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DEVELOPMENT OF A CARBON-FIBER COMPOSITE REPAIR SYSTEM FOR OFFSHORE RISERS

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ABSTRACT

Composite systems are a generally-accepted method for repairing corroded and mechanically-damaged onshore pipelines. The pipeline industry has arrived at this point after more than 15 years of research and investigation. Because the primary method of loading for onshore pipelines is in the circumferential direction due to internal pressure, most composite systems have been designed and developed to provide hoop strength reinforcement. On the other hand, offshore pipes (especially risers), unlike onshore pipelines, can experience significant tension and bending loads. As a result, there is a need to evaluate the current state of the art in terms of assessing the use of composite materials in repairing offshore pipelines and risers. The significance of the body of work presented herein is that this study is the first comprehensive evaluation of a composite repair system designed for the repair of offshore risers using a strain-based design method coupled with full-scale prototype testing.

This paper presents findings conducted as part of a joint industry effort involving the Minerals Management Service, the Offshore Technology Research Center at Texas A&M University, Stress Engineering Services, Inc., and several composite repair manufacturers to assess the state of the art using finite element methods and full-scale testing methods. Representative loads for offshore risers were used in the test program that integrated internal pressure, tension, and bending loads. This program is the first of its kind and likely to contribute significantly to the future of offshore riser repairs. The end result of this study was the development of a carbon-fiber repair system that can be easily deployed to provide significant reinforcement for repairing risers. It is anticipated that the findings of this program will foster future investigations involving operators by integrating their insights regarding the need for composite repair based on emerging technology.

INTRODUCTION

Risers are critical components in offshore operations as they extend the wellhead at the mudline to the surface as shown in **Figure 1**. During operation risers are subject to degradation mechanisms including external corrosion and mechanical damage due to contact with outside forces. To permit risers to operate safely it is sometimes necessary to perform repairs. Conventional repair techniques incorporate external steel clamps that are either welded or bolted to the outside surface of the riser. Challenges exist with installing steel clamps that include issues such as mobilizing the heavy clamp, welding to an operating riser pipe (including safety issues), and installation expenses. For these reasons, alternative solutions such as composite repair sleeves provide an attractive option as they are relatively inexpensive, lightweight, do not require welding, and are relatively simple to install.

What separates this research effort from prior studies is that the evaluation of composite repair technology for offshore applications also includes the development of a design methodology based on limit analysis methods and strain-based design techniques. The actual design coupled with prototype testing is also a unique feature of this research effort.

The sections that follow provide the background, approach, and results of this research program. The *Background* section documents lessons learned from previous research efforts. *Composite Material Performance* includes a brief discussion on material performance as it relates to the repair of risers. The discussion in *Strain-based Design Methods* details how a methodology was developed to evaluate the performance of the repair by determining how strain was reduced in the damaged section of the riser based on the application of certain loading conditions.

The *Development of Riser Composite Repair System* section is the core of this study as it details the analytical methods that were used to design the carbon half-shell system fabricated and tested for this study. The *Development of a Composite Repair System* and *Evaluating the Optimized Repair System* sections details how analysis and full-scale testing were used to validate the quality of design and if the system achieved its intended reinforcement levels based on the prior design work. The *Conclusions* section captures the critical insights gained during the study to assist industry in evaluating this emerging technology.

BACKGROUND

There is a significant body of work that has been conducted to assess the use of composite materials for offshore applications. Most of this work has been focused on assessing the performance of composite and composite-reinforced riser systems. Some work on composite choke and kill lines has also been done. Additionally, a multitude of research and applications publications exist in the area of using composite materials to reinforce onshore pipelines. Independent studies have also been performed to assess various aspects of composite systems including long-term performance. A final area of interest includes prior studies that contributed to the development of reinforcing steel using composite materials. These include investigations on limit analysis and strain-based design methods.

In performing the literature review for this research program, the reviewed documents were grouped into five different categories based on their subject matter. These categories are listed below and correspond to the five subject matters contained within this section.

1. Reasons for repairing pipelines
2. Using composite materials for offshore applications
3. Repairing onshore pipelines using composite materials
4. Assessing the performance of composite materials
5. Strain-based design methods and limit state design.

Reasons for Repairing Pipelines and Risers

Before discussing the specific methods in which pipelines and risers are repaired using composite materials, it is necessary to discuss why and under what conditions repairs are required. Pipelines and risers experience damage and deterioration including corrosion, external damage in the form of dents caused by impact, and excessive loads generated by extreme conditions such as those associated with hurricanes. Corrosion is a metallurgical phenomenon that reduces the wall thickness of carbon steel. The corroded wall reduces the mechanical integrity of the riser pipe and under extreme conditions failure can result in the form of either leaks or ruptures. Most pipeline design and operating codes, such as ASME B31.4, *Liquid Transportation Systems for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia, and Alcohols* [1] and ASME B31.8, *Gas Transmission and Distribution Piping System* [2] have procedures for assessing the severity of corrosion. The procedures in these codes are based primarily on ASME B31G, *Method for Determining the Remaining Strength of Corroded Pipelines* [3].

The variables involved in assessing corroded pipelines include:

- Corrosion depth as a percentage of the uncorroded wall thickness
- Maximum allowable longitudinal extend of the corroded area
- Safe maximum operating pressure for the corroded area.

Basically, the evaluation process involves quantifying the corrosion depth and length and then calculating the safe maximum operating pressure for the given pipe grade. If the desired operating pressure cannot be achieved, the pipeline operator must chose to re-rate the pipeline to a lower pressure, remove the corroded section with a replacement spool, or make a repair.

In addition to corrosion, pipelines and risers can be damaged by impact with external forces. The resulting damage typically manifests itself in the form of dents, gouges, or combinations of both known as mechanical damage. When these defects are identified, an assessment process is required to determine if their severity reduces the mechanical integrity of the pipeline. As with assessments associated with corrosion, if the damage is severe enough operators must chose to re-rate through pressure reduction, remove and replace the damaged section, or make a repair.

Use of Composite Materials in Offshore Applications

In a review of the open literature, it is possible to obtain technical publications representing viable research dating back 20 years in which composite materials were used as construction materials for offshore structures and components is discussed. The most prevalent topic of discussion concerns high-performance composite tubes for riser production. The Institut Francais du Petrole (IFP) started work in the late 1970s assessing the use of composite materials in various applications for the offshore oil industry in water depths up to 1,000 meters. Their efforts, relative to assessments for riser designs, involved full-scale testing on composite tubes subjected to pressure, tension, bending, fatigue, aging, corrosion, and abrasion. The test matrix involved more than 60 samples and included carbon fiber samples, glass fiber samples, and hybrid composite samples involving both carbon and glass fibers [4 and 5]. The conclusions from these efforts demonstrated that it is possible to fabricate high performance composite tubes for offshore riser applications. One closing comment from this reference was that defect tolerance of the tubes was not quantified and that additional studies should be conducted to assess the capabilities of non-destructive examination (NDE) techniques in quantifying imperfections should they exist.

