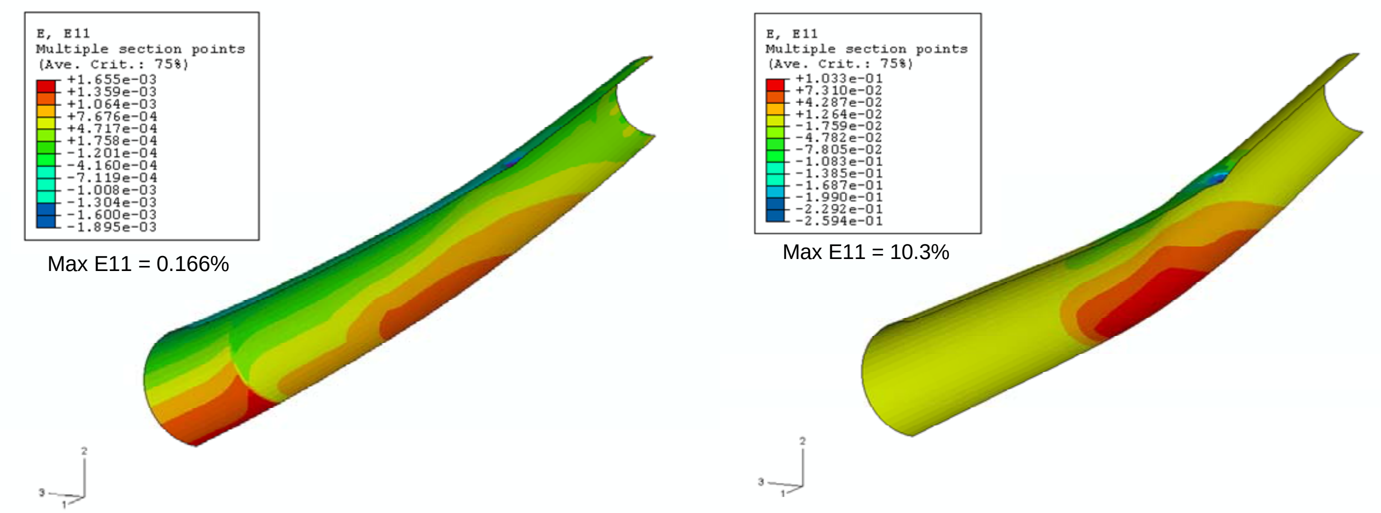

Figure 3 – Axial strains in steel at design (left) and plastic collapse (right) load conditions

