DEVELOPMENT OF A COMPOSITE REPAIR SYSTEM

FOR REINFORCING OFFSHORE RISERS

A Dissertation

by

CHRISTOPHER RICHARD ALEXANDER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2007

Major Subject: Mechanical Engineering

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Approved by:

Co-Chairs of Committee,	Ozden Ochoa
	Harry Hogan
Committee Members,	Thomas Lalk
	Peter Keating
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ABSTRACT

Development of a Composite Repair System for Reinforcing Offshore Risers.
(December 2007)
Christopher Richard Alexander, B.S., Texas A&M University;
M.S., Texas A&M University
Co-Chairs of Committee: Dr. Ozden Ochoa
Dr. Harry Hogan

A research program was conducted to investigate the application of composite materials in repairing corroded offshore risers, leading to the development of an optimized repair using a hybrid carbon/E-glass system. The objective of this research program was to investigate the feasibility of extending onshore composite repair techniques to offshore risers by developing integrated analytical and experimental methods. The study considered loads typical for offshore risers including internal pressure, tension, and bending. To fulfill this objective efforts included a state of the art assessment of current composite repair technology, designing a carbon-based composite repair system optimized by numerical simulation with prototype testing, and providing guidelines for industry in repairing and reinforcing offshore risers using composite materials.

Research efforts integrated numerical modeling, as well as full-scale testing that included four composite repair manufacturers to assess the current state of the art on pipe samples with simulated corrosion reinforced with composite materials. Analysis and testing were also performed on the optimized carbon/E-glass system. The results of this program demonstrated that composite materials are a viable means for repairing corroded offshore steel risers as adequate reinforcement ensures that the steel risers are not loaded beyond acceptable design limits. For corroded risers, the results demonstrated through analysis and full-scale testing efforts that properly designed composite repair systems can provide adequate structural reinforcement to ensure that excessive strains are not induced in the steel when subjected to internal pressure, axial tension, and bending design loads. This was verified experimentally using strain gages placed beneath the composite repair.

This program is the first of its kind and is thought to contribute significantly to the future of offshore riser repairs. It is likely 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. One of the most significant contributions to the existing body of work is the use of limit analysis in developing design limits for the repair of steel pipes using composite materials.

ACKNOWLEDGEMENTS

My life as a student at Texas A&M University started in 1987 as a freshman in the Corps of Cadets. During this 20 year period I have enjoyed many opportunities of life including serving as Drum Major of the Fightin' Texas Aggie Band, marrying my beautiful wife Tanya, working as an engineering consultant in the oil and gas industry, starting businesses, traveling the globe, and being the proud father of two precious daughters, Ashley and Anna.

What is amazing in this 20 year period is the tremendous number of people I have met and befriended. Many of these folks have impacted my life in outstanding ways and hopefully the Lord has allowed me to impact a few lives along the way as well. Provided below are a few of the people that have specifically helped shape my view of the world. They are listed in the order in which they have appeared chronologically in my life.

My father and mother, Dr. Richard and Judy Alexander, set the foundation for my life and instilled in me a passion to lead, impact the lives of others, and honor Christ. Embedded in all of this was a continual desire to learn and use the mind that I was given to solve problems and understand the world around me. To this day, my father and I continue to discuss engineering problems and I am honored to carry on the Aggie M.E. legacy that has contributed so greatly to our family that started with his father before him.

My wife, Tanya, has been a central guiding element in my life over the past 17 years. Without her encouragement the completion of this Ph.D. would have been unlikely. Throughout our marriage she has been a tremendous source of encouragement and her willingness to sacrifice some of her desires has permitted me to accomplish many of mine. Tanya, along with our daughters Ashley and Anna, fuel my desire to be the best that I can be.

I started work at Stress Engineering Services, Inc. in 1993. It is hard to imagine what my life would have been like without the impact of this organization. Like many employees at Stress, I deeply value the impact of Dr. Joe Fowler on my life. He has probably been the greatest example of sacrificial leadership I have ever seen in the business world (and likely the greatest I will ever see). For years he has been my role model as a leader. I will forever be indebted to the opportunity he gave me back in 1993 as a young engineer, and more importantly the opportunity he provided to me in returning to Stress in 2002.

From a technical standpoint, it is safe to say that Richard Biel played a tremendous role in the formative year of my engineering career. Richard challenged me to think deeply and never settle for second best. Like a learned professor, he coached me and encouraged me to develop a passion for engineering. Like many mentors, he is probably not aware of how much his belief in my abilities and encouragement contributed to my love for engineering.

My real interest in repairing pipelines using composite materials took shape in 1997 when I met Fred Wilson, president of Armor Plate, Inc. Like many of my mentors, Fred believed in me and had confidence that I could do great things. To a very large extent, this research program is a direct result of interests that he instilled in me in the late 1990s and his willingness to spend his own money to perform research in developing Armor Plate Pipe Wrap. On a personal note, along with Joe Fowler, Fred started the fire that led to my love for business and contributed greatly to my understanding the important role that vision casting has in terms of building and growing businesses.

In terms of the research program associated with this particular study, there are numerous individuals to whom I am indebted. Cory Duncan, owner of C&M Specialties, fabricated all of the test samples that were used and was instrumental in performing most of the testing reported in this document. Jim Lockwood and Larry Cercone of Comptek Structural Composites, Inc. of Boulder Colorado provided great insights into using carbon composite materials and fabricated the carbon half-shells that were the backbone of this study. Brent Vyvial, who has become my right hand man at Stress Engineering over the past year, contributed greatly to the success of this program and helped keep the Joint Industry Project moving along. I would also like to thank all of the members of the

Joint Industry Program, including the U.S. Minerals Management Service, the four composite repair manufacturers, and the Offshore Technology Research Center at Texas A&M, who willingly contributed their own funds to make this portion of the study possible.

Lastly, and certainly not least, I would like to thank the members of my committee, Drs. Ozden Ochoa, Harry Hogan, Tom Lalk, and Peter Keating, for dealing with a graduate student who is old enough to be a professor. I was fortunate to have as instructors Drs. Hogan, Lalk, and Keating during my graduate and undergraduate days at A&M and appreciate their desire to impact the next generation of engineers. I was fortunate to be a recipient of their talents as professors. I would specifically like to thank Dr. Ochoa for her encouragement and insight throughout this study. Her willingness to partner with me in this study was truly a blessing.

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INTRODUCTION

Risers are critical components in offshore operations as they extend the wellhead from 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 as shown in **Figure 2**. 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.

While composite materials are a generally-accepted for repairing onshore pipelines, the application of this technology for repairing offshore risers and pipelines has not been technically validated. The objective of this research program is to investigate the feasibility of extending onshore composite repair techniques to offshore risers using integrated analytical and experimental methods. The approach to fulfilling this objective includes assessing the current composite repair technology by designing and performing a test program that simulates offshore riser loads. The primary focus of this research program was the development of a carbon-based composite repair system that was optimized by numerical simulation and prototype testing. At the completion of the study guidelines were developed for industry in repairing and reinforcing offshore risers using composite materials.

This dissertation follows the style of Composites Science and Technology.

Results of this program clearly demonstrate that composite materials are a viable means for repairing damaged offshore steel risers. Proper design and installation of a composite repair system on a corroded riser ensures that reinforcement is provided to the steel to reduce strains when subjected to typical riser loads that include internal pressure, tension, and bending. The specific repair technique created and evaluated in this study was a carbon-fiber half-shell system. Another significant contribution is the demonstration of successfully integrated finite element analysis and limit analysis methods to predict the performance of a composite repair system based on critical design parameters. These critical design parameters incorporate geometry of the repair including thickness, type of composite materials including fiber and resin, and orientation of fibers and method of installation.

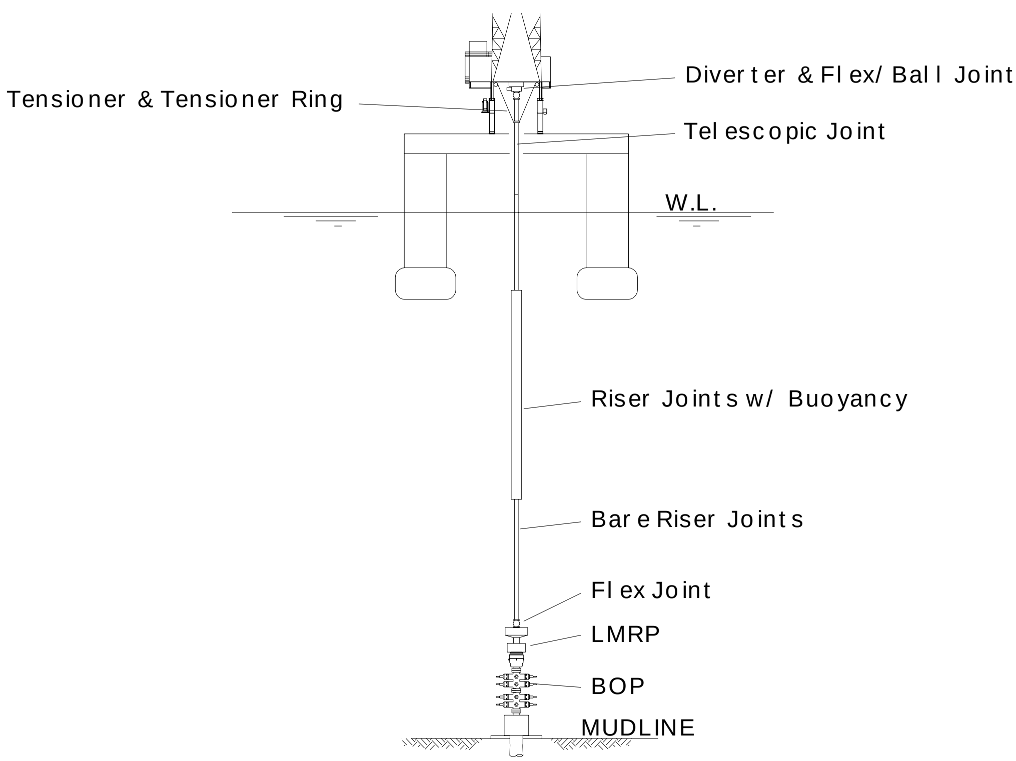

Figure 1 – Layout for a semisubmersible rig showing position of the riser

Figure 2 – A conventional riser repair involving a welded steel clamp

What separates this research effort from prior studies is the evaluation of composite repair technology for offshore applications that 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. This program is the first of its kind and will contribute significantly to the future of offshore riser repairs. It is likely 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.

The sections that follow provide the background, approach, and results of this research program. The *Proposed Research Objectives* section provides the reader with an understanding as to why this study is being conducted and the role it plays in ensuring the mechanical integrity of damaged offshore risers. *Background and Literature Search* documents lessons learned from previous research and provides insights as to how the present program builds the methodology to develop an optimized composite reinforcement system. The *State of the Art Assessment of Composite Repairs* section highlights the knowledge gained from the experimental efforts conducted with the four composite repair manufacturers who participated in a study to assess the ability of their particular systems to reinforce corroded risers in a full-scale test program. Strain gages, along with other instrumentation, were used to monitor the ability of each repair to provide reinforcement to the damaged riser test pipe. Results are presented for each of the repair systems in the form of plots and tabulated data. 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 *Integrated Analysis and Testing Investigation* section provides details on how full-scale testing was used to validate the quality of design and if the system achieved its intended reinforcement levels based on the prior finite element work. The remaining sections include *Discussion*, *Conclusions*, *References*, and *Appendices*. The discussion subject matter includes topics ranging from areas of improvement for the optimized design to discussions on how economics impacts the fabrication, installation, and operating processes.

RESEARCH OBJECTIVES

The repair of pipelines and risers using composite materials encompasses a wide range of subjects including material behavior and its limitations, design issues, optimization, and long-term performance. The objective of this research program is to investigate the feasibility of extending onshore composite repair techniques to offshore risers by developing integrated analytical and experimental methods. The approach to fulfill this objective incorporates three tasks: *(i) to assess the state of the art of current composite repair technology by designing and performing a test program that simulates offshore riser loads, (ii} to subsequently design a carbon-based composite repair system optimized by numerical simulation and prototype testing, and (iii} to provide guidelines for industry in repairing and reinforcing offshore risers using composite materials.*

To positively impact the offshore industry at large, the findings and results of this program must clearly demonstrate the benefits in using composite materials to repair risers. Conventional repair methods involve welding steel sleeves to the outside of the riser. This is expensive, time consuming, and can be dangerous for rig personnel.

Assessing the current state of the art of composite repair technology is a necessary first step in determining how repairs should be made and for determining if any deficiencies exist that precludes the successful expansion to offshore risers. At most there are three to four widely used composite repair systems that employ either E-glass or carbon fibers. While some of these systems have been used offshore, their initial designs focused on onshore repairs where the predominant loading is internal pressure. Consequently, the current-technology composite repair systems are designed to provide circumferential or hoop strength.

The second task, and primary focus of this research effort, was the development of an optimized composite system for reinforcing offshore risers where axial and bending loads are the driving forces. The optimization involves measuring performance of the repair against predefined assessment variables (i.e. key performance variables). From this study the following key performance variables were identified:

- Geometry of the repair including thickness
- Type of composite materials including fiber and resin
- Orientation of fibers and method of installation

The above variables are evaluated for the geometry of a specific composite repair system in terms of their ability to reduce strain in the reinforced steel under load. Other considerations are made to ensure that strains in the composite material do not exceed values that would degenerate the long-term performance of the composite itself.

The final task, and one which builds heavily on insights gained in pursuit of the state of the art and design optimization task, is the development of guidelines for industry in using composite materials to reinforce offshore risers. While completion of this task will not entail prescriptive guidelines, the focus will be to assist industry in selecting and properly using composite materials to satisfy the rigorous design requirements associated with offshore repairs.

BACKGROUND AND LITERATURE SEARCH

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 sections 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

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 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 the use of composite materials 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 [6] and [7]. 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 [8]. 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)

While details provided in this reference concerning damage tolerance are of interest, the more important insights relates to the benefits of acoustic emission as an inspection technique. Acoustic emission (AE) proved to be a technique well-suited for monitoring damage in composite tubes. AE was used in the IFP study to detect the presence of intentional defects, although it was not able to detect delaminations. Comments relating to the inspection of composite materials are critically important to the discussion at hand, because, unlike steel that can be inspected and determined fit for service with some existing flaws, a concern with using composite materials is that adequate inspection techniques are not available at the present time to specifically quantify the magnitude of damage. This is especially important considering that when composite materials are used for reinforcement or repair; they represent the last line of defense in preventing potential failure. The program attempted to evaluate the long-term performance and durability of composite materials through the specified test matrix.

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 [9] through [13]). 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 [13]. The conclusion from these studies was that the prototype composite product riser met the cost, weight, and performance goals of the research program.

Other studies have been undertaken to assess the performance of metal-composite risers. This technology is the most likely to succeed in terms of deep water production due to challenges at the connector. Furthermore, for the study at hand, research addressing the interaction between steel and composite materials provides insights that can be directly applied to the reinforcement of corroded and damaged risers with the external application of composite materials. The Institute of Polymer Mechanics in Russia performed a study assessing the performance of metal-composite risers using numerical simulation techniques [14]. Discussions were presented on appropriate safety factors for the composite material as well as assessing the reduction in metal (i.e. steel and aluminum) due to the contribution of the composite materials.

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 fatigue testing.

For transmission pipelines, Clock Spring® is clearly recognized as the first composite repair system that was widely used to reinforce damaged pipelines. In 1991 the Gas Research Institute (GRI) initiated a research program at Southwest Research Institute

(San Antonio, Texas) and Battelle Columbus Division (Columbus, Ohio) to thoroughly test a composite repair system that had been developed for the pipeline industry. Over the next five years an intense research effort was carried out to assess the performance of Clock Spring® that utilized an E-glass/polyester material with a methacrylate adhesive that bonds pre-cured composite layers [15].

In many regards, Clock Spring® set the standard in terms of expectations associated with the development of composite repairs. GRI was instrumental in gathering both industry and research partners for evaluating the repair system. Some of these efforts involved the following activities:

- Composite material studies and analysis including short and long-term stress-rupture testing
- Adhesive testing in terms of lap shear strengths
- Burst test considering general defects, circumferential defects, long axial defects, and repair of dents, gouges, and mechanical damage.
- Field exposure assessment of Clock Spring® systems installed in 1989 (coupon testing and inspection of installed wraps)
- Development of GRIWrap™ to provide a general procedure for the safe application of Clock Spring®.

A final report for GRI, Development of Fiberglass Systems for Natural Gas Pipeline Service, was prepared by NCF industries [15]. This document spanned a period of time from January 1987 to March 1994 and covered the basic history and development of Clock Spring®.

During the 1990s GRI continued numerous research efforts on Clock Spring® that included field validation efforts [16], long-term-reliability efforts [17], and repair of non-straight pipe geometries such as elbows [18].

In the mid-1990s, the pipeline industry began exploring the use of wet lay-up systems. The first system on the market was a private label product known as StrongBack that is manufactured by Air Logistics Corporation (Azusa, California). StrongBack is a composite reinforcement product that is water-activated, resin impregnated (urethane), and uses glass fiber reinforcement materials. More recently, Air Logistics has also brought to industry an additional water-activated system, Aquawrap™. This system has undergone extensive testing, including full-scale testing to address its use in repairing mechanical damage [19]. Air Logistics self-published a document that detailed research efforts to validate their repair system. Included in this report were data from stress-rupture testing to address long-term performance issues [20].

In 1997, Armor Plate, Inc. started a research program to develop the Armor Plate® Pipe Wrap system [21]. Stress Engineering Services, Inc. was involved in the testing of this system, which employs an E-glass/epoxy material that is impregnated with different resin systems to address specific environmental conditions, such as underwater applications, high temperatures, and cold weather.

Prior to 2000, pipeline companies were generally hesitant to use products other than Clock Spring® because of a waiver requirement specified by the U.S. Office of Pipeline Safety (OPS). However, effective January 13, 2000, the OPS permitted the use of composite materials as long as the following criterion was satisfied in terms of repairing dents and corrosion [22].

> … repaired by a method that reliable engineering tests and analyses show that can permanently restore the serviceability of the pipe.

Additionally, this regulatory document addressed issues relating to industry expectations as reflected in the following statement.

> We recognize that licensed professional engineers may differ on what information is necessary to demonstrate the performance of particular technologies in particular circumstances. But the experience of Clock Spring®

> and Armor Plate wraps can serve as a model in determining the technical issues to resolve and the relevant substantiating tests and analyses.

Once the 2000-edition of the OPS ruling came out, use of composite materials in repairing pipelines increased significantly. In a similar fashion, the number of manufacturers interested in this repair technology increased.

In 2000 WrapMaster, Inc. started a testing program to assess the capabilities of PermaWrap™; a system similar to Clock Spring® in that it employs a pre-cured hard shell with an adhesive installed between layers. The following product description is provided according to the GE Power web site [23].

> The WrapMaster repair system is a coil of high-strength composite material with a configuration that allows it to wrap tightly around pipe of almost any size. The layers of wrap are sealed together with a strong adhesive. The defect is filled with adhesive filler to assist with support and load transfer prior to the WrapMaster installation. This method of repair is ideal for blunt-type defects.

T.D. Williamson, Inc. developed in conjunction Citadel Technologies the Black-Diamond™ Composite Wrap. Although similar in nature to Armor Plate® Pipe Wrap in its use of epoxy products, the T.D. Williamson system uses carbon fibers, which on average have an elastic modulus that is three to four times that of conventional E-glass systems [24].

Assessing the Performance of Composite Materials

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 has 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.

<u>Residual Stresses</u>

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 [25]. 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. Hyer points out that for a particular graphite-reinforced laminate it is observed that cooling causes the composite to experience compression in the fiber direction, while the direction normal to the fibers experiences tension. The physical observation is that upon cooling the free layer wants to expand in the fiber direction and contract normal to the fiber direction. However, the laminate resists both of these actions, resulting in a certain level of compression. This observation has important ramifications for the reinforcement of offshore risers using composite materials. On one hand, compressive residual stresses in the composite can be viewed as advantageous since greater loads can be applied before a tensile strain limit is reached in the composite. However, on the other hand and perhaps more importantly, it is critical that the fibers are engaged and loaded in tension as soon as possible once loads are applied to the riser in order to provide reinforcement. It is possible that this load transfer could be delayed if significant compressive stresses are present in the composite material. 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 [26]. 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 [27 – 29]. 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 cross-ply cracks can appear during the first cycle of loading, provided that the applied stress exceeds the local ply strength that might happen at applied stresses as low as 20% of the ultimate stress [28]. The cross-ply cracks propagate through the entire width of the ply, but are unable to propagate into the adjacent ply. This is especially true if it is a ply having fibers aligned in the direction of loading. Thus, the cross-ply cracks terminate at the interface of the two plies.

The composite undergoes final fracture when its overall strength is weakened by the presence of longitudinal-ply cracks and delamination cracks. The former weaken the longitudinal plies that are responsible for carrying a larger portion of the load, while the presence of the latter prevents distribution between plies. As a result, the composite degenerates into a combination of independent longitudinal plies acting in parallel to support the applied load. The weakest of these longitudinal plies fails and triggers failure of the remaining longitudinal plies [26]. 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 [30], 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 [31]. Because of the potential for developing corrosion at the interface, a boundary must be established between the carbon materials and the steel pipe. While some composite repair systems use epoxy resin as the boundary layer (e.g. Citadel's *Black Diamond* repair system), the use of E-glass with an epoxy matrix is more likely 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 [32]. 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 **Table 1**. The plus/minus values shown in this table correspond to the standard deviation. The tensile strength data are also plotted in **Figure 3** for both the carbon/epoxy and E-glass/epoxy systems. The mechanical data includes the standard deviations based on a typical data set of 6 samples. Also included in **Figure 3** are two solid lines that show design stresses for the carbon and E-glass materials assuming a safety factor of 2.5 on the mean failure stress less two standard deviations.

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: Above data taken from CALTRANS report [32].

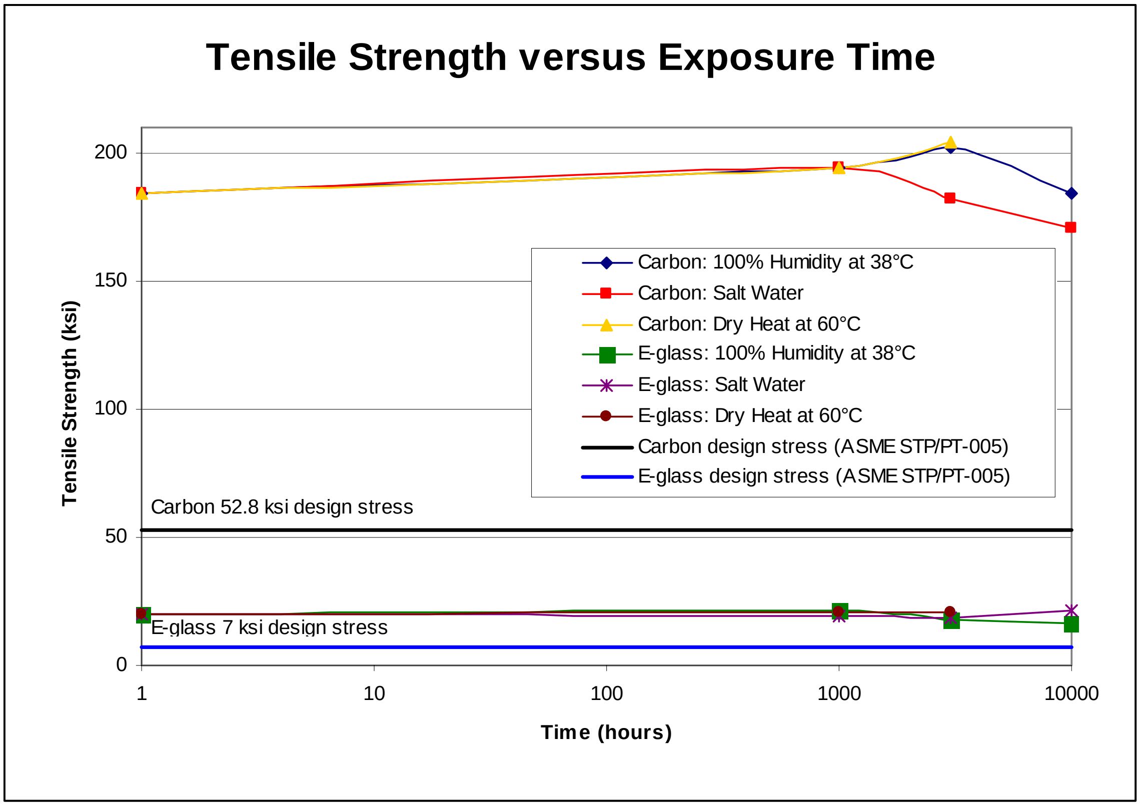

Figure 3 – Tensile strength data from the CALTRANS research program

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. 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* [33]. 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 [33]. 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 [34].

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 [20]. 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.

Strain-based Design Methods and Limit State Design

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. For this reason, a design criterion is required. Conventional design methods employ either stress-based (i.e. strength) or strain-based (i.e. stiffness or displacement) limitations. For steel components where loading of the primary structure is predominantly in the elastic regime, placing a safety factor on yield strength or ultimate tensile strength is acceptable. However, when loads necessitate and require a certain amount of material nonlinearity in the steel (i.e. plasticity) in order to transfer load from the steel to the composite, linear elastic design methods are not useful and may not be acceptable as they are often limiting and unnecessarily conservative. Examples include the laying of offshore pipelines where it is possible to induce strains exceeding 1 percent under certain conditions (API Recommended Practice 1111 [5]). Another example is the make-up of flanges where elastic stresses up to two times the yield strength are permitted (ASME Boiler & Pressure Vessel Code, Section VIII, Division 2, Appendix 4 [11]).

Since the inception of finite element analysis and its widespread use in design over the past 30 years, limit state design methods have permitted the integration of plasticity into the design process. The objective of a limit load analysis is to size a vessel or structure considering nonlinearities such as elastic-plastic material properties and non-linear strain-displacement relations. It is even possible to use experimental methods to determine the loading capacity of a structure. In subsea and offshore environments, there are several installation and operating conditions that necessitate the use of limit analyses [4]. 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.

A search of the open literature reveals several reliable sources of information on design efforts based on limit state methods. Much of the work done in this area has been in the design of high pressure equipment where the need to account for plasticity at the inner bore of thick-walled vessels is necessary to reduce what would be an otherwise overly-thick vessel. Mraz discusses how plasticity should be used in the process of optimizing pressure vessels for high pressure service [35]. Although the paper does not specifically address how to integrate finite element methods as part of the design process, it does discuss the role of permitting plastic flow in design. 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 [36]. 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 [37] contains three documents that contain an exhaustive body of research associated with limit analysis. Provided below is text from the Foreward of WRC Bulletin 254. This documentation provides background on the history of limit analysis in terms of pressure vessel design.

> For over two decades, the various subcommittees under the Design Division (ASME, added) have been carrying out analytical and experimental research on the plastic behavior of pressure components consisting of pressure vessel heads, cylindrical piping, curved piping and elbows, nozzles in spherical vessels, nozzles in cylindrical shells, and flat circular plates. The analytical methods developed to quantify the plastic strength were primarily based on the concept of limit analyses which is strictly applicable to idealized elastic/perfectly plastic materials. Due to the obvious differences between the ideal and actual material behavior, several different methods were used to determine the plastic strength in experimental investigations. Discussions among members of the ASME Boiler and Pressure Vessel Code as well as among the active investigators indicated that there is a considerable amount of controversy about the basis and applicability of these methods. Since plastic strengths, determined by the methods of limit analysis as well as experimental procedures, have been used in the ASME Boiler and Pressure Vessel Code as an alternative basis for setting allowable limits on primary loadings, the Design Division of the PVRC felt it necessary to resolve this controversy. Consequently, the Task Group on Characterization on Plastic Behavior of Structures was set up in 1975.
>
> Briefly, the objective of the Task Group was to critically review plastic behavior data and information, obtained under various PVRC Subcommittees as well as by other resources, to establish definitions of limit and plastic collapse loads, and

finally, to recommend uniform procedures and standards, for determining limit and plastic collapse loads for use in design criteria. [37]

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 [38] provides specific guidance in using modern finite element codes. Details including required model input and interpretation of results are discussed.

A final reference by Walters [39] 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 [33] 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.

Recommendations for further research are also provided in the ASME design document, in particular the development of rules to provide design life dependent design factors relative to stress rupture for 15-year design lives. In terms of application for the current study, the ASME guideline recommends that for long-term performance that the stress or strain in the composite materials be limited to 40 percent of the short-term rupture capacity. Another area for further research, as conveyed by several of the cited references, concerns the ability to inspect composite materials and then developing methods for quantifying the effects of defects on mechanical integrity and performance.

Closing Comments

The proper design of a composite repair system should draw on knowledge from previous experience and studies. Of particular interest are the performance characteristics of composite repair systems originally designed for onshore pipelines. In studying the behavior of these respective systems, insights are gained in terms of how to design improved composite repair systems for reinforcing offshore risers. Subject matters such as the aforementioned damage mechanisms and long-term performance issues must be considered in the design development process. Additionally, because of the rigorous offshore service environment and presence of combined loads (i.e. internal pressure, axial tension, and bending), it is necessary that a design methodology be used that not only captures the correct loads, but also integrates the shared load distribution between the carrier riser pipe and reinforcing composite material. As discussed, a strain-based design method is selected that integrates limit analysis to capture strains generated in both the steel and composite materials. To account for long-term degradation and installation quality unknowns, a strain limit is imposed on the composite material. Limit analysis provides calculated strains in both the steel and composite material that are then assessed relative to allowable strain limits.

STATE OF THE ART ASSESSMENT OF COMPOSITE REPAIRS

To date there has been no single study directed at assessing composite repair technology subject to offshore riser loads. A common approach for performing a state of the art assessment involves surveying industry and manufacturers about their use of a particular technology. Although this is a valid preliminary approach, it has the potential for failing to capture the deficiencies in an existing technology and the requirements for improving the associated technology. In the current effort a Joint Industry Program (JIP) was formed that involved the evaluation of four different composite repair systems using a full-scale test program. Manufacturers were invited to participate in this study, resulting in a program that independently evaluated four different composite repair systems. The primary purpose of the JIP study was to identify and confirm the critical elements required for an effective composite repair. Having practically unlimited access to manufacturers with the ability to understand the overall mechanics of each repair, the author was provided with insights useful for developing an optimized repair system.

The program incorporated 8.625-inch x 0.406-inch, Grade X46 pipe test samples that were prepared with simulated corrosion by machining. The program destructively tested a total of 12 separate tests where three different samples were repaired by four composite repair manufacturers. The tests included a burst test (increasing pressure to failure), a tension-to-failure test (pressure held constant with increasing axial tension loads to failure), and a four-point bend test (pressure and tension held constant with increasing bending loads to achieve significant yielding in steel pipe) for each of the repair systems.

State of the Art Repair System Assessment Overview

The four-team JIP was formed to assess the current state of the art. Each repair system was evaluated considering a combination of pressure, tension, and bending loads. To maintain anonymity, each company's product was assigned a letter reference designation as noted below.

Product A – this system uses an E-glass fiber system in a water-activated urethane matrix. The fiber cloth is a balanced plain-weave with orthogonal fibers aligned at 0 and 90 degrees relative to the axis of the pipe[1]. During installation, the cloth was oriented either axially or circumferentially to achieve the desired level of reinforcement.
Product B – this system uses an E-glass fiber system in a water-activated urethane matrix. The cloth for this system also uses a balanced weave. This particular repair incorporated an epoxy filler material in the corroded region, as opposed to placing composite material in this region of the repair. All of the other manufacturers chose to install fibers in the corroded region. During installation, the cloth was oriented either axially of circumferentially to achieve the desired level of reinforcement. Due to issues encountered during testing with uncured resins, no results are presented for this system.
Product C – this system uses a carbon fiber system in an epoxy matrix. The cloth is a stitched fabric with uniaxial fibers. During installation, the fibers were aligned at 0 and 90 degrees relative to the axis of the pipe to achieve the desired level of reinforcement.
Product D – this system uses an E-glass fiber system in an epoxy matrix. The cloth has fibers that are oriented at 0, 90, and +/- 45 degrees. Additionally, a layer of chopped strand fibers is sprayed on the underside of the cloth. During installation, the cloth was oriented either axially of circumferentially to achieve the desired level of reinforcement.

Because of the lack of available performance data on composite repairs subject to tension and bending loads, the need for integrating these load types was identified. Additionally, discussions with participating manufacturers focused on the need to ensure that their repair systems would be designed in a manner that could provide adequate reinforcement in terms of both bonding to the pipe and also providing sufficient bending

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[1] The plain weave is the simplest composite fabric that is available. The yarns are interlaced in an alternating fashion over and under every other yarn, providing maximum fabric stability and equal strength in both the warp and fill directions.

strength to reinforce the corroded section of pipe. Fundamentally, bonding to the pipe involves shear strength of the adhesive (or resin used in fabricating the composite) as well as available shear area. In other words, even with a strong adhesive, shear failure is possible if there is an inadequate bond area.

In terms of bending strength, the manufacturers were encouraged to integrate a sufficient percentage of fibers in the axial direction. This required additional consideration for all participants as their systems have preferential orientations directed at circumferential reinforcement. The problem in having insufficient fibers in the axial direction was resolved by rotating a certain percentage of the fabric during installation to align with the axis of the pipe.

As will be shown in the following sections, by and large the manufacturers were able to use their existing hoop-dominated repair systems with slight modifications to achieve acceptable reinforcement for the imposed riser loads. This is an important observation as the key to repairing damaged structures is to first identify the potential load conditions and then design a repair system that adequately reinforces the anticipated loads. It is also important to note the role that installation quality plays in the success of a composite repair system.

Technical Details of the Test Program

A test program was devised to evaluate the performance of the repair systems subject to internal pressure, tension, and bending loads. To provide greater clarity in assessing the performance of a particular load type (i.e. pressure, tension, or bending), three specific tests were developed to decouple the interactions between the three load types. Details are provided in the sections that follow.

Recognizing the potential for significant variability in the repair systems developed by each manufacturer, it was communicated to each manufacturer that the axial length of the repair was limited to 60 inches. This length ensures that an 18-inch length of the repair extends on both sides of the 24-inch long corrosion section. Additionally, all manufacturers were told that each repair on the three test samples had to be identical. This ensured that there was no variation among the test samples from a single manufacturer, ensuring that each design was ultimately subjected to the pressure, tension, and bending loads. The testing variable was the type of loading, and not the repair itself. In actual service, a composite repair can not selectively determine the loads to which it will be subjected, but rather a given load must be able to withstand the anticipated pressure, tension, and bending loads.

<u>Three samples were prepared to test each composite repair system</u> (e.g. four systems required 12 total samples). After the pipe samples were fabricated, the composite repair manufacturers were invited to install there repair systems on the three prepared test samples, which were then destructively tested. These three samples included:

1. <u>Pressure only test</u> – sample destructively tested by increasing internal pressure to failure.
2. <u>Pressure-tension test</u> – sample destructively tested by increasing axial tension to failure while holding internal pressure constant (2,887 psi).
3. <u>Pressure-tension test</u> – sample destructively tested by increasing bending load to induce gross plastic deformation while holding internal pressure (2,887 psi) and axial tension (145 kips) constant.

Provided in **Appendix A** are two important documents associated with the JIP study.

- *Test Package and Protocol for Manufacturers* – this document was provided to each manufacturer prior to testing. It included specific details about the types of tests that were to be conducted and important technical aspects that warranted careful consideration. An example included ensuring that the length of the composite repair was sufficient to withstand the designated axial tension loading.

- *Test Procedure for Jip Composite Repair* – this document was used prior to and during testing to ensure that exact testing standards were maintained for all JIP participants. This document was also made available to participants and also served as the guiding document for what work was completed as part of the test program.

Prior to installation of the repair systems, each pipe was sandblasted to near white metal to ensure a quality adhesive bond between the steel and composite materials. Prior to testing, details on the importance of having adequate repair length were provided to each of the manufacturers. If a sufficient reinforcing length is not available, during tension loading premature failure of the repair will ensue because of the inability of the repair to remain attached to the pipe. As a point of reference, consider that an axial length of 18 inches exists on each side of the repair. If an adhesive lap shear strength of 1,000 psi exists (a conservative estimate considering the performance of most epoxy adhesive systems), a tensile capacity of approximately 490 kips exists prior to failure of the adhesive bond between the steel pipe and composite material. For the nominal pipe wall of the test samples, this results in an axial stress of 44.5 ksi.

Pressure Test

The purpose of this test type was to assess the performance of the composite repair in providing hoop strength. **Figure 4** is a schematic showing the unrepaired sample geometry. An axisymmetric groove was machined in the center of the 8-ft long sample to simulate corrosion. It is recognized that actual corrosion never possesses the uniformity of the simulated corrosion; however, the uniform test conditions this geometry is appropriate for consistency. Prior to installation of the repair, bi-axial strain gage rosettes were installed on the samples to measure hoop and axial strains. **Figure 5** shows the location of the strain gages. Nine strain gages were placed on the steel pipe and three were placed on the outside surface of the repair once it had been installed. The design pressure of the given test sample is 2,887 psi based on the API RP 1111 design basis [4].

The gages that provide the greatest information, relative to the performance of the repair, are those located in the center of the corrosion groove beneath the repair (i.e. Gages 1 through 3). These gages indicate the level of reinforcement provided by the composite material and at what point load is transferred from the steel to the composite material.

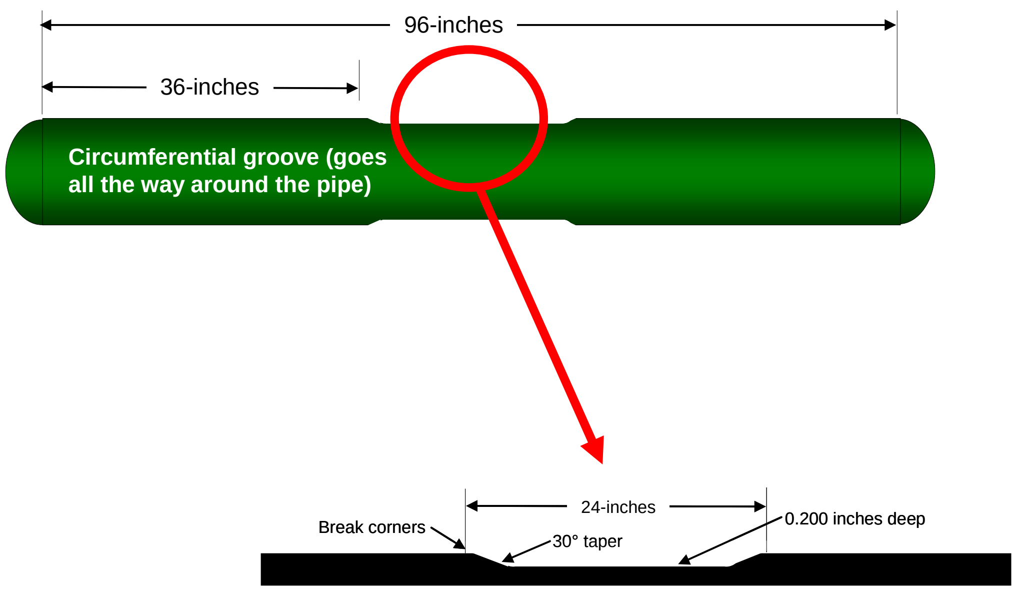

Figure 4 – Schematic diagram showing pressure only test sample

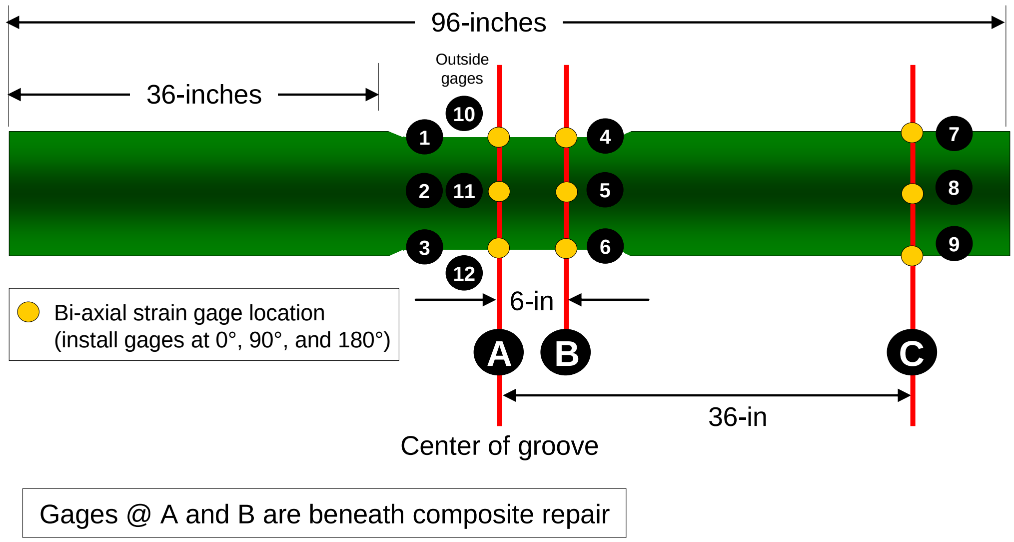

Figure 5 – Location of strain gages on the pressure and pressure/tension samples

Pressure-tension Test

The next series of tests involved a sample similar to the pressure only sample; however, the focus was on axial tension capacity. In this test, pressure was held constant (2,887 psi based on the API RP 111 design basis), while axial tension was increased to the point of failure. **Figure 6** shows the schematic for this test, which is identical to the pressure only test except that instead of elliptical dome caps, 7-1/2 inch diameter STUB ACME threaded end caps were used to interface with the tension load frame. As with the pressure only sample, strain gages were installed on the tension-pressure sample at the same locations shown in **Figure 5**. API RP 1111 [4] was used to determine that the limit an axial tension loads was 145 kips.

Prior to testing, details on the importance of having adequate repair length were provided to each of the manufacturers. If a sufficient reinforcing length is not available, during tension loading premature failure of the repair will ensue because of the inability of the repair to remain attached to the pipe. As a point of reference, consider that an axial length of 18 inches exists on each side of the repair. If an adhesive lap shear strength of 1,000 psi exists (a conservative estimate considering the performance of most epoxy adhesive systems [21]), a tensile capacity of approximately 490 kips exists prior to failure of the adhesive bond between the steel pipe and composite material (this tension loads significantly exceeds the design axial tension load of 145 kips). For the nominal pipe wall of the test samples, this results in an axial stress of 44.5 ksi. Samples were taken to failure by increasing the axial tension in the sample to the point where failure in the corroded region occurred. The indication of failure was when pressure in the sample could no longer be maintained.