In a follow-up effort, IFP published another paper at the Offshore Technology Conference (OTC) fours years following the initial 1988 paper. The topic of this paper addressed defect tolerance and nondestructive testing [6]. The program objectives associated with the IFP study included the following:

- Assessment of the influence of defects on the ultimate performance of composite tubes
- Impact study
- Fatigue tension testing of tubes with deliberate built-in or applied defects
- Assessment of NDE methods for detecting the presence and evolution of deliberate defects
- Evaluation of acoustic emission for assessing the ultimate performance of used tubes (especially those subjected to fatigue damage)

In the late 1990s, an extensive research program included Lincoln Composites, Shell Oil Company, Conoco, Hydril, University of Houston, Hexcel Corporation, and Stress Engineering Services, Inc. that was undertaken to assess the capabilities of composite production risers for deep water depths up to 5,000 feet (cf. references [7] through [11]). In a program similar to the one conducted by IFP, this program incorporated a total of 80 test samples that were fabricated and tested. This program also included stress-rupture testing and generated data that were used to establish confidence in the long-term behavior of composite materials under sustained load [11]. The conclusion from these studies was that the prototype composite product riser met the cost, weight, and performance goals of the research program.

Repairing Onshore Pipelines Using Composite Materials

For more than a decade composite repair systems have been used to repair damaged pipelines. The majority of this remediation work has involved the repair of onshore pipelines subject to corrosion that has involved restoration of circumferential or hoop strength due to local wall loss of the steel. A review of the open literature demonstrates that addressing this stress state has been the primary focus of research efforts up to this point in time. Because approved composite materials have been accepted as a viable repair options in both the ASME B31.4 and B31.8 pipeline codes, it should be noted that composite materials are primarily used to re-rate corroded pipelines. In other words, if the repair or cut-out options were not invoked by the operator, the only other option would be for the operating pressure to be reduced. Conversely, if the composite material option is used, the operating pressure will be partially or fully restored. Additionally, mechanical damage (e.g. dents with gouges) has been repaired in situ using composite materials and validated experimentally using both burst and cyclic pressure fatigue testing.

Readers interested in learning more about the history of onshore pipeline repairs using composite materials are encouraged to read the paper by Alexander and Francini presented at the 2006 International Pipeline Conference in Calgary [12].

COMPOSITE MATERIAL PERFORMANCE

As with any new application of existing or emerging technology, resources are available for assessing predicted behaviors. Previous background information has been cited on studies and research associated with the application of composite materials in offshore applications. This work focused on assessing the use of composite materials in fabricating fully-composite or hybrid designs using a steel liner with a composite overwrap. Provided in this section are reviews of research not specifically aimed at offshore applications, but are contributory in nature to assessing the use of composite materials in reinforcing offshore risers. Subjects considered in this section include residual stresses, damage mechanisms, as well as discussions on environmental effects and long-term performance.

Residual Stresses

The open literature has only sparse data and guidance for industry on the subject of "residual" stresses generated in composite materials during manufacturing. Hyer addressed environmentally induced stresses in laminates, with specific discussions on residual thermal stresses generated during curing of the resin in the composite [13]. Recognizing that during curing it is not unreasonable to experience exothermic reaction temperatures of epoxy resins on the order of 220°F, a resulting temperature differential on the order of 150°F results when cooling down to ambient conditions. As a result, depending on the composite architecture and coefficients of thermal expansion, compressive stresses on the order of 5,000 to 6,000 psi are possible. While this topic is noted as important, due to the overall complexity of this subject, it is likely that experimental efforts are best-suited to quantitatively determine if a problem actually exists.

Damage Mechanisms

As part of the design process, it is important to identify the potential failure mechanisms for the riser composite repair system. The effects of fatigue, impact, and environmental effects are considered in this discussion.

Fatigue

In addition to considering static loads, it is important to consider the effect that cyclic loads have on the performance of a composite repair system. It is possible for composites that are subjected to cyclic loads to fail at stresses significantly less than the ultimate strength of the respective materials. Unidirectional continuous-fiber-reinforced composite are known to possess fatigue resistance in the fiber direction, because the load is primarily carried by the fibers that generally exhibit resistance to fatigue [14]. This observation is important in terms of selecting materials for the composite repair system. Numerous studies have been performed that addresses damage initiation and propagation during fatigue of composite laminates [15 – 17]. Damage first initiates by separation of the fibers from the matrix (i.e. debonding) in the fiber-rich regions of the plies in which the fibers lie perpendicular to the principal direction of loading. Elevated stress concentrations at the fiber-matrix interface initiate these cracks. After initiation the crack typically propagates along the interface between the fibers and the matrix and can extend over the entire width of the ply. The composite undergoes final fracture when its overall strength is weakened by the presence of longitudinal-ply cracks and delamination cracks. From a performance standpoint, in the presence of fatigue mechanisms, there is a gradual decrease in the static strength (and modulus of elasticity) of the composite material as it is subjected to an increasing number of cycles at a given stress level.

Impact

In the design of composite repair system for offshore risers, the role of impact resistance is critical. Factors such as wave motion and contact with other structures such as ships and other risers are examples of impact. The metric for assessing the ability of a composite to withstand damage after impact is energy absorption, often measured in ft-lbs/in^2. Based on results from Broutman and Mallick [18], E-glass-epoxy laminates exhibit the highest energy absorption level per unit area (222 ft-lbs/in^2), whereas graphite fiber epoxy laminates (GY-70) exhibited the lowest energy absorption capacities (5.85 ft-lbs/in^2) of the materials considered in their study. In terms of the present study, it is important that, as a minimum, E-glass materials be used as an outer wrap of the repair to provide protection when carbon materials are used as the primary reinforcing material in the system.

Environmental Effects

One of the concerns in using carbon fiber materials to repair steel pipeline relates to the potential for developing corrosion at the interface. Experimental results show that when carbon fiber/epoxy resin composite materials are joined with high-strength titanium alloys, aluminum alloys, stainless steel (i.e. l% Cr l8% Ni 9% Ti), or other structural materials, galvanic corrosion and crevice corrosion take place at the interface boundaries. This corrosion is primarily determined by the electrochemical properties of the materials. It is also related to the materials' mutual coupling situation, treatment technology, and environmental conditions. Galvanic corrosion is affected by the coupled materials' static energy of corrosion, galvanic currents, and other dynamic closed-circuit properties [19]. Because of the potential for developing corrosion at the interface, a boundary must be established between the carbon materials and the steel pipe. The use of E-glass with an epoxy matrix is a viable option to prevent contact between the carbon and steel materials.

Long-term Performance Characteristics

One of the general concerns across industry regarding the use of composite materials is their long-term performance and the potential for degradation in strength. In the absence of long-term data, designs using composite materials have been the use of large safety factors. One of the more significant bodies of research conducted to date on the long-term performance of composite materials was performed for the State of California Department of Transportation (CALTRANS) by Steckel and Hawkins of the Space Materials Laboratory in assessing the use of composite materials for infrastructure applications such as highways bridge columns [20]. This ninety plus page document provides extensive data on the long-term performance of selected composite systems including carbon-epoxy and E-glass/epoxy. The effects of environmental exposure on the mechanical and physical properties of these select systems are summarized in **Figure 2** and **Table 1**. The plus/minus values shown in this table correspond to the standard deviations.

In addition to the CALTRANS research, another important document was referenced in order to determine an acceptable design stress for the composite fiber materials. ASME commissioned the Hydrogen Project Team and Becht Engineering Co., Inc. to develop 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* [21]. 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 [21]. 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 [22].