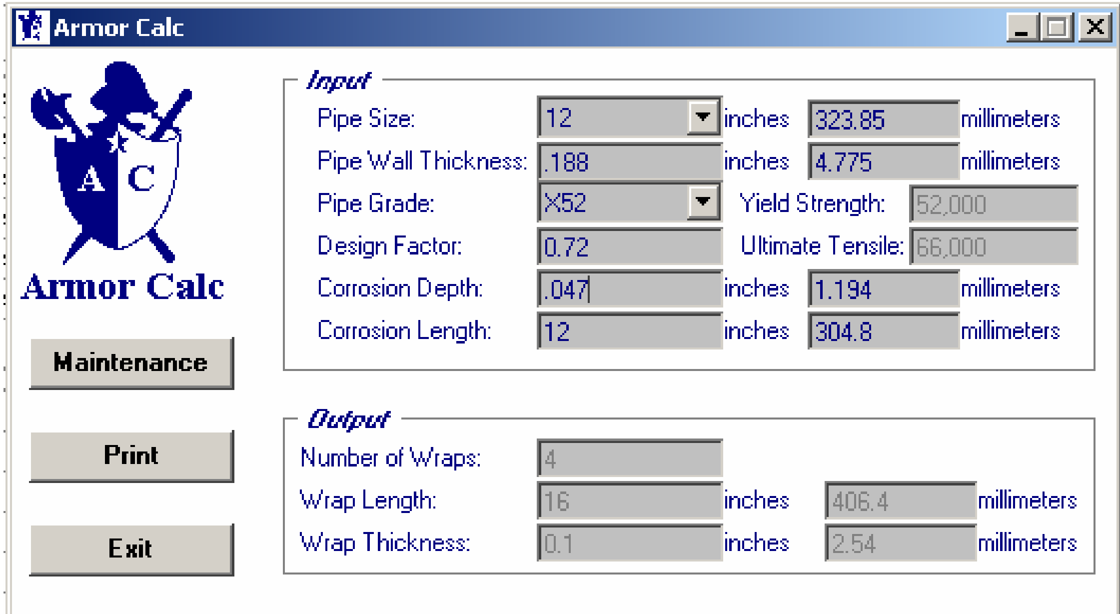

Figure 4 – Screenshot of the ArmorCALC™ computer program for Armor Plate® Pipe Wrap