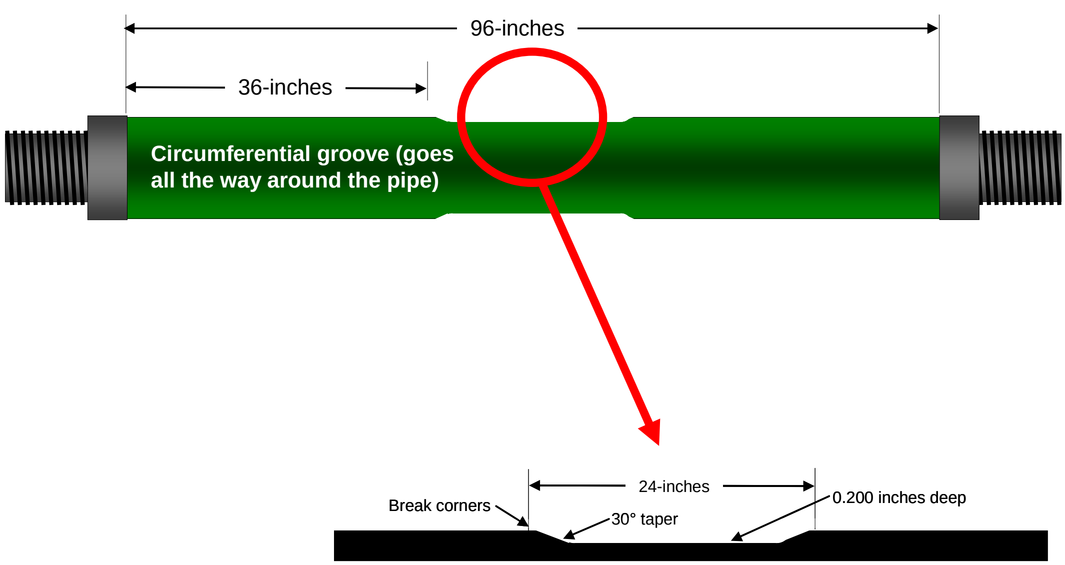

Figure 6 – Schematic diagram showing pressure-tension test sample

Pressure-tension-bending Test

This test combined all three load types: internal pressure, tension, and bending. The variable load of interest in this round of testing was bending. During testing, internal pressure and tension were held constant at 2,887 psi and 145 kips, respectively. Bending loads were applied using a four-point bend configuration as shown in **Figure 7**. Holding pressure and tension constant, the bending load was increased by incrementally increasing the force applied by the two hydraulic rams. Due to safety concerns, testing was terminated once significant plastic flow in the reinforced corrosion area occurred and axial strain in the unreinforced region of the pipe outside of the repair approached 10,000 microstrain (1.0% strain). This also corresponded to the point where load was transferred from the steel to the composite material as observed by the strain gages positioned beneath the reinforcement.

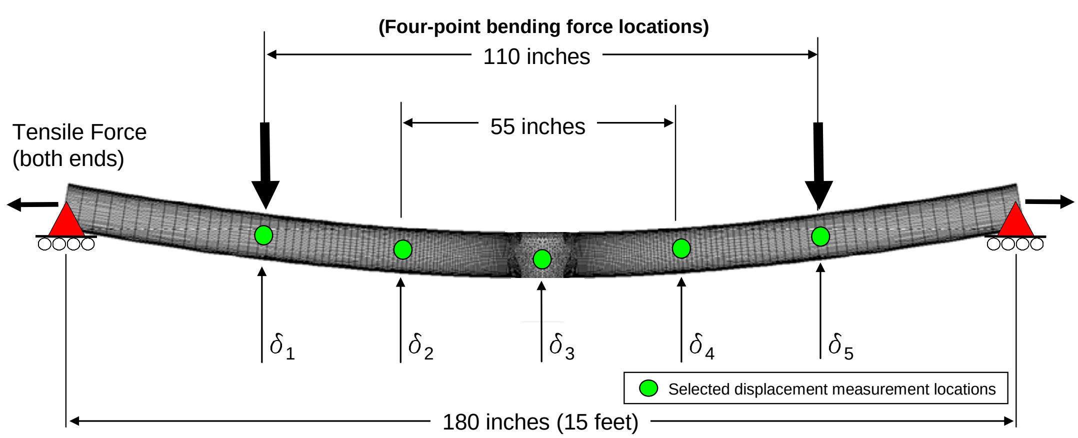

Figure 7 – Four point bending configuration for pressure-tension-bend testing7

Figure 8 shows the location of the strain gages placed on the pressure-tension-bend samples. As with the other two tests, nine strain gages were installed on the pipe and three were installed on the outside surface of the composite repair after curing had taken place. **Figure 9** shows the load frame used for the bend tests. This load frame has an axial tension capacity of 1 million lbs and can apply bending loads up to 750 kip-feet.

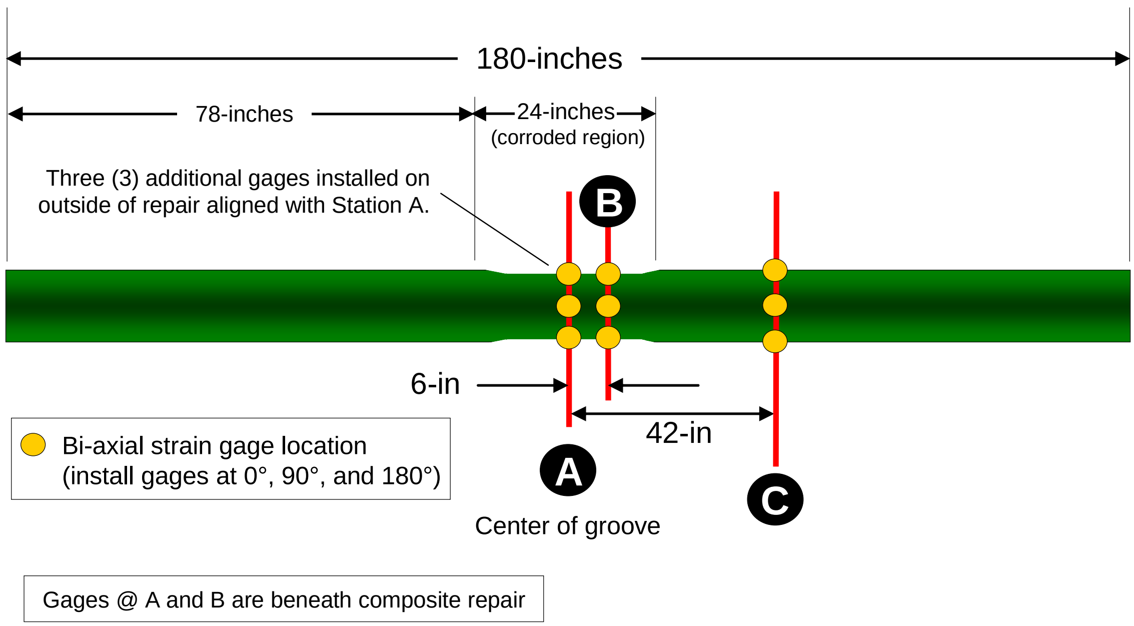

Figure 8 - Location of strain gages on the pressure-tension-bend samples

Figure 9 – Load frame used for pressure-tension-bend testing

Test Results

Over a five week period, tests were performed on one set of unrepaired samples and four different composite repair systems. Results are presented for the four repair systems and the unrepaired sample in the sections that follow. Considering all phases of testing, data were recorded for a total of 159 strain gages. However, presentation of results is limited to gages located beneath the repairs in order to demonstrate the level of reinforcement provided by each of the repair systems.

It should be noted that results for Product B are not included. The manufacturer of this repair requested that their results not be included after sub-standard performance resulted due to uncured adhesives.

Pressure Test

Results for the pressure-only test are provided in **Figure 10**. This phase of testing represents the initial benchmark of the test. To a certain extent, it presents the most basic test as it only addresses the performance of the repair in reinforcing hoop strength.

In reviewing the test data in **Figure 10**, there are several noteworthy points.

- In limit state design, one must address the limit state, or the maximum capacity a structure can withstand. Although fundamentally this involves failure, more practically it involves assessing the load at which unbounded displacements (or strains) occur. In pressure vessel design, this condition is known as the collapse load. The strain gage results presented in **Figure 10** show the pressure at which unbounded displacements occur, typically near 2000 microstrain (or 0.2 percent strain). The *unbounded* condition occurs when minimum increases in load (i.e. internal pressure) results in disproportionate increases in hoop strain.

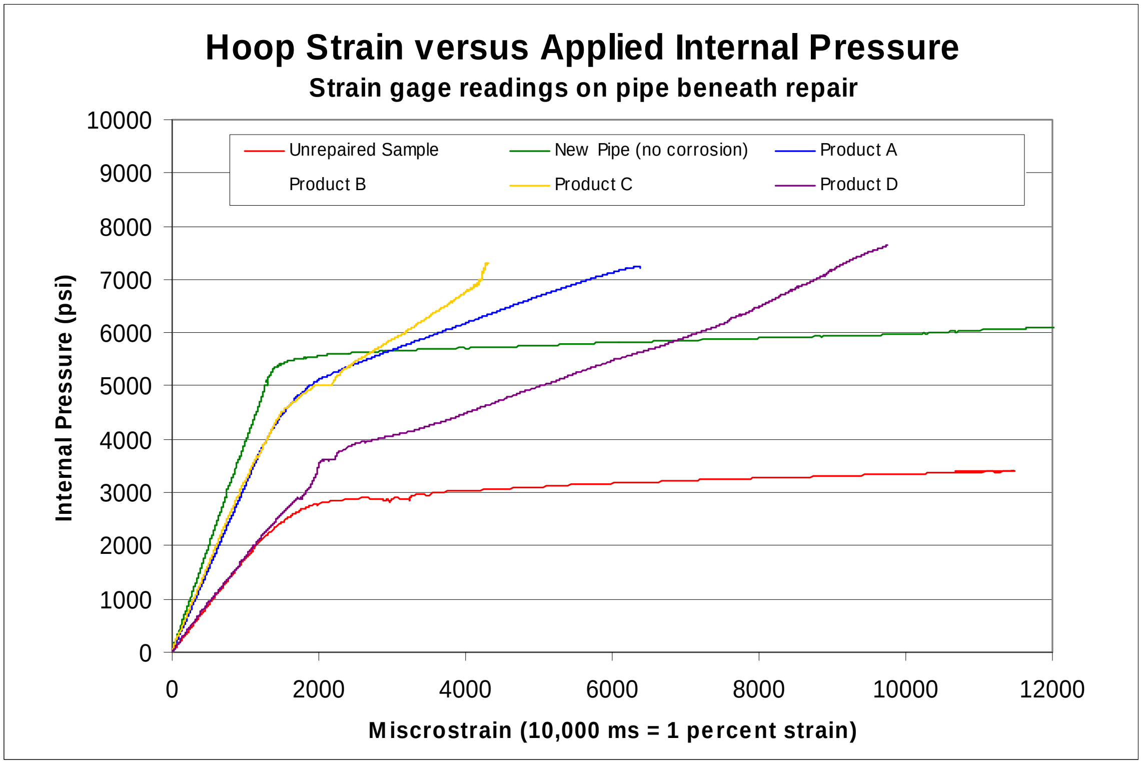

Figure 10 – Test results from pressure-only testing

- The post-yield slope in the strain-strain curves observed for each of the repair systems is the result of reinforcement being provided to the corroded region of the steel pipe. This occurs once plasticity initiates in the steel and load is transferred to the reinforcing composite material. This bi-linear stress-strain curve is typical for structures reinforced using composite materials subject to hoop tensile loading [16, 17, and 39].
- The unrepaired sample failed at a pressure of 3,694 psi. Failures in the test samples prepared using Products A, C, and D occurred in the steel away from the repaired region. **Figure 11** shows the failure in the unrepaired sample, while **Figure 12** shows the failure in the Product C repaired sample outside of the repaired region in the base pipe. This failure was typical for the repaired samples. The failure pressures for the four repaired samples are listed below.
    - Unrepaired – 3,694 psi

- Product A – 6,921 psi
- Product B – data not reported
- Product C – 7,502 psi
- Product D – 7,641 psi

- The strain gage results provide measurements of the strains in the pipe during pressurization. The measurements of greatest significance are those that that demonstrate behavior once yielding initiates in the steel and the point at which load is transferred from the steel into the composite material. This latter observation is the best indicator for determining how much reinforcement is provided by the composite material. Product C provides the greatest continuous reinforcement, while Product A provides similar results up to 2,500 microstrain (0.25 percent strain). As noted, Product D did not provide the same level of strain reduction beneath the repair as the other two systems.

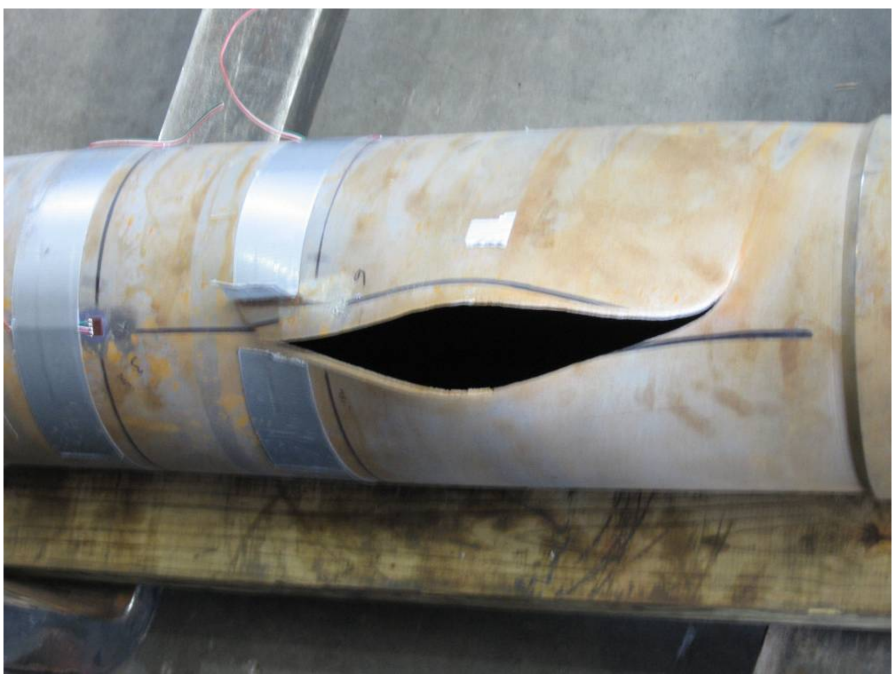

Figure 11 – Failure in unrepaired test sample

Figure 12 – Failure in burst sample using Product C

Pressure-tension Test

Results for the pressure-tension test are provided in **Figure 13**. This phase of testing primarily assessed the lap shear strength of the adhesive that bonded the composite reinforcement to the steel pipe. This failure condition was anticipated prior to testing and was the basis for the minimum repair length of 60 inches. Several noteworthy observations are made in reviewing the test data presented in **Figure 13**.

- Product C shows the greatest axial rigidity of all the repair systems. The basis for this observation is that Product C was fabricated using carbon fibers, with a large percentage of fibers being oriented axially. Products A and D show similar levels of reinforcement up to 200 kips, while after this point Product D shows greater reinforcement.
- The following tension failure data were recorded.
    - Unrepaired sample – 317 kips
    - Product A – 492 kips

- Product B – data not reported
- Product C – 562 kips
- Product D – 579 kips

Figure 14 provides several photos showing the post-failure surface of the pressure-tension sample for Product D. As shown, the inner steel in the corroded region failed due to tensile overload. The adhesive at the interface between the composite and steel is used to transfer load into the composite material. At some point during loading, the strength in this bond is exceeded and the composite is no longer able to carry the tensile load. As shown in **Figure 14** (lower right hand side photo), the composite material remains intact.

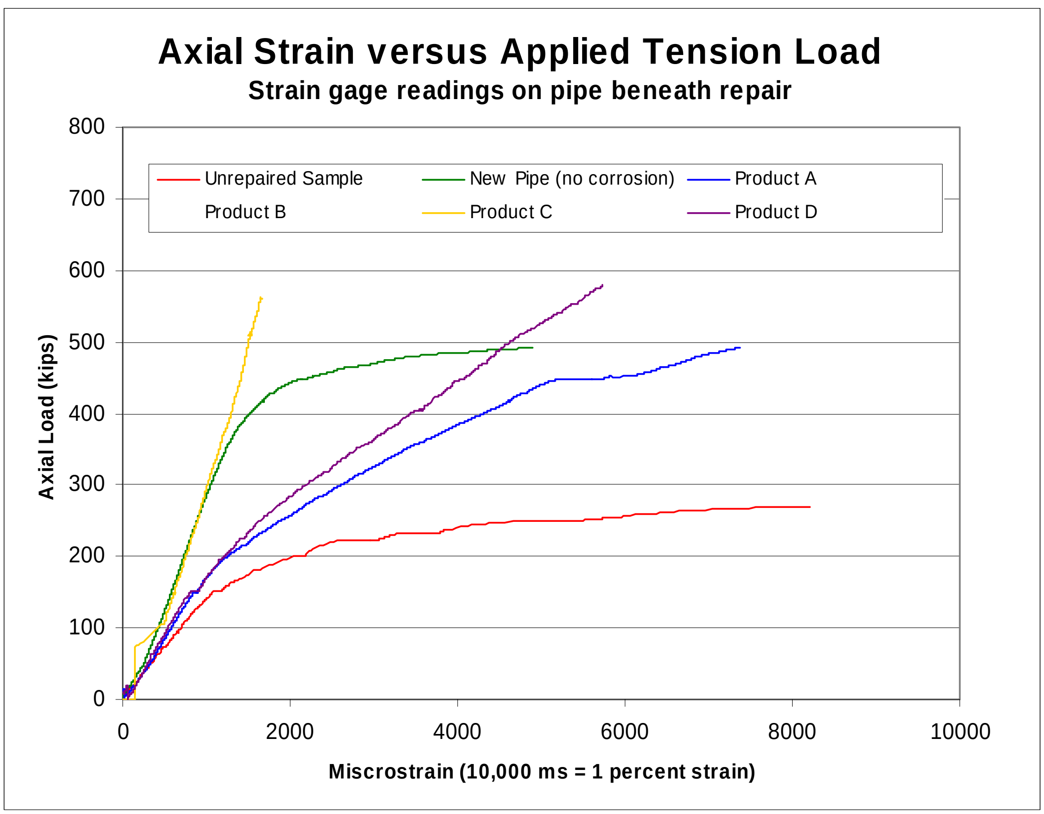

Figure 13 – Test results from pressure-tension testing

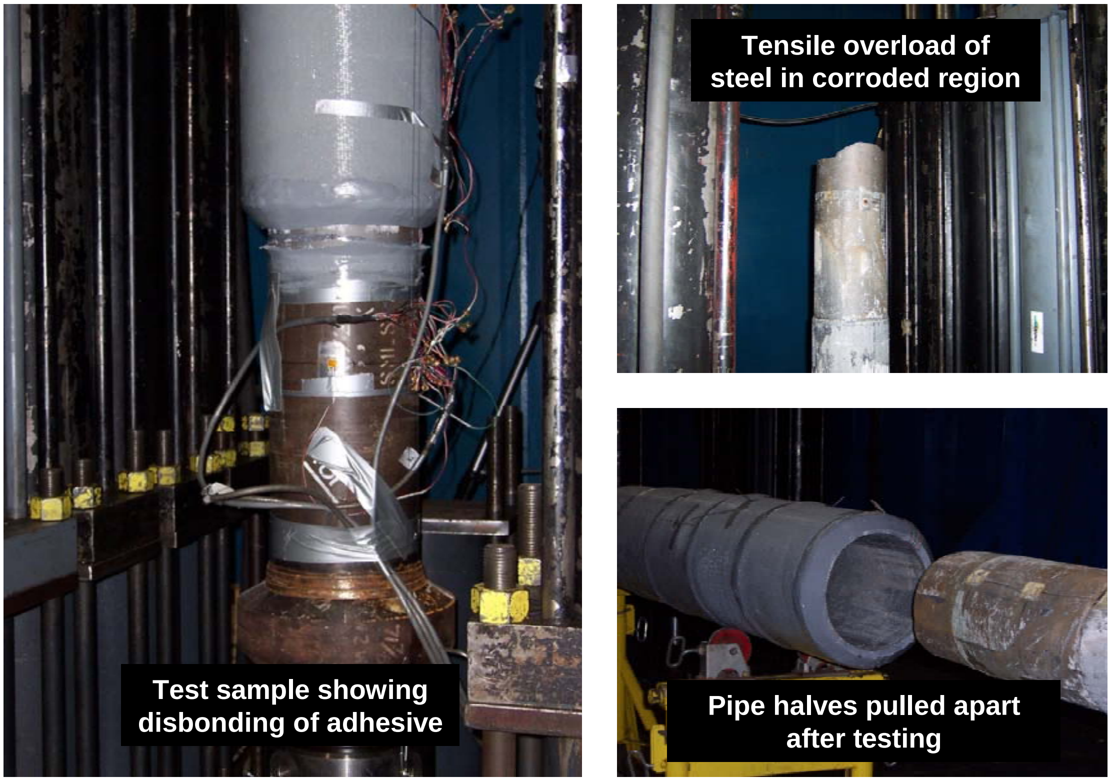

Figure 14 – Post-failure photos of Product D pressure-tension test

Pressure-tension-bending Test

Prior to starting the testing phase of work, this particular test was recognized as the most likely challenge of the three test configurations. It not only combined constant pressure (2,887 psi) and constant axial tension (145 kips), it integrated bending loads that would induce significant axial strains in both the corroded steel and composite material. Unlike the pressure-tension tests where the primary focus was on the interfacial adhesive bond, this phase of testing integrated the needs for adequate bond strength, but the repair was also required to have sufficient strength and stiffness in the composite to reinforce the corroded steel.

Results for the pressure-tension-bending test are provided in **Figure 15**. There are several noteworthy observations in reviewing the plotted data.

- Unlike the other tests, there is a unique pattern observed for the level of reinforcement provided by each of the respective repair systems. As expected, the carbon in Product C provides the greatest level of reinforcement because for any given bending load it had the lowest measured strain. For comparison purposes, consider the strain in the steel at a bending load of 40 kips (bending moment of 116.7 ft-lbs) for each of the repair systems:
    - Product A – 4,130 microstrain
    - Product B – data not reported
    - Product C – 2,150 microstrain
    - Product D – 3,022 microstrain

- In assessing the relative performance of the composite systems, the objective of the repair is to reduce the strain in the corroded steel during bend testing, as well as provided reinforcement in the circumferential and axial directions due to internal pressure and axial tension loads, respectively. As noted in **Figure 15**, at some point the strain gage results appear to stop changing with increasing load (plotted lines trend vertical). It is at this point that gross plastic deformation as recorded by the strain gages occurs outside of the reinforced region and that deflection is occurring primarily in areas outside the composite reinforcement. The sooner this transformation takes place, the more effective the repair is in reinforcing the corroded region.

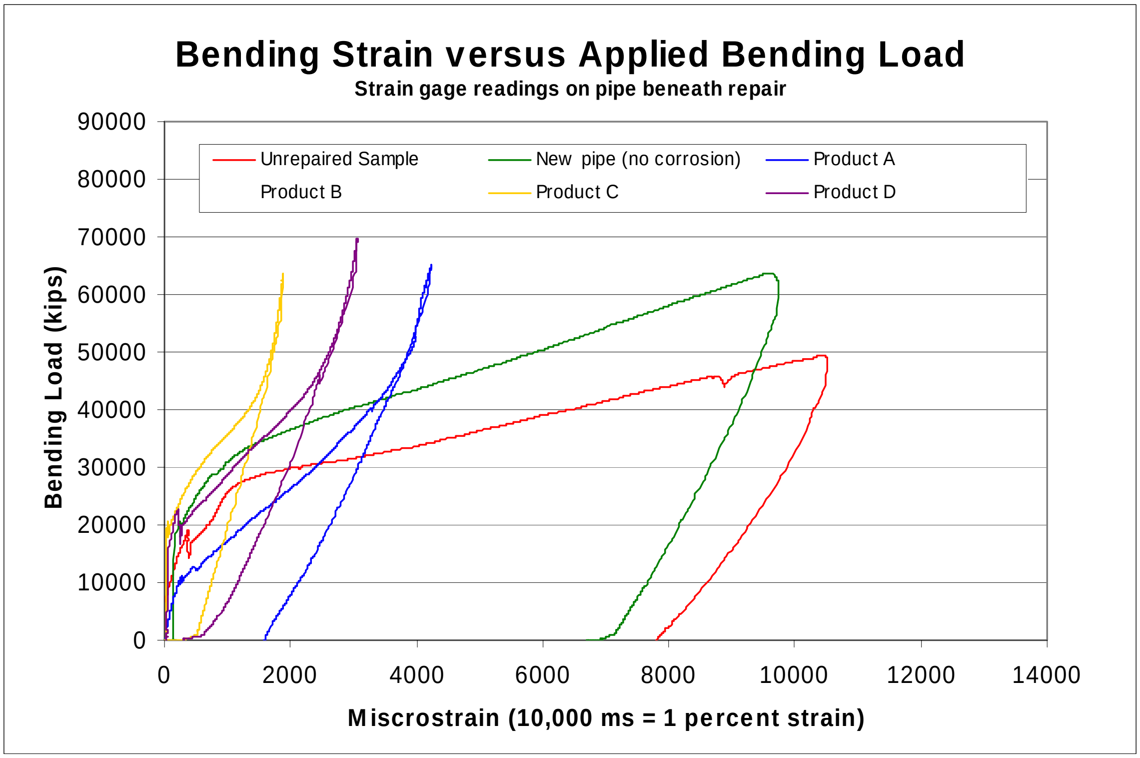

Figure 15 – Test results from pressure-tension-bending testing

- Another option for assessing the relative performance of the composite repair systems is to determine the applied bending moment at a specified strain value. If the strain limit is 0.20 percent, the following bending forces and moments are extracted. This method is a better assessment of the relative performance of the repair systems. It should be noted that the unreinforced sample did not include internal pressure as failure would have occurred at a lower bending load.
  - Unrepaired sample – 30 kips (87.5 kip-feet)
  - Product A – 26 kips (75.8 kip-feet)
  - Product B – data not reported
  - Product C – 70 kips (204.2 kip-feet)
  - Product D – 40 kips (116.7 kip-feet)

Figure 16 is a photograph of the Product C repair in the load frame prior to bend testing.

Figure 16 – Photo showing Product C prior to bend testing

General Observations on the JIP Test Results

In assessing the overall performance of the repair system, it is clear that all of the reported data show clear benefit in using composite materials over the unrepaired configuration. **Table 2** is presented that shows the test results relative to the design performance criteria. As noted, the composite repair systems exceed the design loads by a relative large margin.

Specifically, the following average design margins were calculated for all of the repair systems. These were calculated by dividing the failure load by the specified design loads listed in **Table 2**. For example, the design margin for Product A considering internal pressure is calculated by dividing its burst pressure of 6,921 psi by the design pressure of 2,887 psi, or 2.40.

- Pressure testing – average design margin of 2.56
- Tension testing – average design margin of 3.75
- Bend testing – average design margin of 2.59

Table 2 – Summary of test results relative to design conditions

Loading Conditions	Design Load	Failure Loads				
		Unrepaired	Product A	Product B	Product C	Product D
Internal pressure	2,887 psi	3,694 psi	6,921 psi	N/A	7,592 psi	7,641 psi
Tension Load	145 kips	317 kips	492 kips	N/A	562 kips	579 kips
Bending Force (Moment)	17.5 kips (51 kip-feet)	30 kips (87.5 kip-feet)	26 kips (75.8 kip-feet)	N/A	69.9 kips (204.2 kip-feet)	40 kips (116.7 kip-feet)

Notes:

(1) The unrepaired bending sample did not include internal pressure at the time of testing. The decision to run this test without internal pressure was based on safety concerns and recognizing the possibility for failure at relatively low bending loads due to large strains.

(2) The ratio of average failure loads for the repaired samples to the unrepaired sample for the internal pressure and tension load samples are 2.0 and 1.72, respectively.

(3) The unrepaired sample exhibited failure loads exceeding the specified Design Load for both the pressure and tension tests.

As seen with values listed previously based on the **Table 2** test data, the tested composite reinforcement systems possess an adequate safety margin for their intended service conditions relatively to the ASME design standards [33 and 36].

Closing Comments on State of the Art Assessment

In using composite materials to reinforce damaged and corroded risers, it is critical to integrate design methodologies that assess the strain in the reinforced steel. This is especially important in offshore design as risers in the splash zone are subjected to

combined loads including internal pressure, axial tension, and bending loads, as compared to onshore repairs that primarily involve restoration of hoop strength.
As demonstrated in this effort, use of strain based design methods is the ideal approach for assessing the interaction of load transfer between the reinforced steel and the reinforcing composite material. Industry should be cautious of any design methodology that does not capture the mechanics associated with the load transfer between the steel and composite materials during the process of loading. The two keys are to first determine strain limits based on acceptable design margins, and then assess strain levels in both the steel and composite reinforcement using either analysis methods, or the preferred approach involving full-scale testing with strain gages.

The primary purpose of the state of the art assessment and associated JIP study was to identify and confirm the critical elements required for an effective composite repair. Having practically unlimited access to manufacturers with the ability to understand the overall mechanics of each repair, the author was provided with insights useful for developing an optimized repair system.

Other benefits were also derived in the execution of the program, including the development of guidelines for industry and regulators and providing the manufacturers with the opportunity to assess their given repair systems subject to loading conditions associated with offshore risers.

DEVELOPMENT OF A RISER COMPOSITE REPAIR SYSTEM

The principal aim of this study is 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. To achieve this aim several steps are required and addressed in this section. First, the *Design Requirements* section provides details on identification and ranking of the critical design elements. In *Design Concepts* specific aspects are outlined including geometry and architecture of the composite repair system. A design basis is identified to which the calculated stresses and strains are compared as presented in *Method for Determining Allowable Design States*. Due to the complex mechanics associated with combined loads and the transfer of load between steel and composite materials, strain-based limit state methods are used and a tutorial is presented on the double elastic slope method in *Strain Limitations fir the Repaired Steel Section*. Lastly, a composite repair system is developed based on classical mechanics and finite element methods. A central element of this process is evaluating the optimized design relative to design requirements based on limit analysis methods. *Features of the Selected Composite Repair System* includes detailed discussions on specific aspects of the system. All of these elements contribute to the primary aim of this study which is to develop a composite system for repairing offshore risers.

The design requirements for this effort is 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 17 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 17** are details initiating at the preliminary design phase through completion of the final design verified using finite element analysis and prototype testing.

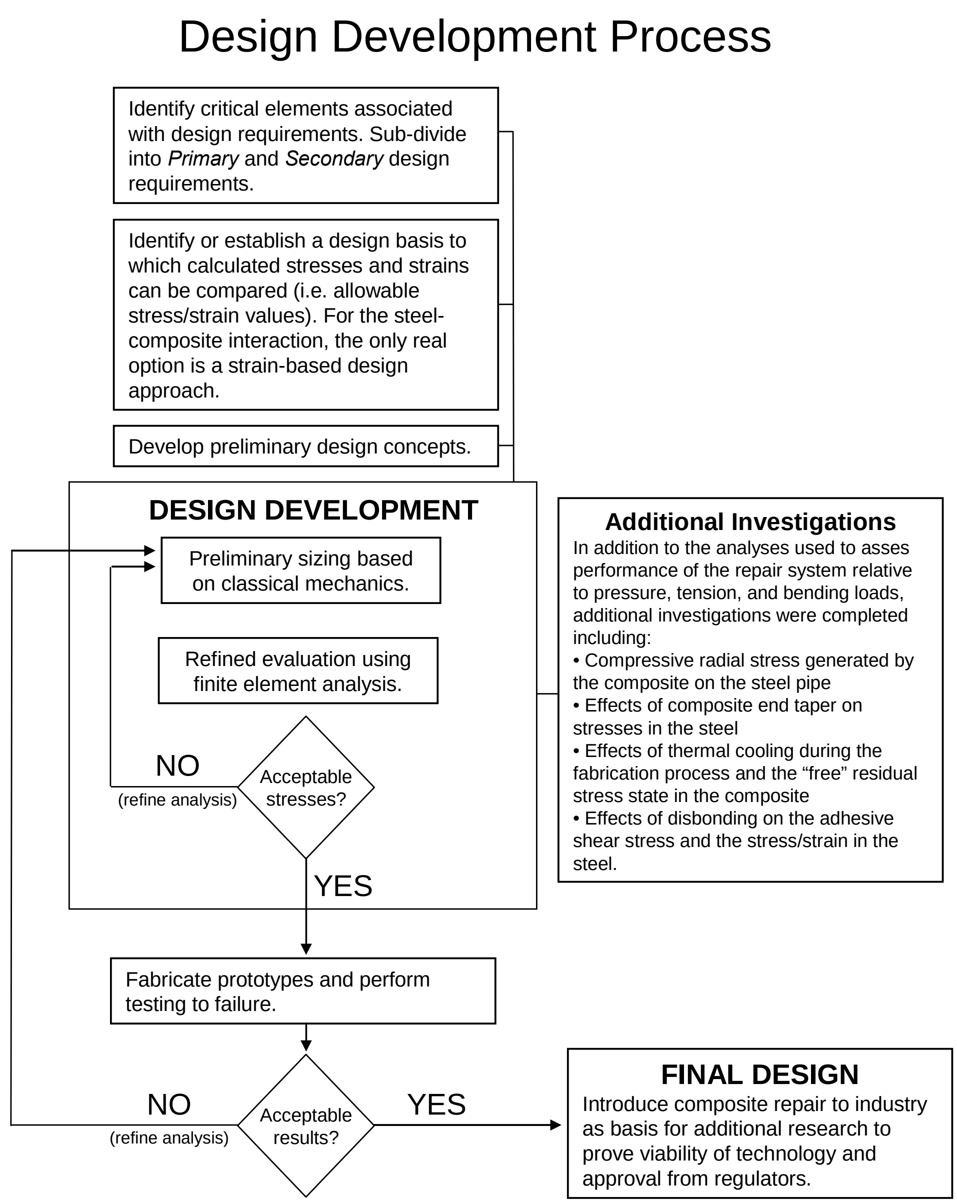

Figure 17 – Steps involved in the optimization process

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. It should be noted that the work reported in this section of the dissertation was completed prior to the fabrication of the optimized repair system. The following section, *Integrated Analysis and Testing Investigation*, provides specific insights on the performance of the repair in testing relative to the specified design requirements for pressure, tension, and bending.

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.

<u>Primary Requirements</u>

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. However, if the composite reinforcement disbonds due to an insufficient adhesive bond between the steel and composite, performance of the repair deteriorates and the repair is unlikely to provide the required reinforcement, even if it has been designed to provide sufficient reinforcement for the pressure and bending loads. This can be achieved by ensuring that the repair length is long enough so that the force required to break the bond (i.e. the maximum expected tension load) is greater than the lap shear load multiplied by an appropriate design factor (e.g. SF = 3).

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 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 amount composite reinforcing material that exceeds the design requirements. 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 are used to determine acceptable design conditions, but also to optimize a particular repair system. The sections that follow provide specific details on the design limits for the steel and composite materials, respectively.

<u>Strain Limitations for the Repaired Steel Section</u>

One of the primary purposes when performing any structural repair is reduction of loads carried by the repaired member. In providing reinforcement, the primary load path is no longer carried just 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. Conventional design methods are based on elastic performance of the steel. Although limitations on the total strain in the repair region of the riser are needed, it is necessary that the strain limit be permitted to some level of strain beyond the elastic range. 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. **Figure 18** is a graphic that shows the steps to establish strain limit on the reinforced steel material. **Appendix B** has a discussion on limit analysis methods, with specific emphasis on how to select appropriate strain limits for the steel and composite materials with the highlights presented herein.

Step #1: Determine the Limit Load for Undamaged Risers

The primary expected aim of repair system is to restore risers back to their original condition through repair. As shown in **Figure 18**, limit analysis methods are used to calculate the limit load of the structure considering all primary loads (pressure, tension, and bending for the splash zone region of the riser). The analysis utilizes the double elastic slope procedure for determining the plastic analysis collapse load (refer to **Appendix B** for details on this procedure which is based on the methodology designated in Appendix 6 of the ASME Boiler & Pressure Vessel Code, Section VIII, Division 2). Basically, the double elastic slope method is used to define the collapse load as the intersection between the load-deflection curve and a line with a slope that is two times that of the elastic portion of the load-deflection curve.

Step #2: Calculate Design Load Using an Acceptable Design Margin

Once the limit load is determined, a design load can be found by the application of a suitable design margin. There are a range of accepted design margins, but a reasonable conservative value is 2.0, and is supported by previous additions of the ASME Boiler & Pressure Code, Section VIII, Division 2 (Paragraph 4-136.5), although the current version of the code uses 1.5. If the design margin of 2.0 is used, this implies that during normal operation the load in the steel is limited to one-half the load required to achieve plastic collapse of the structure.

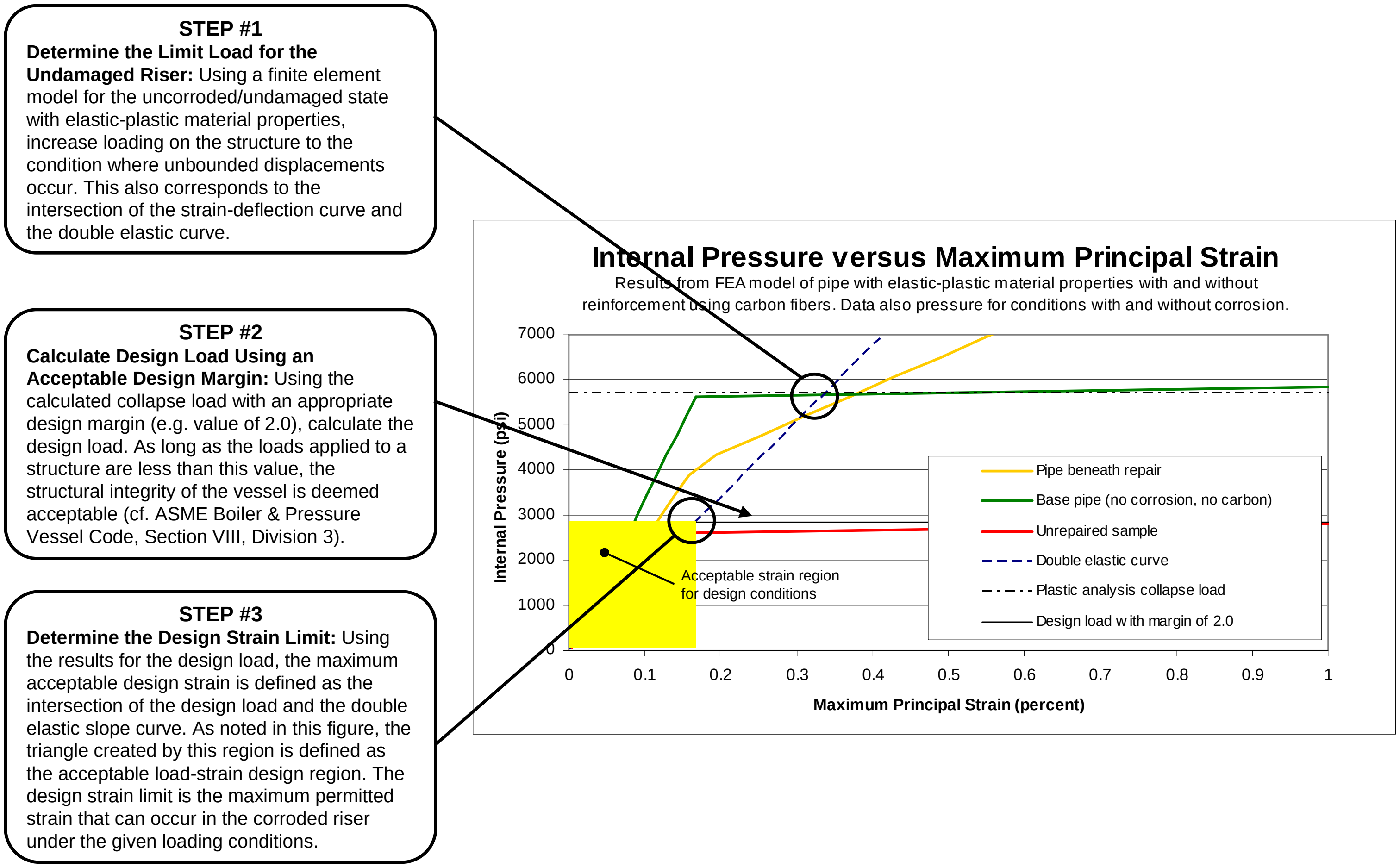

Figure 18 – Process for establishing strain limits on the reinforced steel

Step #3: Determine the Design Strain Limit

Once the design load is established, the design strain limit can be determined. The concept is that once the repair has been made, strain in the steel is required to be less than this specific strain limit. Referring once again to **Figure 18**, the acceptable strains are those that fall within the yellow triangular highlighted region near the intersection of the ordinate and abscissa. What ultimately defines the strain limit is the design load, which is based on the lower bound collapse load. The maximum permitted strain is any strain that is less than the value determined by the intersection of the double elastic slop line and the horizontal line designating the design load. The maximum permitted strain shown in **Figure 18** is approximately 0.2 percent.

The section that follows discusses what limitations are to be placed on the composite material. It is important to consider the combined resistance to load from both the steel and composite. If stresses in the composite material are beyond an acceptable level, it may fail. As a point of reference, ASME STP/PT-005 [33] limits the stress in the composite to be 40 percent of the short-term failure strength for the composite. Failure of the composite may overload the steel carrier pipe, resulting in failure of the riser to function as originally designed.

<u>Stress Limits on the Composite Reinforcing Material</u>

Similar to discussions on limiting strain the reinforced steel, it is necessary to limit stresses or strains in the composite reinforcing material. In a search of applicable codes, standards, and papers, there are a variety of limitations placed on composite materials used to reinforce steel and aluminum pressure containing structures. Provided below are several design margins expressed in the open literature that relate to the discussion of riser repair.

ASME PCC-2 Repair Standard (Article 4.1, Non-Metallic Composite Repair Systems for Pipelines and Pipework: High Risk Applications): For continuous loads where the axial elastic modulus of the composite material is less that one-half the elastic modulus in the circumferential direction, that design margin of circumferential and axial strain are 4 and 10, respectively.

ASME Boiler & Pressure Vessel Code, Case 2390-1 Composite Reinforced Pressure Vessels Section VIII, Division 3, 4.0 DESIGN, 4.1 Rules for CRPV (i): *The primary membrane circumferential stress in the laminate layer shall not exceed 36% of the ultimate tensile strength of the laminate at design conditions. The primary membrane circumferential stress in the laminate layer shall not exceed 60% of the ultimate tensile strength of the laminate under the hydrostatic test load.*

ASME STP/PT-005 Design Factor Guidelines for High Pressure Composite Hydrogen Tanks: This document was developed to provide for industry a technical basis for determining appropriate design margins for composite-wound tanks (typically involving an aluminum liner with an E-glass wrap). According to Section 7 Recommended Short-term (static) Design Factors for Composite Tanks), for transport tanks the stress ratio must be less than 40 percent of the working pressure for hoop-wrapped tanks. The stress ratio is defined as the ratio of the stress in the reinforcing fibers at working pressure to the initial ultimate (tensile) strength of the fibers, as demonstrated by the short-term burst tests.

Recognizing that if the reinforcing material is properly designed to ensure that strains in the steel remain below the designated design limit (as discussed in the preceding section), a design margin for the reinforcing composite of 2.5 is acceptable (and reflected with precedent in the ASME STP/PT-005 document). For example, if a carbon-epoxy material with a tensile strength of 100 ksi is used for reinforcement, during normal operation stresses in these carbon layers should not exceed 40 ksi.

Features of the Composite Repair System

Having established design conditions for the steel and composite materials, limit analysis methods are used to determine the geometry for the E-glass/carbon hybrid repair system. Before analysis efforts were started, carbon was selected as the primary load-carrying material due to its relatively high elastic modulus and ability to provide greater reinforcement to the steel carrier pipe than the E-glass material for the same composite thickness. It is possible that E-glass can be used; however, the short-term stiffness and long-term performance of carbon make it the optimum choice. The discussions that follow outline the process used to design the repair system. Primary emphasis was place on determining the required thickness and orientation of the carbon layers. Loads considered included internal pressure, axial tension, and bending loads.

Preliminary Concepts

Provided below are elements of the composite repair system design. 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* (refer to **Figure 19** 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

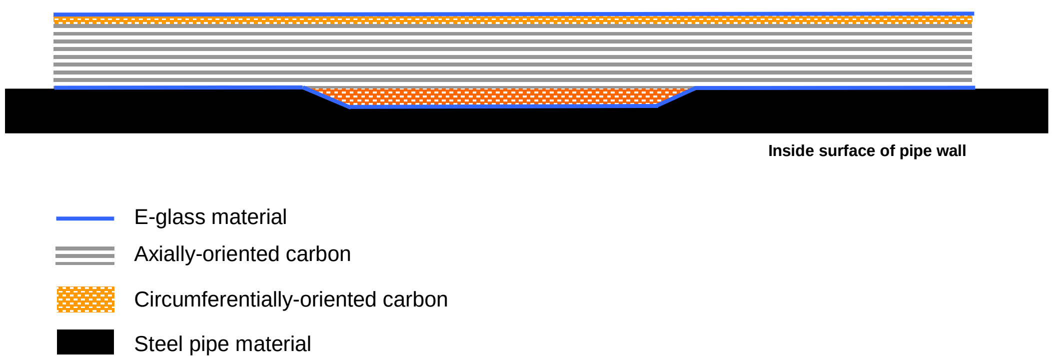

Figure 19 – Generalized layout for optimized E-glass/carbon composite repair

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.