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 [24]. 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 [25] 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

In terms of applying finite element methods to limit state design, WRC Bulletin 464 by Kalnins [26] provides specific guidance in using modern finite element codes. Details including required model input and interpretation of results are discussed.

In his text, Walters [27] 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 [21] 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.

DEVELOPMENT OF A COMPOSITE REPAIR SYSTEM

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 includes 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.

Figure 3 presents the steps involved in the design process. Because of the unique nature of this process, no single design document exists that can designate the design requirements for a composite repair in a prescriptive manner. This process involves both design efforts as well as identification of a design limits to which the calculated stresses and strains can be compared. Included in **Figure 3** 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

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

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

One of the challenges in developing a repair system that possesses adequate strength and stiffness to reinforce a given pipe section involves determining 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 subject to appropriate 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.

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 strain levels in the riser pipe 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.

EVALUATING THE OPTIMIZED REPAIR SYSTEM

This paper has presented details on the design requirements associated with developing a composite repair system. This section provides specific details on how a composite repair system (hereafter referred to as the *CRA system*) was designed and evaluated relative to a pre-established set of design criteria. For the problem at hand this fundamentally involved determining the appropriate fiber orientation and thickness to resist internal pressure, tension, and bending loads associated with the operation of an offshore riser. The evaluation process used strength of materials, along with finite element modeling, to determine the best configuration for reinforcing the corroded riser.

The following sections provide details on the analysis, fabrication, and testing of the CRA repair system. Through experimental verification, the design methods and resulting composite repair system are evaluated using prototype fabrication and full-scale testing.

Preliminary Concepts

Provided below are elements of the composite repair system design for the specific pipe geometry evaluated in this study. The materials for the optimized design integrated a combination of carbon and E-glass fibers.

1. Inner and outer layers of E-glass. The inner layer acts to protect the pipe from potential corrosion due to carbon interaction with steel (i.e. formation of a galvanic cell), while the outer layers protect the carbon fibers.
2. Circumferentially-oriented carbon fibers placed in the region of corrosion.
3. Outside of the inner circumferential fibers, the majority of the fibers are oriented axially to provide rigidity in bending and tension.
4. The length of the repair should be at least 16 inches on each side of the corroded region. A repair length of 60 inches was selected, providing 18 inches on each side of the 24-inch long corroded region.
5. The following thicknesses are used for the CRA optimized design, hereafter referred to as the *CRA system* (see **Figure 4** for architecture details).
    a. Inner layer of 50-50 E-glass, spiral wrap, ~ 0.030 inches thick
    b. Circumferential carbon (stitched fabric), 0.200 inches thick
    c. Axial carbon (pre-cured half shells), 0.400 inches thick
    d. Circumferential-spiral carbon (stitched fabric), 0.100 inches thick
    e. Outer layer of 50-50 E-glass, spiral wrap, ~ 0.030 inches thick

The CRA system design has the benefits of a wet lay-up in terms of strength potential; however, the quality control is improved for the carbon half-shells when compared to field applications. Additionally, the time required for installation is reduced. Classical mechanics were used to optimize the design in terms of loads that include internal pressure, tension, and bending. ASME B31.8 was used to establish the design criteria for the 8.625-inch x 0.406-inch, Grade X46 pipe. The internal pressure, tension, and bending requirements were calculated to be 2,887 psi, 145,000 lbs, and 50,000 ft-lbs, respectively. For these design conditions the optimized prototype was analyzed.

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 finite element model was constructed using the PATRAN modeling package and analyzed and post-processed using the general-purpose ABAQUS Standard general-purpose finite element code (version 6.4). The S4R shell element was used in the analysis and the model included internal pressure and appropriate pressure end loads to simulate a capped end condition. One of the primary benefits in using the shell element to model composite materials is the ability to conveniently model layers having different thicknesses, orientations, and materials.

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 the 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:

$$E1, E2, \nu 12 , G12, G23, \text{and } G13$$

where E is the elastic modulus, ν is Poisson's ratio, and G is the shear modulus (G12 and G13 represent the transverse shear moduli).. The directions "1" and "2" correspond to the specific direction of the fiber or cloth. For the steel material, a simple elastic-plastic model was used with yield and ultimate strength of 61 ksi and 74.6 ksi, respectively (based on actual mechanical test results).

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 5** 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 <u>uncorroded</u> 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).

Figure 6 shows the maximum principal strain in the steel at loads equal to the design and plastic collapse loading conditions. There are several noteworthy observations in viewing this figure.

- At the design condition, the maximum strain in the steel that is observed beneath the composite repair is 0.17% (based on the plotted contour data). It should be noted that if the composite reinforcement were not present, the deformation in this region would exhibit gross yielding.
- Once the plastic collapse load is reached, the maximum strain occurs outside the corroded and reinforced region. Once this condition is reached, the composite reinforcement carries a significant portion of the bending load and the maximum bending strain in the pipe actually occurs outside the composite reinforced region.

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 of the Prototype Repair

This section provides documentation including details on fabrication and installation of the hybrid E-glass/carbon half-shells, results from the full-scale test program, correlation with finite element results, and a general discussion on the overall performance of the CRA repair system relative to design margins. An epoxy resin matrix was used in all layers of the system. It includes the pre-cured carbon half shells, as well as all other layers applied as wet lay-ups located beneath and on top of the half shells.

Fabrication 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.

The following material data were measured for the carbon material using ASTM D-3039.

Tensile strength:	88,336 psi (standard deviation of 5,485 psi)
Elastic modulus:	8,696 ksi (standard deviation of 503 ksi)
Elongation:	1.02 percent (standard deviation of 0.05 percent)

This material was also applied as a wet lay-up material beneath the half shells on the pipe in the corroded region to provide hoop reinforcement and also positioned circumferentially on the outside surface of the half shells.

Installation Efforts

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.

Burst Pressure Test Results

Figure 12 plots hoop strain measured in the steel on various sections in the CRA composite repair system during the burst pressure test. The measurements associated with the following hoop strain gages are included in this plot.

- On steel beneath the repair in the corroded region of the pipe
- On the bare pipe outside of the repair (represents results for an undamaged pipe)
- Outside surface of the repair on the outer carbon hoop wrap (axial center)
- On the carbon half shell beneath the outer carbon hoop wrap (axial center) – noted as the *carbon half shell* in the figure legend

There are several noteworthy observations that are made in viewing the strain gage results presented in **Figure 11**.

- The ideal level of reinforcement is one that parallels the initial response of the uncorroded bare pipe (**RED** curve). The plotted data for the strain gage results in the corroded region (**BLUE** curve) show the level of reinforcement that is provided by the repair system.

- Results are presented for the strain gage placed on the carbon half shell (**GREEN** curve). It is observed that the hoop strain in this component of the repair with axial carbon fibers does not measure the same level of strain observed in the other layers dominated by hoop-oriented fibers. This is to be expected as the intent in the design is for the inner hoop layers to provide reinforcement to reduce bulging the corroded region of the pipe.
- Strain gages were installed on the outside surface of the 0.100 inch thick carbon hoop wrap. The purpose of these layers was to restrain the carbon half shells to the pipe. The strain gage results shows for these gages (**GOLD** curve) clearly demonstrate that they are being loaded and that the outer layers are provide restraint to the carbon half shells.