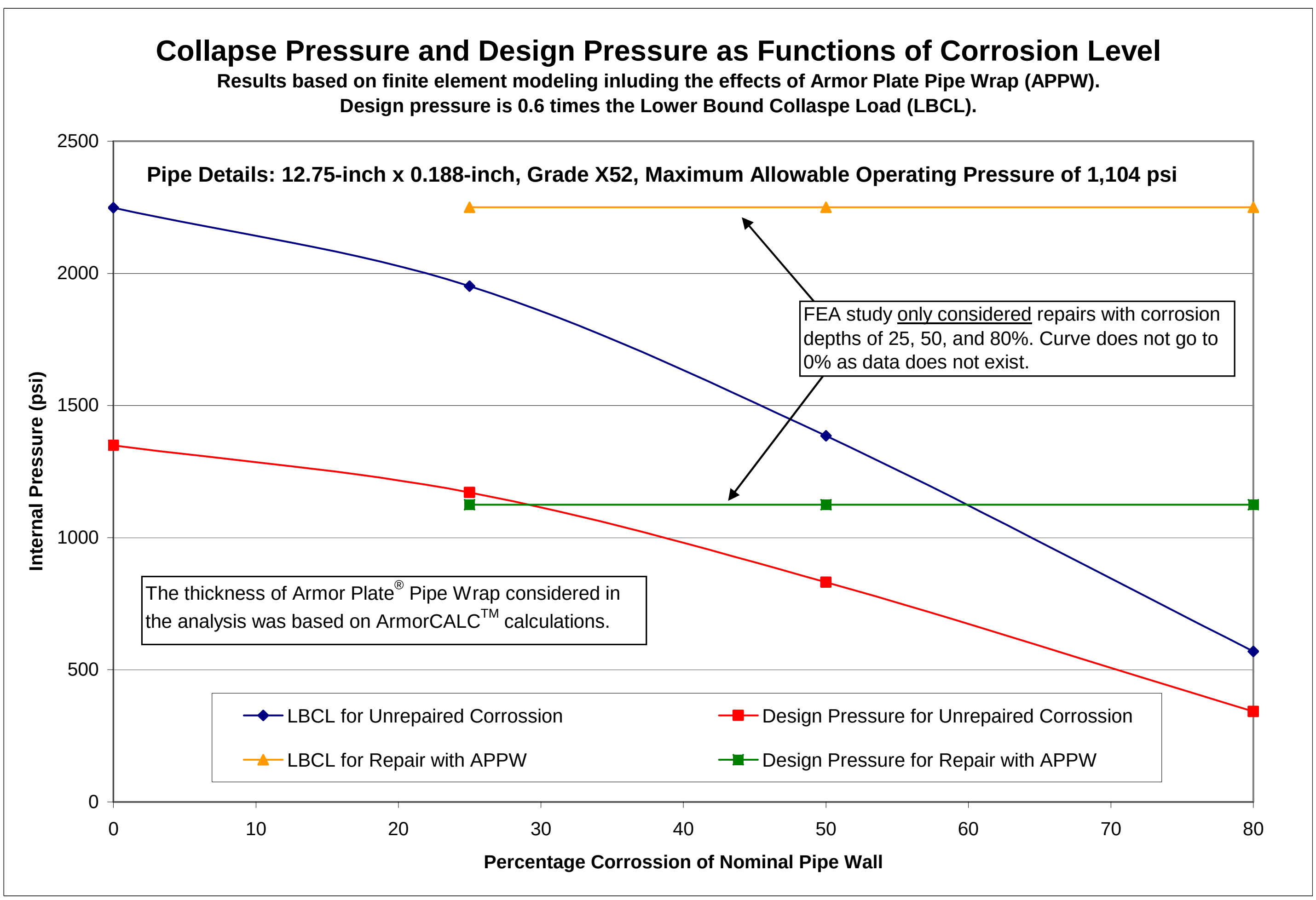

Figure 5 – Results from finite element limit analysis considering composite reinforcement of corroded pipe