The sections that follow provide details on the process used to develop the pre-cured carbon half-shell reinforcement system to reinforce risers subject to pressure, bending, and tension loads. Included in each discussion are calculations based on classical mechanics and finite element analysis.

Design Verification: Internal Pressure Loads

Initial estimates of the required thickness for reinforcing against internal pressure were performed using classical mechanics. The reinforcing system 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.

Assessment Based on Classical Mechanics

The thickness of the reinforcing layer can be selected using the following relation. This equation algebraically combines the strength of the remaining (corroded) steel and the composite material. For completeness, the relation requires that the strength of the repair be at least equal to the burst strength for a non-corroded pipe using the minimum ultimate tensile strength for the respective pipe grade (UTS is 63,000 psi for Grade X46 pipe).

$$P_{burst} = \left[\frac{2 \cdot S \cdot t_{corroded}}{D} \right]_{steel} + \left[\frac{2 \cdot S \cdot t}{D} \right]_{composite}$$

where

P Burst pressure of new pipe considering minimum UTS (psi)

S Tensile strength of steel or composite (psi)

t Thickness of steel (nominal or corroded) and composite (inches)

D Outside diameter of pipe (inches)

This equation can be re-written in terms of tensile strength and thicknesses.

$$t_{composite} \geq \frac{S_{composite}}{S_{steel}} \cdot (t_{nominal} - t_{corroded})$$

Assuming a corrosion depth of 50 percent and the tensile strengths of the steel and carbon as 63 ksi and 100 ksi, respectively, the minimum permissible hoop thickness of the carbon material is 0.126 inches. This thickness assures that with the presence of the carbon material, the burst strength of the repaired section will be at least equal to the non-corroded pipe condition.

Additionally, an estimate of stress in the carbon fibers can be calculated using the following relation.

$$S_{hoop} = \frac{P \cdot D}{2 \cdot tc \cdot \left[1 + \frac{E_s \cdot t_s}{E_c \cdot t_c} \right]}$$

where

t_p	Composite thickness (inches)
E_p	Pipe steel elastic modulus (psi)
t_c	Composite material thickness (inches)
E_c	Composite material elastic modulus (psi)
S_{hoop}	Hoop stress in composite (psi)

$$S_{hoop} = \frac{2887\ psi \cdot 8.625\ inches}{2 \cdot 0.126\ \cdot \left[1 + \frac{30E6 \cdot 0.200\ inches}{10E6 \cdot 0.126\ inches} \right]} = 17{,}149\ psi$$

This stress is less than 40 ksi, which is the allowable composite stress based on the design margin of 2.5 (or also expressed as 40 percent of the composite failure stress). Additionally, these calculations validate that the initial proposed carbon hoop thickness of 0.200 inches is sufficient.

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 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. Provided in **Appendix C** are additional details on the finite element models including an overall discussion on the types of models that were used in this study.

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

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

Consider the text copied in **Figure 20** from an ABAQUS input file used in this study. As noted, the input used to designate the composite materials, *SHELL SECTION, includes details such as layer thickness, orientation, and material type. Another benefit in using shell elements is the ability during post-processing to look at the stress and strain distributions in different layers. Once each analysis is run, it important to be able to assess strains in different layers. Like layers in an onion, the composite can be “sliced” to reveal the contribution each layer makes to the overall reinforcement.

In the input deck material properties are controlled by the *MATERIAL card. As noted, elastic (*ELASTIC) material properties are included for each material and used exclusively for the composite. In terms of interfacing with the element, especially with regards to the composite, the material properties are input in local coordinates of the element. For materials modeled isotropically such as the pipe steel in this study orientation is not important; however, when modeling composite orientation is critically. This especially true when one considers one of the primary advantages in using composite is to be able to control the directional dependence of 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 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 epoxy resin.

The *PLASTIC card is used for the steel to invoke material plasticity with isotropic hardening. For the given input deck, elastic-plastic material properties are used based on mechanical measurements from the steel pipe used in testing. A full stress-strain curve could have been used to account for strain hardening; however, as seen in **Figure 20** a simple elastic plastic model was used with yield and ultimate strength of 61 ksi and 74.6 ksi, respectively.

```
**
*SHELL SECTION, ELSET=CORR, MATERIAL=STEEL
      0.203,       5
*SHELL SECTION, ELSET=TRANSITION, MATERIAL=STEEL
      0.3045,       5
*SHELL SECTION, ELSET=PIPE, MATERIAL=STEEL
      0.406,       5
**
** 90 is hoop and 0 is axial for fiber orientation
**
*SHELL SECTION, COMPOSITE, ELSET=COMP_COR, OFFSET=0.300
0.100, 1, CARBON, 90.0
0.100, 1, CARBON, 90.0
*SHELL SECTION, COMPOSITE, ELSET=HALFSHL, OFFSET=0.500
0.050, 1, E-GLASS, 90.0
0.100, 1, CARBON, 0.0
0.100, 1, CARBON, 0.0
0.100, 1, CARBON, 0.0
0.100, 1, CARBON, 0.0
0.100, 1, CARBON, 90.0
0.050, 1, E-GLASS, 90.0
**
** E-glass material
**
*MATERIAL, NAME=E-GLASS
*ELASTIC, TYPE=LAMINA
      2.0E+6, 2.0E+6, 0.3, 2.0E+5, 385.0, 385.0
**
** Carbon material
**
*MATERIAL, NAME=CARBON
*ELASTIC, TYPE=LAMINA
      1.0E+7, 1.0E+6, 0.3, 3.85E+5, 385.0, 385.0
**
** Elastic-plastic steel
**
*MATERIAL, NAME=STEEL
*ELASTIC, TYPE=ISO
      3.E+7,        0.3
*PLASTIC
51000.0, 0.0
74600.0, 0.20
**
```

Figure 20 – Section of ABAQUS input deck for composite material

The shell finite element models used a quarter-symmetry boundary condition. This configuration implies that loading and geometry permits dissection of the structure in two planes. **Figure 21** is a schematic diagram showing the overall layout for the model. The two symmetry planes are clearly identified in this figure. Also shown in this figure is a close-up view of the section of the carbon half-shell elements. Noted in this figure is the region where the calculated stresses and strains were extracted for both the composite material (i.e. varying layers) and steel.

Also shown are the boundary conditions. At the center symmetry plane of the model (left hand side of the figure) the pipe/composite is free to move vertically but restrained in the longitudinal direction. On the right hand side of the model a simply-supported condition is invoked where the pipe is free to translate axially. This configuration also works well in modeling a four-point simply-supported load condition that will be discussed in a later section.

In terms of modeling the geometry for the pipe and composite, there are several noteworthy points.

- The corroded section of the pipe is modeled by reducing the thickness of the shell elements in the corroded region (**RED** region in **Figure 21**).
- The composite spans 30 inches axially (60 inches if a full symmetry condition had been modeled). To model the composite material, a duplicate set of elements are created that reside on top of the elements used to model the steel. These sets of elements share common nodes, but permit the application of unique material properties for each element set. What is not permitted with this configuration is the ability to assess the effect of disbonding between the steel and composite.

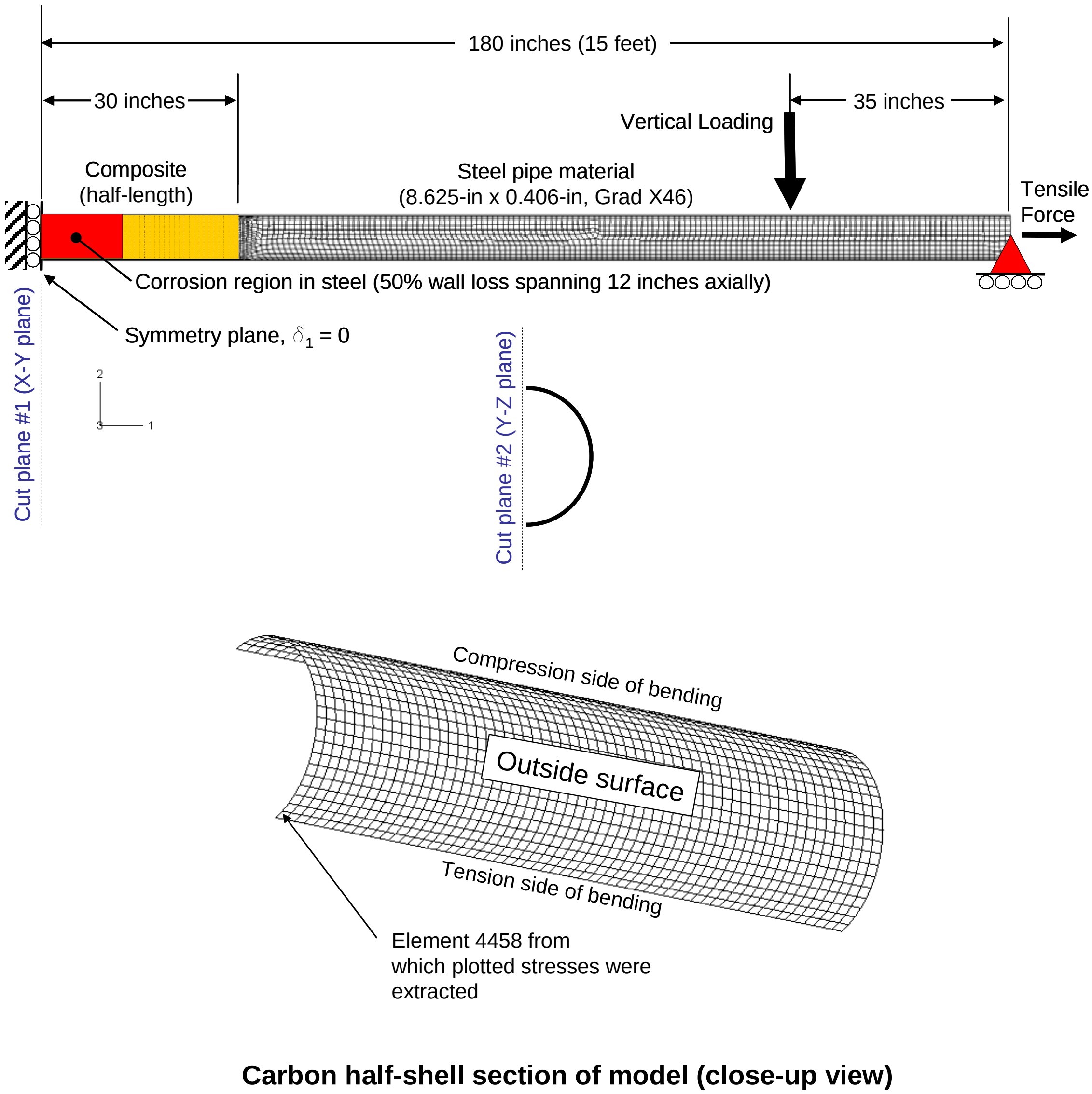

Figure 21 - Schematic diagram showing layout for shell model
(the shell model used for both internal pressure and bending load assessments)

To assess performance of the repair subject to internal pressure loads, internal pressure in the model was incrementally increased to determine the plastic analysis collapse load. **Figure 22** provides data from the finite element model including strains in the steel for reinforced and unreinforced conditions, as well as results for a new pipe with no reinforcement. As stated previously, the objective of any composite repair is to restore the damaged section of pipe back to the original pre-damage state. For purposes of this discussion, the FEA results for the base pipe in its uncorroded state represent this condition (green line). From this data the design load can be calculated. As noted in the figure, the following data points are determined:

- Plastic analysis collapse load of 5,700 psi
- Design load (pressure) of 2,850 psi (design margin of 2.0 on the collapse load)
- At the design condition, the maximum principal strain is 0.169 percent

The data set and curve that are of most interest are those pertaining to the pipe beneath the repair in the corroded region (gold curve). The acceptability of the design is based on whether or not the data fall within the acceptable range. As noted in **Figure 20**, the strains in the pipe beneath the carbon reinforcement are less than the maximum conditions permitted (as noted by the yellow translucent triangle region in this figure).

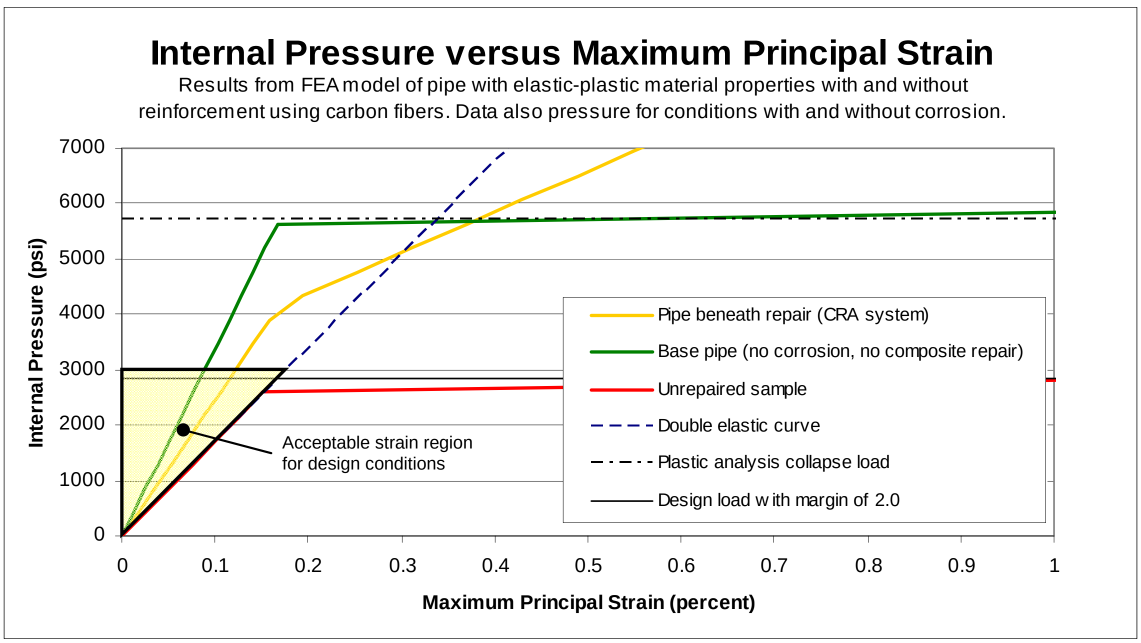

Figure 22 – Pressure loading versus maximum principal strain
(carbon repair with 0.200-inch thick hoop | 0.400-inch axial | 0.100-inch hoop layers)

Design Verification: Tension Loads

The primary focus in the optimization process has been providing reinforcement for the combined pressure, tension, and bending loads. However, in order for the repair to function as intended, it must be of sufficient length to maintain integrity of the interface bond between the repair and steel This can be achieved by ensuring that the length of the repair is long enough so that the force required to damage the adhesive bond is greater than the lap shear load that is then multiplied by an appropriate design factor (e.g. SF = 3 [56]).

Unlike the design verification discussions associated for internal pressure and bending loads that will follow which included calculations based on classical mechanics and finite element methods, the tension load verification only considered classical mechanics. Classical mechanics is sufficient because the response of the adhesive is linear and directly related to the shear strength of the adhesive and bond area of the adhesive.

Figure 23 graphically shows the adhesive bond lengths in question. For conservatism, it can be assumed that the steel does not contribute to axially restraining the repair and that the adhesive bond is responsible for maintaining integrity of the joint. The following relation is used to calculate the minimum required bond length.

$$L \geq \frac{F}{\pi \cdot D \cdot \tau_{adhesive}} \cdot SF$$

where:

L	Length of repair on each side of the defect, minimum (inches)
F	Tensile force (lbs)
D	Nominal outside diameter of pipe (inches)
$t_{adhesive}$	Adhesive lap shear strength (psi)
SF	Safety factor against failure of adhesive bond layer

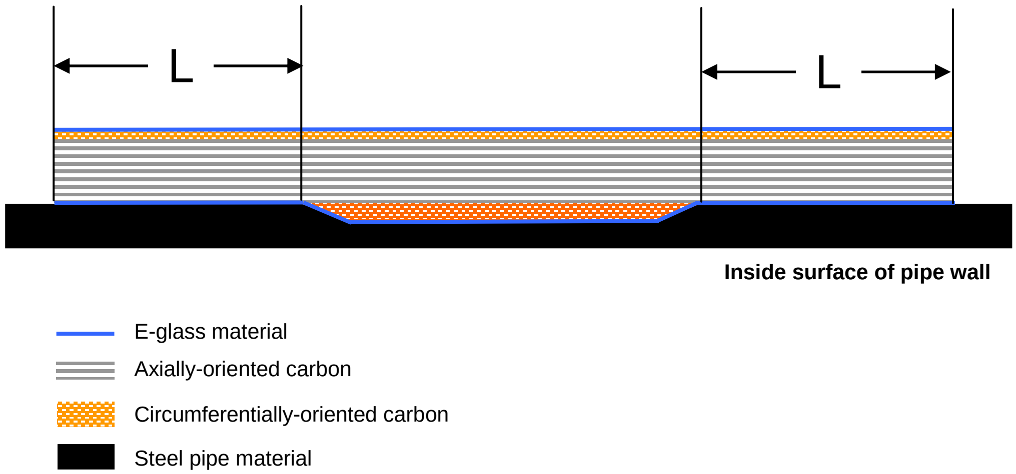

Figure 23 – Required adhesive lengths

For the reinforcement design on the 8-inch pipe, the following calculation is made. It is assumed that the adhesive has short-term lap shear strength of 1,000 psi [21] with an imposed safety factor of 3 to account for long-term degradation. In testing an axial tension of 145,000 was applied.

$$L \geq \frac{145{,}000\ lbs}{\pi \cdot 8.625\ inches \cdot 1000\ psi} \cdot 3.0 = 16.1\ inches$$

The originally-postulated length of the repair was 60 inches. Assuming a corrosion length of 24 inches, the resulting tie-in length with the base (non-corroded portion) of the base pipe is 36 inches. When this is divided by 2, the available adhesive length, *L*, is 18 inches. This length exceeds the minimum required value of 16.1 inches.

Design Verification: Bending Loads

Having established the thickness of the inner carbon hoop fibers, the next phase of the optimization process was to determine the required thickness of the carbon fibers oriented axially to increase the bending rigidity of the corroded section of pipe. Using an approach to the one presented previously for increasing hoop strength, the equations of equilibrium and compatibility of strain are used to estimate the required thickness of the axial fibers subject to bending loads. At the conclusion of this discussion based on classical mechanics, the finite element limit analysis results are presented.

Assessment of Bending Loads Based on Classical Mechanics

The objective in bending is for the reinforced region of the riser to be able to withstand a bending moment equal to the load required to induce a plastic hinge in an uncorroded pipe. This means that when loaded, the strain in the steel region of the riser must be less than a designated strain limit. For this particular discussion, the stress associated with a plastic hinge is set equal to 1.5 times the yield strength (based on the section modulus for a local pipe wall section). From this condition, the moment capacities of the corroded steel and reinforcing composite material are combined algebraically as shown in the following relation.

$$M_{plastic} = M_{steel} + M_{composite}$$

The above equation can also be expressed as,

$$1.5 \cdot \sigma_{yield} \cdot Z = [\sigma \cdot Z]_{steel} + [\sigma \cdot Z]_{composite}$$

where:

σ_{yield} Yield strength of steel (psi)

Z Section modulus (in^3)

σ Bending stress in corroded steel or composite (psi)

Recognizing that the section modulus for the pipe can be expressed as $\pi R^2 t$, a final simplification is made. Note that specific subscripts are added to designate which steel thicknesses (i.e. corroded and uncorroded) should be used.

$$1.5 \cdot \sigma_{yield} \cdot t_{nom} = \left[\sigma \cdot t_{corroded}\right]_{steel} + \left[\sigma \cdot t\right]_{composite}$$

The only unknown is the thickness of the composite material; thus permitting the minimum design geometry can be solved. For additional conservatism, limits of stress are placed on the steel and composite material. For the steel the bending stress is limited to 50 percent of the yield strength[2], while the composite stress is limited to 40 percent of the tensile strength of the material.

$$t_{composite} = \frac{1}{40{,}000\ psi}\left[1.5 \cdot (46{,}000\ psi) \cdot (0.4) - (0.5) \cdot (46{,}000\ psi) \cdot (0.200\ inches)\right] = 0.575\ inches$$

This calculation, based on classical mechanics, was used as the basis for the finite element analysis work and reduced the uncertainty in determining target thicknesses for the axial carbon fibers.

Assessment of Bending Loads Based on Finite Element Methods

As with the design verification to assess internal pressure, the evaluation of the bending loads utilized a model using shell elements. For additional details on the model including geometry, materials, and boundary conditions consult either the previously presented discussion (cf. **Figure 21**) or **Appendix C**.

Because of the complexities associated with the combined stress state for the pressure, tension, and bending case, finite element methods were used to verify the validity of the 0.600-inch axial carbon fiber thickness (minimum thickness of 0.575 inches calculated using classical mechanics). **Figure 24** shows the layout of the CRA system design. The

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[2] ASME B31.4 paragraph 402.3.2(d) of ASME B31.4 states that "The sum of the longitudinal stress due to pressure, weight and other sustained external loadings shall not exceed 0.75 S_A" where S_A cannot exceed 72% SMYS.

finite element analysis was used to vary the thickness of the axially-oriented carbon fibers with thickness levels of 0.005 inches, 0.200 inches, 0.400 inches, 0.600 inches, and 0.800 inches.

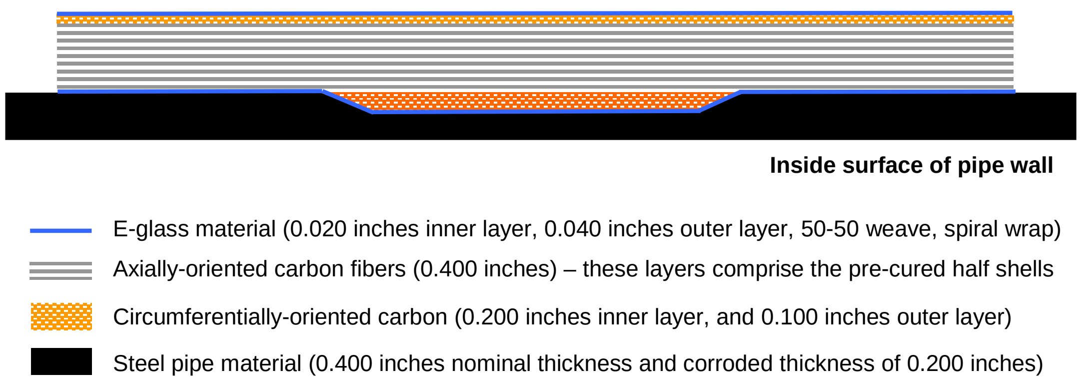


Figure 24 – CRA E-glass/carbon reinforcement system with dimensions

Table 3 provides the results for the four different reinforcement geometries that were modeled. There is a significant amount of data presented in this table; however, the primary objective is to review the calculated stresses and strains relative to the design limits considering four different axial carbon fiber thickness levels (i.e. 0.005, 0.20, 0.40, and 0.60 inches).

To fully appreciate the information provided in **Table 3**, it is necessary to compare the calculated stresses and strains relative to specific design limits. Design limits for the pressure, tension, and bending load case are needed for the following:

- Strain limit on corroded steel beneath the composite repair
- Strain limit on the axial and hoop carbon fibers

Table 3 – Summary of results for design conditions

(2,887 psi internal pressure | 145 kips axial tension | 49.1 kip-ft bending moment)

Industrial Grade Carbon Material						
carbon_a005_h100.inp	**10 Msi Carbon: 0.200-in hoop | 0.005-in axial | 0.100-in hoop**					
Layer	**Material**	**Thickness**	**h/t**	**h/t (sum)**	**e11**	**e22**
0	steel	0.2	0.396	0.000	0.512	
1	Carbon hoop	0.1	0.198	0.594	0.104	0.486
2	Carbon hoop	0.1	0.198	0.792	0.127	0.495
3	Carbon axial	0.005	0.010	0.802	0.500	0.140
4	Carbon hoop	0.1	0.198	1.000	0.152	0.505
carbon_a200_h100.inp	**10 Msi Carbon: 0.200-in hoop | 0.200-in axial | 0.100-in hoop**					
Layer	**Material**	**Thickness**	**h/t**	**h/t (sum)**	**e11**	**e22**
0	steel	0.2	0.286	0.000	0.188	
1	Carbon hoop	0.1	0.143	0.429	0.086	0.171
2	Carbon hoop	0.1	0.143	0.571	0.090	0.175
3	Carbon axial	0.1	0.143	0.714	0.178	0.093
4	Carbon axial	0.1	0.143	0.857	0.182	0.096
5	Carbon hoop	0.1	0.143	1.000	0.099	0.186
carbon_a400_h100.inp	**10 Msi Carbon: 0.200-in hoop | 0.400-in axial | 0.100-in hoop**					
Layer	**Material**	**Thickness**	**h/t**	**h/t (sum)**	**e11**	**e22**
0	steel	0.2	0.222	0.000	0.145	
1	Carbon hoop	0.1	0.111	0.333	0.089	0.125
2	Carbon hoop	0.1	0.111	0.444	0.088	0.128
3	Carbon axial	0.1	0.111	0.556	0.131	0.087
4	Carbon axial	0.1	0.111	0.667	0.134	0.087
5	Carbon axial	0.1	0.111	0.778	0.137	0.086
6	Carbon axial	0.1	0.111	0.889	0.139	0.085
7	Carbon hoop	0.1	0.111	1.000	0.084	0.142
carbon_a600_h100.inp	**10 Msi Carbon: 0.200-in hoop | 0.600-in axial | 0.100-in hoop**					
Layer	**Material**	**Thickness**	**h/t**	**h/t (sum)**	**e11**	**e22**
0	steel	0.2	0.182	0.000	0.134	
1	Carbon hoop	0.1	0.091	0.273	0.090	0.108
2	Carbon hoop	0.1	0.091	0.364	0.089	0.111
3	Carbon axial	0.1	0.091	0.455	0.114	0.089
4	Carbon axial	0.1	0.091	0.545	0.116	0.088
5	Carbon axial	0.1	0.091	0.636	0.118	0.087
6	Carbon axial	0.1	0.091	0.727	0.121	0.087
7	Carbon axial	0.1	0.091	0.818	0.124	0.086
8	Carbon axial	0.1	0.091	0.909	0.126	0.085
9	Carbon hoop	0.1	0.091	1.000	0.084	0.129

Notes:

(blue)	Steel material in model (corroded thickness of 0.200 inches)
(yellow)	Hoop-oriented carbon layers
(orange)	Axial-oriented carbon layers

(1) Strain for Pressure, Tension, and Bending is either E11 or EP1 (maximum principal)

(2) Stress for carbon is S11 and for steel is von Mises equivalent stress

(3) E11 and S11 for the carbon are in material coordinates

(4) Units for stress are in **ksi** and strain is expressed as **percentage (%)**

(5) All presented results assume that 0.200-inch hoop material in corroded region

(6) *h* corresponds to layer thickness and *t* is the total thickness of the pipe wall and repair system

The following discussion provides details on how design limits were determined.

Figure 25 shows data for the design load case for the CRA system considering 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 25** 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**

The data presented in **Table 3** are strains as obtained from the finite element analysis that included internal pressure, tension, and bending loads at the design load condition (2,887 psi internal pressure, 145,000 lbs axial tension, and bending moment of 49.1 kip-feet (or bending load of 16.8 kips)). Strains in the composite material parallel and perpendicular to the primary fiber direction, as well as strains in the steel beneath the reinforcement as presented. The most significant observation is that it is possible to use an axial carbon fiber thickness less than 0.575 inches, the value originally calculated using classical mechanics. The discussions below provide details on how the final geometry of the composite geometry was determined.

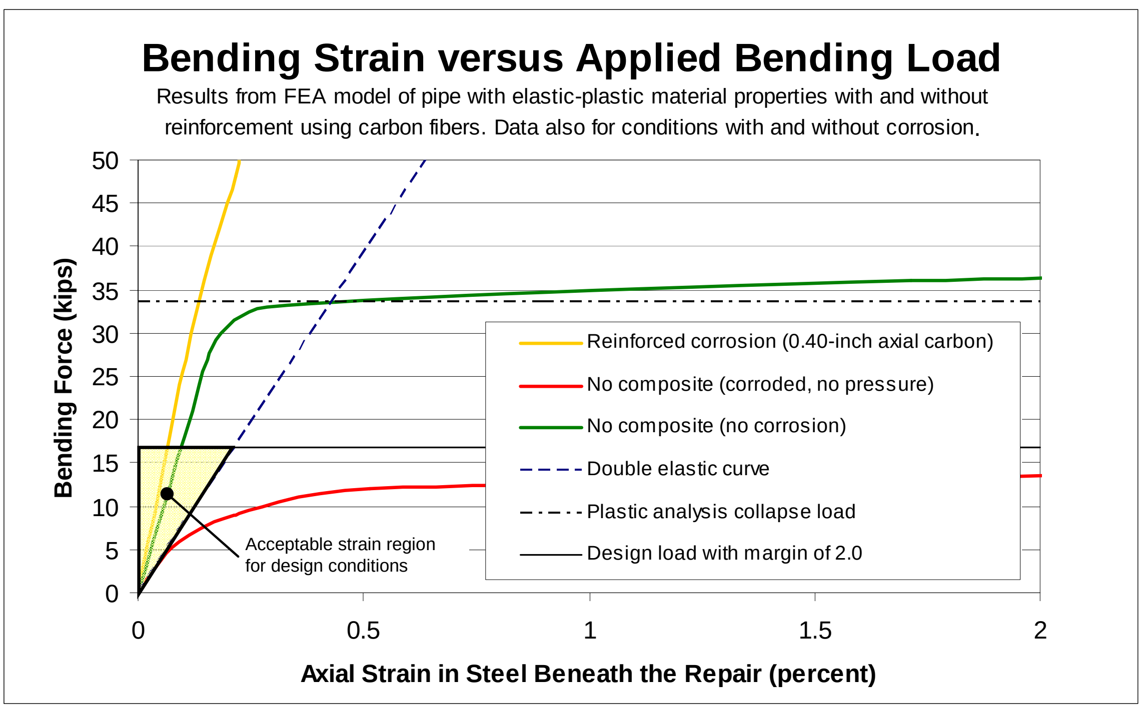


Figure 25 – Bending force versus axial strain in pipe
(carbon repair with 0.200-inch thick hoop | 0.400-inch axial | 0.100-inch layers)

Table 3 presents a comprehensive overview of the calculated results for composite repair configurations considered in this study. The range of half shell thickness values considered in this study are based on the calculations based on classical mechanics that showed a minimum thickness of 0.40 inches was required. Included in this table are the respective ABAQUS input filenames. As noted in the table, the filename: *carbon_a500_h100.inp* includes a designation of the orientation and thickness of each composite layer:

- Inside hoop-oriented layer thickness of 0.20 inches (inside of the carbon half shell)
- 0.005-inch thick axial carbon half shell
- Outside hoop-oriented layer thickness of 0.100-inches

In the table the layers are color-coded with BLUE for the steel material beneath the repair, YELLOW as hoop-oriented carbon-epoxy layers, and ORANGE as the axially-oriented carbon layers. It should be noted that the results for the E-glass material are not included in **Table 3**, although E-glass was included in the finite element model (0.020 inches on the inner surface of the repair and 0.040 inches on the outer surface as shown in **Figure 24**). The only variation among the four evaluated composite repair systems was the thickness of the axially-oriented carbon fiber layers. These layers comprise the geometry for the carbon half shells of the composite repair design evaluated in this study.

The first geometry that was analyzed, *carbon_a500_h100.inp*, had minimal axial reinforcement with the 0.005-inch thick layer of axial epoxy-impregnated carbon fibers and was not expected to provide adequate rigidity for the imposed bending loads. This case basically represents the condition where no axial carbon fiber reinforcement is included. The resulting strain in the steel was 0.51 percent and the maximum strain occurred in the carbon fiber hoop layer near the corrosion region with a magnitude of 0.495 percent. Both of these values exceeded the design strain limits and demonstrate hat it is essential for a minimum thickness of composite materials to be installed axially.

When this does not occur, the integrity of the reinforced steel is compromised, leading to the potential failure of the riser.

The same process of evaluation was repeated for the three other composite repair systems where the thickness of the axially-oriented carbon fibers was increased. As observed in **Table 3**, all resulting strains in the steel and composite layers were less than allowable values. As a point of reference, consider the axial strains calculated for the corroded steel beneath the composite reinforcement. The percent reductions in strain in the steel are presented below with the 0.005-inch thick half-shell as the base case.

- 0.005-inch thick half-shell ε = 0.512% (base case)
- 0.20-inch thick half-shell ε = 0.188% (63.3% reduction)
- 0.40-inch thick half-shell ε = 0.145% (71.7% reduction)
- 0.60-inch thick half-shell ε = 0.134% (73.8% reduction)

In addition to strains in the steel, results are also presented for strains in the composite material functions of the carbon half-shell thickness (ORANGE cells in **Table 3**). Increasing the half-shell thickness reduces strains in the axially-oriented fibers. In developing the CRA system, it is important strains in the carbon half-shell not exceed 0.40 percent. The strain in the carbon half shell is a function of its thickness. Consider strains (e11) calculated on the outer surface of the carbon half-shell.

- 0.005-inch thick half-shell e11 = 0.500% (base case)
- 0.20-inch thick half-shell e11 = 0.182% (63.3% reduction)
- 0.40-inch thick half-shell e11 = 0.139% (72.2% reduction)
- 0.60-inch thick half-shell e11 = 0.126% (74.8% reduction)

In addition to reducing strains in the fiber direction (e11), it is also observed that strain values perpendicular to the axially-oriented fibers (e22) are reduced with an increase in the carbon half-shell thickness. This is especially noted for the circumferentially-oriented carbon fibers closest to the corroded steel as shown below.

- 0.005-inch thick half-shell e22 = 0.486% (base case)
- 0.20-inch thick half-shell e22 = 0.171% (64% reduction)
- 0.40-inch thick half-shell e22 = 0.125% (74.3% reduction)
- 0.60-inch thick half-shell e22 = 0.108% (74.8% reduction)

The results presented up to this point in **Table 3** have only considered axial stresses. The changes in the circumferentially-oriented fibers are less pronounced when considering increases in the carbon half-shell. However, it is noted that once the thickness of the half-shell is increased from 0.005 inches to 0.20 inches, strains are reduced by 29.1% and 34.9% for the inner and outer circumferential layers, respectively.

Figure 26 is a plot showing data from the finite element model for the four (4) different axial thickness values presented in **Table 3** (i.e. 0.005, 0.20, 0.40, and 0.60 inches). From the results plotted in this figure, the following observations are made. It is noted once again that the plotted data correspond to design conditions that include internal pressure (2,887 psi), axial tension (145 kips), and bending (49.1 kip-ft).

- Increasing the thickness of the carbon half-shells reduces strain in both the corroded steel and composite materials. As noted in this figure, a significant difference in strain reduction for both the pipe and composite results when the thickness of the half-shell is increased from 0.005 inches to 0.200 inches.
- Increasing the thickness of the carbon half-shell to a value greater than 0.200 inches does reduce the calculated strains in both the steel and composite materials, although the rate of strain reduction as a function of carbon thickness is less pronounced than observed in the half-shell thickness increase from 0.005 inches to 0.200 inches.

- The strain limits for the carbon material and steel are 0.4% and 0.214%, respectively (as presented previously). These limits are noted in the figure. The selection of the minimum required thickness of the half-shell is determined by ensuring that the calculated strains are less than the strain limits.
- When considering strain in the carbon fiber material, strains below the strain limit of 0.4% are calculated when the thickness of the half-shell is greater than 0.075 inches (based on the intersection of the curves corresponding to strains in the carbon fibers and strain limit).
- In terms of strain in the corroded steel, strains that remain below the strain limit of 0.214% occur when the thickness of the half-shell is greater than 0.200 inches.
- From the above two bullets it is clear that the limiting case is the strain limit of the steel. Consequently, the thickness of the carbon half-shells should not be less than 0.20 inches.

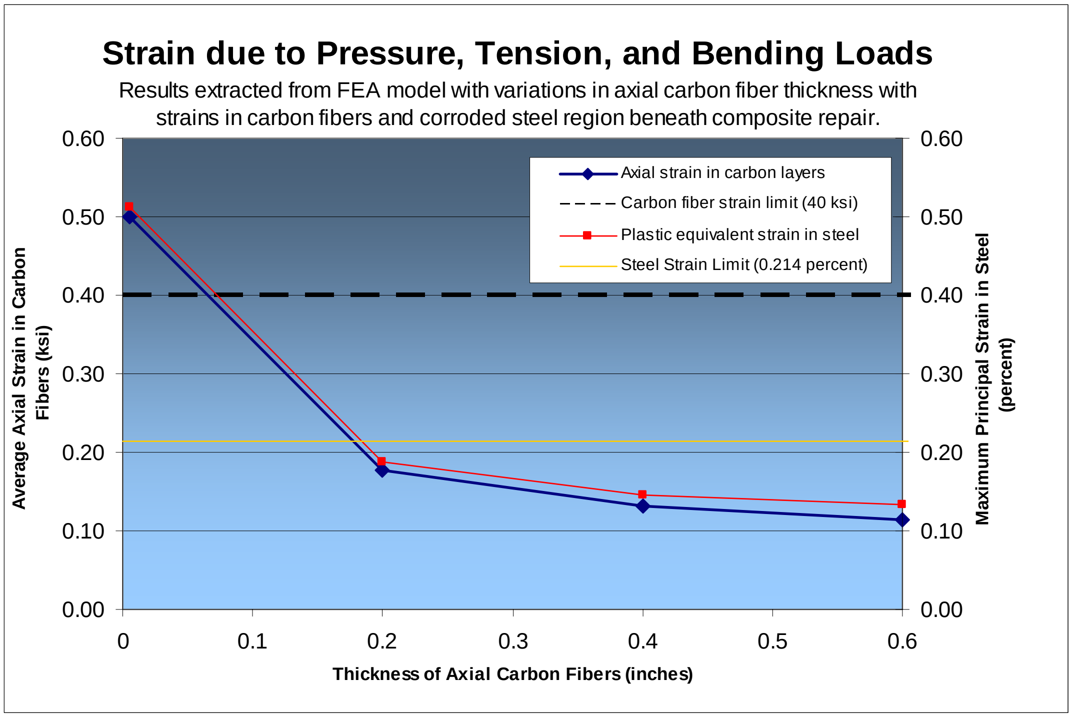
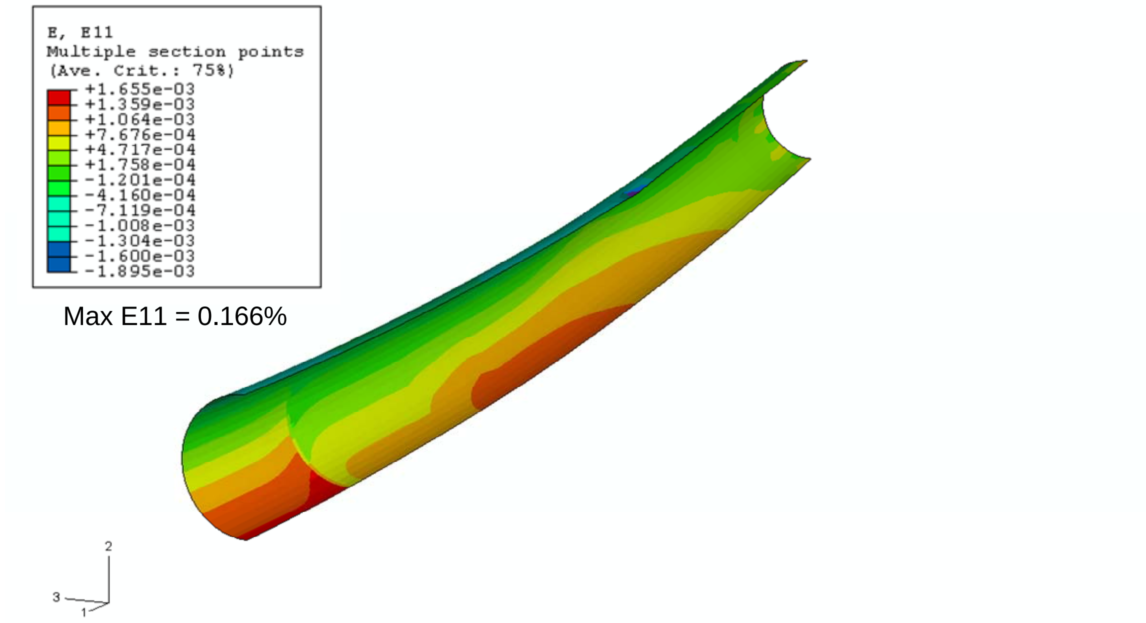


Figure 26 – Results for varying axial carbon thicknesses relative to design limits
(results for the four different FEA models at design conditions)

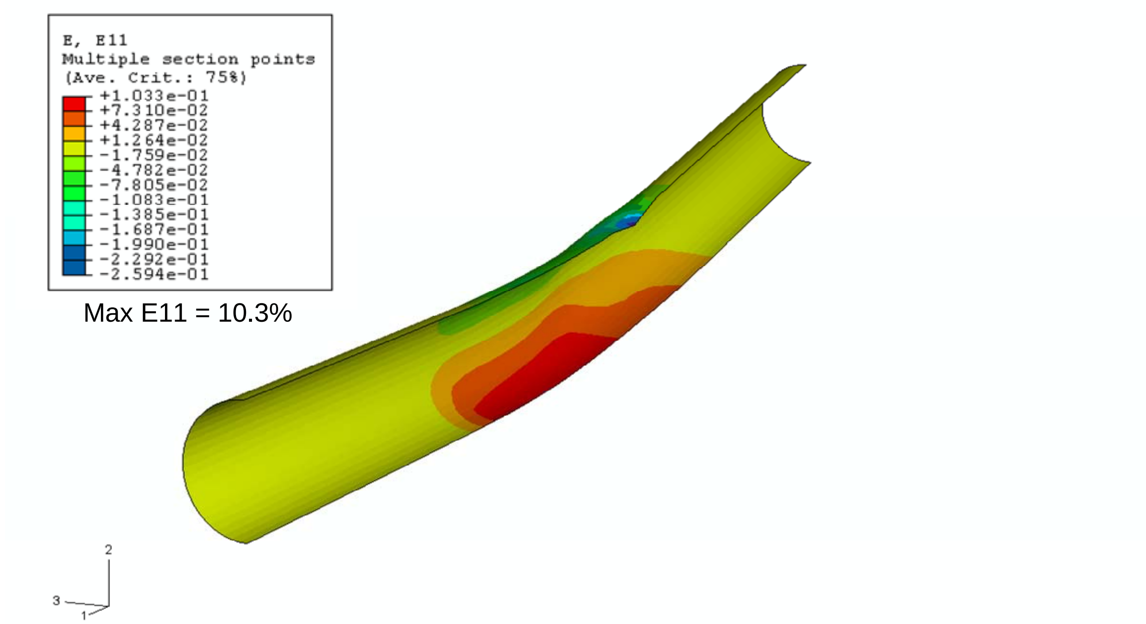
Although one could argue the acceptability of the system having an axial thickness of only 0.20 inches, the selected geometry for the final composite repair system employed an axial thickness of 0.40 inches. This geometry was used to construct the carbon half shells for the prototype testing. The primary reason for selecting the thicker composite configuration is primarily to account for manufacturing issues. The issues include, but are not limited to, variations in fiber volume fraction, carbon fiber layer thickness variations, misalignment of fibers during lay-up, and the presence of residual stresses during curing. By increasing the thickness of the repair to at least 0.20 inches, the capacity of the composite repair to reinforce the steel and reduce strains is improved.