Some final comments are warranted regarding the acceptability of the CRA system design. As discussed previously, in limit state design a lower bound collapse load (LBCL) is selected using the double elastic slope method. This method is used to determine the LBCL based on the elastic response of the loaded structure. The plotted data is annotated and plotted in **Figure 12** showing the collapse and design loads. The lower bound collapse load is calculated to be 5,975 psi and the resulting design load is 2,988 psi. The previously determined design pressure for the base pipe is 2,887 psi, which is 97 percent of the calculated limit state design pressure.

Also provided in the figure is a highlighted region showing the acceptable design pressure and strain levels. It is important to note that the strain in the corroded region of the test sample exists within this region, demonstrating that adequate reinforcement is provided by the composite repair system.

A final comment concerns the level of strain measured in the carbon reinforcement, especially the layers placed directly against the pipe in the corroded region. From a long-term performance standpoint, the strain in the carbon must be limited to be less than 40 percent of the breaking strength of the composite material. For the carbon material used in this repair, the strain must not exceed 0.40 percent. As shown in **Figure 12**, at the design pressure the maximum strain in the hoop wrapped materials are significantly less than this value. At most, the maximum hoop strain is 0.13 percent.

Tension Test Results

Figure 13 plots axial strains measured during loading of the tension test sample (strain gages in this plot are the same as those presented previously for the pressure-only test sample). There are several noteworthy observations that are made in viewing the strain gage results presented in **Figure 13**.

1. As expected, the maximum strain occurs in the corroded steel region of the sample beneath the repair. From the beginning of loading this region carries a greater percentage of load than observed in the composite materials; however, it should be noted that if the composite material were not present the sample would have failed at approximately 320 kips, a value on the order of 50 percent of the 594 kips failure load recorded for this particular sample.
2. Due to the relative stiffness of the steel in comparison to the composite, during the initial stages of loading it carries a higher percentage of the load. However, as yielding occurs in both the corroded region and the base pipe, a greater percentage of the load is distributed to the composite material. This is observed in **Figure 13** where the base pipe (**RED** curve) starts yielding at approximately 450 kips. At this point, axial strains in the carbon half shell (**GREEN** curve) are increased, indicating that the carbon half shell material is carrying an increased percentage of the load.
3. Axial strains measured in the outer hoop wrapped carbon are less than those measured in both the pipe (corroded and uncorroded) and the carbon half shells. This is to be expected as this region is the last to be loaded during the process of applying the axial tensions loads.

Figure 13 includes the limit state design details. Even though the final failure occurred at 594 kips, the LBCL is calculated as 476 kips. Considering the combined load state, this calculated value is not necessarily over-conservative. Based on the calculated LBCL, the design load is calculated to be 238 kips. This value is 64 percent greater than the specified design load of 145 kips.

Also provided in the figure is a highlighted region showing the acceptable design pressure and strain levels. It is important to note that the strain in the reinforced corroded region (**BLUE** curve) generally exists within the acceptable design region, demonstrating that adequate reinforcement is provided by the composite repair system. Another observation is that the strain in the composite material is less than 0.20 percent for all levels of loading, a value less than the 0.40 percent allowable strain for the carbon material.

Bend Test Results

Results are plotted for the bend test results. **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

Results have been presented for both the analysis and testing phases of the CRA system development. The analysis efforts served as the foundation for the final design, especially with regards to establishing the required thicknesses and fabric architecture. Following this effort, fabrication of the carbon half shells was completed, which was then followed by installation of the repair system on the three test pipes.

Table 2 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).

CONCLUSIONS

Extension of onshore composite repair techniques to offshore risers by developing integrated analytical and experimental methods is accomplished by designing a carbon-based composite repair system incorporating computational simulation, prototype fabrication and experimental verification, numerical simulation, and prototype testing. Furthermore, guidelines for industry in repairing and reinforcing offshore risers using composite materials are developed.

Data for strain, deflection, pressure, and bending/tensile forces were recorded during testing. The data were post-processed and compared to the analysis results and both data sets were shown to have good agreement. An additional benefit in comparing the testing and analysis results was confirmation of the analysis methods, as well as demonstrating that the failure loads of the tests pieces validated the safety of the selected design margins. The conclusion is that the CRA system satisfied the research objective and that it is possible to repair offshore risers using composite materials. These repairs can be made in situ using the technology presented in this paper.

This study is a clear demonstration of several important observations. First, the original impetus for this study was concern from government regulators regarding the safety and acceptability of composite materials in reinforcing corroded offshore risers. Secondly, this study shows how industry, academia, and regulators can work together to develop repair methods based on sound engineering judgment. *An eventual outcome of this effort was the development of a design basis based on numerical simulation that can be used by others to develop robust repair systems for safely repairing offshore risers subject to combined loads.* Finally, this study indicates that a systematic method can be used to develop an optimized composite repair system using classical mechanics, finite element methods, and full-scale testing. The validation process investigated in this study leads to improved confidence so that industry can benefit from the use of composite materials in reinforcing and repairing offshore riser systems.

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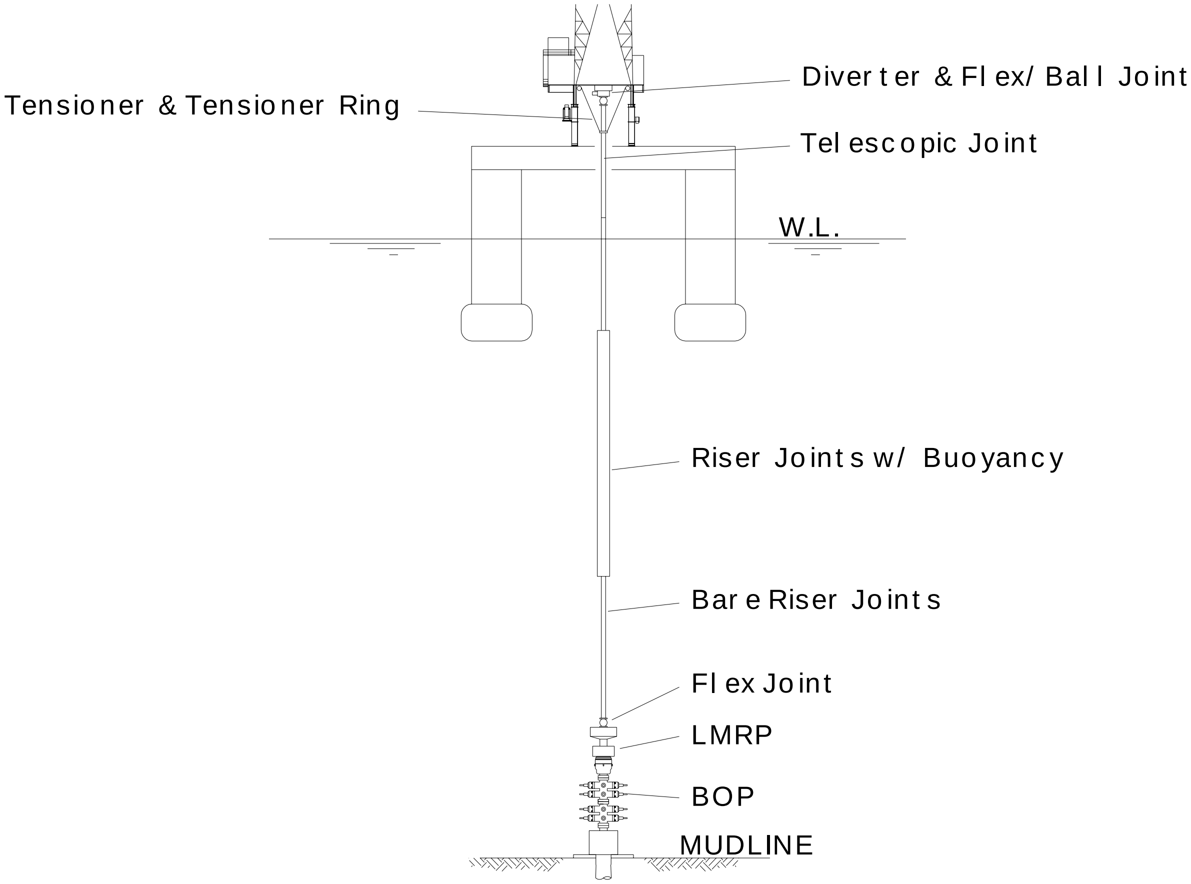