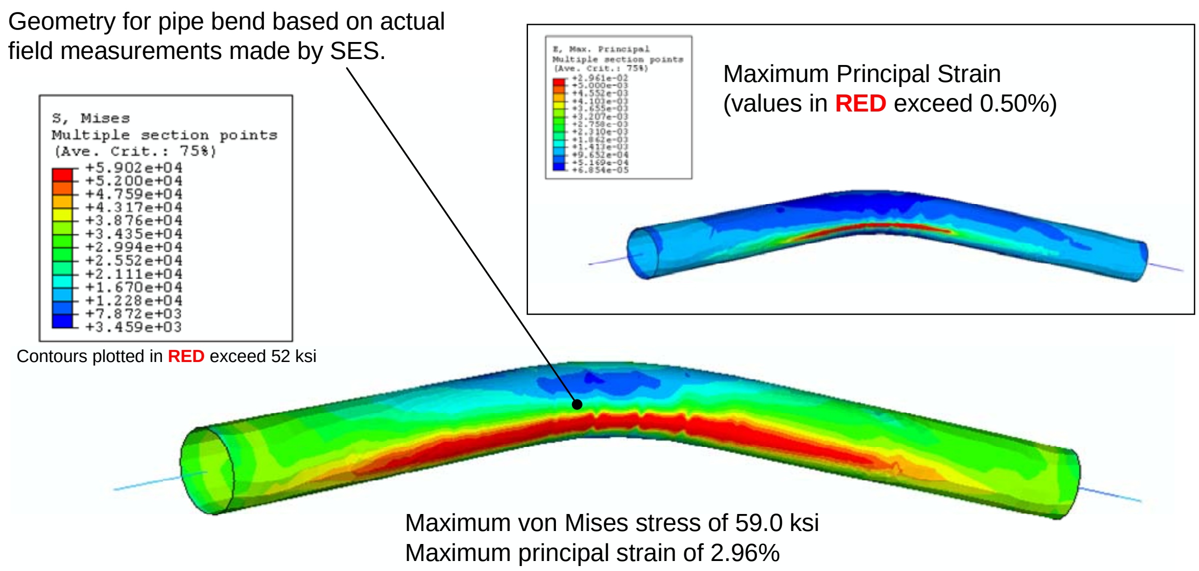

Figure 6 – Contour plot showing von Mises stress at 1,400 psi design conditions

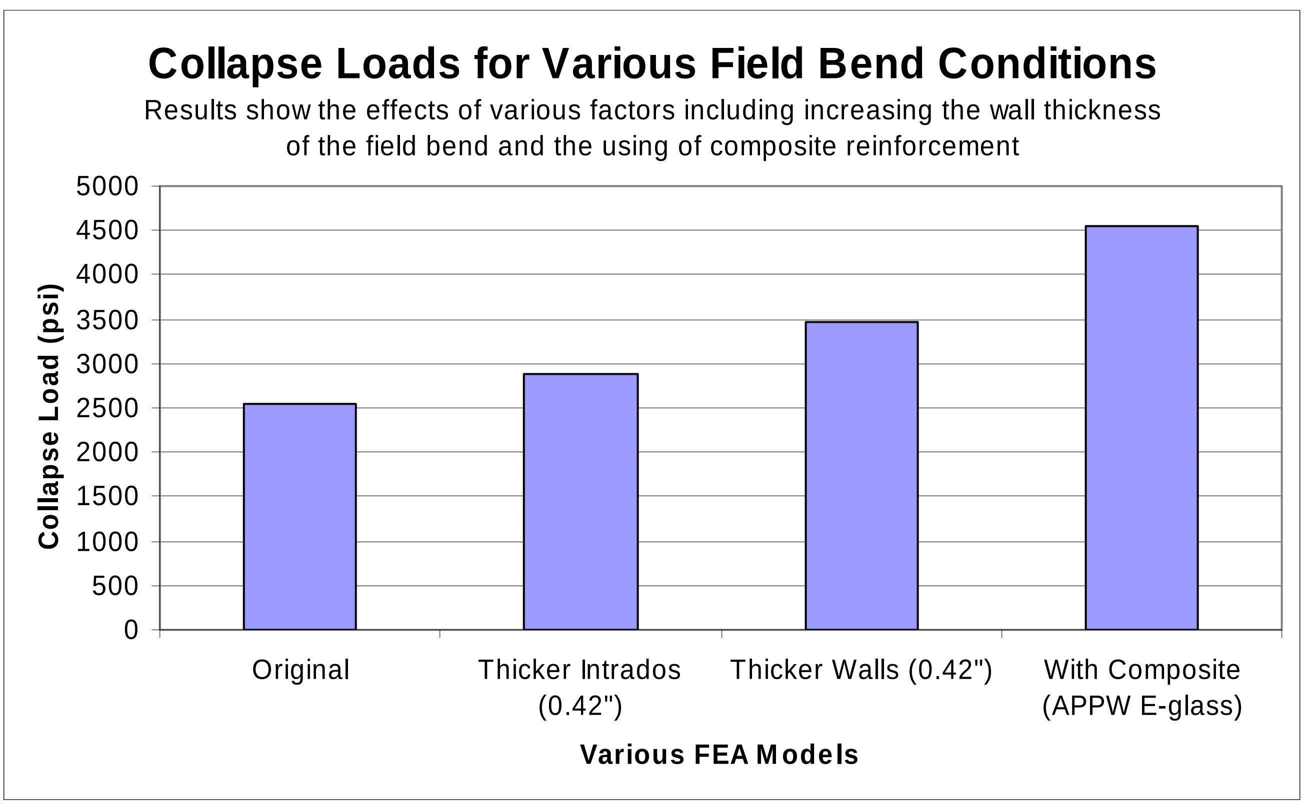

Figure 7 – Results from study on reinforcing field bends using composite materials