Figure 27 shows the maximum principal strain in the steel at loads equal to the design and plastic collapse 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.



Design load conditions (bending moment of 49.1 kip-ft)



Plastic collapse load conditions (bending moment of 98.1 kip-ft)

Figure 27 – Axial strains in steel at design and plastic collapse conditions
(refer to **Figure 21** for details on finite element model geometry)

Concluding Comments on Optimized Design

Considering the calculations that have been presented, the final dimensions include the following in terms of the carbon fiber material:

- Circumferentially oriented carbon fibers in an epoxy resin matrix: 0.20 inches internal and 0.10 inches external relative to the half-shell
- Axially-oriented carbon fibers: 0.40 inches (associated with half shells)
- Carbon half shells that are 60 inches long

Mechanics of Composite Repairs: Unique Focus Topics

To better understand and anticipate the performance of the composite repair, several investigations were conducted using finite element methods to assess the behavior of the composite repair under various conditions. In general, these studies involved some type of parametric analysis where the range of a particular independent variable was modified to assess its effect on the performance of the composite repair. The following studies were conducted:

- Compressive radial stresses during pressurization
- Effects of taper on radial and axial stresses
- Effects of cooling on “free stress” state in composite and results residual stress state
- Effects of disbonding on stress distribution

Compressive Radial Stresses During Pressurization

One concern in using composite materials is the potential for delamination on the outer edges of the repair. As will be demonstrated, the ability of the repair to provide adequate reinforcement is related to its ability to adhere to the pipe. If a compressive stress exists between the inside surface of the repair and the outer pipe surface, the potential for delamination is minimized.

To numerically demonstrate that a compressive stress exists, a model was constructed that integrated axisymmetric continuum elements for the steel and axisymmetric shell elements to represent the composite material. **Figure 28** shows the layout for this particular model where the pipe is modeled using carbon steel with elastic material properties. The material properties used in the axisymmetric analysis are the same as those used previously in the shell analysis (e.g. composite lay-up and elastic-plastic steel properties). The epoxy-impregnated carbon fiber layers are oriented axially and have an elastic modulus of 10 million psi. The thickness and geometry for the modeled components are shown in this figure. An internal pressure of 2,887 psi was applied to the inside surface of the model and the ends of the model were restrained axially as shown in this figure. This boundary condition generates an axial stress that is 30 percent of the hoop stress due to Poisson's effect, compared to 50 percent for a capped end sample.

Refer to **Figure 28** for details on the axisymmetric model. In this particular analysis the steel was modeled using ABAQUS' CAX4 axisymmetric elements; however, the composite material was modeled using the SAX1 axisymmetric shell elements. These axisymmetric shells are two-noded elements placed on the outside surface of the steel. They contribute stiffness and strength in the same manner as the two-dimensional shell elements and the "per layer" thickness and orientation can be changed. In post-processing it is possible to extract in-plane hoop and axial stresses; however, unlike their two-dimensional counterparts, no variation in results is permitted in the circumferential direction. Also shown in **Figure 28** are the loading and boundary conditions that were used. The ends of the pipe are restrained axially, implying that axial stresses in the model will be developed based on Poisson's effect as opposed to a specified pressure end load. For the problem at hand this an acceptable approach.

The only loading directly applied to the axisymmetric model was an internal pressure of 2,887 psi. No consideration for corrosion was made, nor any attempt made to determine the lower bound collapse load by incrementally increasing the pressure to induce failure.

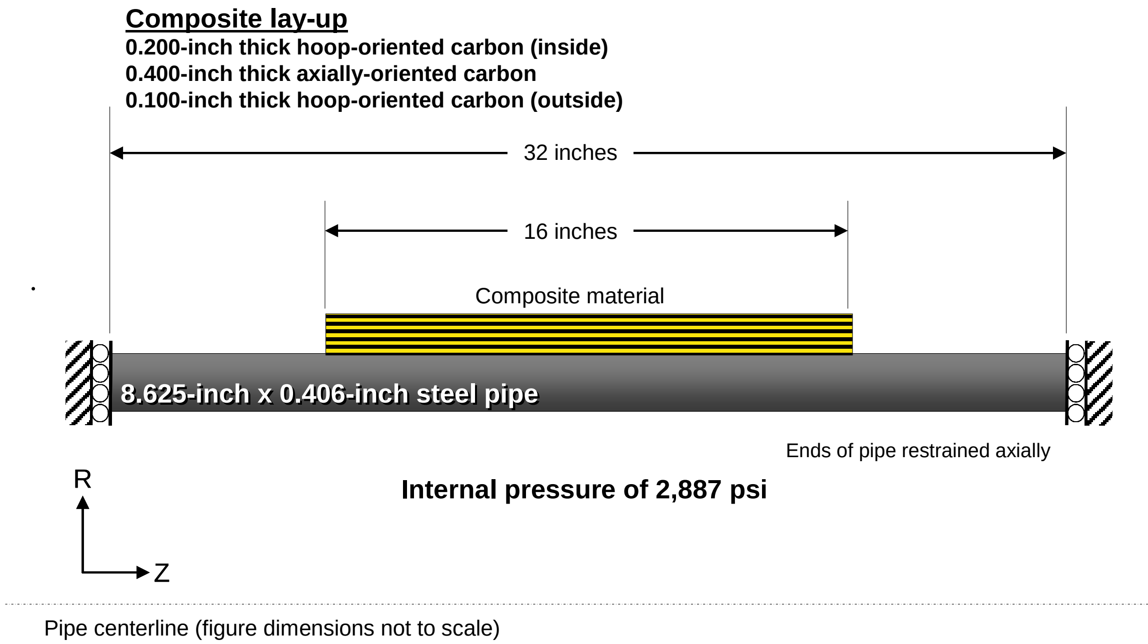


Figure 28 – Axisymmetric FEA model used to assess compressive stresses

The material properties used for the steel and composite layers in the axisymmetric model are the same as those used previously in the shell model (cf. **Figure 20**). The steel was modeled using an elastic-plastic material model with yield and ultimate tensile strengths of 51.0 ksi and 75.6 ksi, respectively. The carbon layers was modeled using lamina properties with elastic modulii of 10 x 10^6 psi and 1 x 10^6 psi parallel and transverse to the direction of the uniaxial stitched fibers, respectively.

From the finite element model, radial stresses were extracted at the interface between the steel and composite materials (i.e. outside surface of the pipe). **Figure 29** shows the radial stresses that were extracted from the model. The data plotted from 0 to 1.0 (X-axis) are for results beneath the repair, whereas data from 1.0 to 1.75 are results outside the repair (the 0 position is at the axial center of the model). As demonstrated, a compressive radial stress exists for all regions beneath the composite reinforcement.

Figure 30 is a contour plot showing radial stress in the model. A magnification displacement of 100X is used in this plot.

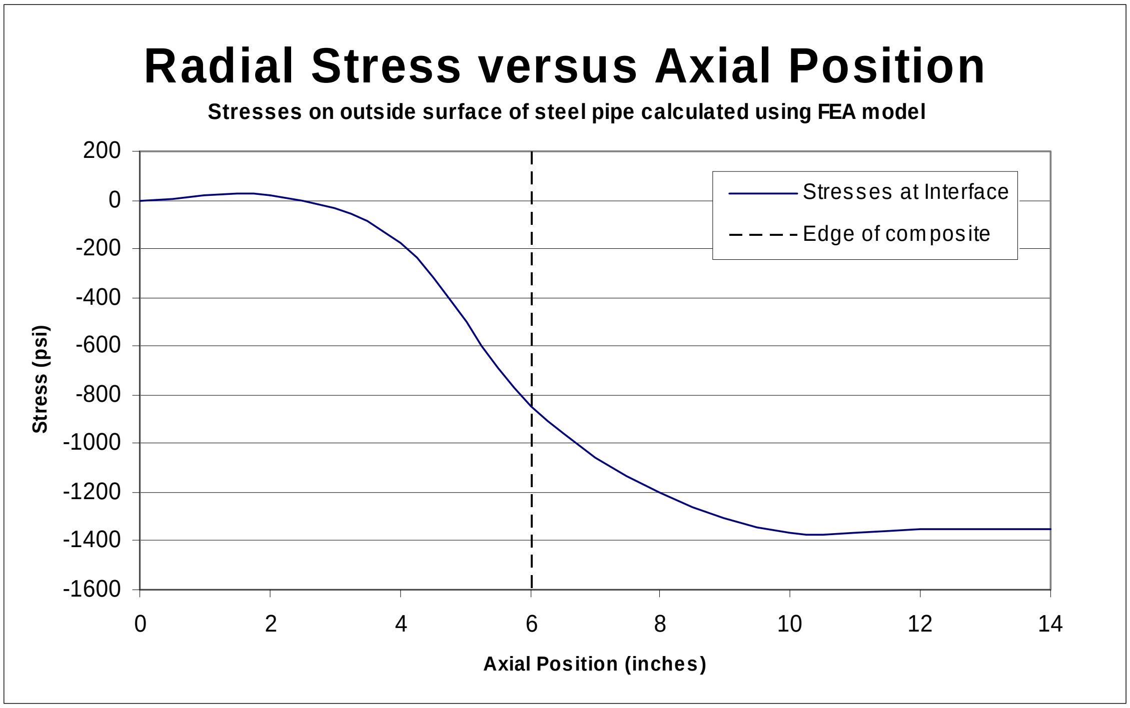


Figure 29 – Radial stress at interface between composite and steel
(Steel thickness of 0.400 inches and composite thickness of 0.200-inch hoop (inside) + 0.400 inches axial + 0.100 inches hoop (outside))

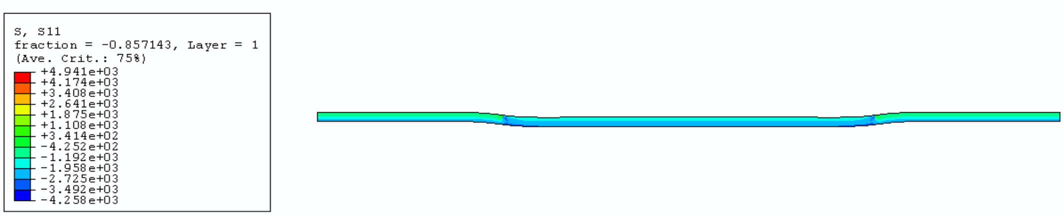


Figure 30 – Radial stresses from the axisymmetric model

Effects of Taper on Radial and Axial Stresses

Once the study used to assess the radial stresses was completed, the subject of tapering the ends of the composite reinforcement was pursued. The fundamental issue was to determine if the presence of a taper in the composite reinforcement significantly reduces stresses in the steel at the outer edges of the reinforcement. Using the same model developed for the radial stress study and discussed in the previous section, a series of finite element models were constructed that varied the level of taper in the geometry of the composite reinforcement. **Figure 31** is a schematic diagram showing how the length was invoked in the model. Taper lengths of 0, 1, 2, and 5 inches were used in the model.

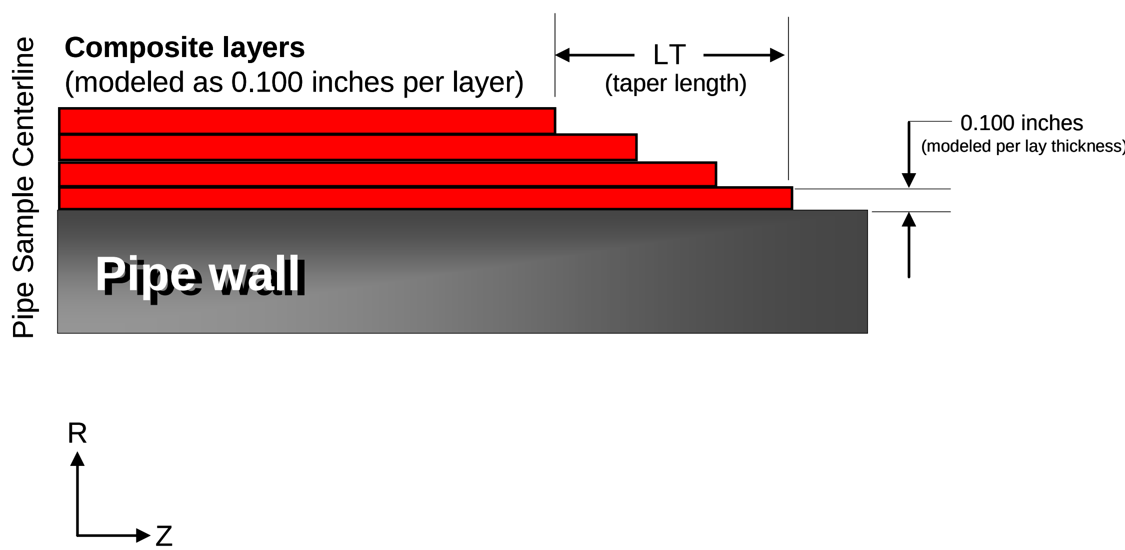


Figure 31 – Schematic showing taper length geometry of taper

Stresses were extracted at the interface between the steel and composite material. The radial, hoop, and axial stresses are plotted in **Figures 32** through **34**, respectively. The ideal stress transition is one that shows minimal difference in the pipe stresses beneath the repair and outside of the repair. In reviewing the plotted data, integration of a taper does not produce sufficient benefits to warrant it as a requirement.

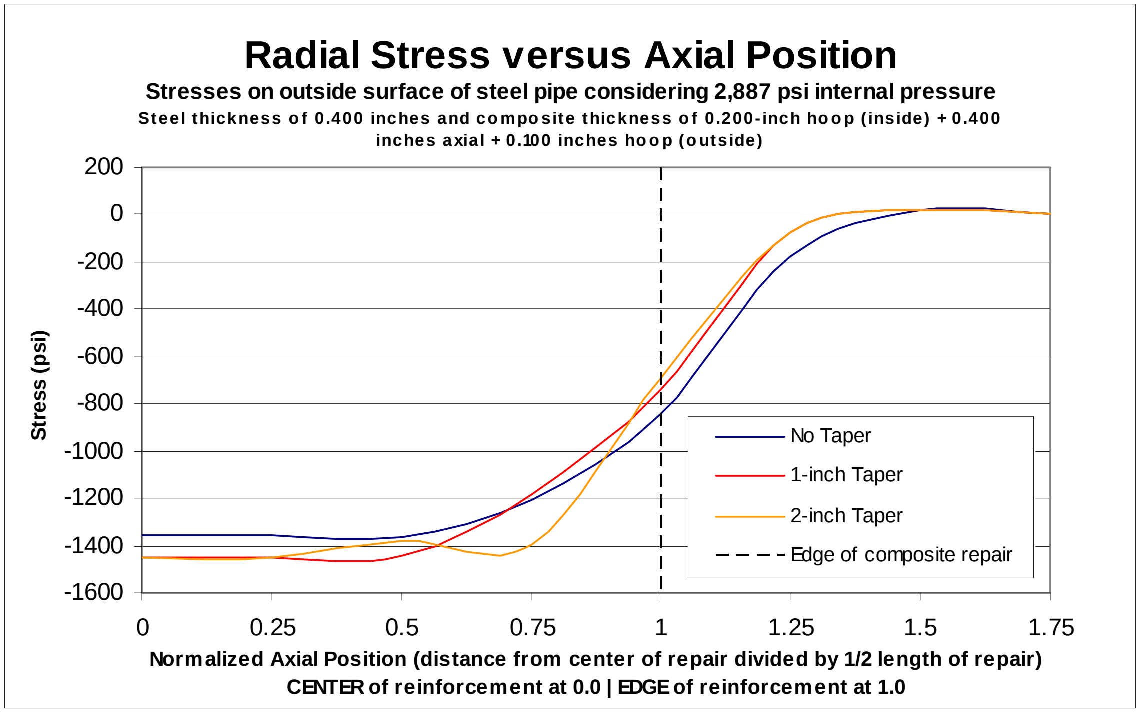


Figure 32 – Radial stresses as a function of taper length

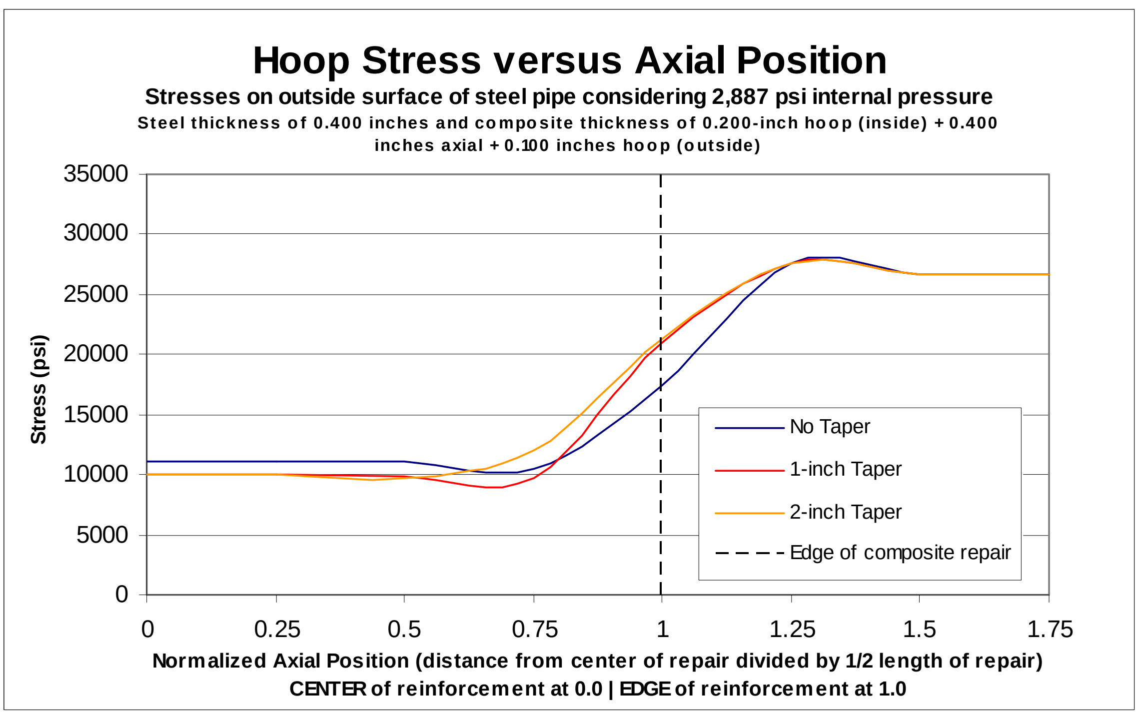


Figure 33 – Hoop stresses as a function of taper length

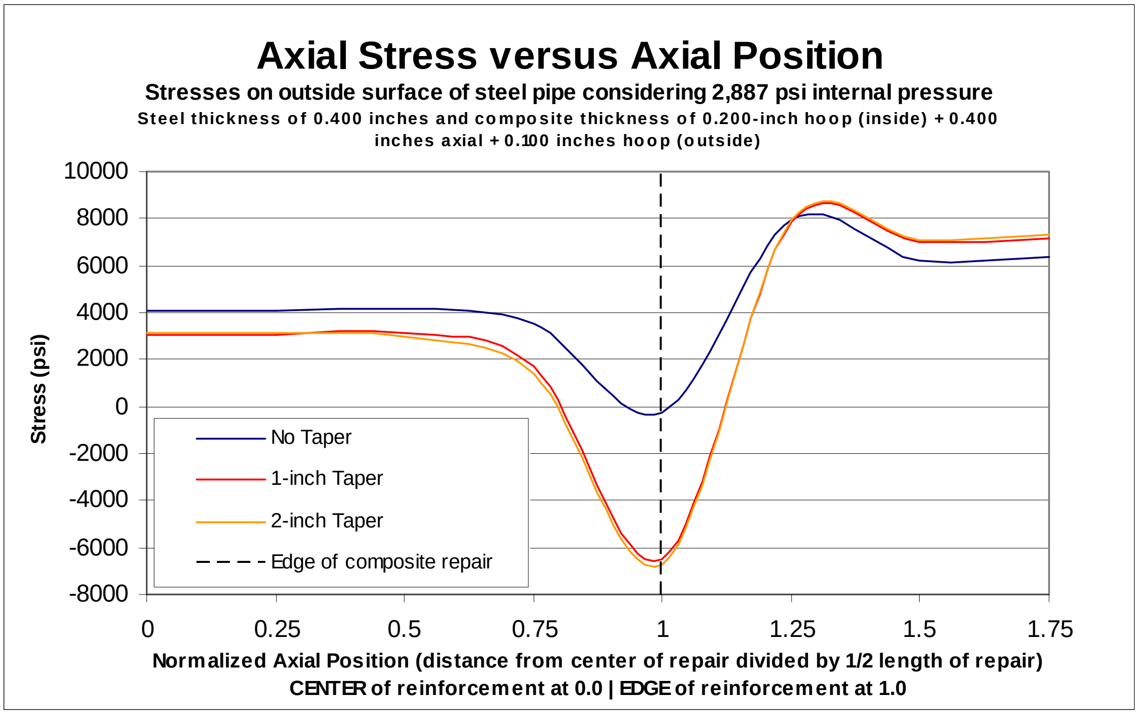


Figure 34 – Axial stresses as a function of taper length

Effects of Cooling on "Free Stress" State in Composite

One issue that has not been addressed by any of the manufacturers in the composite repair industry is the effect of thermal stresses generated during the curing process on the free stress state on the repaired configuration. When the composite repair is installed, it is done so in a wet uncured state. The exothermic reaction of the epoxy resin can cause the temperature of the repair to increase to approximately 200 degrees Fahrenheit (F). As the resin cures, residual stresses are generated in the composite [25]. If the system operates at 70 degrees F, the system actually is loaded at a temperature that is actually lower than the installation temperature. As an example, if the operating temperature is 70 degrees F, the net temperature differential relative to installation is -130 degrees F.

To calculate stresses in the composite repair, a finite element model was constructed. The basis for the model is the same geometry used in the axisymmetric model discussed previously (and shown in **Figure 28**). In the analysis the orthotropic coefficients of thermal expansion were assumed to be $\alpha_{longitudinal} = 0.50x10^{-6}$ in/in °F and $\alpha_{transverse} = 15.0x10^{-6}$ in/in °F. Using these material properties, in conjunction with the elastic modulii, a uniform temperature differential of -130 degrees F was applied to the model. The temperature of the steel was assumed to not change. From the analysis results, stresses and strains were extracted from the model at each of the respective layers for the optimized configuration (0.200 inches inner hoop, 0.400 inches axial, and 0.100 inches outer hoop). The results from this analysis are provided in **Table 4**.

Note that the residual stress state that exists prior to the application of any external loads such as pressure, tension, or bending loads may be considered as a favorable compressive residual stress state. It is also worth noting that the orthogonal nature of both the fiber orientation and material properties (i.e. elastic modulii and coefficients of thermal expansion) generate different stress conditions in the hoop and axially-oriented layers.

Table 4 - Results from thermal stress analysis

(Shell FEA model with *optimized* configuration AND no ΔT in steel)

Layer	Orientation (0.100 inches each)	ΔT = -130°F S11	ΔT = -130°F E11
1	Hoop	-751	-0.0067
2	Hoop	-751	-0.0067
3	Axial	-460	-0.0037
4	Axial	-460	-0.0037
5	Axial	-460	-0.0037
6	Axial	-460	-0.0037
7	Hoop	-751	-0.0067

Effects of Disbonding on Stress Distribution

The ability of the composite repair to reinforce the damaged pipe or riser is directly related to its interaction with the steel. Previous research has shown that when reinforcing corroded pipes subject to only internal pressure, the bond at the interface between the repair and pipe steel is not critical in terms of pre-structural reinforcement. However, when integrating tension and bending loads the interfacial bond between the composite and steel is critical. For this reason, a study was performed to assess the effects of surface bond and regions of delamination on the ability of a composite to reinforce a corroded riser pipe.

The same three-dimensional shell model used in the verification study to assess bending loads was used in this analysis. Once the geometry and boundary conditions were generated for the finite element model, the regions of debonding were selected. There are numerous combinations that could have been chosen; however, to demonstrate general effects only three combinations were selected and listed below.

- Case 1 – outer 18 inches disbonded (Zone A)
- Case 2 – inner 12 inches disbonded (disbonded material on top of corrosion, Zone B)
- Case 3 – no regions of debonding (optimum condition)

Shell elements were used to model both the composite and steel. In regions where bonding between the composite and steel was modeled, the nodes associated with the composite and steel were joined. However, in regions of debonding, contact elements were assigned. The contact elements permit translation of the composite over the steel during loading; however, the composite and steel materials are prevented from penetrating through one another. This modeling technique accurately represents the conditions associated with an actual composite repair. The contact elements provide resistance to internal pressure due to the associated locking mechanism, but minimum resistance is provided when considering tensions loads and possible translation that can occur during the application of bending and axial tension loading. **Figure 35** shows the regions of bonding/disbonding selected for the present study.

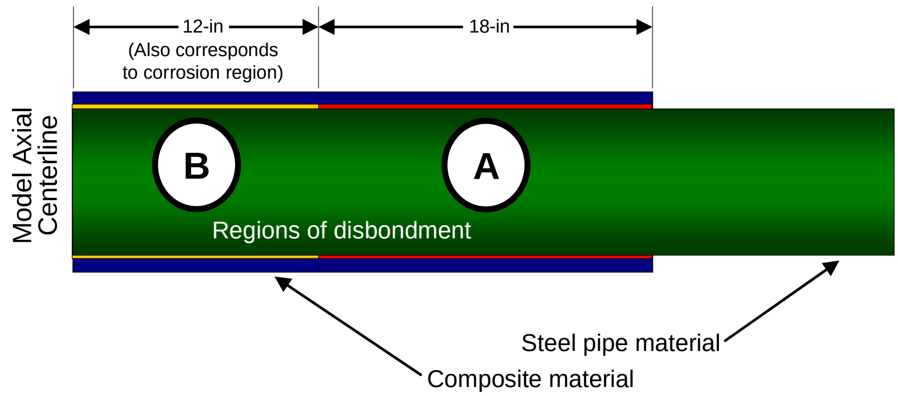


Figure 35 – Zones A and B selected for study on disbonding
(Case 3 assumes NO disbonding)

The loading on the finite element model included an internal pressure of 2,887 psi, an axial tension load of 145 kips, and an applied bending moment up to 175 kip-ft (corresponds to a vertical bending load of 69 kips). This loading condition is sufficient to induce plasticity in the steel as demonstrated by this phase of work as well as preceding efforts. During prior testing efforts, these loading conditions were well beyond design conditions and induced strains sufficient to induce plastic deformation.

From the finite element model strains were extracted in the steel beneath the repair at the axial center of the corrosion. Results are plotted for the three load cases in **Figure 36**. The maximum stress occurs when the outer region disbands (Case 1). It should be noted that the maximum stress beneath the repair occurs in the corroded region; however, the reinforcement contribution from the composite material reduces the stresses to levels below stresses calculated in the base pipe outside the repair.

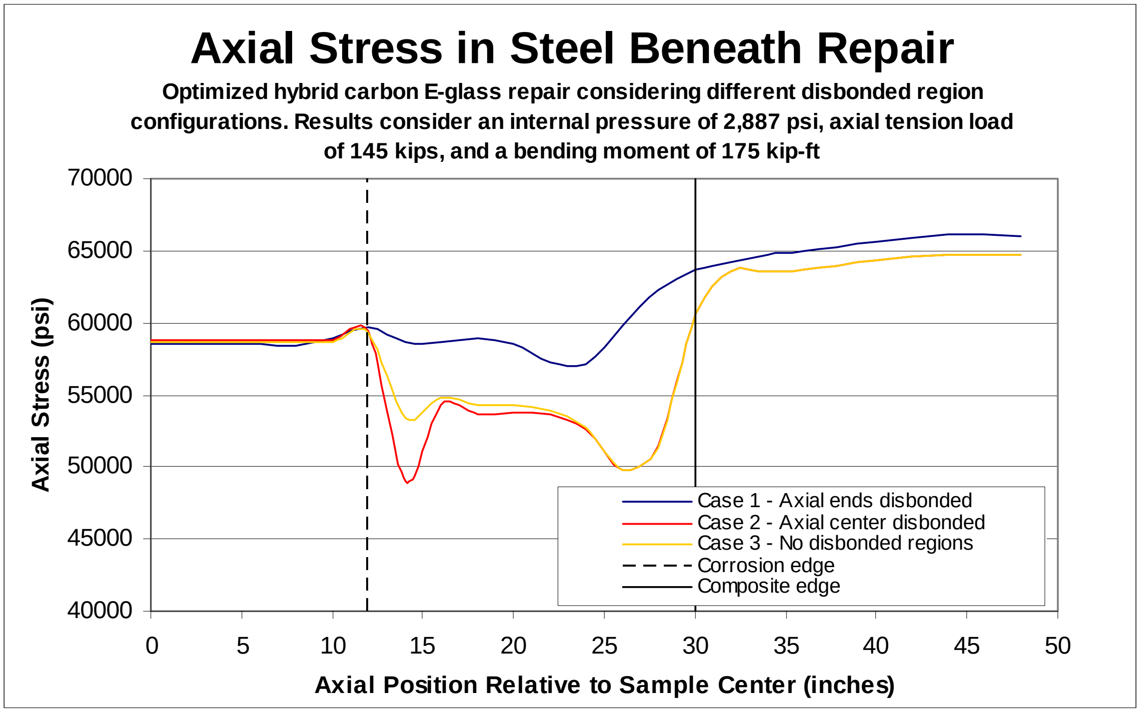


Figure 36 – Strain in the steel considering different debonding configurations

In addition to the extracted stress values, contour plots showing axial strains in the pipe steel and composite material were generated. Contour plots are presented for both the plastic collapse condition and the design condition. The design condition is of primary interest; however, it is important to understand what happens to the reinforced region and the reinforcing composite material once the pipe reaches its ultimate load capacity. Refer to details provided previously in *Strain Limitations for the Repaired Steel Section* on how plastic collapse conditions are determined. For the bending load case, the plastic collapse load (moment) is designated as 98.1 kip-ft.

In terms of strain in the steel pipe, both **Figure 37** and **Figure 38** show that when disbonding occurs toward the outer edge of the repair a significant strain increase in the corroded region occurs. Along the same lines, when debonding occurs in the axial center of the repair (Case 2) equivalent reinforcement is provided as if no disbonding were taking place. Another important observation based on the contour data in **Figure 37** and **Figure 38** is that maximum axial strain occurs when disbonding on the outer edge occurs. This is expected as the steel takes a disproportionate percentage of the load when disbonding occurs. It should be restated that the purpose of the composite repair is to lower strain in the reinforced steel region. Other than optimization of the minimum required thickness and length of the composite material within appropriate design limits, the composite material should be designed to take the maximum level of loading that can safely be applied. Further discussions are provided regarding the shear stress at the steel-composite interface.

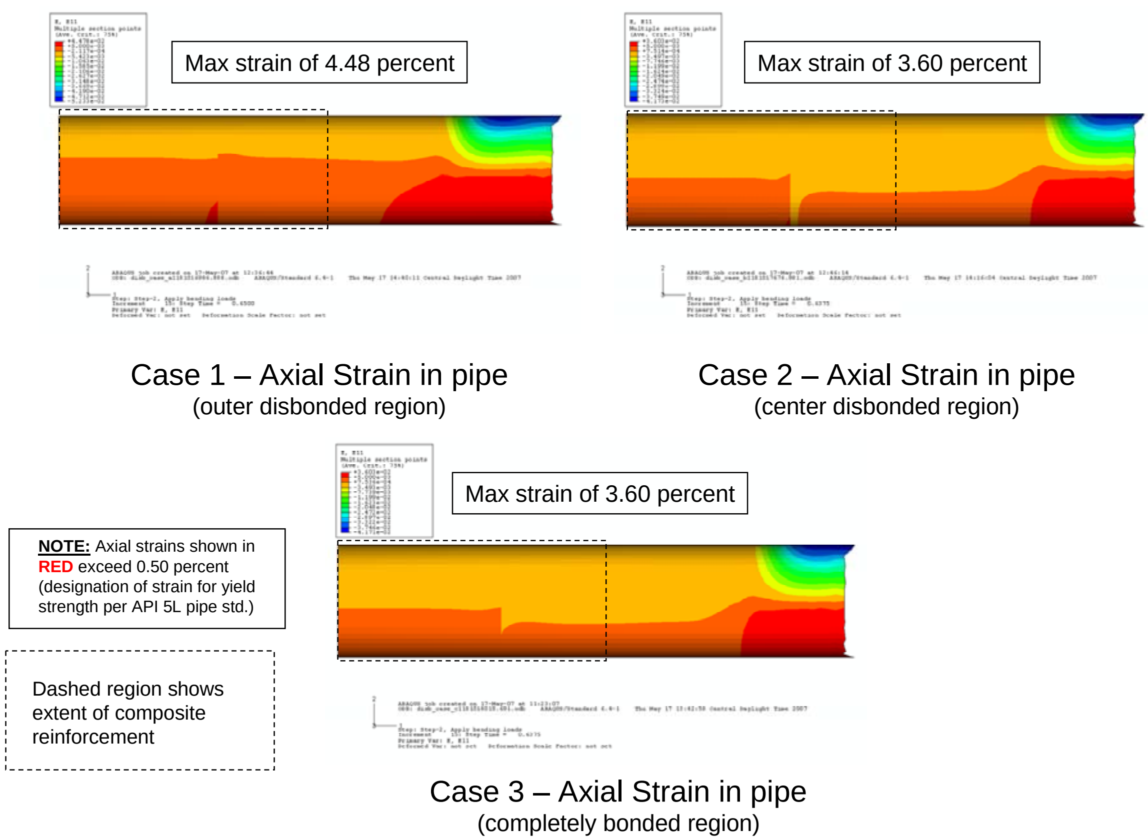


Figure 37 – Axial strain in steel pipe material at plastic collapse conditions
(2,887 psi, 145 kips axial tension, and 98.1 kips-ft bending moments)

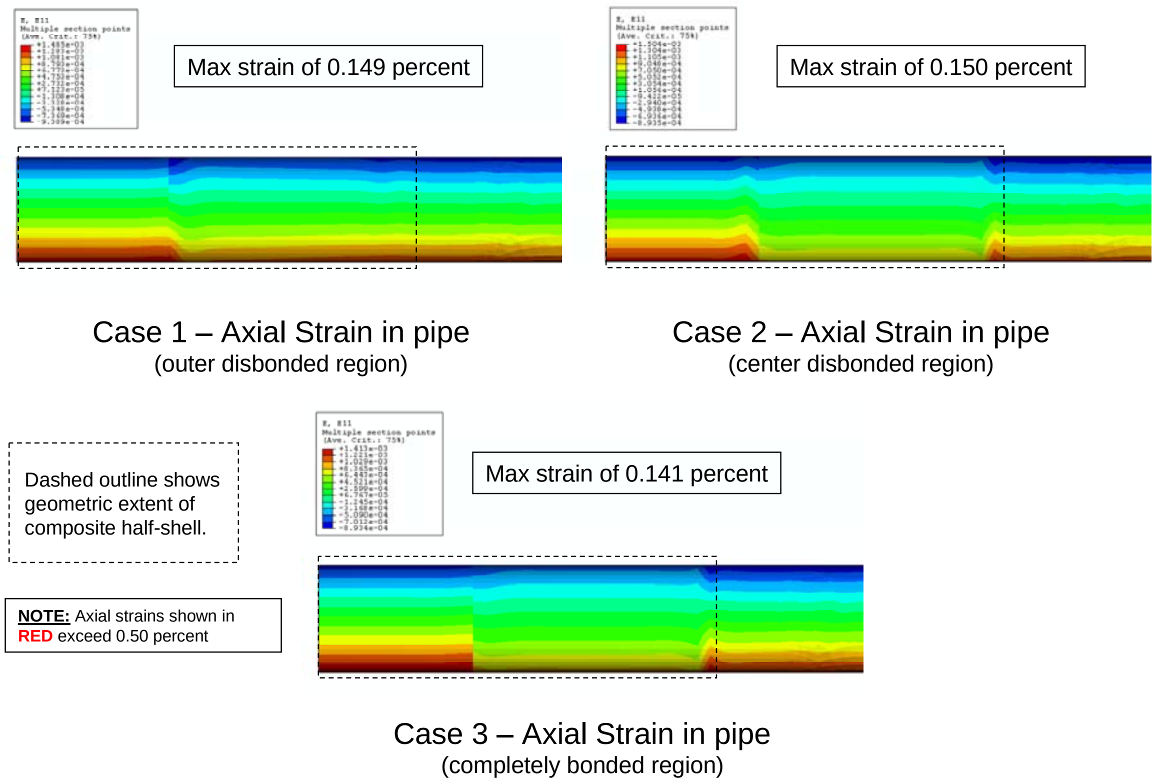


Figure 38 – Axial strain in steel pipe material at design conditions
(2,887 psi, 145 kips axial tension, and 49.1 kips-ft bending moments)

Figure 39 and **Figure 40** are contour plots for Cases 1, 2, and 3 that show axial strain in the inner layer of the carbon half-shell at the plastic collapse and design conditions, respectively. **Figure 41** is a compilation of axial strain in the composite for all seven layers and the steel at design conditions for Case 1. From **Figure 41** it is noted that the minimum strain in the composite materials occurs when the maximum level of bonding takes place. This is to be expected as the composite reinforcement system functions best when it is engaged to the maximum extent. Disbonding between the steel and composite not only increases shear stress in the bonding adhesive, it also results in the local generation of elevated stresses in the composite. This is further demonstrated by the E11 and E22 strain data plotted in **Figure 42** and **Figure 43**, respectively. Remembering that E11 is the primary direction of fiber alignment (especially important with the uniaxial carbon layers 2 through 5), it is noted in **Figure 42** that the outer disbonded Case 1 has the maximum stress at the inner layer of the repair when compared to the other two cases (Case 2 center debonding and Case 3 which has no debonding). This is even observed when compared Case 2 to Case 3, where the center debonding results in generating larger axial stresses in the repair than the completely bonded Case 3.