Figure 1 – Layout for a semisubmersible rig showing position of the riser

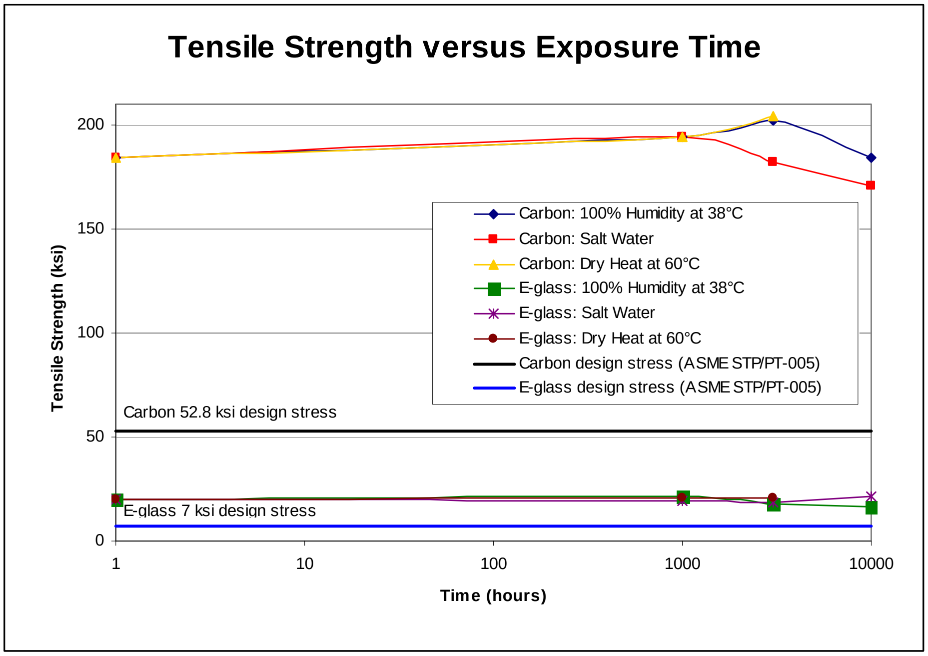
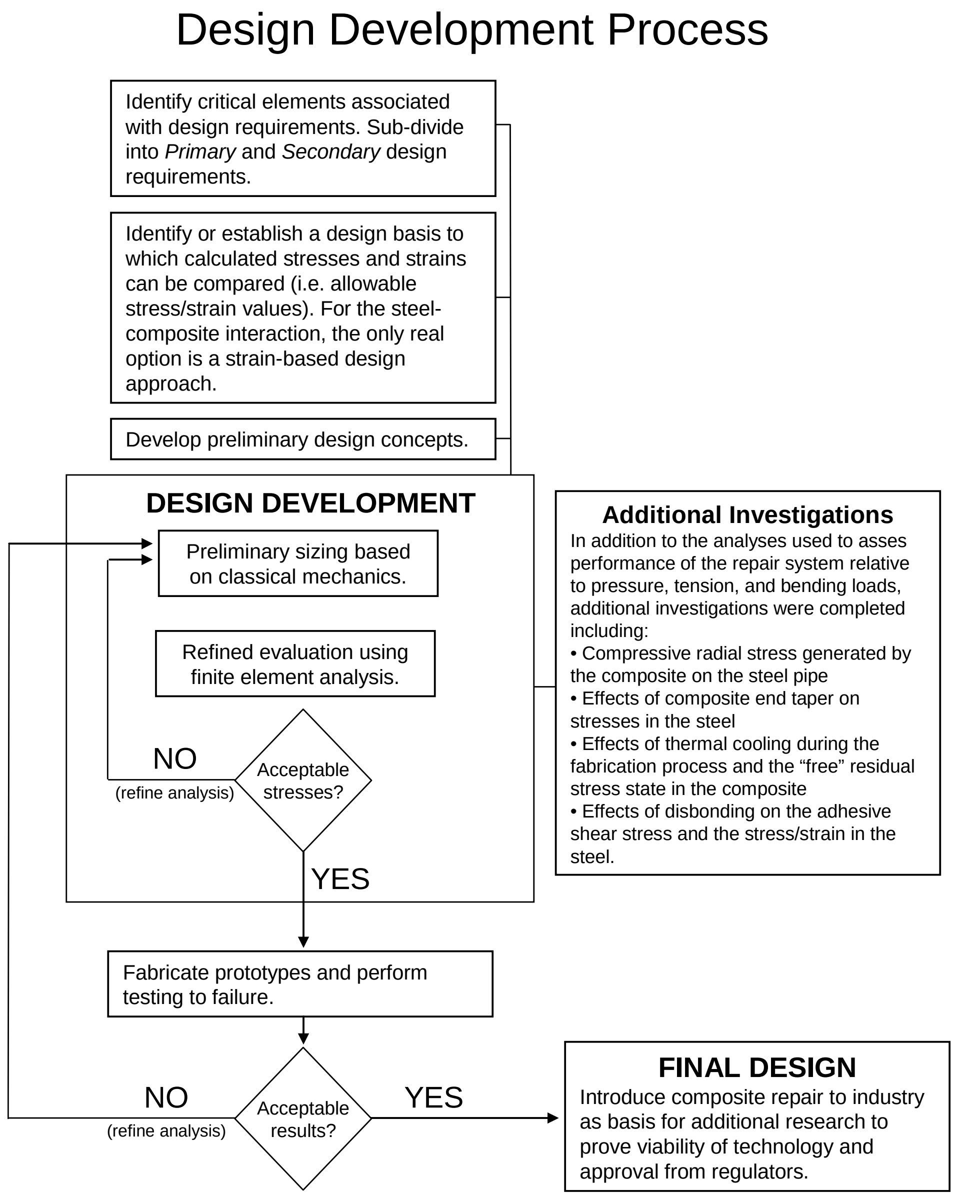