Figure 7 – Installing the hoop wrapped inner carbon layers

Figure 8 – Applying the epoxy adhesive using a slotted hand trowel

Figure 9 – Installation of the carbon half shells

Figure 10 – Final view of cured repair prior to testing

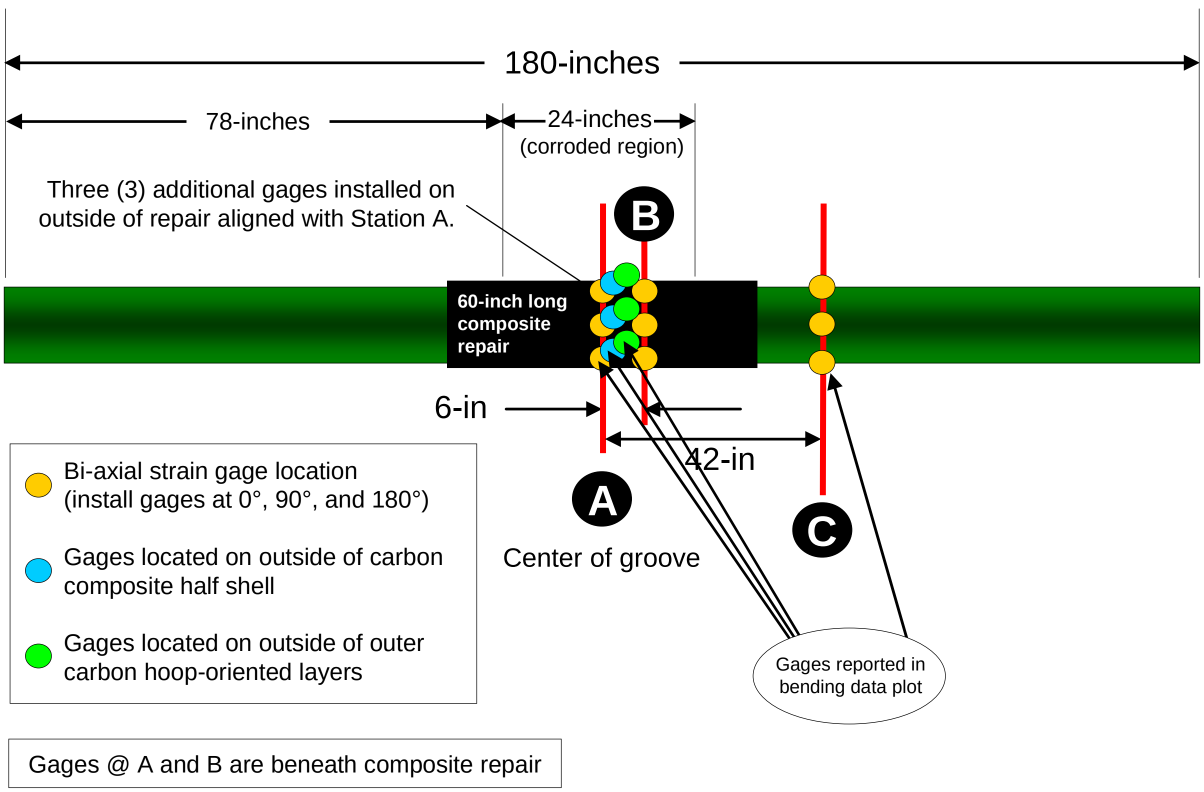

Figure 11 - Locations for strain gages of interest on CRA system samples

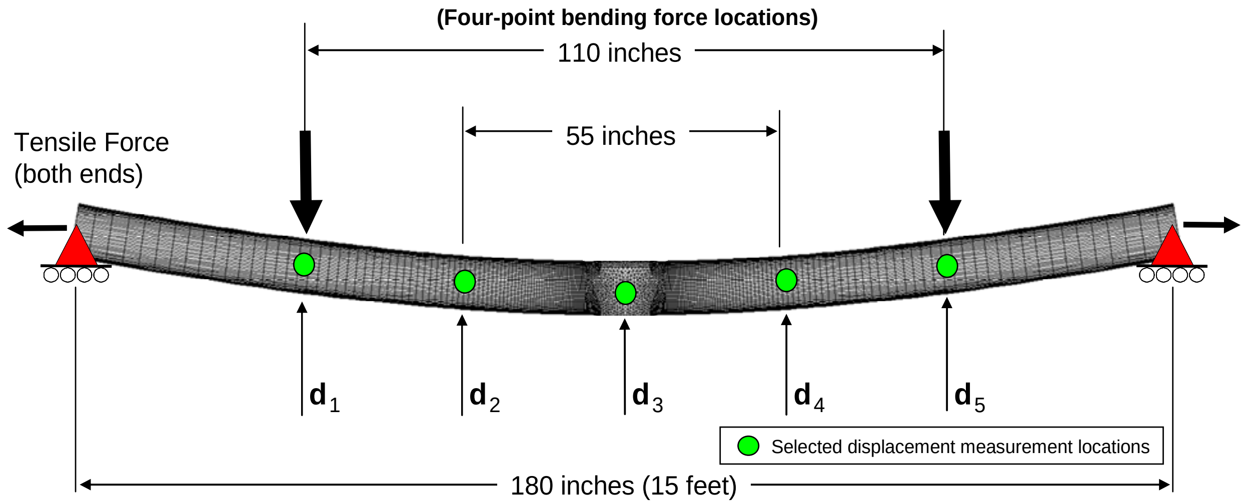

Figure 12 – Schematic showing configuration of loaded sample subject to tension and four-point bending