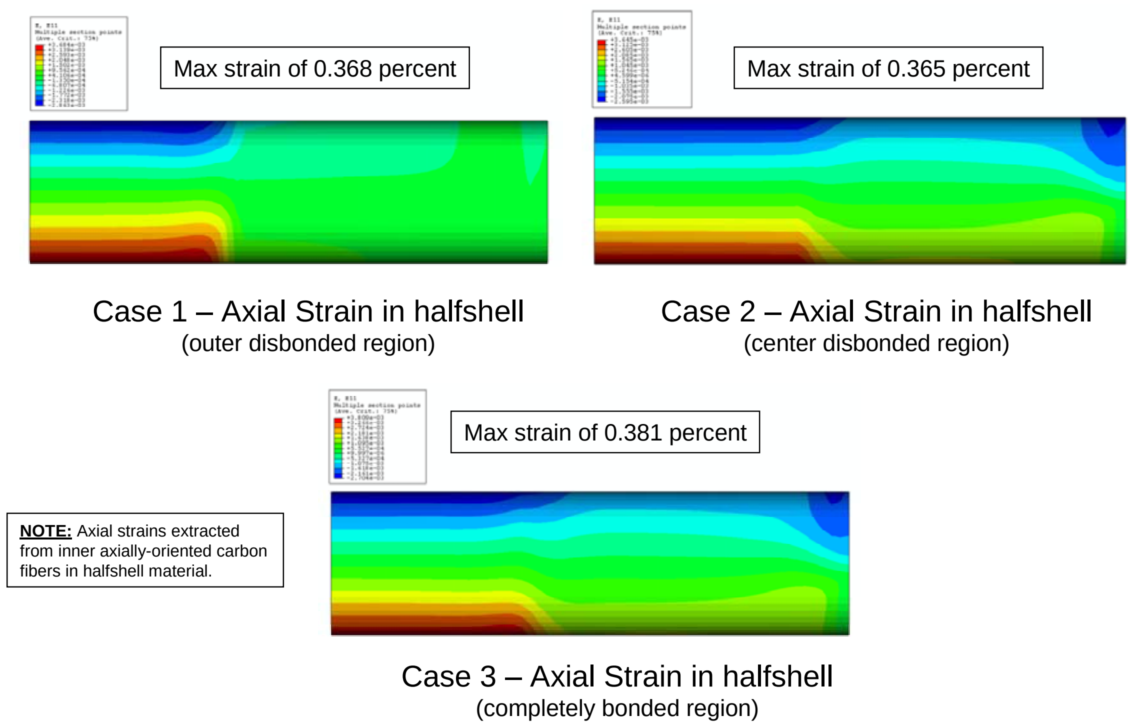


Figure 39 – Axial strain in composite half-shell at plastic collapse conditions
(2,887 psi, 145 kips axial tension, and 98.1 kips-ft bending, inside layer of half-shell)

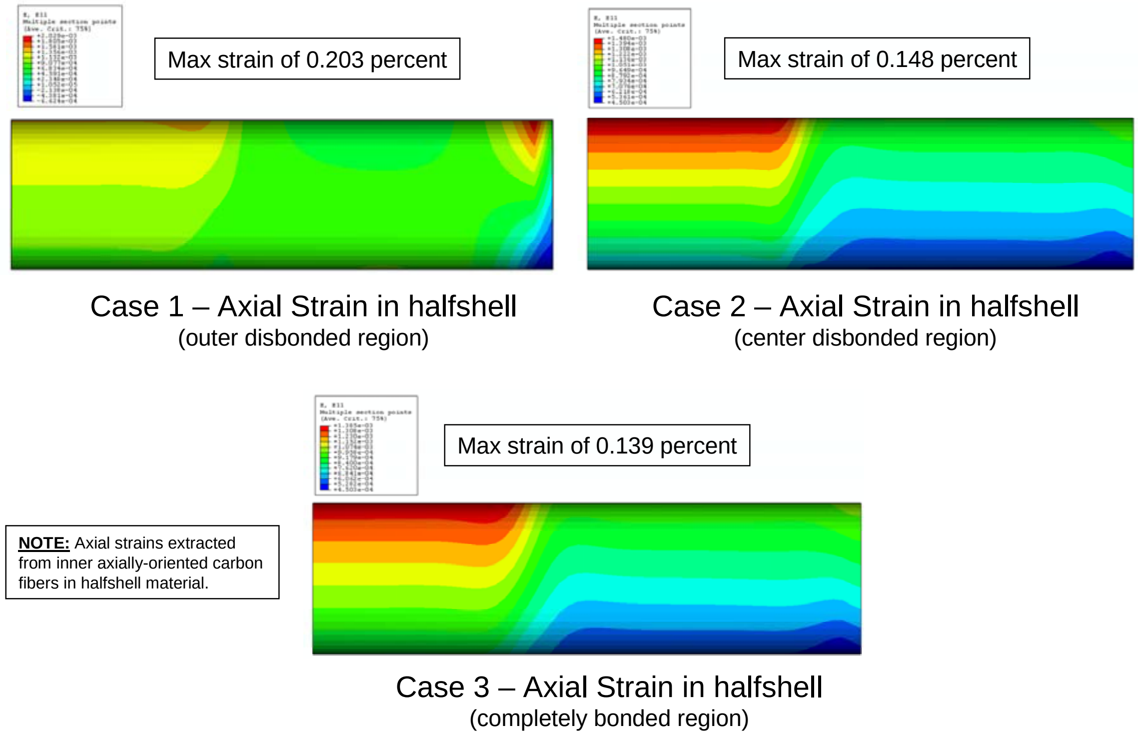


Figure 40 – Axial strain in composite half-shell at design conditions
(2,887 psi, 145 kips axial tension, and 49.1 kips-ft bending, inside layer of half-shell)

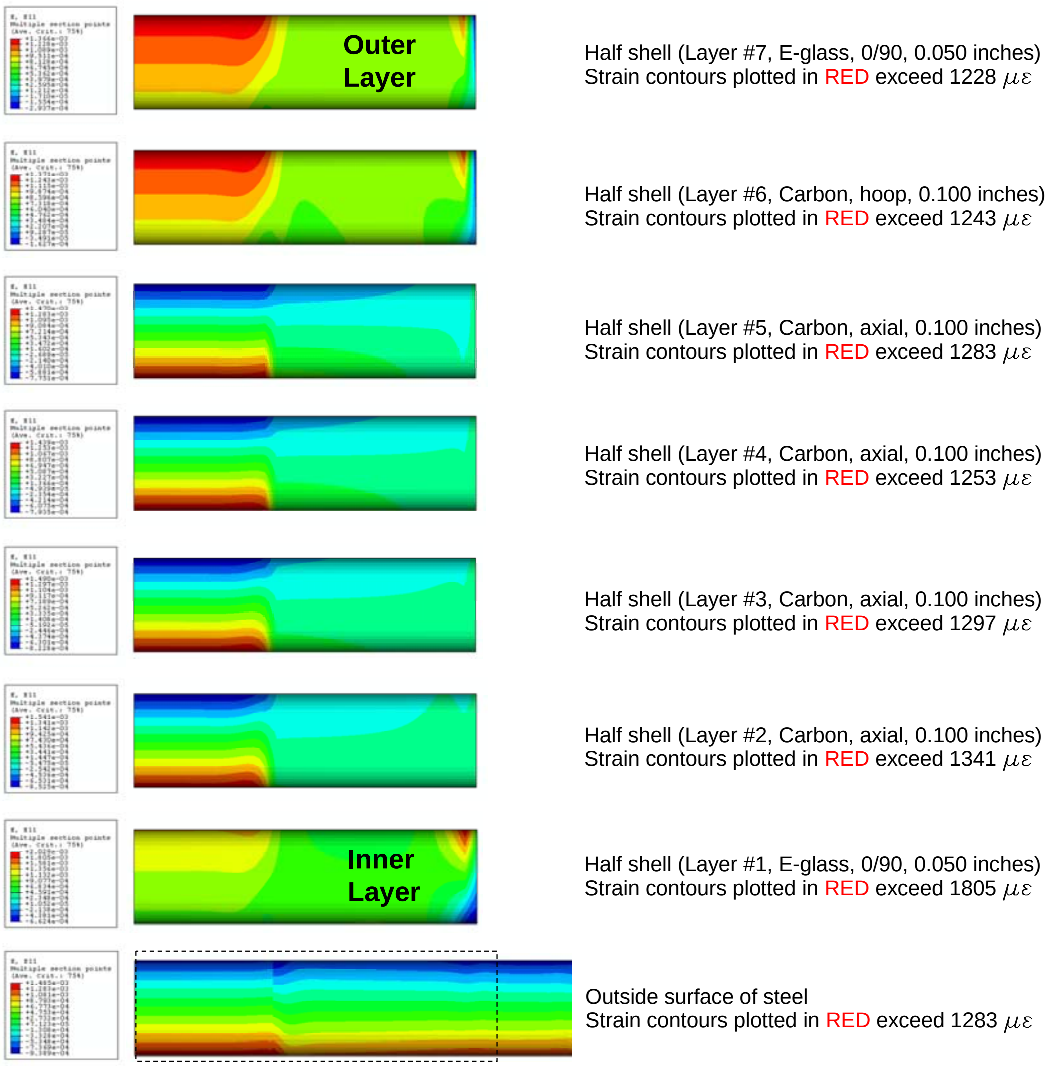


Figure 41 – Axial strain (E11) in composite layers at design condition (Case 1)
(2,887 psi, 145 kips axial tension, and 49.1 kip-ft bending)

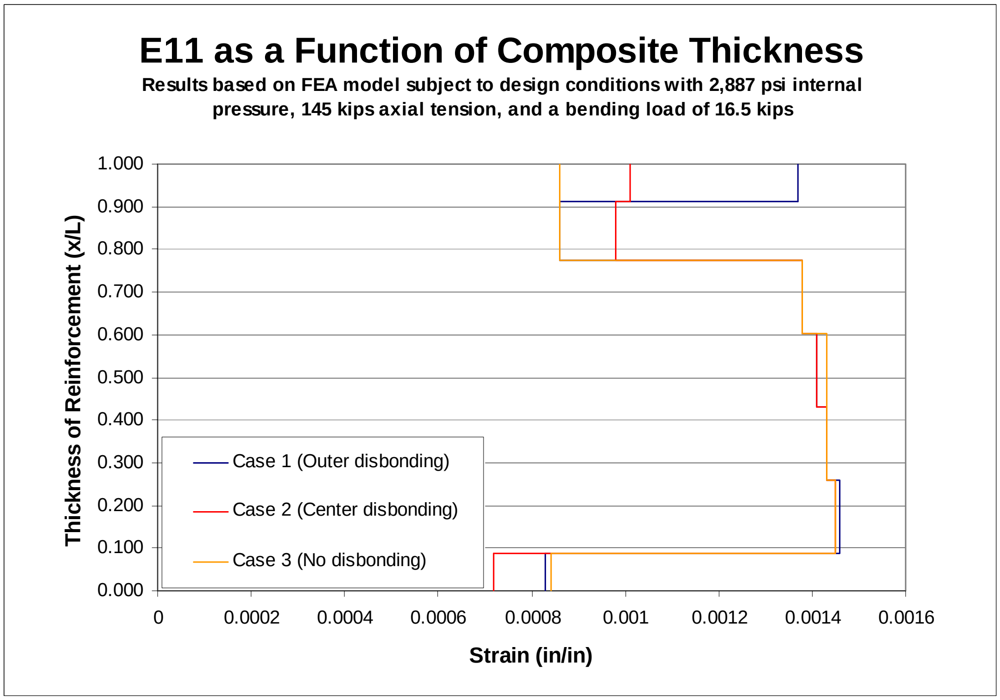


Figure 42 – Axial strain (E11) in composite layers at design bending conditions

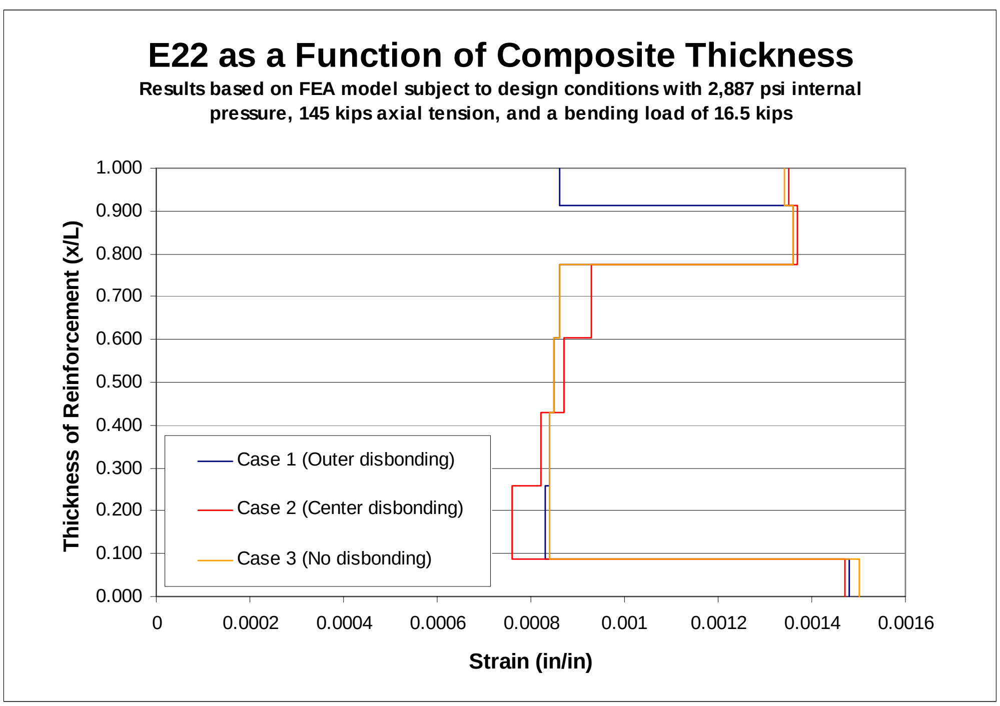


Figure 43 – Hoop strain (E22) in composite layers at design bending conditions

Shear Stress at Steel-Composite Interface

As part of the disbonding study it is possible to extract shear stresses at the interface between the steel and the inner layer of the composite (hereafter referred to as the steel-composite interfacial bond). As discussed previously and observed in the experimental efforts, this adhesive bond is critical in terms of ensuring an axial load distribution between the steel and the composite. Previous research has shown that hoop strength is provided in the absence of a steel-composite interfacial bond due to the concentric nature of the reinforcing composite ring [21]; however, the same cannot be said of tension loads. If sufficient adhesive strength is not present, the steel will carry a disproportionate percentage of the load, effectively bypassing the potential contribution from the reinforcing composite material. In extreme cases when poor bonding takes place, it is possible to dislodge the composite repair from the steel, effectively eliminating the contribution of the composite reinforcement. Two of the most common causes of debonding are poor surface preparation and failure of the adhesive system to cure.

The finite element model used previously to study the effect of disbonding is used to assess the shear stress at the interface between the steel and inner layer of the composite. **Figure 44** and **Figure 45** are contour plots showing shear stress (S12) at the interface for the plastic collapse and design conditions, respectively.

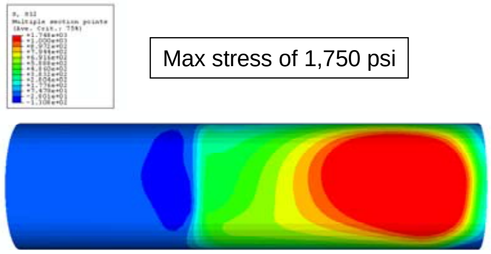
Prior to assessing shear stresses as a function of disbonding, it is important to provide discussion on acceptable stress levels in terms of bond strength for typical epoxy materials. Based on previous lap shear testing by the author the upper bound shear strength for composite-on-steel test configurations using epoxy as the adhesive is on the order of 1,500 psi [21]. Assuming a safety factor of three to account for long-term performance degradation, the maximum allowable shear stress is 500 psi. Additionally, according to Section II-3 of the ASME PCC-2 Article 4.1 composite repair standard, a minimum strength of 580 psi is required for metal substrate lap shear tests [56].

Using the above information in terms of the maximum allowable shear stress, shear stresses for Cases 1, 2, and 3 were extracted from the finite element models and compared to the allowable values to determine if any of the disbonding conditions are unacceptable. The following maximum shear stresses were extracted for the design loading condition (refer to contour plots in **Figure 45**).

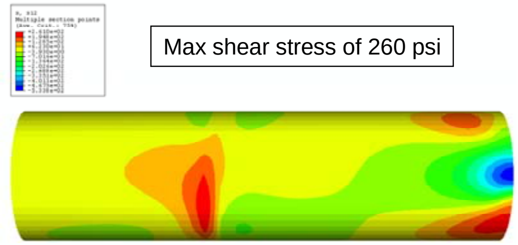
- Case 1 (edge disbonding case spanning 18 inches axially) S12 = 463 psi
- Case 2 (edge disbonding case spanning 12 inches axially) S12 = 56 psi
- Case 3 (no disbonding) S12 = 7 psi

As noted in the above data, a significant disparity exists in terms of the magnitude of stresses associated with the different levels of disbonding. When disbonding occurs on the outer edges (where it is most likely to occur), there is greater potential for elevated stresses. However, even for Case 1 that has a relatively extensive level of debonding, the maximum shear stress is within an acceptable level. It is also important to note that for the other two cases considered, minimal shear stresses are calculated indicating the likelihood for debonding at design conditions is unlikely.

One final comment concerns upset loading conditions that are prone to happen in offshore operations when factors such as hurricanes can generate extreme loading conditions. As illustrated in **Figure 44**, at the plastic collapse condition a maximum shear stress of 1,750 psi is calculated. It is worth noting that during one round of tests performed previously by the author, the maximum recorded shear lap shear strength for a composite on steel sample was 1,755 psi [21]. With this point in mind, it is important that if and when extreme loading conditions occur, it is possible in the presence of existing outer edge debonding that a bond line failure can occur.

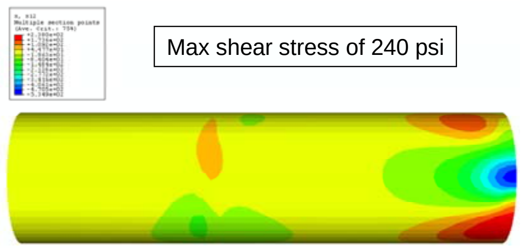


Case A – Shear stress in halfshell bond line
(outer disbonded region)



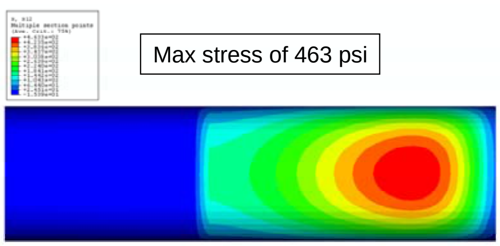
Case B – Shear stress in halfshell bond line
(center disbonded region)

NOTE: Shear stresses extracted from interface bond line between outside surface of steel and inside of composite half shell.

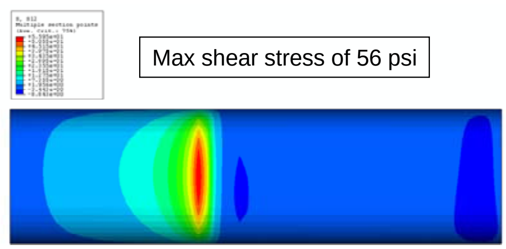


Case C – Shear stress in halfshell bond line
(completely bonded region)

Figure 44 – Shear stress at steel-composite interface (plastic collapse conditions)

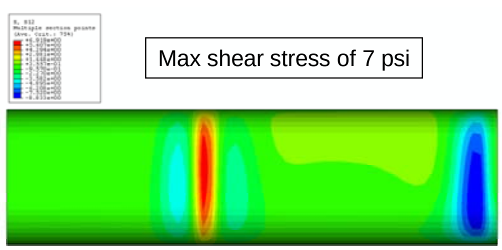


Case A – Shear stress in halfshell bond line
(outer disbonded region)



Case B – Shear stress in halfshell bond line
(center disbonded region)

NOTE: Shear stresses extracted from interface bond line between outside surface of steel and inside of composite half shell.



Case C – Shear stress in halfshell bond line
(completely bonded region)

Figure 45 – Shear stress at steel-composite interface (design conditions)

Summary of CRA System Design

This section has provided specific details on how the CRA system was evaluated relative to a pre-established set of design criteria. For the problem at hand this has 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 has used strength of materials, along with finite element modeling, to determine the best configuration for reinforcing the corroded riser.

What has been demonstrated is that the geometry of the repair adequately reinforces the corroded region of the riser consider internal pressure, axial tension, and bending loads. This was achieved by first ensuring that the corroded region is prevented from bulging due to internal pressure. Additional layers are then used to provide the additional rigidity to withstand the imposed axial tension and bending loads. The following composite architecture is used for the CRA system design including material type, fiber orientation, and thickness. It should be noted that the matrix for all layers in an epoxy resin.

- Inner layer of 50-50 E-glass, spiral wrap, ~ 0.030 inches thick
- Circumferential carbon (stitched fabric), 0.200 inches thick
- Axial carbon (pre-cured half shells), 0.400 inches thick
- Circumferential-spiral carbon (stitched fabric), 0.100 inches thick
- Outer layer of 50-50 E-glass, spiral wrap, ~ 0.030 inches thick

The following section, *Integrated Analysis and Testing Assessment*, presents findings from the composite repair design considering both analysis and testing efforts. Through experimental verification, the design methods and resulting composite repair system are evaluated using prototype fabrication and full-scale testing.

INTEGRATED ANALYSIS AND TESTING ASSESSMENT

The preceding section, *Development of a Riser Composite Repair System*, demonstrated computational simulation to determine an optimized composite reinforcement system. Included in this effort were calculations based on classical mechanics, insights gained from previous research efforts, selection of a design basis, and analysis using finite element methods to determine the architecture for the repair system.

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. For purposes of review, consider the following composite architecture developed using the methodology presented in the preceding section.

- Inner layer of 50-50 E-glass, spiral wrap, ~ 0.030 inches thick
- Circumferential carbon (stitched fabric), 0.200 inches thick
- Axial carbon (pre-cured half shells), 0.400 inches thick
- Circumferential-spiral carbon (stitched fabric), 0.200 inches thick
- Outer layer of 50-50 E-glass, spiral wrap, ~ 0.030 inches thick

An epoxy resin matrix was used in all layers of the system. It includes the pre-cured carbon half shells fabricated by Comptek, as well as all other layers applied as wet lay-ups located beneath and on top of the half shells.

The sections that follow include details on fabrication of the test samples, test results, comparison of CRA test results to those obtained for the JIP members in the state of the art assessment, and comparison of analysis and testing results for the CRA system.

Fabrication of the Half-Shell Repair System

Provided in **Appendix D** is a pictorial directory showing the specific steps involved in the fabrication of the pre-cured carbon half shells of the CRA system. 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. As shown in **Appendix D**, the half-shells were cured under a vacuum seal. The completed half shells were shipped to Stress Engineering Services, Inc. in Houston.

Provided in **Appendix F** are the material properties for the carbon material used to fabricate the carbon half shells for the CRA system repeated here as a summary. The following data were measured for this 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 of the Half-Shell Repair System

Prior to testing and installation of the repair system, three (3) steel pipe test samples were fabricated in the same manner as those fabricated for the JIP program. The samples were fabricated using 8.625-inch x 0.406-inch, Grade X46 pipe. A 50 percent simulated corrosion 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

The half shells were installed at the Stress Engineering Services, Inc. lab in Houston on May 30 and 31, 2007. 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 (72 inches in order to accommodate the 60-inch long repair). **Figure 46** shows a pipe prior to installation of the repair.
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 47** and **48** 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 as shown in **Figure 49**. Perforation of the plastic wrap was done to permit the excess resin to extrude. The stricter wrap creates a small compressive load on the material and ensures a relative uniform surface to the carbon half shells can be bonded. The hoop wrapped material was permitted to cure overnight.
4. After the stricture wrap material was removed, the Spabond 340 two-part epoxy was mixed using a mixing gun as shown in **Figure 50**. The mixed gray epoxy was hand applied using a slotted trowel with ¼-inch by ¼-inch square grooves as shown in **Figure 51**.
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 52** 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. **Figure 53** shows one of the banding clamps being

installed. 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 as shown in **Figure 54**. As before, the 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 55** shows the final repair including the carbon half shells and outer carbon hoop wrapped material.

The figures that are provided on the following pages show what steps were involved fabricating the test samples used in all phases of the program for the CRA system. The test samples including pressure only, pressure-tension, and pressure-tension-bending. 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.

Figure 46 – Sandblasted surface of pipe prior to installed work

Figure 47 – Saturating the uniaxial stitched carbon cloth

Figure 48 – Installing the hoop wrapped inner carbon layers

Figure 49 – Installing stricter wrap material around the outside of the repair

Figure 50 – Epoxy mixing gun used to mix the epoxy Spabond 340 adhesive

Figure 51 – Applying the epoxy adhesive using a slotted hand trowel

Figure 52 – Installation of the carbon half shells

Figure 53 – Installing steel banding clamps on the outside of the half shells

Figure 54 – Installation of the outer hoop carbon and stricter wrap material

Figure 55 – Final view of cured repair prior to testing

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 56 shows the location of the strain gages on the 8-ft samples (burst and tension samples). Additionally, at Station A gages were installed as follows:

- Two gages installed on the outside surface of the carbon half shells at 0 and 180 degrees (in line with Gage #1 and #3, respectively)
- Three gages were installed on the outside hoop-wrapped layers at 0, 90, and 180 degrees

The above combination results in a total of 14 gages on the 8-ft test samples.

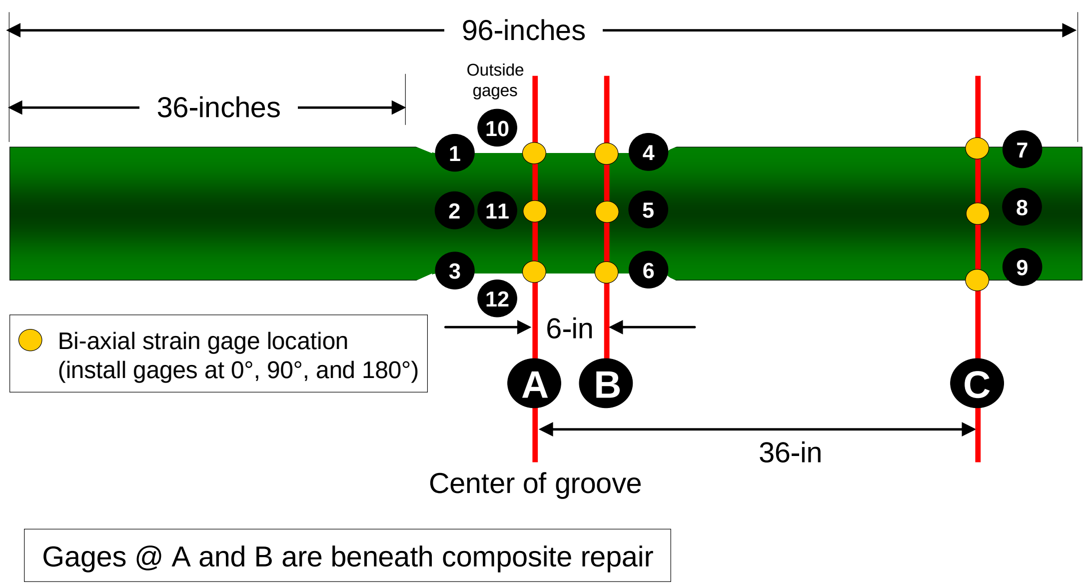


Figure 56 – Strain gages positions on 8-ft burst and tension samples

A greater number of strain gages were installed on the 15-ft bending sample than on the two 8-ft samples. The reason for this is that interest existed in determining strain distribution within the system considering bending loads. **Figure 57** shows the position of nine (9) strain gages installed beneath the composite repair on the base pipe (same configuration as used previously on the 8-ft samples). An additional 17 strain gages were installed, 15 of which were installed on the composite materials. **Figure 58** shows the following:

- Two (2) strain gages were installed on the base pipe beneath the carbon half shells to assess the edge effects of the repair
- Six (6) strain gages were installed on the top and bottom carbon half shells (positioned at 0 and 180 degrees, with 90 degrees being the neural axis of bending)
- Nine (9) strain gages were installed on the outside surface of the external hoop wraps. Gages were installed at 0, 90, and 180 degrees.

The above combination results in a total of 26 bi-axial strain gage rosettes. During testing, data for each of these gages were recorded at a rate of 1 scan per second. As discussed previously, having strain gages at specific locations permitted a detailed assessment of the level of reinforcement provided by the repair system.

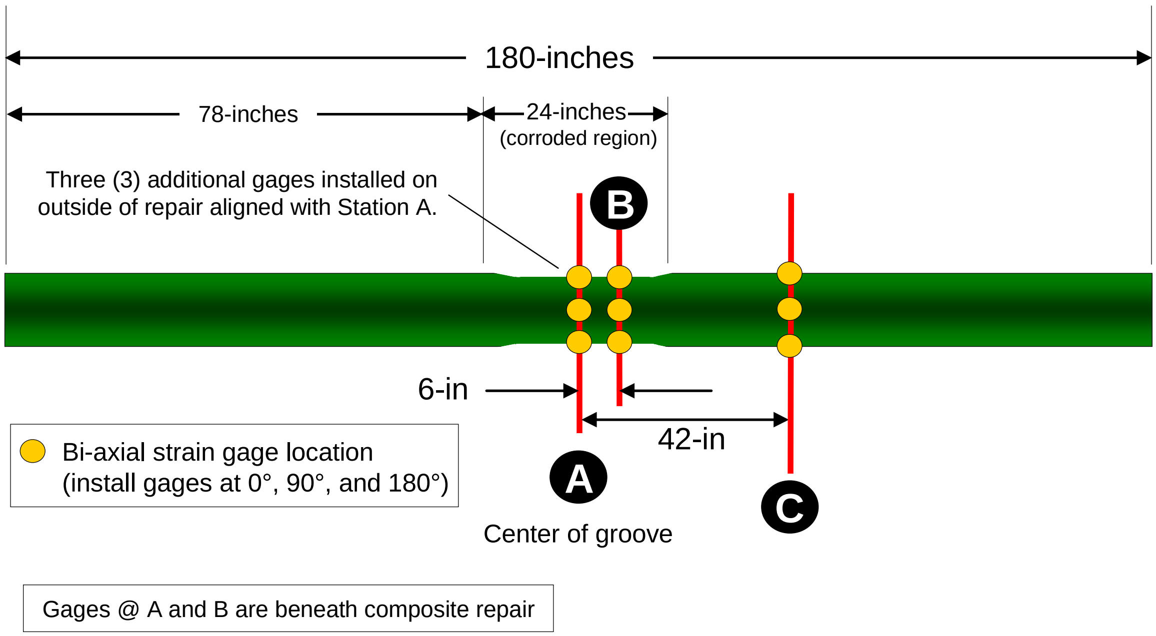


Figure 57 – Strain gages installed on 15-ft sample beneath composite repair

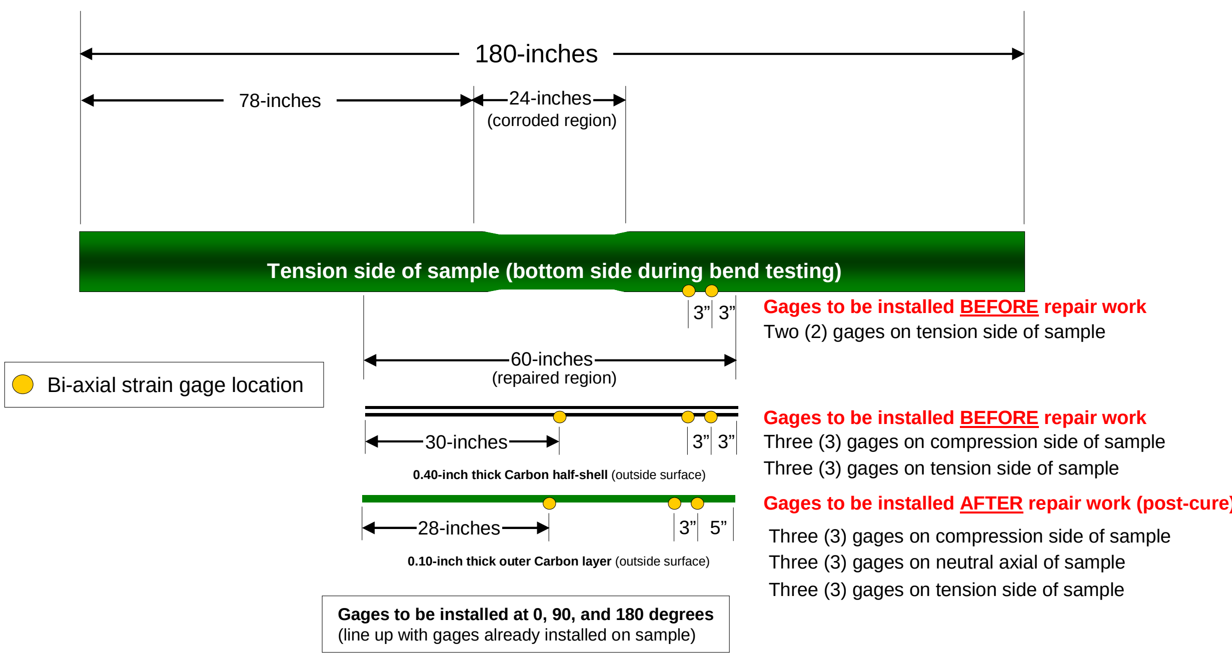


Figure 58 – Additional strain gages installed for bending test sample

Test Program Results

A significant body of strain gage data was acquired during the course of completing the test program. The data will be presented in two formats. First, the strain gage readings beneath the composite repair will be plotted against the other composite repair systems as a benchmark for performance. This was done for the pressure, tension, and bending tests. Secondly, data will be presented that looks specifically at the strain distribution of the repair as a function of position within the repair. Regions of interest include strain readings beneath the repair in the corroded region, in the base pipe outside the repair, on the carbon half shell, and readings measured on the outside hoop-wrapped uniaxial carbon fibers.

Evaluation of CRA System in Terms of Measured Strains

Presented in this section of the dissertation 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 will provide comparison of results of the CRA system with results for the JIP participants and also compare results calculated for the system using finite element methods.

Burst Pressure Tests

Figure 59 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

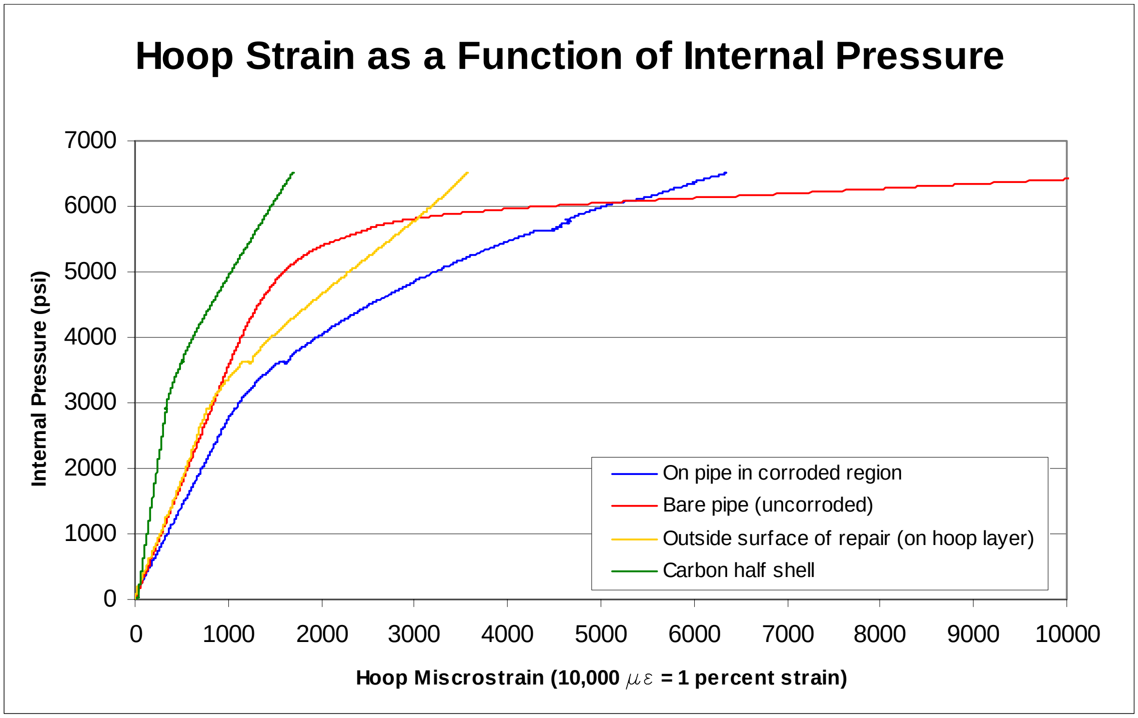


Figure 59 – Strain gage results for pressure testing the CRA system

There are several noteworthy observations that are made in viewing the strain gage results presented in **Figure 59**.

- 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. Additionally, a delay in load transfer of circumferential loading between the pipe and carbon half shell is to be expected as the primary purpose of the half shells is to provide rigidity for tension and bending loads.

- 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. The fact that hoop strain is being measured is important as it shows that the outer layers are providing restrain to the carbon half shells.

Figure 60 is a schematic showing the location of the strain gages installed on the CRA system test samples. Note that in this figure 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 material being placed over the carbon half shells to restrain them). This configuration was used for all three test samples: pressure, tension, and bending.

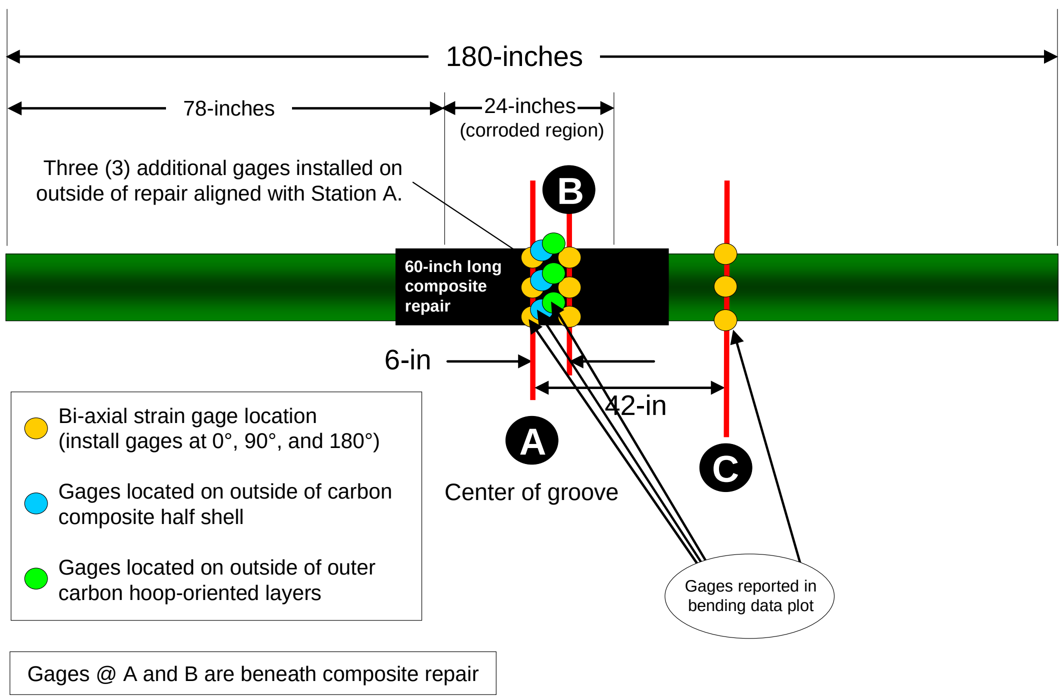


Figure 60 - Locations for strain gages of interest on CRA system samples

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 61** 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 61**, 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.

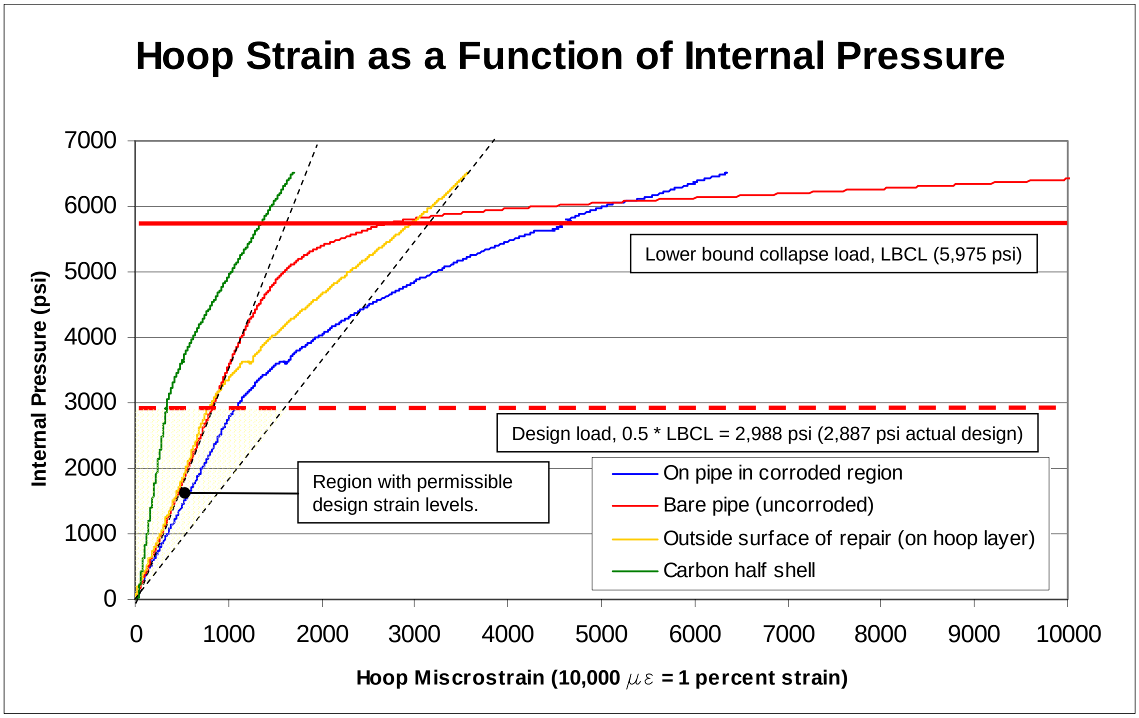


Figure 61 – Annotated pressure test plot showing limit state design parameters

Tension Test

Figure 62 plots axial strains measured during loading of the tension test sample. Measurements associated with the following axial 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
- 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 62**.

1. As expected, the maximum strain occurs in the corroded steel region of the sample. 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 both in the corroded region and the base pipe, a greater percentage of the load is distributed to the composite material. This is observed in **Figure 62** 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.

One final comment concerns the failure load recorded by the tension test sample. As with observations on the other composite repair systems, the ability of the CRA system to provide axial rigidity is directly related to both the stiffness of the composite as well as the adhesive bond strength between the composite repair and the steel pipe. The results measured with the CRA system are no exception. The progressive failure of the tension sample is observed in the following steps.

1. Both the steel and the composite are loaded in tension in proportion to their relative stiffness as compatibility is maintained. For purposes of this discussion, axial tensile stiffness is the product of elastic modulus and material thickness.
2. As increased tensile loading and elongation occur, plasticity is eventually induced in the corroded region of the steel. Based on the data plotted in **Figure 62**, for the CRA repair system this occurred at approximately 450 kips. The plasticity of the steel results in greater compliance, which in turn transfers a greater portion of load to the

composite material. The resulting load response is dominated by the stiffness of the composite materials.

3. The onset of failure occurs once the adhesive bond occurs between the composite material and the steel. For the CRA system, the shear stress in the adhesive at the failure load was calculated to be 1,220 psi (594 kips divided by 488 in^2 for the 18-inch long bond line on each side of the corroded region of the test sample).

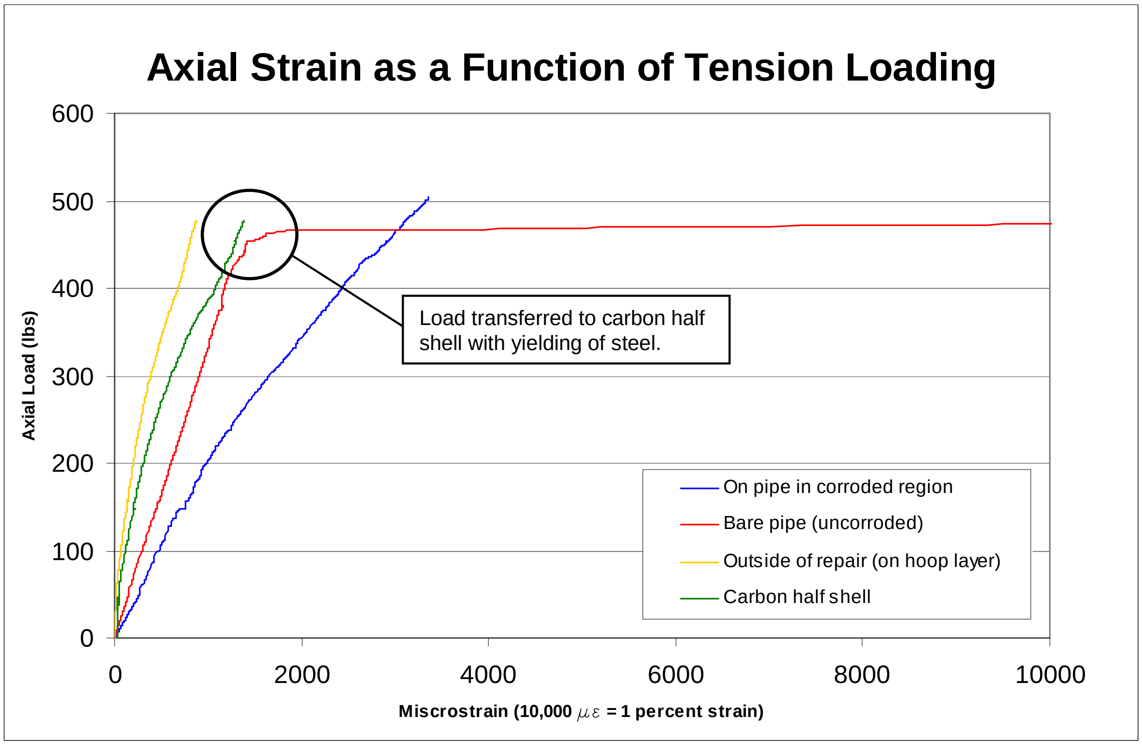


Figure 62 – Axial strains measured during loading of the tension test sample

Figure 63 plots the strain gage results for the CRA system including 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 important observation is that the strain in the composite material is less than 0.20 percent for all levels of loading. Considering that the long–term performance requires strain levels to not exceed 40 percent of the breaking strain (approximately 1 percent), the 0.20 percent value is significantly less than the 0.40 percent allowable strain.