Figure 2 – Tensile strength data from the CALTRANS research program

Table 1 – CALTRANS composite long-term performance data

Environmental Exposure	Young's Modulus (Msi)	Tensile Strength (ksi)	Failure Strain (%)	Matrix T_g (°C)
Carbon/Epoxy System				
Control Sample	13.1 ± 0.6	184 ± 26	1.37 ± 0.17	113
100% Humidity at 38°C				
1,000 hours	13.2 ± 0.5	194 ± 10	1.44 ± 0.10	111
3,000 hours	13.8 ± 0.3	202 ± 7	1.48 ± 0.05	109
10,000 hours	12.6 ± 0.2	184 ± 5	1.41 ± 0.04	106
Salt Water				
1,000 hours	12.9 ± 0.3	194 ± 10	1.45 ± 0.06	114
3,000 hours	13.8 ± 0.1	182 ± 6	1.32 ± 0.03	109
10,000 hours	12.7 ± 0.3	171 ± 8	1.30 ± 0.05	107
Dry Heat at 60°C				
1,000 hours	12.9 ± 0.4	197 ± 15	1.45 ± 0.10	121
3,000 hours	13.9 ± 0.1	204 ± 7	1.45 ± 0.04	121
E-glass/Epoxy System				
Control Sample	1.60 ± 0.08	20.3 ± 1.4	1.77 ± 0.14	88
100% Humidity at 38°C				
1,000 hours	1.60 ± 0.09	21.4 ± 0.6	1.85 ± 0.10	95
3,000 hours	1.68 ± 0.13	17.8 ± 0.7	1.56 ± 0.11	103
10,000 hours	1.46 ± 0.06	16.1 ± 0.3	1.37 ± 0.07	102
Salt Water				
1,000 hours	1.48 ± 0.04	19.1 ± 0.7	1.80 ± 0.16	90
3,000 hours	1.76 ± 0.14	18.6 ± 0.9	1.63 ± 0.17	98
10,000 hours	1.50 ± 0.10	21.6 ± 1.3	1.95 ± 0.12	88
Dry Heat at 60°C				
1,000 hours	1.64 ± 0.07	20.6 ± 0.7	2.12 ± 0.14	109
3,000 hours	1.85 ± 0.07	20.9 ± 1.0	1.75 ± 0.21	111

Note: The above data taken from CALTRANS report [32].



Identify critical elements associated with design requirements. Sub-divide into *Primary* and *Secondary* design requirements.

Identify or establish a design basis to which calculated stresses and strains can be compared (i.e. allowable stress/strain values). For the steel-composite interaction, the only real option is a strain-based design approach.

Develop preliminary design concepts.

Fabricate prototypes and perform testing to failure.

In addition to the analyses used to asses performance of the repair system relative to pressure, tension, and bending loads, additional investigations were completed including:

- Compressive radial stress generated by the composite on the steel pipe
- Effects of composite end taper on stresses in the steel
- Effects of thermal cooling during the fabrication process and the “free” residual stress state in the composite
- Effects of disbonding on the adhesive shear stress and the stress/strain in the steel.

Introduce composite repair to industry as basis for additional research to prove viability of technology and approval from regulators.

Figure 3 – Steps involved in the optimization process

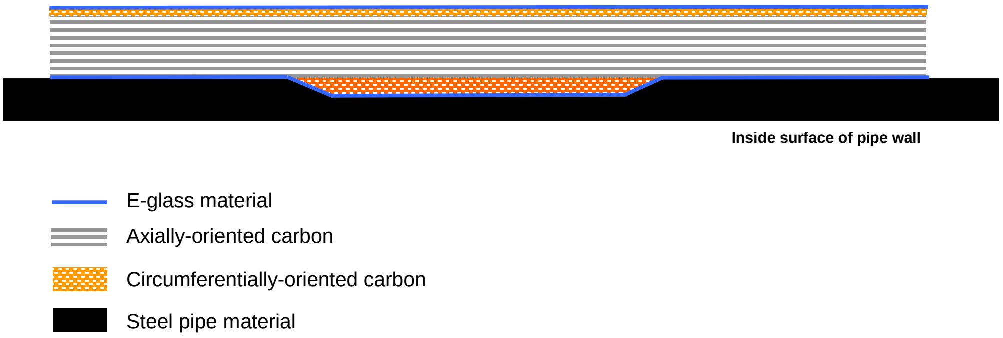


Figure 4 – Generalized layout for optimized E-glass/carbon composite repair

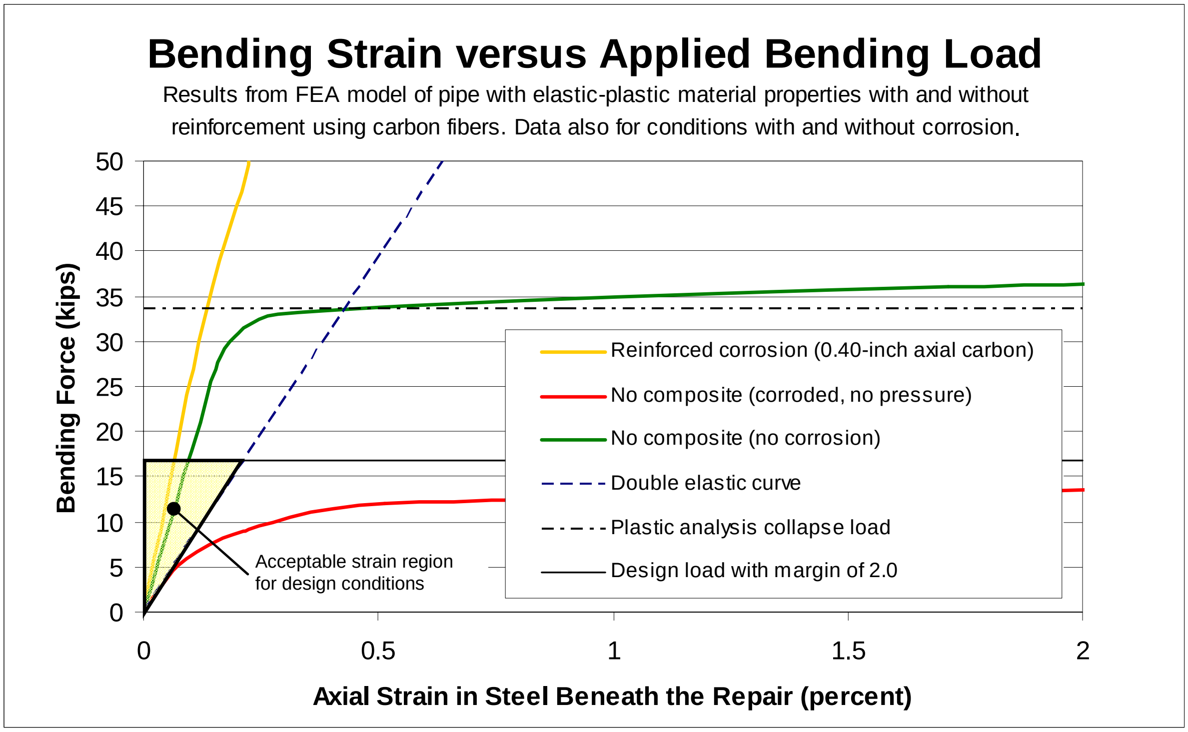


Figure 5 – Bending force versus axial strain in pipe
(carbon repair with 0.200-inch thick hoop | 0.400-inch axial | 0.100-inch layers)