Figure 13 – Photograph of pressure-tension-bending load frame test set-up

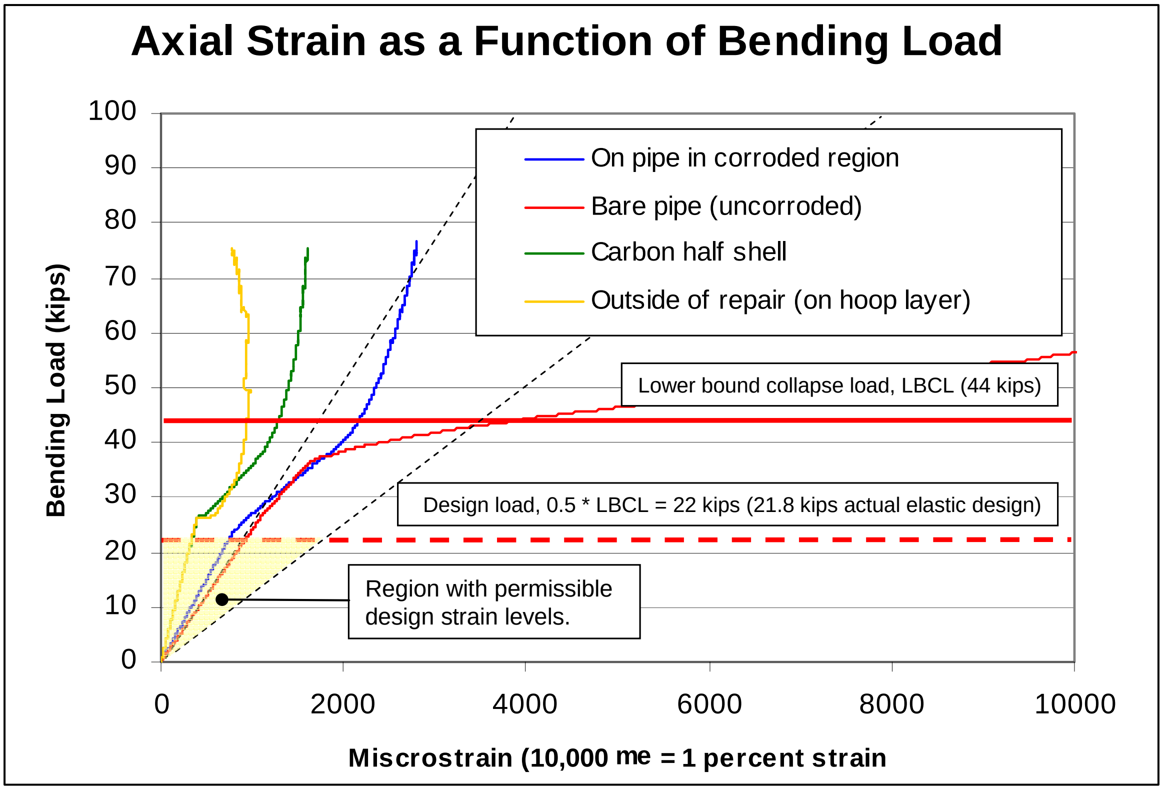

Figure 14 – Annotated bending test plot showing limit state design parameters

Table 1 – Comparison of strains in reinforced steel

Configuration	Design Strain Limit [1]	Calculated Strain (Analysis)	Experimental Measured Strain (Testing) [2]
Loading at Design Conditions			
Pressure Loading (at 2,887 psi)	**0.169 percent**	**0.116 percent**	**0.106 percent**
Bending Loading (at 16.5 kips bending load)	**0.214 percent**	**0.057 percent**	**0.055 percent**
Loading at Lower Bound Collapse Load Conditions			
Pressure Loading (at 5,700 psi)	**N/A**	**0.370 percent**	**0.458 percent**
Bending Loading (at 34 kips bending load)	**N/A**	**0.138 percent**	**0.152 percent**

Notes:

1. Design Strain Limit based on finite element results for undamaged pipe subject to specified loading.
2. Experimental Measured Strains were extracted from strain gage positioned on steel beneath composite repair in center of corrosion region.