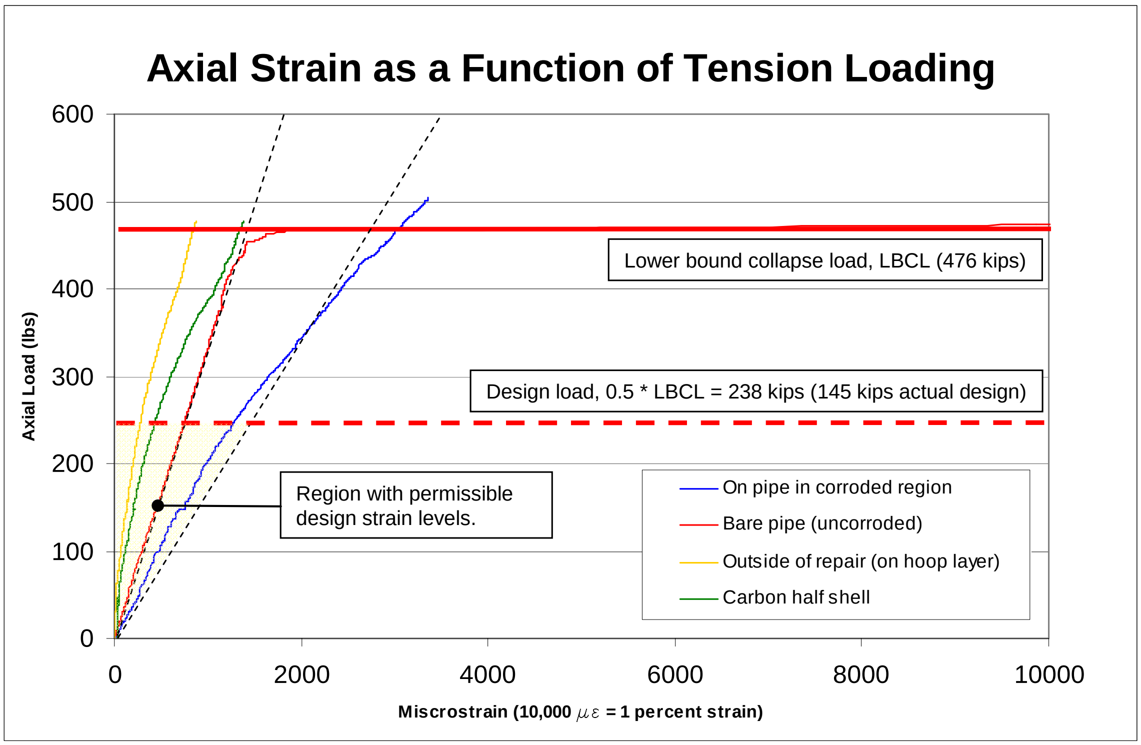


Figure 63 – Annotated tension test plot showing limit state design parameters

Bending Test

Results are plotted for the bend test results. **Figure 64** 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. Measurements associated with the following axial 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
- 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

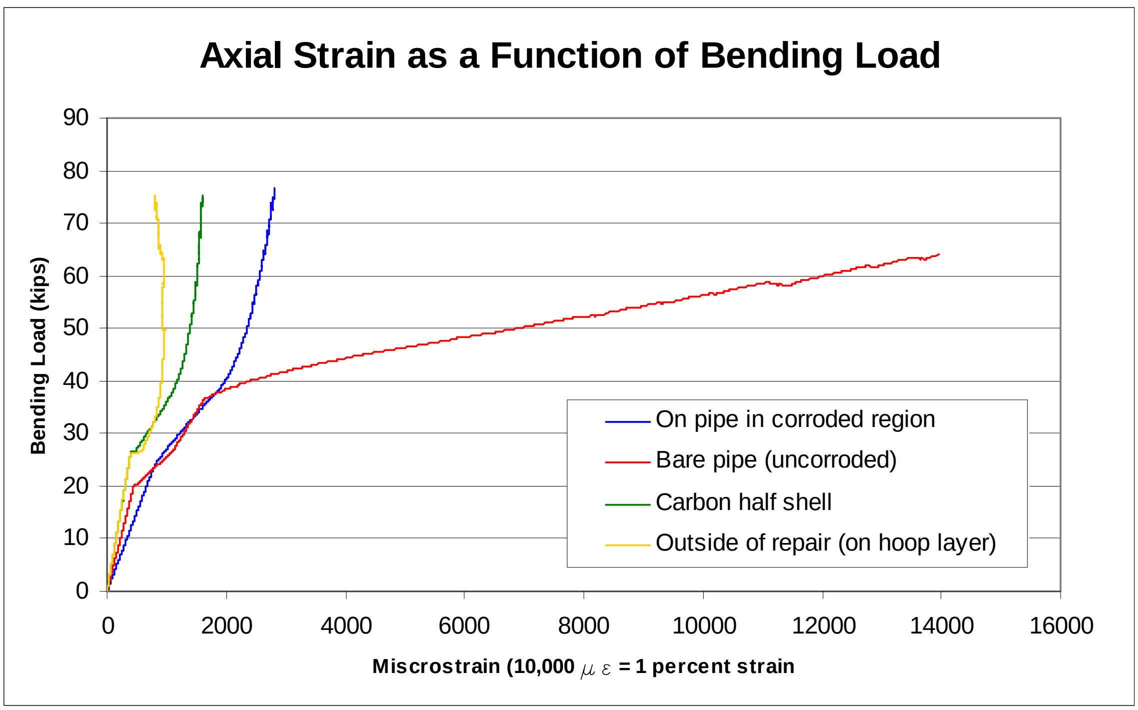


Figure 64 – Axial strains measured during loading of the bending test sample

The following observations are made in viewing the results plotted in **Figure 64**. 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.

$$\sigma_{axial} = \frac{F}{A} + \frac{M}{\pi \cdot r^2 \cdot t} = \frac{145\ kips}{\pi \cdot (4.31\ inches)^2 \cdot (0.4\ inches)} + \frac{25\ kips \cdot 35\ inches}{\pi \cdot (4.31\ inches)^2 \cdot (0.4\ inches)} = 44\ ksi$$

- 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. Additionally, the axial strain on the outside surface of the repair is the least engaged; although this is expected as these fibers are circumferentially-oriented and not intended to provide axial rigidity.
- 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 pipe where local bending stresses are the greatest. **Figure 65** shows the

local plastic deformation that occurs in the test sample at the point of contact with the hydraulic cylinders.

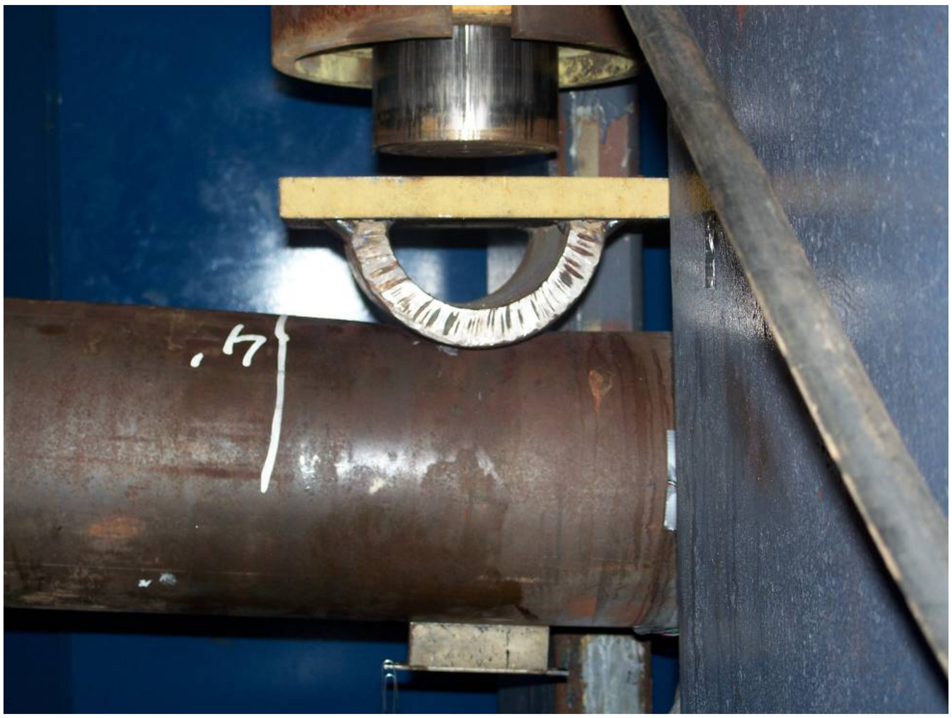


Figure 65 – Plastic deformation near the hydraulic cylinder point of contact

As with the presentation for the pressure and tension samples, an annotated version of the limit load plot is provided for the bend test sample. **Figure 66** is the annotated sample that shows 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 by reducing strains in the corroded region of the pipe.

A final comment is warranted with regards to design requirements. Note that in both strain gages installed on the composite material the recorded strain levels never exceed 0.30 percent. This is important as the allowable strain in the context of this particular design is 0.40 percent (cf. *ASME 2006 Design Factor Guidelines for High Pressure Composite Hydrogen Tanks*).

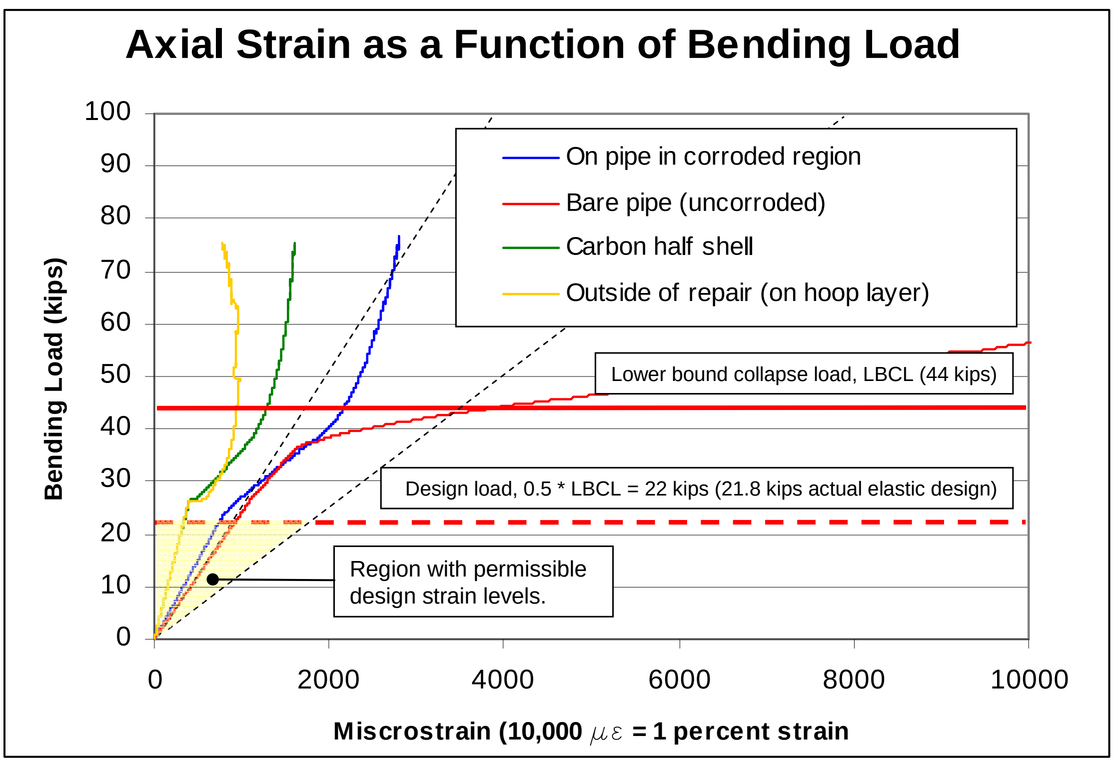


Figure 66 – Annotated bending test plot showing limit state design parameters

<u>Performance of CRA System versus JIP Repair Systems</u>

This section of the dissertation presents results for the CRA repair system subject to internal pressure, tension, and bending loads compared to results measured for the repair systems that participated in the JIP program. For review purposes, the four systems involved in testing included the following components.

- **Product A** –E-glass fiber system in a water-activated matrix. The cloth is a balanced weave with orthogonal fibers aligned at 0 and 90 degrees relative to the axis of the pipe. During installation, the cloth was oriented either axially of circumferentially to achieve the desired level of reinforcement.
- **Product B** –E-glass fiber system in a water-activated matrix. The cloth is a balanced weave with orthogonal fibers aligned at 0 and 90 degrees relative to the axis of the pipe. This particular repair involved using an epoxy filler material in the corroded region, as opposed to placing composite material in this region of the repair. All of the other repairs actually installed fibers in the corroded region. During installation, the cloth was oriented either axially of circumferentially to achieve the desired level of reinforcement.
- **Product C** – this system uses a carbon fiber system in an epoxy matrix. The cloth is a stitched fabric with all uniaxial fibers. During installation, the fibers were aligned at 0 and 90 degrees relative to the axis of the pipe depending on the desired level of reinforcement.
- **Product D** – this system uses an E-glass fiber system in an epoxy matrix. The cloth has fibers that are oriented at 0, 90, and +/- 45 degrees. Additionally, on the underside of the cloth a layer of chapped strand fibers is installed. During installation, the cloth was oriented either axially of circumferentially to achieve the desired level of reinforcement.

Burst Pressure Test

Figure 67 plots strain gage readings measured beneath the repair. In terms of performance relative to the other systems, the CRA system provided an average level of reinforcement (i.e. less hoop strain that Product D, but more hoop strain that Products A and C).

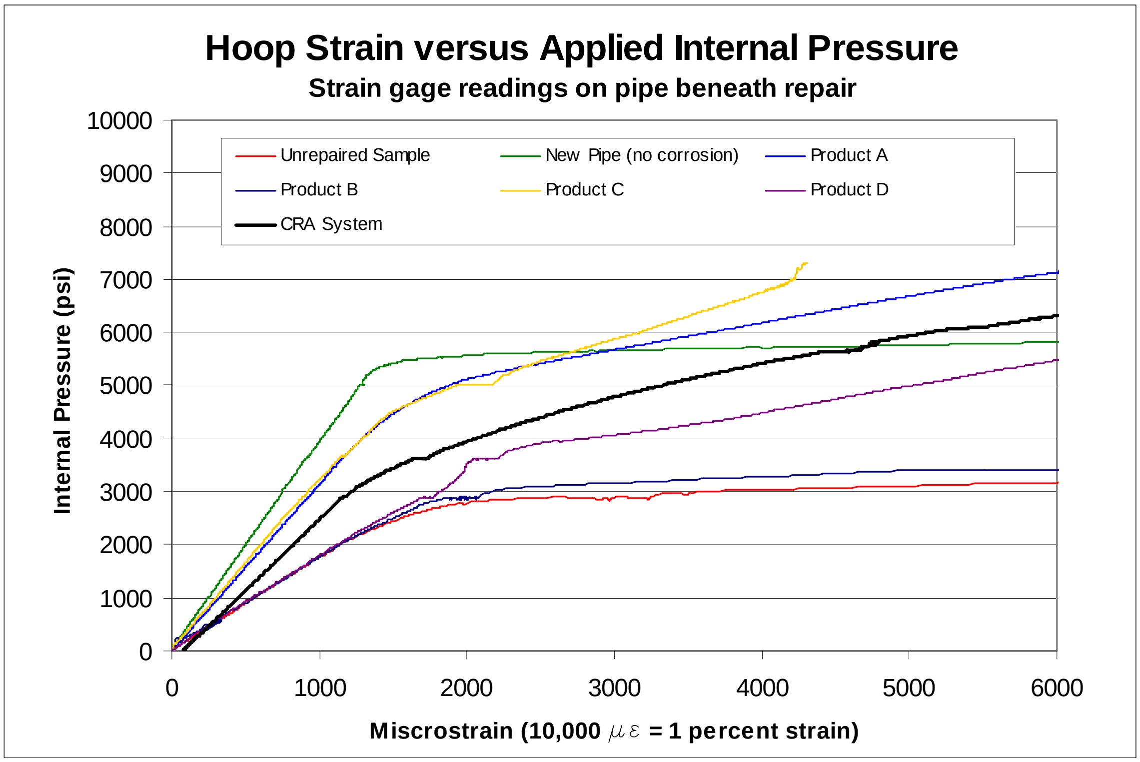


Figure 67 – Hoop strain measured during burst testing

Figure 68 is a photograph that shows the failure that occurred in the burst sample with the CRA system. Note that the failure occurred in the corroded region of the repair at a pressure of 6,517 psi (2.25 times the operating pressure of 2,887 psi).

Figure 68 – Photo of burst test sample showing failure

Tension Test

Figure 69 shows the axial strain gage readings acquired during the tension testing. **Figure 70** is a photograph showing the post-failure fracture of the CRA system. In reviewing the plotted axial strain data, it is noted that the rigidity provided by the CRA system was second only to the other carbon system, Product C. This observation indicates that the relative rigidity of the axial carbon half shells and adhesive bond provide a reasonably high level of axial reinforcement to the corroded region. A comparison of the unreinforced test sample (**RED** line) shows the relatively high level of reinforcement that is provided by the CRA system.

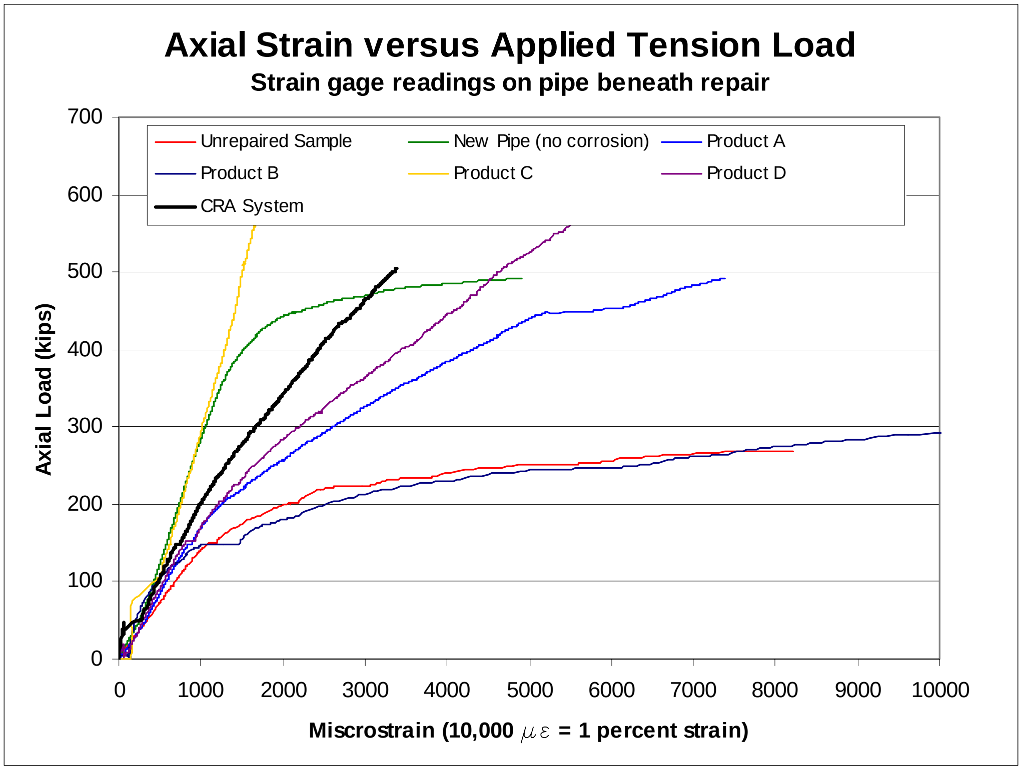


Figure 69 – Axial strain measured during tension testing

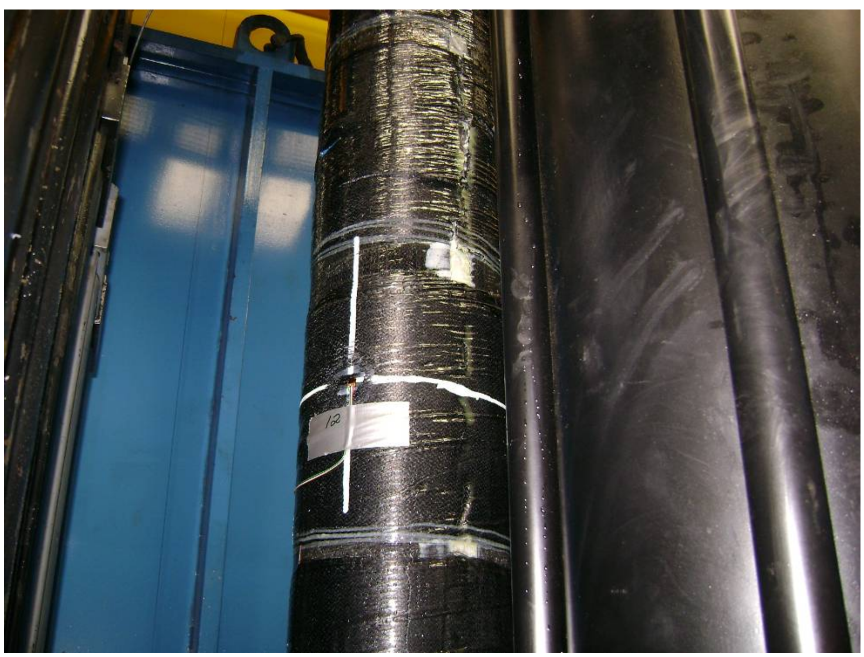


Figure 70 – Photo of tension test showing fracture

Bending Test

As with the tension test results, in bending the CRA system provided reinforcement to the corroded pipe that was second only to the Product C carbon system. The corresponding results are plotted in **Figure 71**. During testing, the test sample reinforced with the CRA system was loaded with a bending moment of 225 kip-ft. This bending moment is greater than the bending moment applied to any of the other systems, although this does not imply that the level of reinforcement provided by the CRA system exceeded the reinforcement provided by Product C. **Figure 72** is a photograph that shows displaced configuration of bending sample. What is significant in viewing this photograph is recognizing that the test sample was initially horizontal. The imposed bending loads deformed the test sample to the configuration shown in this figure. Another noteworthy observation is the rotation that occurs at the end of the sample, consistent with the intention of performing a four point bend test with simply-supported bend conditions.

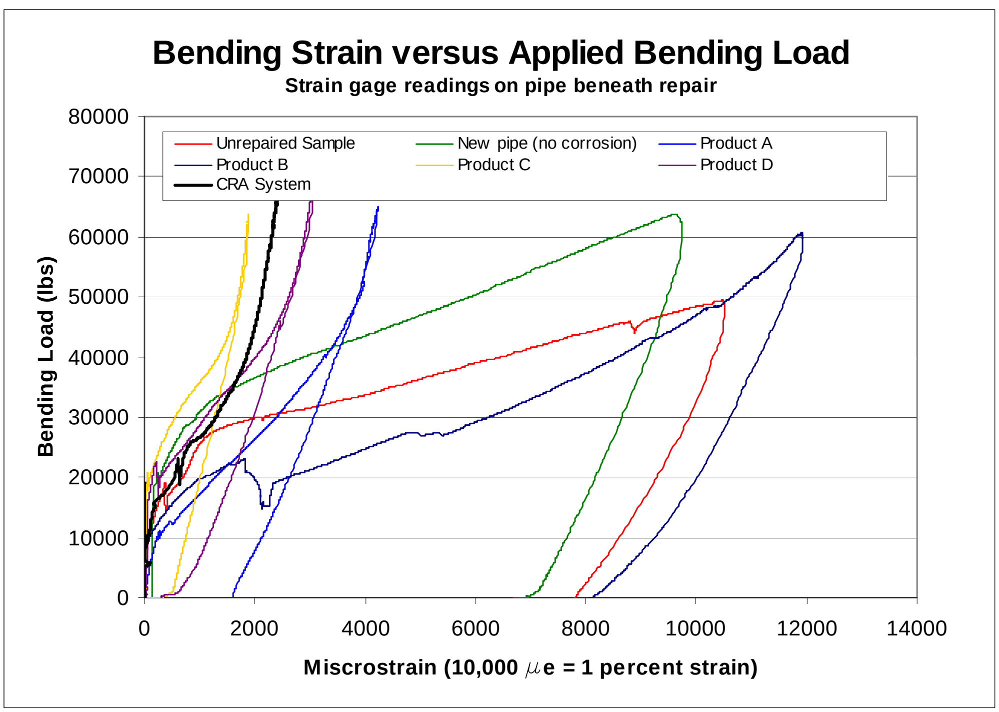


Figure 71 – Axial strain gage results subject to bending for all tested systems

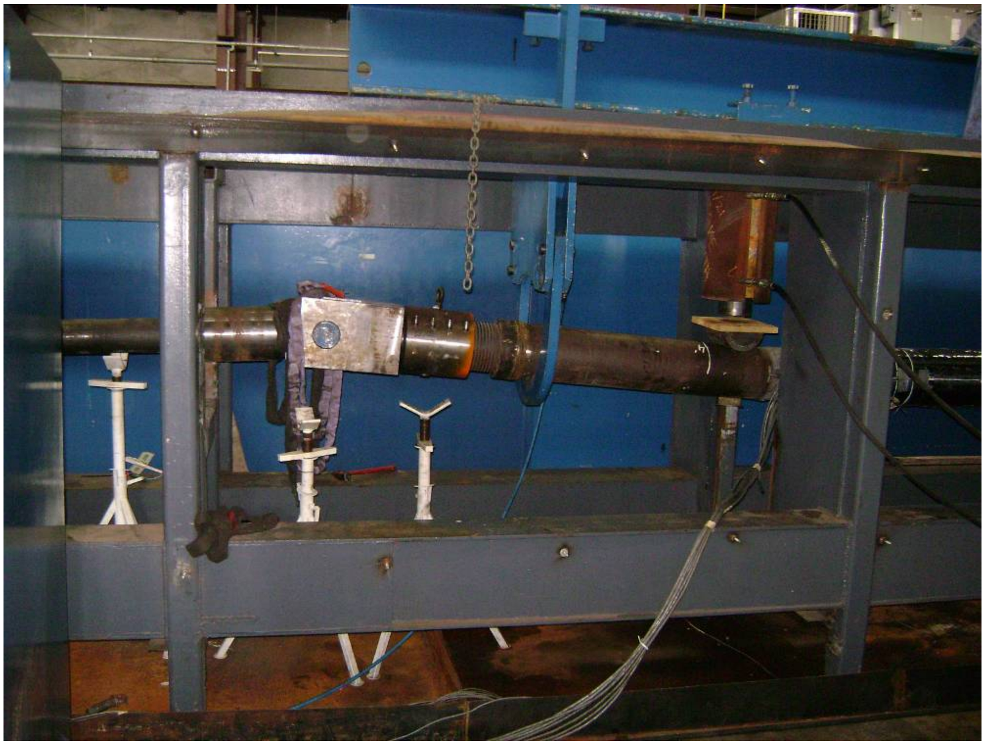


Figure 72 – Photograph showing displaced configuration of bending sample

Comparing Analysis Findings with Test Results

At this point 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.

Strain gage readings at design conditions are compared to those calculated during the analysis phase of this study. A design that is deemed acceptable is one where the measured strains, especially those in the reinforced steel region, are less than those determined analytically. A comment is warranted regarding why strains in the steel beneath the corroded region are critical. It is possible to improperly install a repair in a manner that induces low stresses in the reinforcing composite material; however, when improper installations are made there is also a strong potential that excessive strains in the steel will develop. When this exists, the design strain limit is exceeded due to inadequate reinforcement conditions.

Table 5 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). Although the burst failure pressure was of significant magnitude, the fact that failure actually occurred in the repaired region indicates that a less than ideal performance condition existed.

Table 5 – 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.

Figure 73 and **Figure 74** provide comparisons of analytical and experimental results for the CRA system considering internal pressure and bending loads, respectively. Note that the bending load also includes an internal pressure of 2,887 psi and an axial tension of 145 kips, both held constant during the application of the incrementally-increased bending load. Included in both of these plots are the following data sets:

- *On pipe in corroded region* – these data were taken by strain gages placed in the corroded region of the sample (0.200 inch wall thickness) beneath the composite repair system.
- *Care pipe (uncorroded)* – these data were taken by a strain gage placed on the outside surface of the pipe sample away from the composite repair (0.406 inch nominal wall thickness).
- *Outside surface of repair (hoop layer)* – on the outside of the carbon half shells a hoop-wrapped carbon layer was installed being 0.100 inches thick. A strain gage was installed on the outside surface of this layer and data were recorded.

- *Carbon half shell* – strain gages were installed on the outside surface of the carbon half-shell prior to their placement on the pipe. These gages were located beneath the outer carbon hoop-wrapped layers.
- *FEA results for steel beneath the repair* – from the finite element model strains were extracted from the steel in the corroded region of the pipe model beneath the CRA composite repair system.

In both of these plots the data sets to be compared relative to one another are *On pipe in corroded region* (**BLUE** curve) and *FEA results for steel beneath repair* (**PURPLE** curve). The former curve corresponds to strain gage readings measured on the pipe beneath the repair, while the latter corresponds to strains calculated from the finite element model and extracted from the elements used to represent the corroded steel beneath the repair.

The significant observation is that both of these curves show strong similarities, especially during the early stages of loading. Possible sources of deviation include material properties (e.g. yield strength, strain hardening, and elastic modulus) as well as differences in actual wall thickness in the location where strain gages were installed. In effect, the strong correlation validates the analysis methods used in developing and designing the CRA system through iteratively altering the architecture of the composite.

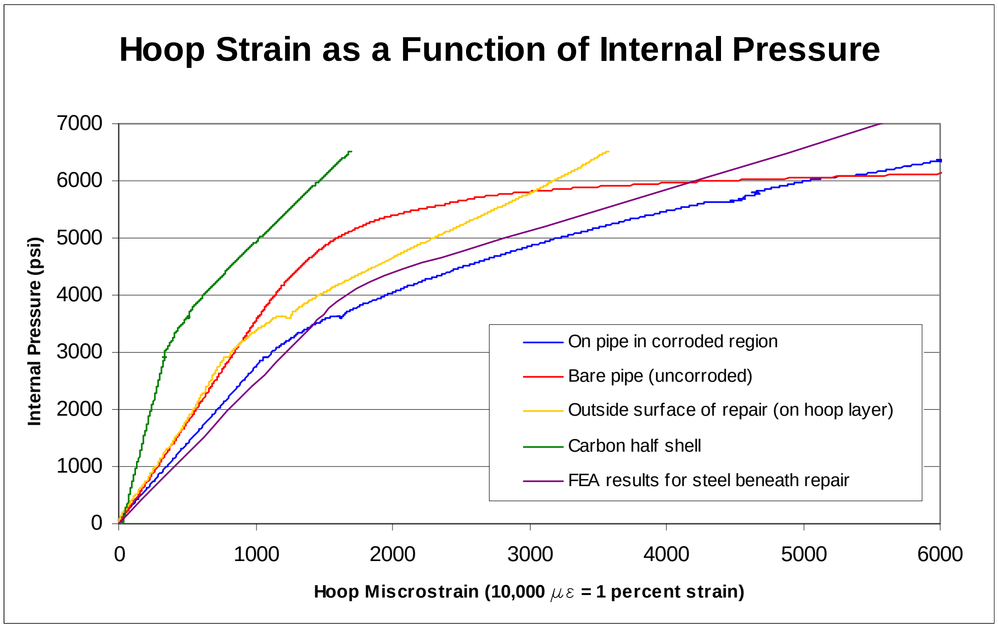


Figure 73 – Analysis and testing results for internal pressure loads

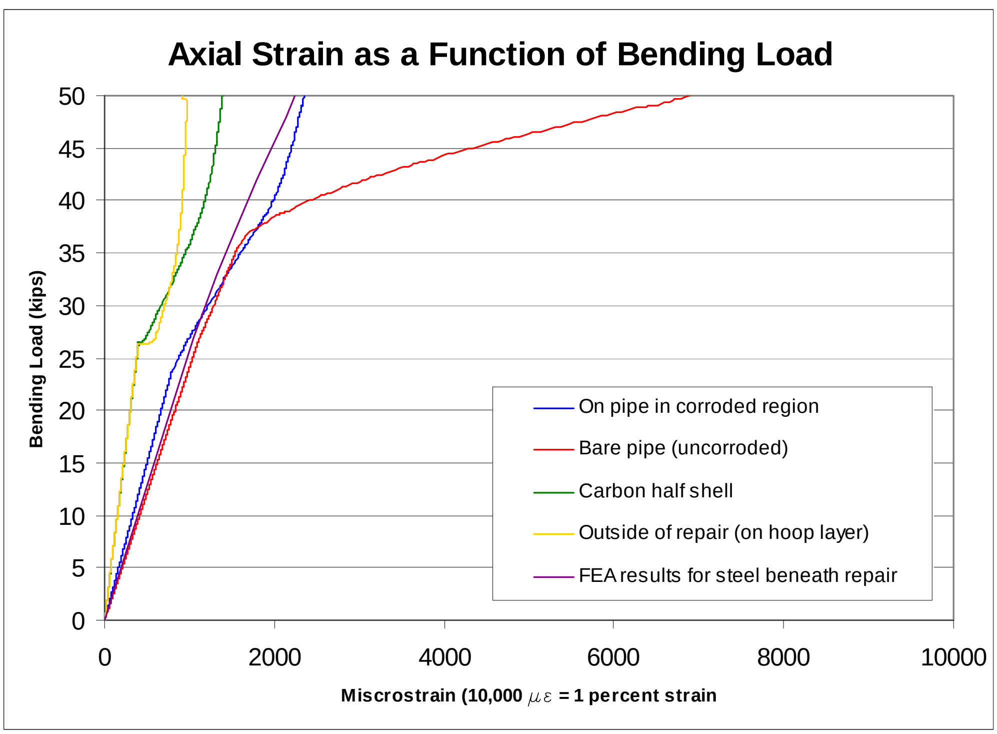


Figure 74 – Analysis and testing results for bending loads
(2,887 psi internal pressure and axial tension of 145 kips held constant)

Performance of the CRA System Relative to Design Margins

Also included in **Table 5** is each of the calculated design strain limits presented previously in the *Proposed Composite Reinforcement* section. The design strain limit values are based on limit load analyses calculated using the finite element model for the CRA design. As noted in this table, the measured strains did not exceed the specified strain limits for either the tension or bending load cases.

Establishing a design strain limit for the reinforced steel is a critical part of both the assessment and design process. It is the author's observation that when composite materials have been used in the past, there has been failure to account and address strains in the reinforced region of the steel. Most of the emphasis has been on strains in the composite material; however, as discussed previously, it is possible with an improperly installed repair to achieve low strains in the composite material and fail to adequately reinforce the corroded steel. Additionally, it is possible to generate failures in the reinforced steel when pipes are subjected to cyclic pressure service if the design does not ensure reduced strains in the reinforced section of the pipe. The corresponding failure is typically ductile overload that can be accelerated by cyclic pressure loading.

DISCUSSION

Herein a salient discussion of results are undertaken to highlight the translation of these findings into general guidelines for industry by stating current shortcomings as well as future recommendations. Prior to the current research effort there was no single document that provided guidance as to how the composite repair system should be designed. The majority of composite repairs have been limited to restoration of hoop strength for onshore pipes based on elementary mechanics. The combinations of loading presented in this study, which is typical for offshore risers, have required a more sophisticated method of assessment, namely strain-based to permit the combination of pressure, tension and bending loads to account for a certain level of plasticity in the steel. An additional benefit in the design approach presented herein is the continual focus on assessing the performance of the repair in terms of strain in the steel. Failure to assess strain in the steel could lead to disastrous consequences. By placing a strain limit on both the steel and composite materials subject to a variety of loading conditions, engineers can design composite reinforcements that consider the repair as a system and not just individual components. Additionally, a relatively simple process has been identified, employed, and validated using both experimental and analytical methods.

One topic discussed throughout this document, although never specifically addressed, relates to long-term performance. The conventional thought among users of composite materials for reinforcing pipelines involves two schools of thought. The more cautious approach requires the system demonstrates that it has the ability to provide long-term performance. This involves actual testing under sustained loading conditions representative of in situ conditions. The other camp tend to rely on a combination of safety factors and sub-scale tests intended to reflect some elements of actual in situ conditions. The author leans towards the requirements of the former as opposed to the latter, especially with regards to the repair of offshore risers that involve not only a complex set of loading conditions, but also an aggressive corrosion environment where the potential for installation problems exists. From a design standpoint, long-term performance is important in terms of knowing how to assess potential degradation mechanisms. Once this information is known, it can be used to design the reinforcement. Examples include determining the length of the repair based on long-term strength of the adhesive, as well as designing the thickness and architecture of the composite repair based on long-term strength of the composite.

The determination of an appropriate design margin is critical to the long-term deployment of composite materials in repairing and reinforcing offshore risers. If the design margin is too large, the use of composites becomes cost prohibitive, if too low, the potential for failure increases resulting in reduced reliability and user confidence. Using the fiber stress ratio of 0.4 in accordance with ASME STP/PT-005, along with the expected minimum tensile strength (short-term 95% confidence), the composite design stress limit is calculated.

One of the most significant contributors to the design of a composite repair system involves material performance. This includes the constitutive properties of both the reinforced steel and the reinforcing composite. Due to the isotropic properties for steel, it is conventional in oil field design to define material strength on either the minimum specified properties according to a given standard (e.g. API Specification 5L for line pipe [44]) or use actual data acquired from mechanical testing that typically include yield strength, ultimate tensile strength (UTS), and elongation. Test data used for the pipe material used in this study are provided in **Appendix F**. Included in this appendix are material properties including yield strength, UTS, elongation, Charpy toughness, chemistries, as well as a strain-stress curve acquired during the pull test. It is noted that only one single mechanical pull was acquired in accordance with API 5L. In this regard it is not necessary to obtain data using multiple samples as typical design methods use minimum specified material properties (e.g. for Grade X46 pipe material the yield strength used in design is 46,000 psi even though the actual material properties could be higher). With this approach design engineers can be assured that as a long a material meets the minimum material requirements per the given standard, it can be safely used. In terms of assessing material strength for composite materials, a different approach is required. Due to the anisotropic nature of composite materials and recognizing the potential for variability in manufacturing and fabrication, a larger sampling is required than with steel. As a minimum the sampling should include 10 test specimens. One reason for using multiple samples is to determine the standard deviation that can be used in setting the allowable stress for design purposes. Provided in **Appendix E** are test results for the uniaxial carbon. Included in this appendix are properties for the carbon material that include stress at failure, strain at failure, and elastic modulus. Mean and standard deviations are provided for each measurement type.

From a design standpoint, one must determine the minimum properties, which for the composite material include stress, strain, and elastic modulus. In terms of this study, the most important value is the strain at failure. From a design standpoint it is appropriate to designate a strain limit value as the mean strain minus two standard deviations (2σ). Using this approach implies that with a normal data sampling distribution, approximately 95 percent of the values are within two standard deviations of the mean. Using the carbon data in **Appendix F**, where the mean strain at failure is 1.023 percent with a standard deviation of 0.053 percent, a short-term strain limit, ε_{ST_limit}, is calculated as 0.917 percent as shown in the following equation.

$$\varepsilon_{ST\_limit} = \varepsilon_{mean} - 2\sigma = 1.023 - 2 \cdot (0.053) = 0.917 \text{ percent}$$

To account for long-term degradation the ASME STP/PT-005 *Design Factor Guidelines for High-Pressure Composite Hydrogen Tanks* standard [33] recommends that the maximum strain be limited to 40 percent of the short-term breaking load, or strain in this particular case. Therefore, from a design standpoint, and to account for the inherent variability in composite manufacturing, the recommended strain limit for the carbon material used in this study is 0.37 percent (40 percent of 0.917 percent). This method for limiting strain has a sound technical basis, but should not discourage the execution of studies to determine the long-term strength capacity of composite materials.

It is recognized that every design is subject to potential improvements, and the efforts associated with this study are no exception. An example includes the selection of the composite material. As noted in the JIP study, the two composite materials of choice were E-glass and carbon. While carbon clearly outperforms E-glass in terms of strength per weight, it does come at an economic price [52]. Carbon is on the order of five times as expensive as E-glass. Of the four major composite repair systems used in the U.S., only one company has chosen to use carbon materials (all others use E-glass). Additionally, concerns exist regarding the potential for the formation of a galvanic cell if carbon is allowed to come into contact with steel. Concerns such as this, along with the high price, have resulted in reluctance of the pipeline industry to adopt carbon materials. However, if the goal is to reduce strain in the steel, the clear choice is carbon.

One subject alluded to in a prior discussion was the design methodology developed as part of this study. It is recommended that the future development of composite repair systems be based on strain-based design methods. The methods outlined in this study, especially those presented in **Appendix B** should serve as the foundation for future studies. The limit analysis should assess the strain in the reinforced steel and ensure that the composite provides adequate reinforcement to reduce strain in the steel. Additionally, the composite manufacturer should provide to the user the range of capabilities and the maximum loads that can be safely applied to the reinforced riser (or pipe). Calculations based on classical mechanics should be used for sizing purposes; however, finite element methods should be used to perform a limit state analysis. If appropriate and justifiable, full-scale testing should be used. Additionally, in the absence of long-term test data, the design must use appropriate design factors to account for long-term and in-service degradation mechanisms.

One impetus for this study was concerns raised by the MMS regarding the acceptability of composite materials for repairing offshore risers. Even though composite materials have been used to repair offshore risers in the splash zone, it has been the author's observation that some of these repairs have been done with a rather cavalier approach that failed to take into account the potential for tension and bending loads. Provided in **Appendix G** is a copy of guidelines that were developed for MMS. While the document in its entirety is provided in the appendix, a portion of the Executive Summary is provided below. Note the emphasis on the importance of sound practices with regards to design, installation, and maintenance.

> For the past decade the use of composite materials in repairing offshore systems has been of interest to operators and regulators. Risers are one of the most important elements in an offshore system and are often susceptible to damage and degradation including outside impact and corrosion. While risers have been repaired using composite materials, to date there has not been a program to specifically assess the use of this technology relative to mechanical integrity requirements. For this reason MMS sponsored a research program starting in 2006 with the Offshore Technology Research Center (OTRC) to assess existing composite repair technology. One primary aim of this work was to develop guidelines to assist regulators, operators, and manufacturers in using composite technology to repair risers.
>
> The development of this guideline is based on findings of the funded research that also involved co-sponsored research activities from four manufacturers in the form of a joint industry project (JIP). The aim of this document is to provide guidance to industry in terms of the following areas: (1) design and development, (2) installation and implementation, and (3) operating and maintenance. The sections that follow provide details on each of these areas, with each serving a

> critical role in the deployment of effective repairs for long-term service. (*Executive Summary* of **Appendix G**)

One item not specifically addresses in this study is that of quality control, especially with regards to installation techniques. This subject is important in any discussion, but even more so when considering the installation of composite materials in an offshore environment. This is true even when accounting for manufacturing variations through the limitations imposed on allowable strains in the composite material (e.g. 40 percent of mean short-term failure strain minus two standard deviations). The complexity of the installation is exacerbated to an even greater extent when considering that the repair of risers involves repair of a vertical pipe in a splash zone. The results of the test program presented in this study involved repairs that were all done horizontally in a controlled lab setting. It is likely that prior to widespread acceptance of composite materials for offshore applications, additional studies will be required for assessing the performance of repairs in an offshore environment. Additionally, for composite repairs to be effective in solving offshore deterioration, underwater repairs will eventually have to be made. Several of the manufacturers who participated in this study have underwater resins that have been used offshore previously. To the author's knowledge, at least one of the underwater adhesive systems has undergone extensive testing by one of the major operators in the Gulf of Mexico.

The final discussion concerns economics. Although cost of materials has been discussed previously, a cost analysis of the overall repair process has not been presented in this study. When discussing offshore repairs, a fundamental metric is the day rate of the rig. Consider the following quote from Spector of the Wall Street Journal [53],

> To compete with international markets, Gulf of Mexico producers will have to pay higher rates to lease rigs. In February, BP PLC agreed to pay Transocean Inc. $520,000 a day to keep a massive drill ship in the Gulf; the three-year contract starts at the end of 2007. BP leased the same ship in 2004 for $184,500 a day.

When one considers a rig day rate on the order of $500,000 per day, time is of the essence in making repairs. It should be noted that one of the advantages of the composite reinforcement method is that production can continue during composite installation work. However, when day rates are expensive, it is likely that barge time required for repair work will also be high. That being said, any pre-fabrication work that can be done prior to field work provides significant advantages over installations that are completely done in the field. During the JIP study, the author made mental notes regarding the amount of time required by each of the manufacturers in repairing their respective systems. Although the data provided below is not purely scientific, it does provide a general means for comparing the time required for installation work. The installation teams ranged from three to four people.

Product A	30 hours
Product B	24 hours
Product C	30 hours
Product D	8 hours (installation work done by professional field labor personnel)
CRA System	5 hours (does not include shop time required for pre-fab work)

The time required for installation work is critically important because labor and equipment rental will be the single-most expensive element of the repair process. Another important consideration concerns cost of the repair from a materials standpoint. As a point of reference, Product D performed well, but had a thickness that was 3.5 times the thickness of the CRA carbon-based system. Additionally, the carbon material in the CRA system generally outperformed all of the competing E-glass systems. The point is that even though the carbon material is more expensive, when used in a pre-fab manner its superior strength performance, combined with reduced material requirements and time efficiency during installation, make it an optimum choice.

A final comment concerns the future of composite repair systems in reinforcing offshore risers. Provided below is a list of topics for further consideration that should be considered by manufacturers, operators, researchers, and industry prior to acceptance of this repair technique.

- Assess long-term performance of materials and adhesives as questions remain concerning durability and long-term performance
- Perform a study to determine the range of dimensions required for repair of risers (e.g. pipe outer diameters and thicknesses)
- Techniques for improving efficiency of pre-fab work to permit mass production
- Development of a stand-alone design document that is accepted by interested participants (having uniform acceptance standards increases the quality of repairs and reduces deviation from a centrally-accepted norm)
- Perform studies in simulated offshore environments including underwater repairs (e.g. installation in a wave tank)
- Assess performance of repairs that are installed with loading on the riser (e.g. internal pressure and axial tension) at the time of installation

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.

The key performance variables, along with the strain-based design method, were used to develop and fabricate the CRA system, a carbon-based half shell system to be installed on the outside surface of the riser. Limit state design methods based on strain limits were used to address combined loads as well as assess the integral performance of three different materials (i.e. steel, E-glass, and carbon). The detailed simulations were realized through the proposed limit design approach that was integrated with the finite element method. The results clearly demonstrate that the computational models, along with selective full scale tests, can indeed assess performance of the repair both locally and globally. The practical outcome is to assure that strain in the steel is maintained below an acceptable value and, secondly, that strain in the composite material does not exceed a value acceptable for long-term performance. Future repair systems can be developed using the processes developed as part of this study.