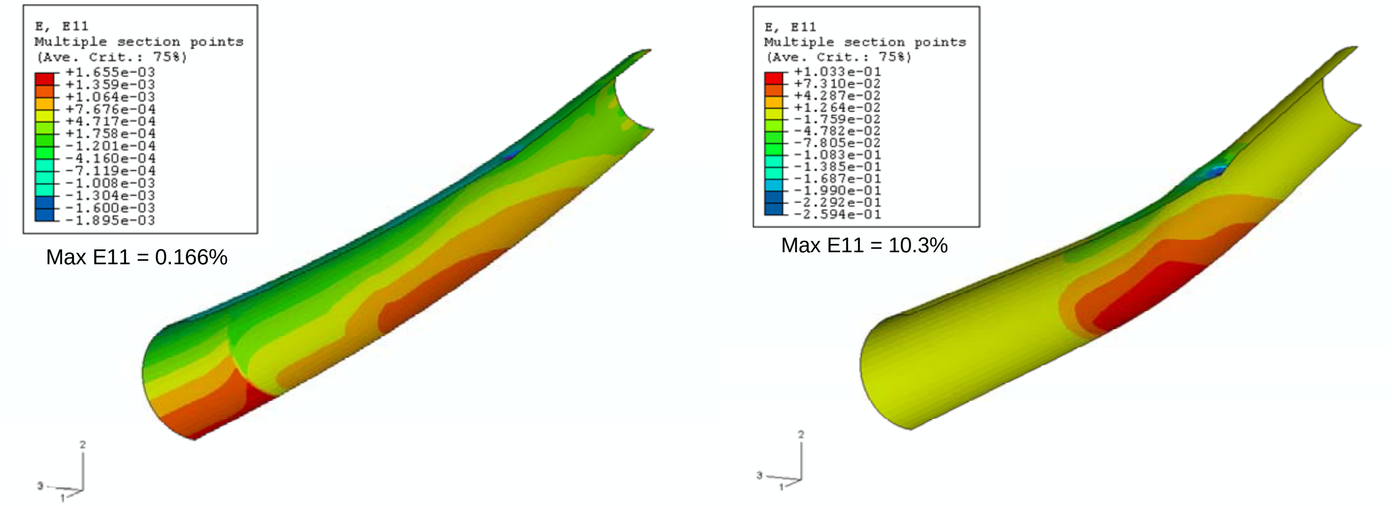


Figure 6 – Axial strains in steel at design (left) and plastic collapse (right) load conditions