The CRA prototype and design was initiated with classical mechanics in order to develop the basic geometry for the repair, namely the thickness and orientation of the composite materials. Sequentially, a rigorous evaluation was performed using finite element methods to understand the load paths. Manufacturing induced residual stresses as fiber type, orientation, and layer thickness were varied. This approach enabled the assessment of shear stress at the steel-composite bond line; and evaluating strain in both the steel and composite materials at different load states including design and plastic collapse conditions. Once these iterations were completed and the optimal configurations was selected, fabrications of the prototype was completed at Comptek Structural Composites, Inc. in Boulder, Colorado. Three sets of E-glass/carbon half shells were fabricated and sent to Houston for testing including pressure, pressure/tension, and pressure/tension/bending loads. The comparison of experimental data obtained with strain gages to those predicted by the finite element models revealed that indeed the proposed techniques are successful in identifying failure loads within the selected design margins.

Data for strain, deflection, pressure, and bending/tensile forces were recorded during testing. The data were post-processed and compared to the analysis results. 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.

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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APPENDIX A

TEST PACKAGE AND PROTOCOL FOR MANUFACTURERS

JOINT INDUSTRY PROJECT TO ASSESS THE PERFORMANCE OF USING COMPOSITE MATERIALS IN REPAIRING OFFSHORE RISER PIPES
Test Package and Protocol for Manufacturers

The purpose of this package is to provide detailed information for each of the participating manufacturers on the JIP test program including objectives, expectations and responsibilities, test protocols, and scheduling. If any questions exist prior to testing, please contact Chris Alexander by phone at 281-897-6504 (direct) or by e-mail at chris.alexander@stress.com.

Background and Objectives

This test program is an outgrowth of interest in repairing offshore risers from the oil industry, manufacturers, researchers, and regulators. Active interest in using composite materials to repair offshore risers dates back into the 1990s. Although some field installations have been performed, there has not been a comprehensive study assessing the use of composite materials in repairing risers. Based on some discussions with offshore operators, the success of these repairs have been less than expected as issues have occurred due to tension and bending loads not present in typical onshore applications. Recognizing the need for additional studies, in early 2006 the Minerals Management Service (MMS) contracted the Offshore Technology Research Center (OTRC) at Texas A&M University to undertake a study to assess the current state of composite technology in repairing offshore risers. Once the engagement had been executed, the staff at OTRC contacted Chris Alexander at Stress Engineering Services, Inc. (SES) about being involved in the study. After some discussions, it was apparent that existing composite manufacturers could be brought into the study to expand the overall program and actually assess the current state of technology through limited full-scale testing and analysis methods. SES contacted five manufacturers who elected to participate.

The objective of the current program is to assess the current state of composite technology in repairing offshore riser pipes using full-scale testing. The test program has been designed to assess the effects of internal pressure, tension, and bending. During testing, specific test sequences will be employed to assess the capacity of each composite repair system in restoring strength to corroded riser pipes.

Testing Program Details

Three separate tests will be performed to assess the capability of the composite repair systems in reinforcing the corroded pipes. The three tests will consider the following loading combinations.

- Sample #1: Internal pressure
- Sample #2: Internal pressure and tension
- Sample #3: Internal pressure, tension, and bending

8.625-inch x 0.406-inch, Grade X46 pipe material will be used in the test program. Each of the three test samples will be machined to simulate corrosion that is 0.200 inches deep (50 percent of the pipe wall), 24 inches long, and exists circumferentially around the pipe. **Figure A1a** is a schematic that shows the sample layout for Sample #1 and #2. **Figure A1b** is layout for Sample #3. As noted in these figures, the corrosion length and depth is exactly the same for all samples. The only difference is that Sample #3 is long enough to permit the use of a four point bending configuration.

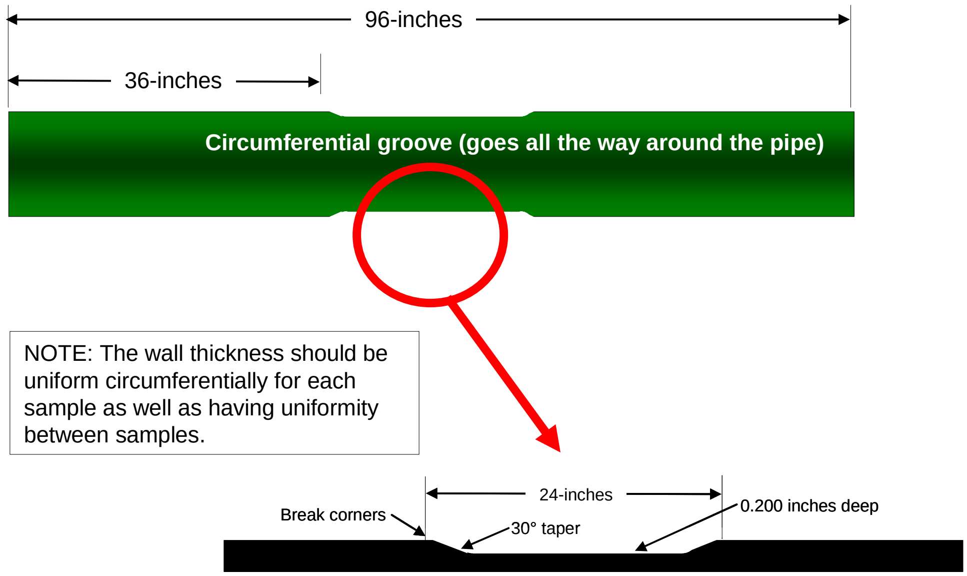


Figure A1a – Layout for Sample #1 and #2
(Pressure and Pressure plus Tension samples)

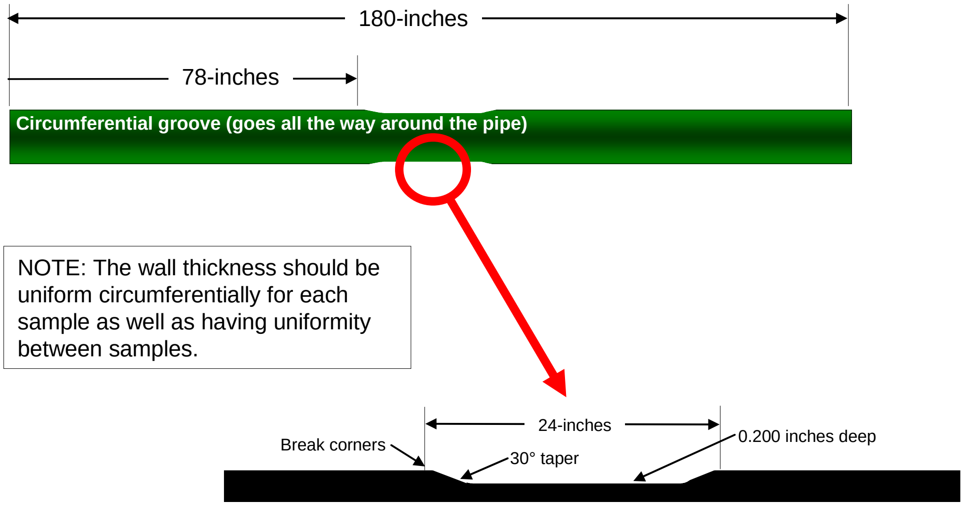


Figure A1b – Layout for Sample #3
(Pressure, Tension, and Bending samples)

In selecting the appropriate loads for the test program, design codes used for offshore risers have been reviewed: ASME B31.8 and API Recommended Practice 1111. This test program has opted to use the design methodology adopted by API RP 1111, Section 4.3 because of its reliance on strain-based design criteria.

Manufacturers are encouraged to consider the following minimum design loads associated with the different loading conditions. The repaired section should, as a minimum, be able to ensure that the damaged sections of pipe can withstand the intended design loads. These have been calculated considering the following information:

- Pipe geometry (8.625 inches x 0.406 inches)
- Pipe material properties (Grade X46, minimum specified yield strength of 46,000 psi)
- Combined loading including internal pressure (hoop stress), tension (axial stress) and bending (axial stress)
- Allowable stresses based on a percentage of burst strength

The discussions below provide basic details on the testing approach that will be used to assess the performance of each repaired test sample. As stated previously, the intent is for each test sample to demonstrate the capability of the composite repair materials in reinforcing the pipes.

<u>Sample #1: Internal pressure</u>
Sample pressure will be increased to failure. As a minimum, pressure holds will occur at Design Pressure (2,887 psi) and Hydrostatic Test Pressure (3,609 psi).

<u>Sample #2: Internal pressure and tension</u>
Sample pressure will be maintained at 2,887 psi (design) and tension will be increased after a hold at 145 kips (axial stress corresponding to 60 percent of yield that includes the effects of internal pressure end loading). The tension will be increased to either failure or to a point where thru-wall plasticity has established the lower bound collapse load. Refer to point #5 in the **Manufacturer Responsibilities** section of this package.

<u>Sample #3: Internal pressure, tension, and bending</u>
Sample pressure will be maintained at 2,887 psi (design) and tension will be held at 145 kips. Bending will be increased to either failure or to a point where thru-wall plasticity has established the lower bound collapse load.

Manufacturer Responsibilities
To ensure consistency in testing and corresponding results, all manufacturers are encouraged to consider the following requests and suggestions.

1. Manufacturers are responsible for providing all necessary supplies for performing the repairs. SES will provide pipe stands and a location for you and your staff to install the repairs.
2. Manufacturers are responsible for shipping all necessary supplies and equipment to SES prior to their assigned installation week.

3. All manufacturers are responsible for providing staff necessary for completing installation efforts. SES will not provide staff to assist in the repair efforts.
4. All manufacturers are responsible for determining how to repair the defects. While SES can provide general guidance, it is the ultimate responsibility of each manufacturer to know the capabilities of his particular system and how the repairs should be made. Please refer to information regarding the corrosion defects for each test sample and the loading that will be applied.
5. Manufacturers should have repair lengths that are long enough to prevent lap shear failure from limiting the axial tensile capacity of the repair. Calculation can be made to determine the lap shear capacity of the repair versus axial strength of the repair.
6. SES will install strain gages in the corroded regions of each test sample. SES will make every effort to reduce the overall profile of these gages to ensure the maximum performance of the repair systems.
7. Although each of the three test samples is assessing and testing different loads, all three test samples should be repaired using the exact same configuration. In other words, there should be no difference in how each of the three samples is repaired.
8. Manufacturers and their staff are welcome to attend all testing of their products on Thursday and Friday; however, SES requests that no outside guests be permitted to attend without prior SES approval.
9. It should be noted that some outside SES guests will be observing various installation and testing phases of the study. These individuals will include staff from MMS, OTRC, and Texas A&M University.
10. All test results will be kept confidential and test results will only be provided to each manufacturer. At the completion of the test program, a compilation of test results will be prepared that include non-descript data references such as Product A, Product B, etc.

Weekly Schedule

To ensure consistency in the weekly scheduling, each manufacturer will be given the same amount of time for installation efforts, curing time, and testing efforts. Provided below are the daily activities that will take place during each week. Lunch will be provided to you and your staff on every day of the week except Wednesday (if you are interested in joining us). The SES lab orders lunch for the engineers and technicians working in the test lab on a daily basis.

Monday	Manufacturers arrive at SES and start installation efforts (9:00 AM)
Tuesday	Continue installation efforts
Wednesday	No activity by manufacturer (curing day and SES prep day)
Thursday	Morning: Burst test using Sample #1
	Afternoon: Tensile test using Sample #2
Friday	Bending test using Sample #3

You are welcome to ship your supplies up to one week prior to your testing week.

Testing Efforts

Before testing is started, SES will provide to each manufacturer a detailed write-up showing the planned testing activities.

Stress Engineering Services, Inc.
13800 Westfair East Drive
Houston, Texas 77041
www.stress.com

TEST PROCEDURE FOR JIP COMPOSITE REPAIR
(Testing started August 14, 2006)

Project Number:	PN115661CRA
Project Manager:	Chris Alexander
Client:	JIP Participants, MMS, and OTRC
Testing Date:	Monday, August 14, 2006 (start date)
Testing Description:	Full-scale testing of 8-inch pipe with composite repair materials

Project Description

This project involves full-scale testing on 8.625-inch x 0.406-inch, Grade X46 pipe. The objective of the program is to assess the level of reinforcement provided by composite to corroded riser pipes considering internal pressure, tension, and bending loads.

Activities (unless otherwise noted) associated with the test program will involve the following tasks:

1. Attach end caps and end fixtures to each test assembly comprised of the 8-inch NPS pipe. Make sure 6-feet of center section of each sample is sandblasted. The three test samples will integrate the following load combinations (refer to **Figure A2**):
    a. Pressure
    b. Pressure and tension
    c. Pressure, tension, and bending
2. Install strain gages at selected locations to the three samples (refer to **Figure A3**).
    a. Nine (9) gages before repairs made
    b. Three (3) gages after repairs made (on outside of composite repair)
3. Measure wall thicknesses using UT meter at all strain gage locations
4. Place the test assembly in the Mohr 1 million lbs load frame and connect necessary hardware and instrumentation (**Figure A4** and **Figure A5**).
5. Perform testing to simulate in situ conditions and then take each assembly to failure or load at which significant plasticity is achieved.
    a. Pressure – **pressure** failure
    b. Pressure and tension – **tension** failure
    c. Pressure, tension, and bending – **bending** failure
6. Provide a summary report after each that includes results.

Equipment Needed

- The following load frames and locations:
  - Test pit – pressure sample
  - Vertical frame (1 million lbs capacity) – pressure/tension sample
  - Horizontal frame (1 million lbs capacity) - pressure/tension/bending sample
- Two hydraulic cylinders to provide four point bending loading (100 kip minimum).
- Load cell to measure vertical forces on bending test sample (100 kip minimum).
- Five (5) yo-yos to measure vertical displacement (12” minimum).
- One (1) yo-yo to measure horizontal displacement (12” minimum).
- Twelve (12) two-gage rosettes for measuring strain (refer to **Figure A3**).
- DAQ system to record strain, loads, and yo-yo displacements.
- Straps to restrain test assembly during failure testing.
- Safety lighting (RED).

Safety Procedures

The following steps will be carried out to ensure the safety of SES lab personnel, guests, and equipment.

- Barricades will be used to provide protection in the event of a failure of test assembly during the *failure phase* of testing
- Restraining straps and/or chains will be placed around the pipe during testing.
- A RED light will be running continuously during testing during the period of imminent failure to designate that testing is in progress.

Testing Procedure

Pre-testing procedures:

1. Fabricate test samples.
2. Mark the locations for strain gages and install. NOTE: Make sure three strain gages installed on outside of composite repair after installation has been done.
3. Connect all pressure equipment and measurement devices required for testing. Make sure that yo-yos are calibrated for the anticipated lengths of displacement.
4. Install chains and harnesses around the pipe and testing assembly.
5. Have proper safety indicator lighting available and notify lab personnel that testing is to start.

Testing procedures:

There are basically three phases of testing: (a) Pressure, (b) Tension, and (c) Bending.

Pressure Sample

1. Start the data acquisition system in order to record data. Record data at 1 scan per second.
2. Apply loading in the following sequence (pressure calculated using API RP 1111):
   a. Increase pressure to Design Pressure of **2,887 psi** at a rate of 10 psi per second and hold for 5 minutes.
   b. Increase pressure to Hydrostatic Test Pressure of **3,609 psi** at a rate of 10 psi per second and hold for 5 minutes.
   c. Increase pressure to failure at a rate of 10 psi per second (NOTE: failure at 70 ksi hoop stress is approximately 6,590 psi).

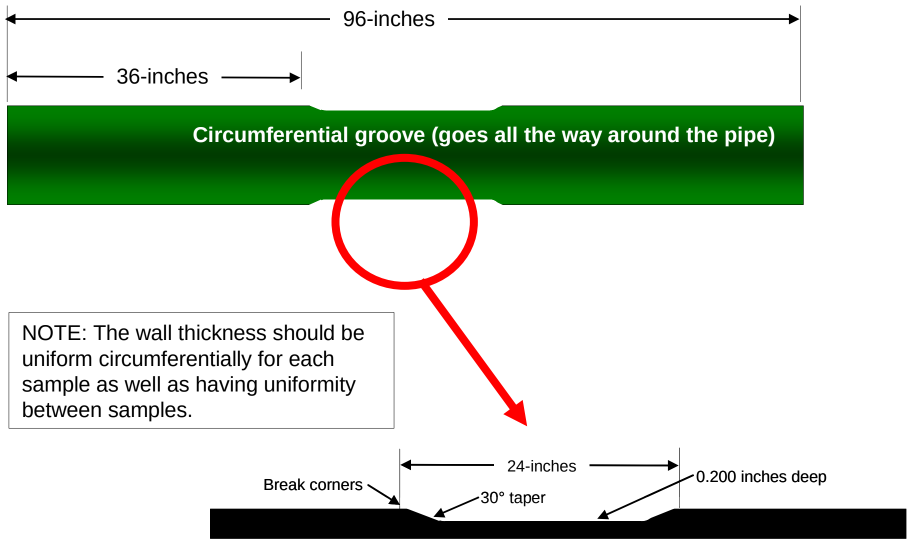
Tension Sample

1. Start the data acquisition system in order to record data. Record data at 1 scan per second.
2. Apply loading in the following sequence (pressure calculated using API RP 1111):
    a. Increase pressure in sample to Design Pressure of **2,887 psi** at a rate of 10 psi per second and hold during rest of test.
    b. Make sure that hydraulic cylinders out ports are OPEN (so that proper axial tension develops in sample due to internal pressure).
    c. Apply axial load to test sample and increase to **145 kips** at a rate of approximately 250 lbs per second. Hold for **5 minutes** (axial load corresponds to 60 percent of yield that includes the effects of internal pressure end loading) and observe strain distribution in the test assembly.
    d. Increase axial tension to failure at a rate of 250 lbs per second (NOTE: failure at 70 ksi axial stress is approximately 770 kips).

Bending Sample

1. Start the data acquisition system in order to record data. Record data at 1 scan per second.
2. Apply loading in the following sequence (pressure calculated using API RP 1111):
    a. Increase pressure in sample to Design Pressure of **2,887 psi** at a rate of 10 psi per second and hold during rest of test.
    b. Make sure that hydraulic cylinders out ports are OPEN (so that proper axial tension develops in sample due to internal pressure).
    c. Apply axial load to test sample and increase to **145 kips** at a rate of approximately 250 lbs per second. Hold for this load for the remainder of the test. Observe strain distribution in the test assembly.
    d. To apply bending t the sample, increase the downward displacement of the two hydraulic cylinders (four-point bending configuration). The reaction force will be monitored to determine the corresponding applied bending moment.
        i. Apply bending moment to achieve yield: 141.9 kip-ft (**4.05 kips force at rams**) at a rate of 100 lbs per second
        ii. Increase bending moment to achieve plastic hinge (1.5 times yield): 287.9 kip-ft (**8.23 kips force at rams**) at a rate of 100 lbs per second
        iii. If plastic collapse has not occurred, increase ram load to the point of failure

Configuration for 8-ft Samples



Configuration for 15-ft Samples

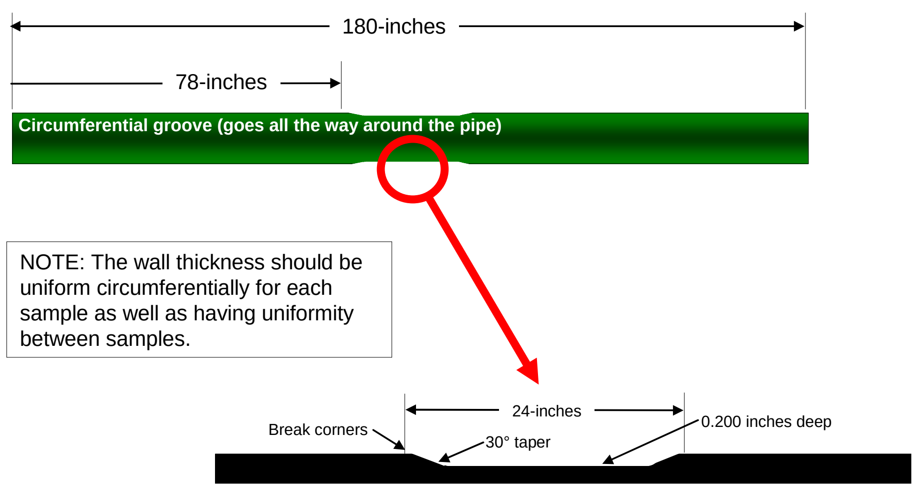
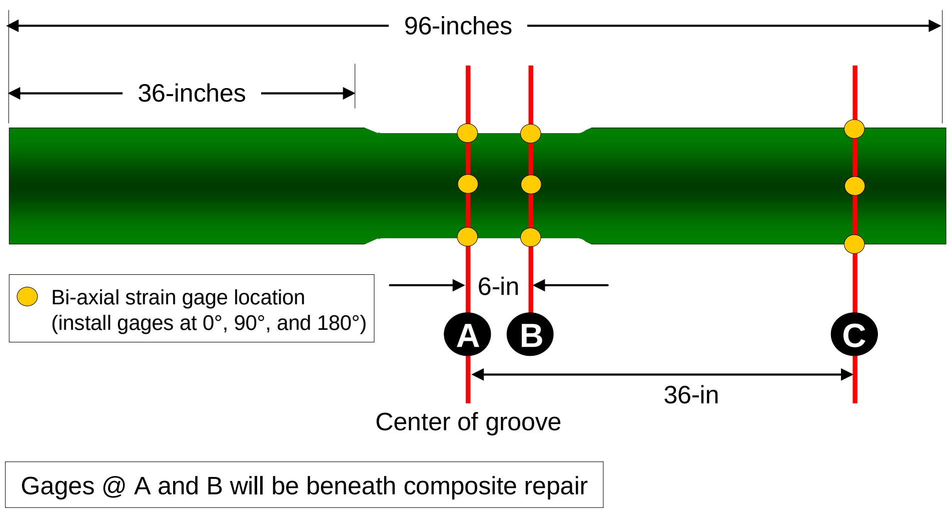


Figure A2 – Test samples

Strain gage locations for 8-ft samples
(9 total gages per sample)



Strain gage locations for 15-ft samples
(9 total gages per sample)

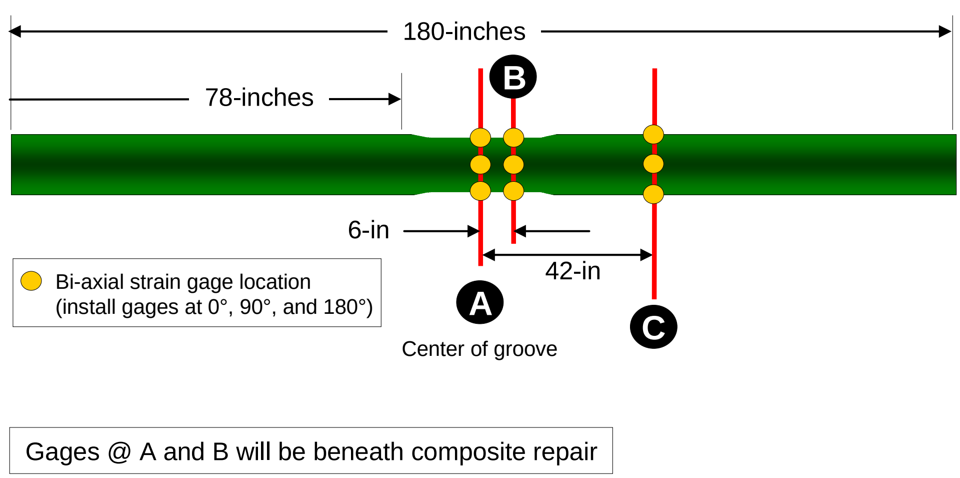


Figure A3 – Location of strain gages for test samples

<u>Gage Numbering</u>

Center	1 (top)	2 (neutral axis)	3 (bottom)
6-inch from center	4 (top)	5 (neutral axis)	6 (bottom)
Base pipe	7 (top)	8 (neutral axis)	9 (bottom)
Center (**<u>outside</u>** of composite)	10 (top)	11 (neutral axis)	12 (bottom)

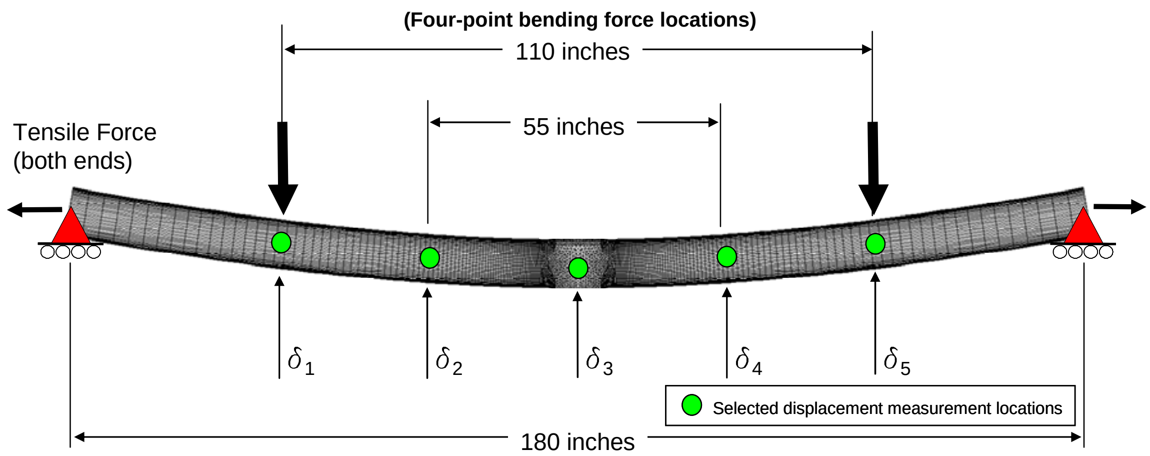


Figure A4 – Schematic of test assembly including loads and yo-yos

Figure A5 – Photos of test set-up from previous testing
(horizontal 1 million lbs load frame with top-side bending beam)

APPENDIX B

DESIGN METHOD BASED ON LIMIT ANALYSIS TECHNIQUES

Design Method Based on Limit Analysis Techniques

At the present time there is no single design document or standard that governs the use of composite materials in reinforcing offshore risers. One of the primary aims of this study, in conjunction with the development of an optimized repair system, was to develop a design basis for evaluating the acceptability of a given reinforcement design. There are several design codes and standards used in the oil and gas industry. *Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design) API Recommended Practice 1111*, which is a strain-based design method, is commonly used for the design of offshore risers, along with ASME B31.8, *Gas Transmission and Distribution Piping Systems*, the latter being based on elastic design methods. Another useful resource, although not conventionally used for the design of pipelines and risers, is the ASME Boiler & Pressure Vessel Code, Section VIII, Divisions 2 and 3 and the Nuclear Code, Section III. Divisions 2 and 3 and Section III recognize the use of elastic-plastic design methods, including both analytical and experimental methods. Using these three design standards as references, this study developed a single unified design basis that included the following elements.

- Ability to account for the contribution of different materials (i.e. steel and reinforcing composite)
- Integration of combined loads applied simultaneously to calculate strains in the reinforced steel and reinforcing composite materials
- Means for determining the maximum strain and design load limits for the reinforced steel based on the ultimate capacity on an undamaged riser section (or any other structural member for that matter)
- Calculate the maximum safe load that can be sustained by the reinforced section of riser, which is then compared to the maximum strain and design load limits

This appendix covers a range of subjects that include background on limit state design methods in terms of current practices including how to perform a limit state analysis followed by a discussion on how to determine allowable design loads and strain limits for structures reinforced with composite materials.

Limit State Design Using Existing Standards and Codes

At the very core of limit state design is determining either analytically or experimentally the ultimate capacity a structure can withstand before plastic collapse occurs. From a loading standpoint this is the condition at which unbounded displacements occur. NB-3213.28 of Section III (Nuclear Code) defines the limit analysis collapse load as *the maximum load a structure assumed to be made of ideally plastic material can carry*.

The ASME Boiler & Pressure Codes (Section III and Section VIII) provided the most prescriptive design methods of any of the codes referenced. Within these design codes there are two competing schools of thought regarding determination of the collapse load: Limit Analysis Collapse Load (Section III, NB-3228.1 and Section VIII) and Plastic Analysis Collapse Load. Review the details provided below on these two methods.

Limit Analysis Collapse Load

- FEA model that represents the geometry, loading, and boundary conditions (but not material) of a real structure.
- Analysis must use small deflection theory
- Must use an elastic-perfectly plastic material model based on $1.5S_m$
- Loading only includes primary loads such as pressure and weight
- Design limit set as specified loading that does not exceed two-thirds of the lower bound collapse load.
- Per NB-3213.28: The maximum load that a structure assumed to be made of ideally plastic material can carry is the Limit-Analysis Collapse Load.

Plastic Analysis Collapse Load

- Can give higher allowable loads:

  - Material model can use actual YS and UTS values (not just perfectly plastic)
  - Does not account for two-factor definition of S_m, which may result in significantly higher allowable loads for high-strength steels
  - Large deformation may or may not be used, but requires use of double-elastic slope method
- Per NB-3213.25: The collapse load is the load at the intersection of the load-deflection or load-strain curve and the collapse limit line.

After reviewing the available options, the Plastic Analysis Collapse Load was selected. This was done for several reasons, the primary being the concrete methods for mathematically determining the collapse load based on the intersection of the load-strain curve and the collapse limit line. This method is also referenced in the experimental limit analysis section 6-153 of ASME Section VIII, Division 2. This technique for determining the collapse load is also known as the double-elastic slope method. Consider details provided in **Figure B1**. This curve was generated from finite element data associated with internal pressurization of a thick-wall pipe. The pressure-displacement data is plotted and used to determine the collapse load using the following five step process.

1. Find a load where the entire structure is elastic.
2. Find the corresponding displacement (u) at the maximum elastic load and then double this value (2u)
3. Draw the straight collapse line through this new point (2u)
4. Determine the point of intersection between the loading line and the collapse line – this defines the collapse load.
5. Apply appropriate margin to determine the design load.

As shown in this figure, two design loads were calculated: one point using a design margin of 1.8 (395 psi) and the other having a design margin of 2.0 (355 psi). The design margins typically range from 1.5 to 1.732. For this particular study, a design margin of

2.0 will be used. Although this design margin exceeds several of the more commonly design codes, the additional margin is used to account unknown factors such as variations associated with quality of installation.

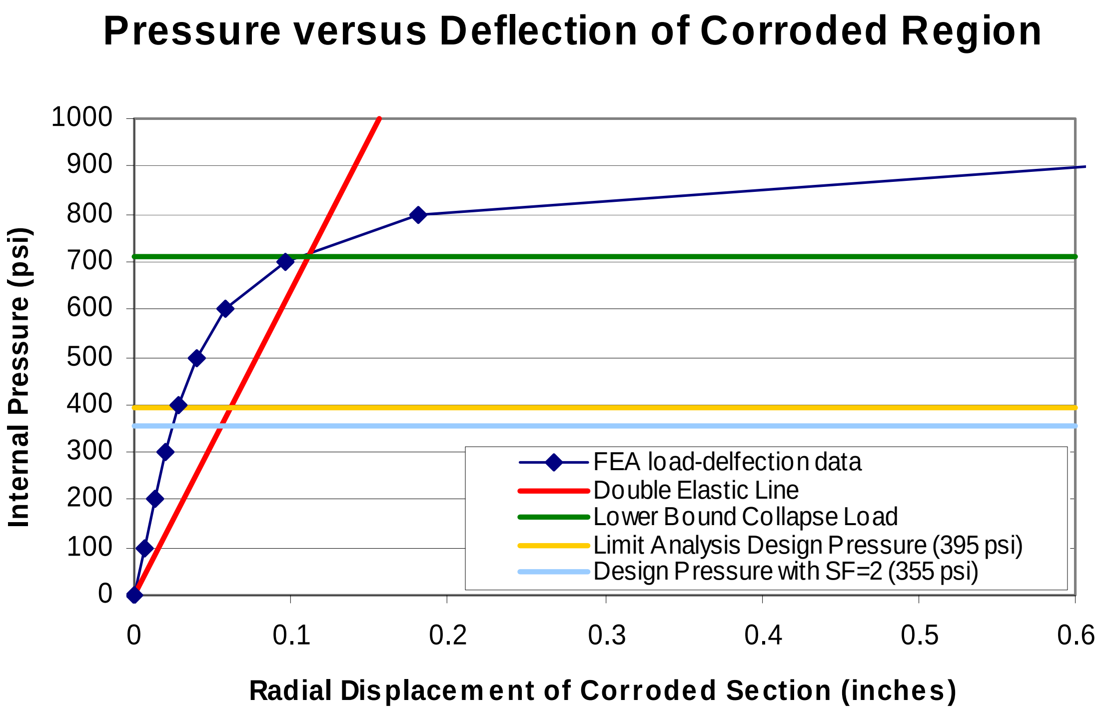


Figure B1 – Exemplar pressure-deflection plot used to determine collapse load

In interpreting the data plotted in **Figure B1**, the conclusion is that the pipe can be safely operated at 355 psi assuming a design margin of 2.0.

How to Determine Allowable Design Loads and Strain Limits

Having presented details on how to perform a limit state analysis, it is appropriate to discuss how to properly use this technique to establish the design load and strain limit for composite reinforced sections. The reason for the additional discussion is that the purpose in reinforcing a damaged section is to restore that section to have the integrity of an undamaged section subject to the same loading conditions. It should be noted that this procedure can be completed using either experimental techniques or results calculated using finite element methods.

Essentially, two analyses are conducted. The first involves assessing the limit state design for an undamaged structure. Once this is done, these data are used to define the design load and acceptable range of strains. Consider the experimental data provided in **Figure B2** showing pressure versus strain for an 8.625-inch x 0.406-inch, Grade X46 pipe. The reference data set is the RED curve that plots pressure-strain data for an uncorroded pipe. Using the double elastic slope method, lower bound collapse load is calculated as 5,975 psi. Two important calculations are performed using this value.

- Using a design margin of 2.0, the maximum permissible design load (or pressure) is calculated to be 2,998 psi.
- Using the triangular region created by the intersection of the double elastic curve and the design load curve, the permissible range of strains is identified. Using the data plotted in **Figure B2**, the strain limit is 0.17 percent.

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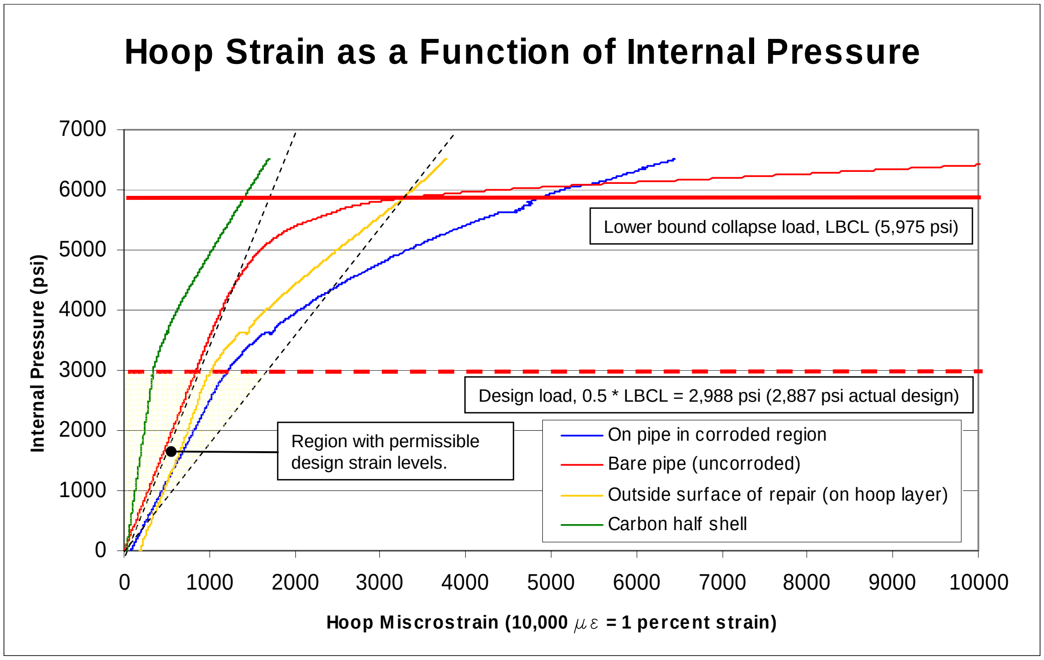

Figure B2 – Exemplar test plot showing limit state design parameters

Once the design limits are identified, the next step is to compare either calculated or experimentally measured strains to the strain limit. In **Figure B2**, consider the solid **BLUE** curve that presents data measured by a strain gage installed in the corroded region of the repair beneath the composite repair. As shown, this curve resides within the acceptable load-strain range. On the other hand, consider the data plotted in **Figure B3**. Three curves are plotted, two of which are the same data sets included in the previous plot. However, strain data for an unreinforced corroded pipe section is also plotted (**BLACK** curve). As shown in this figure, the data for the unreinforced sample clearly reside outside the acceptable load-strain region. Another option would be to use the double elastic slope method to determine the maximum the plastic analysis collapse load and corresponding design pressure. If this were done on the unreinforced data set, the calculated design load is approximately 1,400 psi. This is approximately one-half the actual design load of 2,988 psi for the undamaged pipe section.

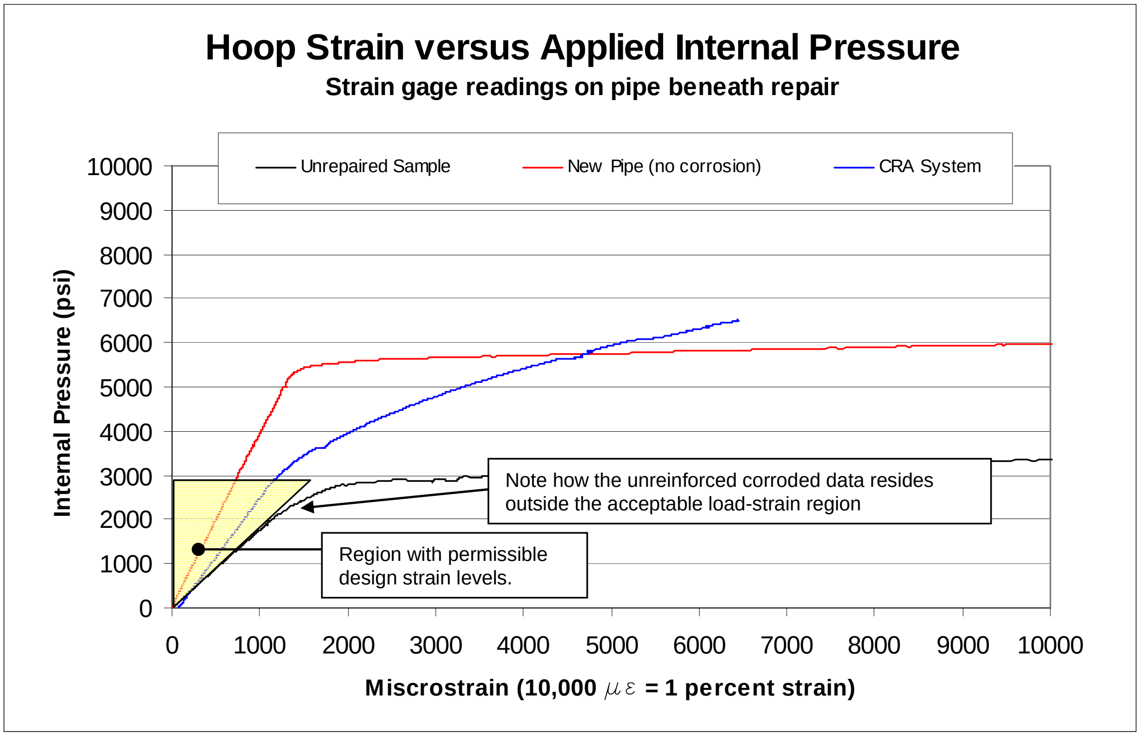

Figure B3 – Exemplar plot including corroded/unreinforced data

The methods presented in this appendix were used in this study to determine acceptable design loads and corresponding strain limits. In post-processing the experimental data, strains measured in the steel beneath the composite reinforced sections were evaluated relative to the strain limit. The reinforcement was deemed acceptable when the measured strains remained below the specified strain limit for the respective loading condition.

APPENDIX C

FINITE ELEMENT MODELING TECHNIQUES

Finite Element Modeling Techniques

Finite element analysis (FEA) played an important role in the development of the CRA composite repair system. FEA permitted the analyst to assess the effects of changes in different design variables on the overall performance of the repair. What was primarily monitored during the analysis work was the strain in the steel beneath the composite reinforcement. Using limit analysis methods, acceptable strain limits were determined and changes in the geometry of the composite reinforcement were made in order to achieve an optimized design. The evaluation process included studies addressing the following subjects:

- Load transfer between the steel and the composite
- Strain in the steel and composite at different stages of loading (namely the design and plastic collapse conditions)
- Assessing the effects of changes within the composite including thickness, architecture, and fiber type
- Determining the effects of debonding at the steel-composite interface
- Calculating compressive stress due to the addition of reinforcement and stiffness mismatch between the steel and composite
- Evaluating the effects of taper angle at the edge of the composite on stresses in the steel at the edge of the repair

Due to the complex nature of both the loading conditions and the composite variations and the intent to seek unique solutions, several different finite element model types were used. A model using shell elements was the primary vehicle used to assess the overall response subject to pressure, tension, and bending loads. However, to calculate compressive stresses and evaluate the effects of the taper length, an axisymmetric model was used. Discussions follow that provide specific details on these models and how they were used as part of the overall optimization process. The models were constructed using the PATRAN modeling package, while processing and post-processing were performed using the ABAQUS (version 6.4) general-purpose finite element code. The sections that follow provide details on the finite element models used in this study and address following topics:

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

Before engaging in detailed discussed associated with the different model types, a few comments are warranted on why and how FEA models contributed to the overall effort. It is common practice in many engineering disciplines and industries to combine analysis methods with full scale testing, especially when considering the development of a prototype system. In this particular program, insights from previous studies and the JIP program were used to set the foundation for the geometry of the CRA system. FEA was used to fine-tune the selection of materials and geometry. An additional benefit was that "sub-analysis" studies could be conducted using the existing models to assess factors such as adhesive debonding and taper length. The economic benefit in making changes to a FEA model, as opposed to actually having to re-run tests to assess changes in different variables, is significant. Another important observation, one that lends credibility to the methods employed in this study, is that there was sound agreement when comparing the analysis results with those measured experimentally. Even unconventional variables such as shear strength showed good correlation with what was expected and has been observed in the field.

Analyses Using FEA Shell Models

The primary model type in this study used the shell element. Analyses assessing the performance of composite materials typically involve shell elements. 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 sections that follow provide details on materials, geometry and boundary conditions, loads, and post-processing.

Materials

Consider the text copied in **Figure C1** from an ABAQUS input used in this study. As noted, the input used to designate the composite materials, *SHELL SECTION, includes details such as layer thickness, orientation, and material type. With rather minor modifications to the input deck, the geometry, material, and architecture including stacking sequence can be changed. Another important benefit is the ability during post-processing to look at the stress and strain distribution in different layers. Once each analysis is run, it important to be able to assess strains in different layers. Like layers in an onion, the composite can be "sliced" to reveal the contribution each layer makes to the overall reinforcement.