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

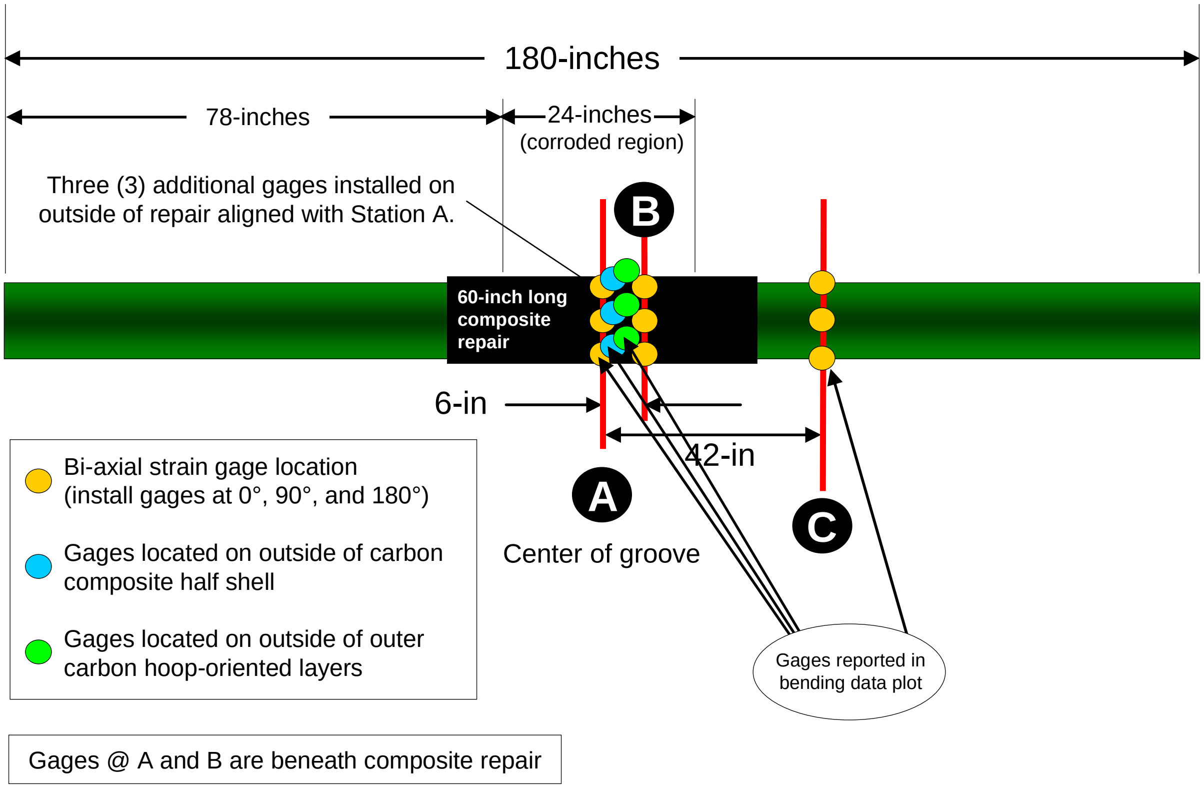


Figure 11 - Locations for strain gages of interest on CRA system samples

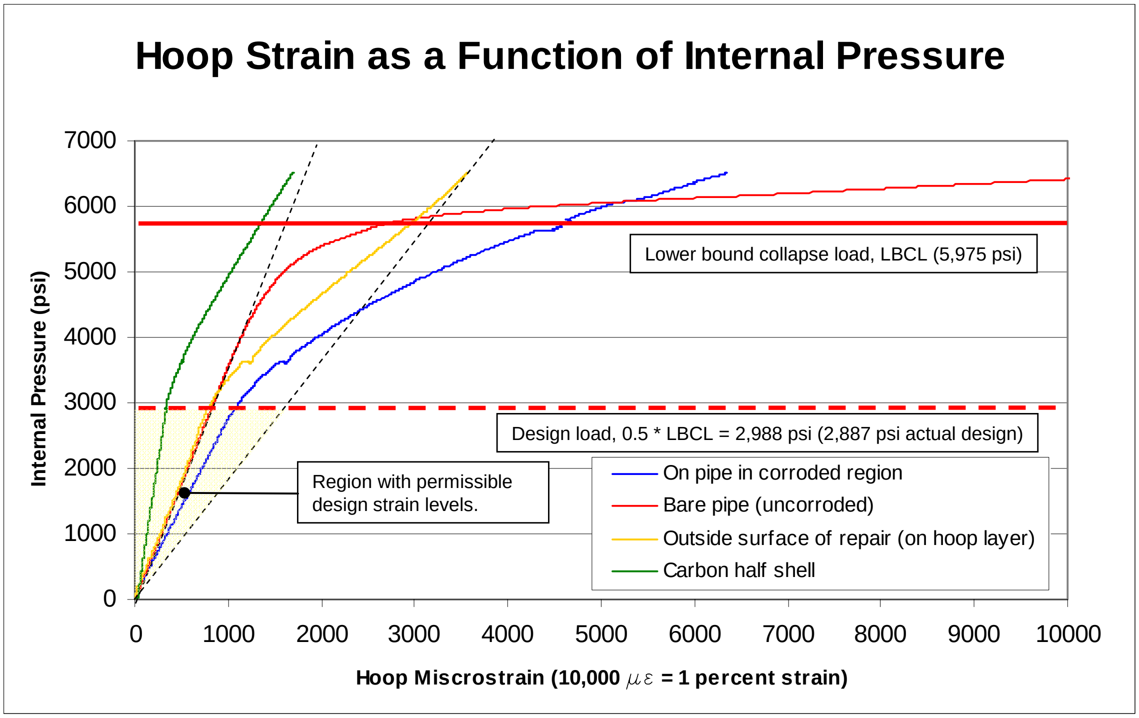


Figure 12 – Annotated pressure test plot showing limit state design parameters

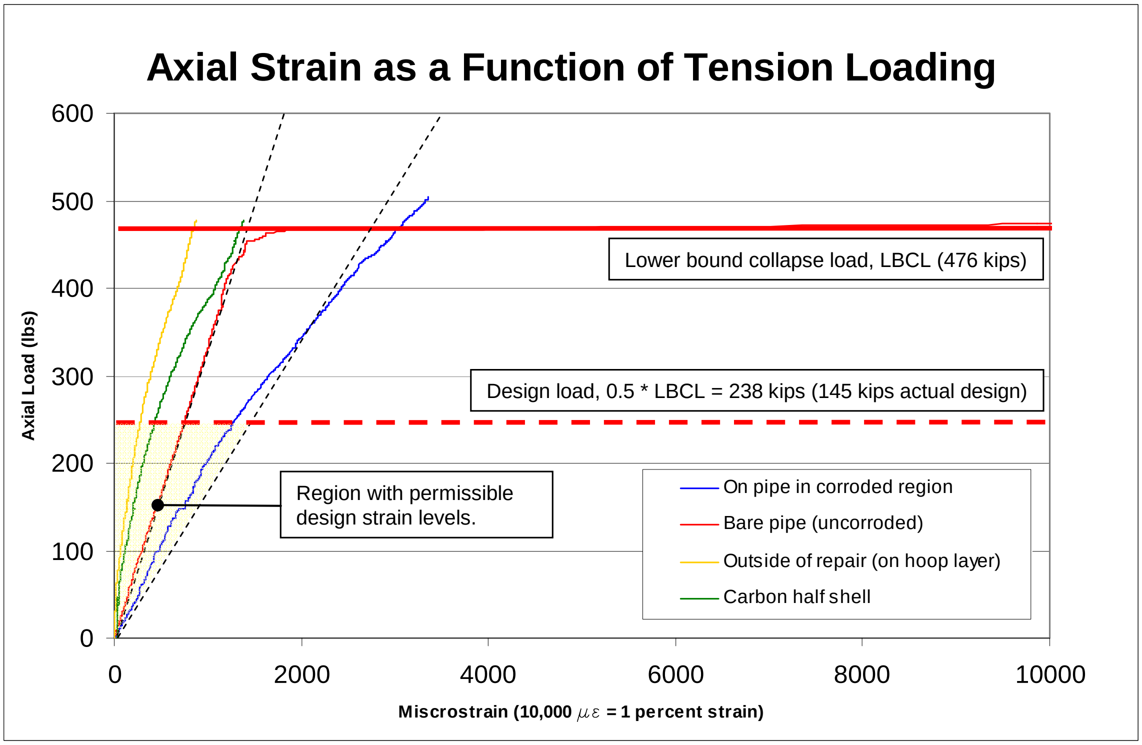


Figure 13 – Annotated tension test plot showing limit state design parameters

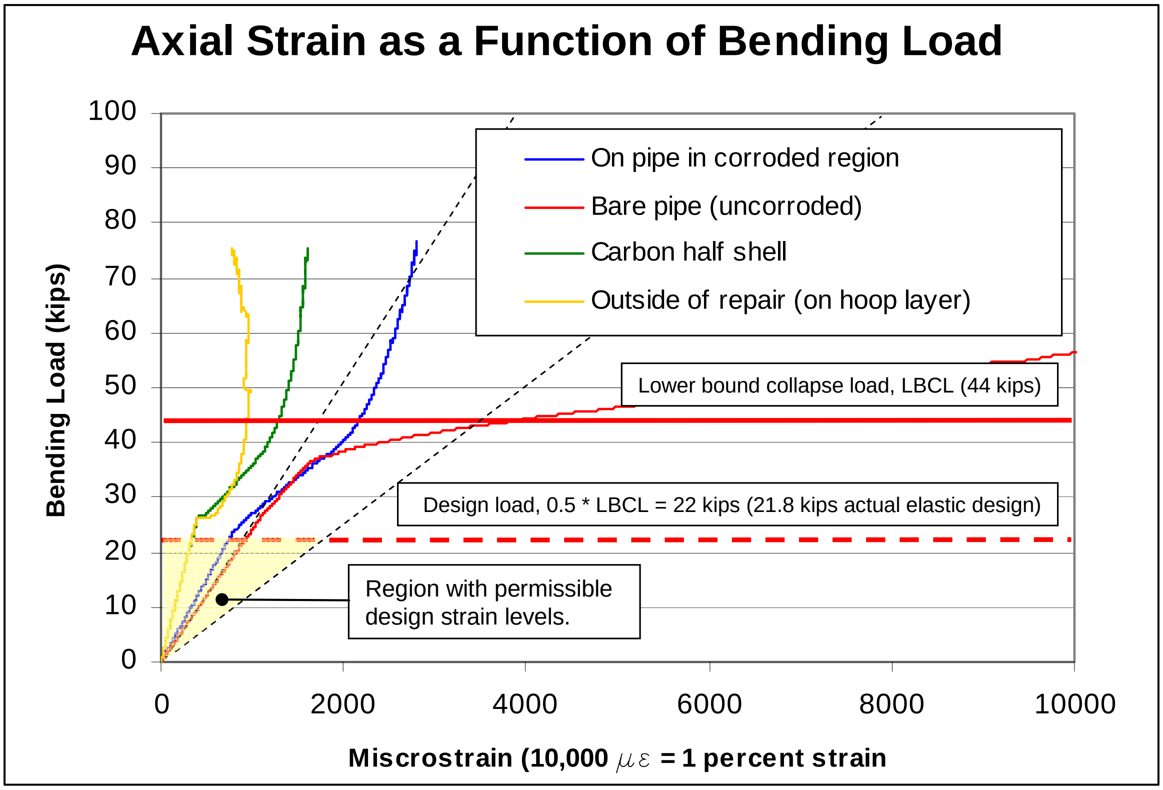


Figure 14 – Annotated bending test plot showing limit state design parameters

Table 2 – 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.