In the input deck material properties are controlled by the *MATERIAL card. As noted, elastic (*ELASTIC) material properties are included for each material and used exclusively for the composite. In terms of interfacing with the element, especially with regards to the composite, the material properties are input in local coordinates of the element. For materials modeled isotropically such as the pipe steel in this study orientation is not important; however, when modeling composite orientation is critically. This especially true when one considers one of the primary advantages in using composite is to be able to control the directional dependence of properties. The listing of elastic properties listed after 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 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 epoxy resin. The *PLASTIC card is used for the steel. For the given input deck, elastic-plastic material properties are used based on mechanical measurements from the steel pipe used in testing. It is possible that a full stress-strain curve could have been used to account for strain hardening.

```
**
*SHELL SECTION, ELSET=CORR, MATERIAL=STEEL
    0.203,     5
*SHELL SECTION, ELSET=TRANSITION, MATERIAL=STEEL
    0.3045,     5
*SHELL SECTION, ELSET=PIPE, MATERIAL=STEEL
    0.406,     5
**
** 90 is hoop and 0 is axial for fiber orientation
**
*SHELL SECTION, COMPOSITE, ELSET=COMP_COR, OFFSET=0.300
0.100, 1, CARBON, 90.0
0.100, 1, CARBON, 90.0
*SHELL SECTION, COMPOSITE, ELSET=HALFSHL, OFFSET=0.500
0.050, 1, E-GLASS, 90.0
0.100, 1, CARBON, 0.0
0.100, 1, CARBON, 0.0
0.100, 1, CARBON, 0.0
0.100, 1, CARBON, 0.0
0.100, 1, CARBON, 90.0
0.050, 1, E-GLASS, 90.0
**
** E-glass material
**
*MATERIAL, NAME=E-GLASS
*ELASTIC, TYPE=LAMINA
    2.0E+6, 2.0E+6, 0.3, 2.0E+5, 385.0, 385.0
**
** Carbon material
**
*MATERIAL, NAME=CARBON
*ELASTIC, TYPE=LAMINA
    1.0E+7, 1.0E+6, 0.3, 3.85E+5, 385.0, 385.0
**
** Elastic-plastic steel
**
*MATERIAL, NAME=STEEL
*ELASTIC, TYPE=ISO
    3.E+7,      0.3
*PLASTIC
51000.0, 0.0
74600.0, 0.20
**
```

Figure C1 – Section of ABAQUS input deck for composite material

Geometry and Boundary Conditions

The shell finite element models used a quarter-symmetry boundary condition. This configuration implies that loading and geometry permits dissection of the structure in two planes. **Figure C2** is a schematic diagram showing the overall layout for the model. The two symmetry planes are clearly identified in this figure.

Also shown are the boundary conditions. At the center symmetry plane of the model (left hand side of the figure) the pipe/composite is free to move vertically but restrained in the longitudinal direction. On the right hand side of the model a simply-supported condition is invoked where the pipe is free to translate axially. This configuration also works well in modeling a four-point simply-supported load condition that will be discussed in a later section.

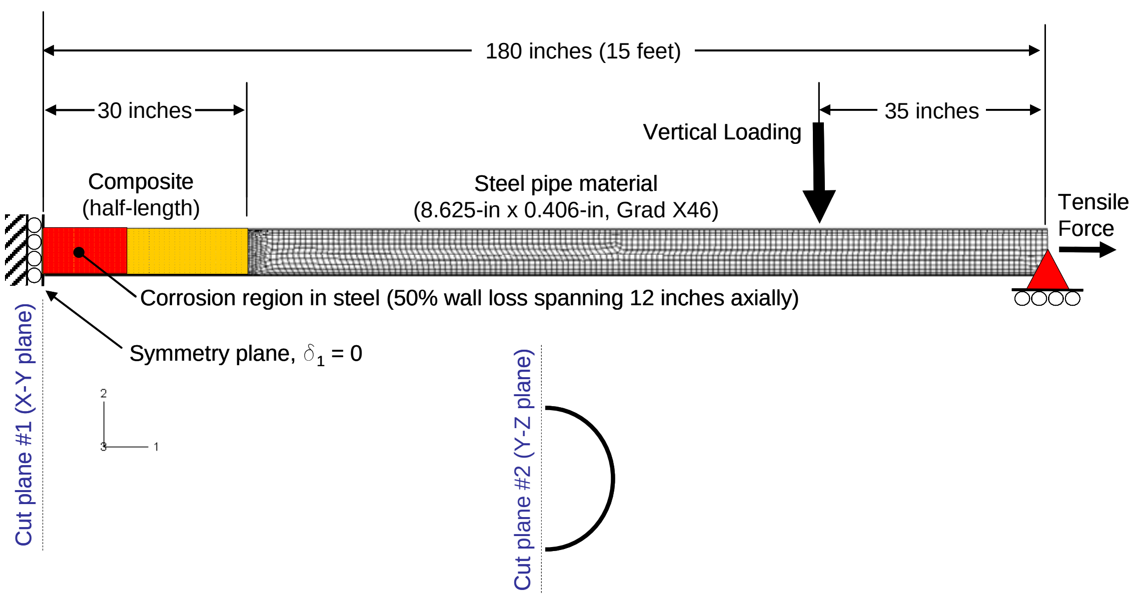

Figure C2 - Schematic diagram showing layout for shell model

In terms of modeling the geometry for the pipe and composite, there are several noteworthy points.

- The corroded section of the pipe is modeled by reducing the thickness of the shell elements in the corroded region (**RED** region in **Figure C2**).
- The composite spans 30 inches axially (60 inches if a full symmetry condition had been modeled). To model the composite material, a duplicate set of elements are created that reside on top of the elements used to model the steel. These sets of elements share common nodes, but permit the application of unique material properties for each element set. What is not permitted with this configuration is the ability to assess the effect of disbonding between the steel and composite (refer to details in the following bullet).
- One of the questions developed during the course of this study was assessing the potential for disbonding between the steel and composite. This condition is a reality, especially when one considers that during the experimental phase of work a tensile test was performed to assess the shear strength of the bond at the steel-composite interface. There are several methods for modeling debonding, several being relatively sophisticated worthy of a study in and of themselves; however, the approach elected for this study is a simplified approach that models contact between non-joined sections. **Figure C3** shows two regions of debonding that were simulated, “A” the outer section and “B” the center section. Debonding was modeled by creating duplicate elements and nodes for the composite material, but the nodes were not joined (*equivalenced* using the PATRAN modeling package nomenclature) as done previously when both the steel and composite shared the same nodes. To prevent materials from moving through one another in the radial direction, contact elements were invoked. Using this configuration, when the pipe expands due to internal pressure it transfers radial contact stresses to the composite material. However, when the steel is loaded in axial tension, only those composite elements intimately connected to the steel (through the sharing of common nodes) provide axial reinforcement. The technique was an effective means for modeling debonding.

A review of the current ABAQUS literature indicates there are several relatively sophisticated techniques for modeling adhesive bond lines and capturing shear stress failure conditions.

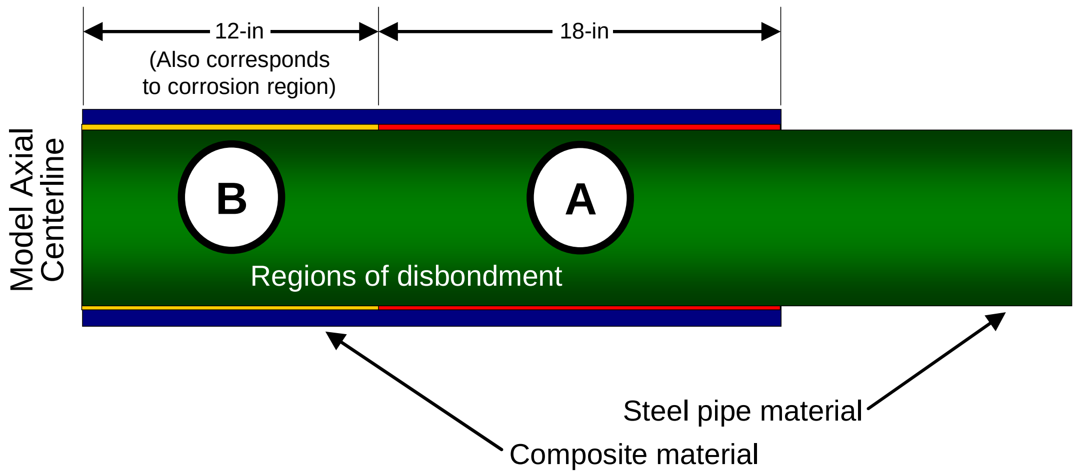

Figure C3 – Regions of debonding

Loading Conditions

The loading simulated conditions used during the experimental phase of the study. For the shell model these loads included an internal pressure of 2,887 psi, an axial tension load of 145 kips, and bending load increased incrementally up to 156 kip-ft. The pressure and tension loads were held constant, but the bending load was increased incrementally to determine the lower bound collapse load. Refer once again to **Figure C2** showing the locations on the model where the axial tension and vertical bending loads were applied.

A final comment addresses checking the model prior to post-processing. Calculations based on classical mechanics were used to estimate stresses associated with the pressure, tension, and bending loads. Once the models were analyzed, stresses were checked in the model away from local discontinuities to ensure that the model was properly loaded. Additionally, forces were summed in the model to ensure that equilibrium was maintained. This latter point is critically important when considering the quarter-symmetry condition that was used. As a point of reference, due to the transverse half-symmetry condition in the pipe, only 30 kips is applied to the model even though in actuality a total 60 kip load is applied.

Post-processing Analysis Results

Once the models were completed and processed, results from the analyses were extracted. These generally involved extracting component stresses near the axial symmetry plane for both the steel and composite materials. Presentation of results included tables, graphs, and contour plots. The key is post-processing is to most effectively present the information required so that assessment relative to a design standard can be made.

One of the more effective methods for presenting results involved plotting load-deflection data, most often in the form of bending load versus strain. **Figure C4** is an exemplar plot showing bending load versus axial strain in the steel and composite materials. Also included in this figure are lines showing the *Plastic Analysis Collapse Load* and the *Design Load*. These data sets were discussed in greater detail in the preceding appendix; however, it should be noted that the finite element analysis results were used to designate acceptable design loads. This was accomplished by integrating a combination of loads and assessing the combined rigidity of both the steel and composite. This can be accomplished experimentally as demonstrated in this study; however, the ability to extract critical information and assess the effects of different design variables is effectively limited to techniques using finite element methods.

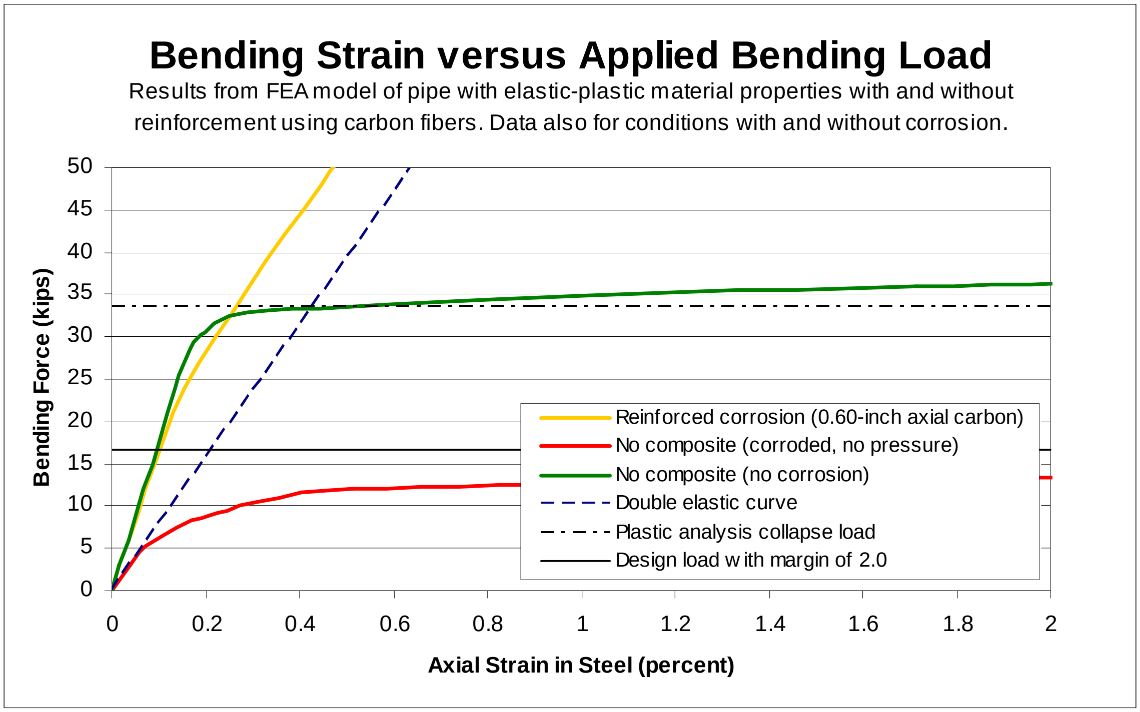

Figure C4 – Exemplar load-deflection curve based on finite element results

<u>Analyses Using Axisymmetric 2-D Continuum Models</u>

While the shell element models were able to address and capture most of the information required for design assessment, the ability to capture radial stresses is limited to either two or three-dimensional continuum elements. This aspect of the study was an outgrowth of questions posed regarding the likelihood for delamination of the composite from the steel during normal operations. Experience has shown that when effectively used, composite materials reinforcing pipes subject to internal pressure provide a compressive clamping force on the outside of the pipe. This compressive stress acts to reduce the likelihood for debonding. To quantitatively address this issue, a two-dimensional axisymmetric continuum model was built.

Material Properties

The material properties used in the axisymmetric analysis are the same as those used previously in the shell analysis.

Geometry and Boundary Conditions

Refer to **Figure C5** for details on the axisymmetric model. In this particular analysis the steel was modeled using ABAQUS' CAX4 axisymmetric elements; however, the composite material was modeled using the SAX1 axisymmetric shell elements. These axisymmetric shells are two-noded elements placed on the outside surface of the steel. They contribute stiffness and strength in the same manner as two-dimensional shell elements and their per layer thickness and orientation can be changed. In post-processing it is possible to extract in-plane hoop and axial stresses; however, unlike their two-dimensional counterparts, no variation in results is permitted in the circumferential direction.

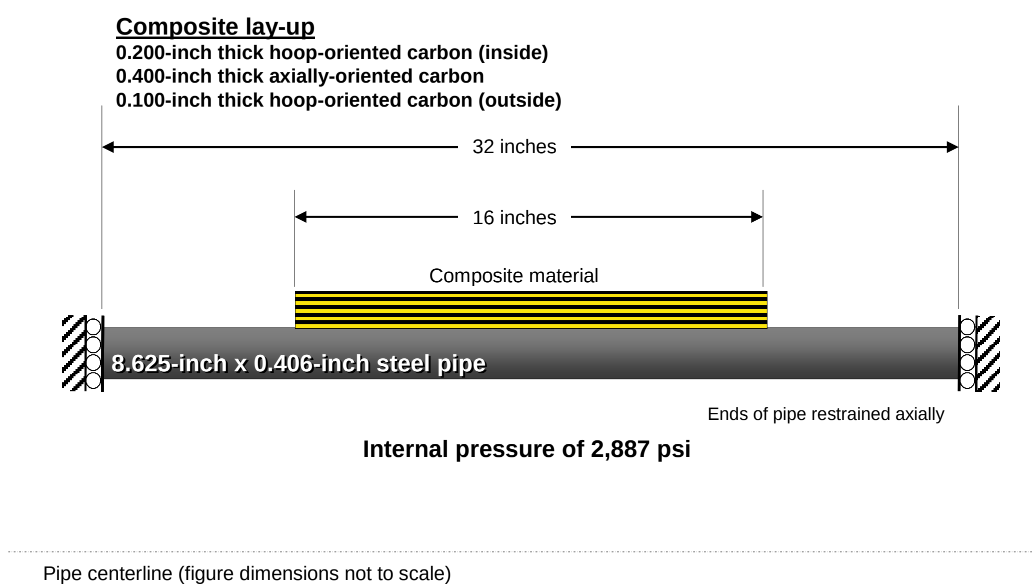

Figure C5 – Schematic diagram for axisymmetric finite element model

Also shown in **Figure C5** are the loading and boundary conditions that were used. The ends of the pipe are restrained axially, implying that axial stresses in the model will be developed based on Poisson's effect as opposed to a specified pressure end load. For the problem at hand this an acceptable approach.

Loading

The only loading directly applied to the axisymmetric model was an internal pressure of 2,887 psi. No consideration for corrosion was made, nor any attempt made to determine the lower bound collapse load by incrementally increasing the pressure to induce failure. The primary purpose of this study was to quantify radial stresses generated by the pressurization of the pipe at design conditions.

Post-processing Analysis Results

Post-processing results from the axisymmetric model involved extracting stresses on the outside surface of the pipe, some being positioned beneath the composite. Hoop, axial, and radial stresses were extracted along the length of the pipe. **Figure C6** is an exemplar plot showing the radial stress as a function of axial position.

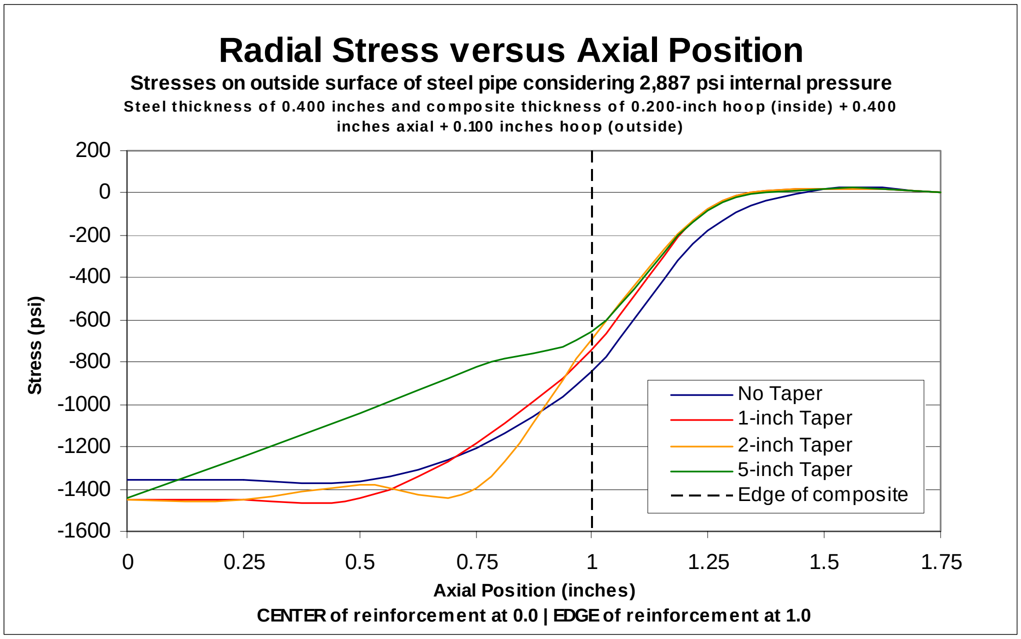

Figure C6 - Exemplar radial stress plot based on finite element results

APPENDIX D

FABRICATION OF CARBON HALF-SHELLS (PICTORIAL DIRECTORY)

FABRICATION OF CARBON HALF SHELLS

Prepared by Chris Alexander (May 1, 2007)

The information that is provided in this document details the steps involved in fabricating the carbon half-shells. The shells were fabricated using an inner layer of 0.050 inch thick 50-50 balanced weave E-glass cloth combined 0.400 inch thick axially-oriented stitched carbon fiber cloth (20 layers with each layer being 0.020 inches thick).

Task Description | **Corresponding Photographs**

Selection of base pipe used for mold
An 8.625 inch OD PVC pipe was selected as the base piece for the half-pipe mold. PVC was selected rather than steel or aluminum because of its light weight and inexpensive cost.

Mold build-up using E-glass
In order for the carbon half-pipes to properly align on the outside surface of the 8-inch nominal diameter steel pipes during repair work, it is important to have a gap between the outside of the pipe and the inside surface of the half-shell. For this purpose, the outside surface of the PVC pipe was increased 0.25 inches diametrically using E-glass cloth.

Applying epoxy overcoat
Once the E-glass material had cured, the outside surface was coated with epoxy using a paint brush. After curing, three layers of Johnson wax were applied to the outside surface to permit release of the fabricated half-shells.

Position mark on mold
To ensure proper alignment of the E-glass and carbon fiber cloth during installation, marks are installed on the outside surface of the mold. The boundary of the marks is slightly larger than the target axial and circumferential lengths of 60 inches and 180 degrees. Cuts made with an abrasive wheel are used to control final production dimensions.

Installation of release ply
Release ply was wrapped over the outside surface of the mold. This orange-colored polypropylene material has small pin holes spaced periodically to permit this plastic material to breath. The wrap is taped in place prior to installation of the composite material.

Wetting out the E-glass material
The inner E-glass material serves an important role as it functions as a protective layer on the inside surface of the shell. Two part epoxy (bisphenol A with a slow set catalyst) was used to saturate the E-glass (the same resin was also used to saturate the carbon material).

Install the E-glass material
The E-glass material is placed directly on the release ply. One layer of E-glass is installed, with each layer being approximately 0.050 inches thick. The pipeline industry in general has concerns that if carbon is placed directly on the surface of the steel a galvanic cell will form, this inducing corrosion of the steel carrier pipe. The inner E-glass layer prevents this from taking place.

Wetting out the Carbon material
Two part epoxy was used to saturate the carbon material. As shown, the epoxy is applied by hand and a roller is used to ensure that maximum saturation takes place. Prior to saturation, each layer is cut to length and the width of the cloth is 12 inches. To cover 180 degrees some circumferential overlapping takes place.

Installing the carbon material
Alignment of each layer on the mold is important. Scribe marks on the mold part are used to ensure this takes place. Each layer is approximately 0.02 inches thick and a total of 20 layers were installed to create a total thickness of 0.40 inches. Carbon fibers are aligned axially during the installation process.

Aligning the carbon material layers
After installation, each layer is smoothed by hand to ensure that no voids are present so that proper alignment is achieved.

Clean non-bonded surface
After all of the layers have been installed, excess resin is removed form the mold in preparation for the vacuum sealing process. Acetone is used to remove the excess resin.

Preparation work for vacuum sealing
After the epoxy resin is removed from the non-bonded region of the mold, preparatory work is performed by installing double sided vacuum sealing tape (zinc chromate) to which the vacuum sealing bag is mounted. This tape is installed in a manner to form a complete border around the outside of the half-shell.

Apply outer release ply layer
Release ply was wrapped over the outside surface of the carbon material. The small pin holes spaced periodically permit the material to breath during the curing process and for excess resin to extrude from the composite. The wrap is taped in place.

Apply bleeder ply layer
A white-colored porous bleeder ply is wrapped over the outside surface of the release ply. Vacuum ports are also attached with tape to the bleeder ply in anticipation of installing the hose lines from the vacuum pump.

Install the vacuum sealing bag
The polypropylene vacuum bag material is placed on the outside surface of the part. The outer perimeter is pushed onto the vacuum sealing tape to ensure that an air-tight bond exists. This involves some work to ensure that a total seal develops.

Connect hoses to vacuum pump
After the vacuum bag has been installed, the vacuum pump is connected to the bag using the ports attached previously to the bleeder ply. Holes are cut in the vacuum sealing bag to permit the pump ports to penetrate the bag.

Starting the vacuum pump
The vacuum pump is started in order to apply a vacuum to the part. It is possible that leaks might be present, requiring the application of additional sealing tape. The vacuum pump is started only after the epoxy has had time to partially cure so that excessive amounts epoxy will not be extruded from the part. This partial cure time is on the order of 45-60 minutes.

Monitoring the vacuum process
As shown in the photo to the right, when the vacuum engages the vacuum bag draws against the mold and part. The bleeder ply is also saturated with epoxy as is extrudes through the pin-holes in the release ply. The vacuum pump is run for a minimum of 12 hours to ensure that proper curing has taken place.

Removing the molded part
After the epoxy has cured, all of the vacuum sealing materials are removed and the part is disengaged form the mold. Because of excess resin on the outside surface of the part, some prying effort is required.

The cured half-shell
The photo shows the removed part. After removal the part maintains its proper shape, although some finishing work is required before the part can be installed onto a riser pipe.

Finishing the parts
The carbon half-shells are trimmed using an abrasive cutting wheel. The ends are cut to length so that a part with an axial length of 60 inches is produced. Additionally, the edges are also trimmed to ensure proper alignment during installation.

APPENDIX E

MATERIAL TEST DATA FOR UNIAXIAL STITCHED CARBON FABRIC

Bcomtesting

Job no. **011907-1**

Customer: Comptek Structural Composites
P.O.#: Verbal/ Larry Cercone
Date: January 22, 2007

Product: Composites Laminates
Product codes: 5 plies carbon composites panels

Report presented to:

Larry Cercone
Comptek Structural Composites
4699 Nautilus Ct., Unit 401
Boulder, CO 80301

5107-E Unicon Drive, Wake Forest, NC 27587 Ph.919-569-9922 Fax.919-569-9920 www.Bcomtesting.com

Bcomtesting

Job no. 011907-1

Customer: Comptek Structural Composites
P.O.#: Verbal/ Larry Cercone
Date: January 22, 2007

Product: Composites Laminates
Product codes: 5 plies carbon composites panels

IMPORTANT NOTICE: This report summarizes the results of certain tests conducted under the request of our customer. The results reported herein are a function of controlled laboratory conditions and could differ from the results an end-user might achieve under actual production conditions. Variations in end-user production processes including changes to the formula, manufacturing procedures, or raw materials, as well as variations in manufacturing conditions such as temperature and humidity could affect the end-user's process and ultimately the performance characteristics of the end-users' finished products.

The information contained herein are not intended to substitute for the end-user's own testing of such materials. Nothing herein shall constitute any warranty, either express or implied including fitness for particular purpose of the tested products.

5107-E Unicon Drive, Wake Forest, NC 27587 Ph.919-569-9922 Fax.919-569-9920 www.Bcomtesting.com

Bcomtesting

Job no. **011907-1**

Customer: Comptek Structural Composites
P.O.#: Verbal/ Larry Cercone
Date: January 22, 2007

Product: Composites Laminates
Product codes: 5 plies carbon composites panels

Testing request: Mechanical testing properties of carbon composites laminates in 0° direction.

Resin/matrix used: Epoxy, type unknown

Initiator used: Unknown

Cure conditions: Unknown. Tested as received.

Laminates panels description: 2 panels of 5 plies

Test requested: **ASTM D3039-00** Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials

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Bcomtesting

Job no. **011907-1**

Customer: Comptek Structural Composites
P.O.#: Verbal/ Larry Cercone
Date: January 22, 2007

Product: Composites Laminates
Product codes: 5 plies carbon composites panels

Test*	5 Plies
ASTM D-3039	
Tensile Strength (psi)	88336.52
std.dev.	5485.92
Tensile Modulus (ksi)	8696.14
std.dev.	503.18
Elongation (%)	1.02
std.dev.	0.05

* Summary only. Details of each test including graphs are included in addendum

5107-E Unicon Drive, Wake Forest, NC 27587 Ph.919-569-9922 Fax.919-569-9920 www.Bcomtesting.com

Bcomtesting

Addendum

5107-E Unicon Drive, Wake Forest, NC 27587 Ph.919-569-9922 Fax.919-569-9920 www.Bcomtesting.com

Bcomtesting
5107-E Unicon Drive
Wake Forest, NC 27587

ASTM D3039- 10000lbs load cell 10% axial extens.

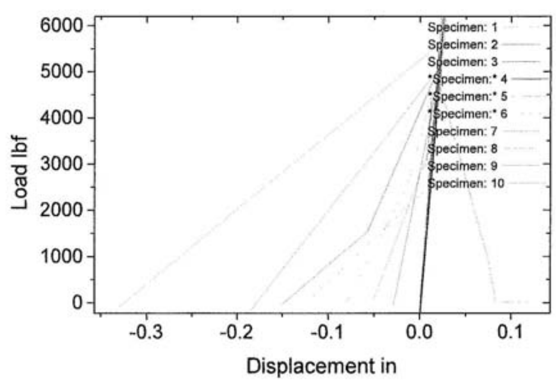
Test type: Tensile
Operator name: Operator 1
Sample Identification: Tensile011907-1
Interface Type: 5500
Sample Rate (pts/secs): 10.0000
Crosshead Speed: 0.0500 in/min

Instron Corporation
Series IX Automated Materials Testing System 8.27.00
Test Date: Saturday, January 20, 2007

Humidity (%): 50
Temperature: 73 F

	Thickness (in)	Width (in)	Load at Peak (lbf)	Stress at Peak (psi)	% Strain at Peak (%)	% Strain at Break (%)	Young's Modulus (ksi)
1	0.112	0.535	5477.410	91412.039	1.062	1.062	8613.551
2	0.111	0.520	5143.230	89106.555	0.969	0.969	9614.481
3	0.120	0.521	5093.254	81465.992	0.989	0.989	8264.059
Excluded	0.109	0.522	3914.299	68795.008	0.861	0.861	8352.250
Excluded	0.114	0.529	3377.730	56009.852	0.646	0.646	8672.825
Excluded	0.112	0.534	3719.254	62186.570	0.655	0.655	8074.044
7	0.106	0.524	5098.630	91794.438	1.066	1.066	8612.554
8	0.105	0.538	4665.002	82581.023	1.026	1.026	8047.173
9	0.108	0.518	4774.144	85337.898	0.958	0.958	8865.512
10	0.110	0.530	5635.141	96657.648	1.093	1.093	8855.671
Mean	0.110	0.527	5126.687	88336.516	1.023	1.023	8696.143
S.D.	0.005	0.008	346.687	5485.918	0.053	0.053	503.181

Sample ID: Tensile011907-1



APPENDIX F

MATERIAL TEST DATA FOR GRADE X46 CARBON STEEL PIPE

Houston Metallurgical Laboratory Inc.

2400 Central Parkway, Suite R
Houston, TX 77092-7712
Phone: (713) 688-2777
Fax: (713) 688-2818
Email: houmet@swbell.net

TO: Stress Engineering
13800 Westfair East Dr.
Houston, TX 77041-1101
ATTN: Chris Alexander

TEST NO: 300-07
P.O. NO:
DATE: 01/03/07

DATE OF TEST: 01/03/07
REPORT OF TENSILE AND CHARPY TEST

MATERIAL/DESCRIPTION: One (1) piece 8" OD x 21-1/2" long pipe
IDENTIFICATION: #3 15611 CRA
DATE RECEIVED: 12/29/06
SPECIFICATIONS: Client Instructions
TEST EQUIPMENT: T.O. S/N 120990-1 Ext. CL5284
Tinius Olsen Model 74:264 Ft./Lb. 16.8 Ft./Sec. S/N 121155
Gefran 4T 48 S/N 04056843

TECHNICIAN: M. Steel / D. Chalmers
PROCEDURE: HML-TTM-1-94 Rev. 1
HML-CVN-1-94 Rev. 1

TENSILE TEST RESULTS

SPECIMEN NO.	DIMEN. IN.	SQ. AREA INCH	YIELD STRENGTH PSI .2% OFFSET	TENSILE STRENGTH PSI	% ELONG. IN 2 IN.	%ROA
longitudinal						
300-07	1.498 x .397	.5947	54,400	74,600	37.4	51.5

.50% EUL – 55,200
.60% EUL – 65,400
.70% EUL – 57,400

CHARPY IMPACT TEST RESULTS
ASTM E23 TYPE: A SIZE: 10mm X 10 mm.

SPECIMEN NO.	TEST TEMP.	NOTCH LOCATION	FT. LBS.	% SHEAR	LAT. EXP. (MILS)
300-07	longitudinal				
#1	Ambient	Base	100	99	78
#2	"	"	103	99	84
#3	"	"	106	99	87

AS MACHINED

REVIEWED BY:

RONALD R. RICHTER
PRINCIPAL/QA MANAGER

Houston Metallurgical Laboratory Inc.

2400 Central Parkway, Suite R
Houston, TX 77092-7712
Phone: (713) 688-2777
Fax: (713) 688-2818
Email: houmet@swbell.net

TO: Stress Engineering
13800 Westfair East Dr.
Houston, TX 77041-1101
ATTN: Chris Alexander

TEST NO: 300-07
P.O. NO:
DATE: 01/03/07

DATE OF TEST: 01/03/07
REPORT OF CHEMICAL ANALYSES

MATERIAL/DESCRIPTION: One (1) piece 8" OD x 21-1/2" long pipe
IDENTIFICATION: #3 15611 CRA
DATE RECEIVED: 12/29/06
SPECIFICATIONS: Client Instructions
TEST EQUIPMENT: LabTest #1537

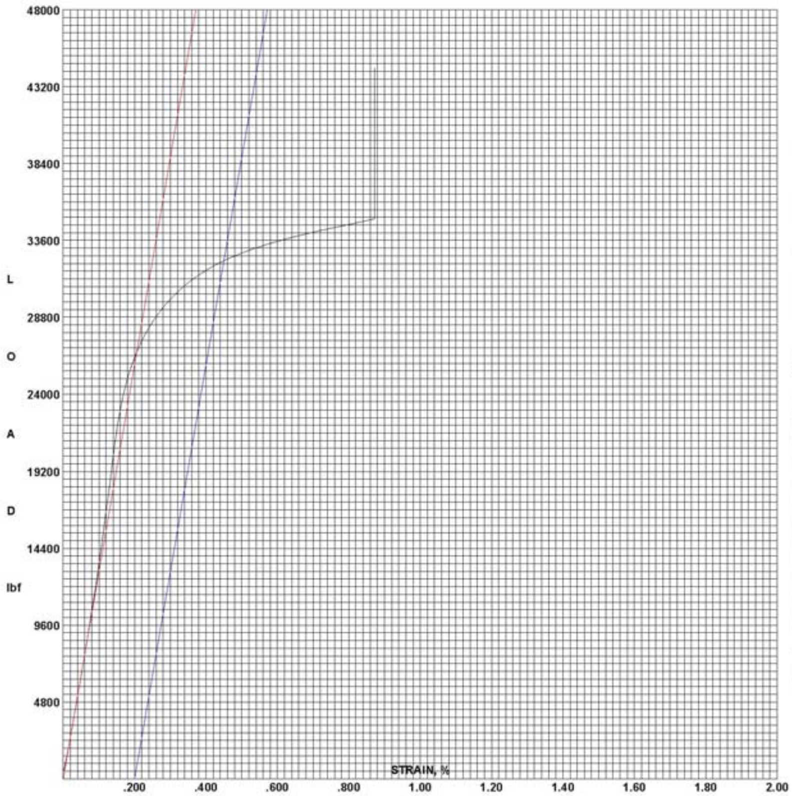
TECHNICIAN: Derek G. Chalmers
PROCEDURE: HML-CM-1-94 Rev. 2
COMPLIANCE: -----

CHEMISTRY TEST RESULTS

ELEMENTS		**% CONTENT**
CARBON	C	.18
MANGANESE	Mn	.74
PHOSPHORUS	P	.011
SULFUR	S	.005
SILICON	Si	.16
MOLYBDENUM	Mo	<.01
NICKEL	Ni	.04
CHROMIUM	Cr	.08
COPPER	Cu	.14
VANADIUM	V	<.01
ALUMINUM	Al	.02
TITANIUM	Ti	<.01
NIOBIUM	Nb	<.01

REVIEWED BY:

RONALD R. RICHTER
PRINCIPAL/QA MANAGER



Houston Metallurgical Laboratory, Inc.
2400 Central Parkway Suite R
Houston, TX 77092-7712

Tensile Test Report

Customer	Stress Engineering
Specification	client instructions
PO Number	<empty>
Material / Description	8" OD pipe
Procedure	HML-TTM-1-94 Rev 1
Test Equipment	120990-1 TO
Technician	MJS
Test Number	300-07
Report Name	ENG D&T
Date Received	12/29/06
Print Date	January 12,2007

Sample Number:	**1**
Width, in:	**1.498**
CS Area, in²:	**0.5947**
OFS @ 0.2, lbf:	**32300**
OFS @ 0.2, psi:	**54400**
Ultimate, lbf:	**44300**
Ultimate, psi:	**74600**
EUL @ 0.5, lbf:	**32800**
EUL @ 0.5, psi:	**55200**
EUL #2, lbf:	**33500**
EUL #2, psi:	**56400**
EUL #3, lbf:	**34100**
EUL #3, psi:	**57400**
Modulus, psi:	**21700000**
Red Area, %:	**51.5**
TE (Man), %:	**37.4**
Compliance:	
Date:	**01/03/07**
Time:	**09:06:25**

Metals Tensile - Chart Data
Jan 12, 2007 11:34:36 AM
Graph Restricted to Grid

APPENDIX G

GUIDELINES PREPARED FOR THE MINERALS MANAGEMENT SERVICE

DEVELOPMENT OF GUIDELINES FOR MMS

For the Repair of Risers Using Composite Materials

EXECUTIVE SUMMARY

For the past decade the use of composite materials in repairing offshore systems has been of interest to operators and regulators. Risers are one of the most important elements in an offshore system and are often susceptible to damage and degradation including outside impact and corrosion. While risers have been repaired using composite materials, to date there has not been a program to specifically assess the use of this technology relative to mechanical integrity requirements. For this reason MMS sponsored a research program starting in 2006 with the Offshore Technology Research Center (OTRC) to assess existing composite repair technology. One primary aim of this work was to develop guidelines to assist regulators, operators, and manufacturers in using composite technology to repair risers.

The development of this guideline is based on findings of the funded research that also involved co-sponsored research activities from four manufacturers in the form of a joint industry project (JIP). The aim of this document is to provide guidance to industry in terms of the following areas: (1) design and development, (2) installation and implementation, and (3) operating and maintenance. The sections that follow provide details on each of these areas, with each serving a critical role in the deployment of effective repairs for long-term service.

Also included is information presented and gathered at a workshop hosted by the OTRC at Stress Engineering Services, Inc. in Houston, Texas on March 29, 2007. The workshop was attended by representatives from MMS and other regulatory bodies, academia and research organizations, oil and gas companies, service/consulting firms, and composite repair manufacturers. A beneficial exchange of information and ideas took place as participants learned about the background of composite repairs as well as the critical aspects of integrating this technology for the repair of offshore risers.

BACKGROUND

Composite repair systems have been used to repair damaged pipelines for almost 20 years. The majority of this remediation work has involved the repair of onshore pipelines subject to corrosion. Repairing corrosion in this manner involves the restoration of hoop strength, and as any review of the open literature will demonstrate, addressing this stress state this has been the primary focus of research efforts up to this point in time (1-5). [3] Additionally, mechanical damage (e.g. dents with gouges) has been repaired using composite materials (6, 7). Information available to industry is based in large part on the results of several research programs that integrated composite coupon tests, as well as full-scale burst and fatigue testing on pipelines with simulated damage.

The ASME codes for gas (ASME B31.8) and liquid (ASME B31.4) pipelines address the use of composite materials (10, 11). However, more recently, ASME has developed a document focused on the repair of pressure equipment, *PCC-2-2006 Repair of Pressure Equipment and Piping Standard* (12). Specifically, Article 4.1 of this document, Non-metallic Composite Repair Systems for Pipelines and Pipework: High Risk Applications, provides details on how composite materials are to be used to repair pipes. Specifically, the repair system in this document is defined as the combination of the following elements for which qualification testing has been completed: substrate (pipe), surface preparation, composite material (repair laminate), filler material, adhesive, application method, and curing protocol. What is not specifically addressed in this document is the repair of offshore pipelines or risers.

The engineering community to a large extent has relied on existing research to assess the use of composite repair technology. In terms of repairing offshore pipelines and risers that are subject to loads different than their onshore counterparts, there is a gap in the information technology. As a point of reference, onshore pipelines are typically concerned with circumferential stresses associated with internal pressure. However, in addition to internal pressure, offshore risers are subject to tension and bending loads due to their suspended nature in the water. For this reason, any composite system used to repair offshore risers should address these loading conditions to ensure that the system perform as intended. Several operators have used composite materials to repair offshore risers (13). In spite of the use of this repair technique, many in the industry recognize the need for additional research to address the use of composite materials in repairing offshore riser systems. Through additional investigations, industry will gain insights regarding the capabilities and limitations that exist with current composite technology.

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[3] Numerical values provided in parentheses correspond to documentation cited in the Reference section.

INTRODUCTION

As stated previously, this guideline is intended to be a resource for regulators, operators, and manufacturers. To effectively assess composite technology, and in particular any specific repair system, it is important to divide the assessment process into several specific subject areas. The first involves *design and development*. This subject area involves ensuring that the composite technology has been designed with the appropriate service conditions in mind, and most importantly, that the manufacturer has properly addressed and accounted for factors that can lead to inadequate performance and long-term degradation. It is the responsibility of the manufacturer to ensure that the design of their particular system meets minimum design and service requirements. It is recognized that enforcement and performance requirements will likely come from operators and regulators. The second subject area concerns *installation and implementation*. History has shown that even with the best designs, when technology is not properly used the potential for sub-standard performance exists, sometimes with catastrophic results. For this reason, guidelines are provided herein to ensure that the repair of risers is done correctly, with an emphasis on quality assurance and consistent methodology. The third subject area concerns *operations and maintenance*. Once the composite materials have been installed, it is important for operators to conduct periodic inspection and perform maintenance as appropriate. Long-term performance is directly related to how well the composite materials are protected and maintained. Failure to properly maintain these repair systems will result in sub-standard performance.

The sections that follow provide specific discussions on the three above-mentioned subject area topics. While not overly-prescriptive, the intent is to provide general guidelines to be used by industry to assess existing technology and develop new composite repair systems as required to address the ever-increasing demands of offshore conditions (such as deep water applications). In large part, these guidelines are a direct result of insights gained in performing tests associated with the MMS-sponsored JIP program.

Several appendices are provided that provide specific information. **Appendix A** provides a list of recommended material testing that should be performed to assess the performance of any repair system used to repair offshore risers. In **Appendix B** one finds the proceedings of the workshop on repair of risers using composite materials, *Repair of Risers Using Composite Materials Workshop*, held at Stress Engineering Services, Inc. on March 29, 2007. The final appendix, **Appendix C**, contains copies of the presentations made at the workshop.

DESIGN AND DEVELOPMENT

From a recommendation standpoint, this guideline does not favor any one particular composite repair technology over another. It is recognized that whether a manufacturer elects to use carbon or E-glass, epoxy resin or urethane, or pre-cured or in situ cured the reason for doing so will largely be determined by technology requirements and economic viability. However, it is possible to provide guidelines that specifically address technology requirements when composite materials are used to repair offshore risers.

The sections that follow provide a list of design requirements, as well as recommendations for manufacturers in documenting that their particular system satisfies the appropriate design requirements.

Design Requirements

The list below captures design elements that should be specifically addressed by manufacturers in the development of their system. The primary means of verifying that a particular system meets the design requirements should involve full-scale testing, preferably efforts that involve testing to failure in order to determine the limit capacity for a particular repair system.

1. **Loading assessment** – the composite repair system should be designed to provide adequate reinforcement to the steel riser pipe considering all possible loads. As a minimum, these loads should include internal pressure, tension, and bending. Other possible load requirements include impact from external forces, and fatigue loading.
2. **Allowable stress and strain states** – the composite system must evaluate the performance of two components: the repaired steel and the composite reinforcing material. Using available design codes such as API RP 1111 and ASME B31.8, the system must ensure that stresses and strains within each respective component are less than a specified maximum value. As a point of reference, consider the following:
    a. **Steel riser material** – once the repair is installed, the stress (or strain) in the steel should be reduced when subjected to increased loading to the point where plasticity initiates in the steel due to increased compliance. To increase the level of reinforcement, conventional methods employ using a composite with greater stiffness by either increasing the composite thickness or selecting a material having a greater elastic modulus.
    b. **Composite material** – unlike steel whose mechanical properties do not degrade over time due to sustained loading, the properties of composite systems can degrade over time (often due to degradation of the resin). For this reason, any repair using composite materials must consider the degraded long-term strength as part of the design. By designing so that the stress in the composite material is less than a specified threshold, long-term performance is enhanced.
3. **Material qualification** – composite materials are identified based on their particular constituent components including fiber and matrix selection. Material qualification is a critical aspect of the design process. **Appendix A** provides a list of the recommended tests based on ASTM procedures.

4. **Repair life** – the design of the repair system should adequately address long-term performance requirements. This includes accounting for all load types, environmental effects, and material degradation.
5. **Geometry of repair** – the geometry of the repair should be based on sound engineering principles. The governing factors for the design include the extent of damage to the riser (e.g. corrosion depth and length) and material properties of the composite including stiffness, tensile strength, elongation to failure, and adhesive lap shear strength. These factors will be used to determine the thickness and length of the repair.
6. **Type of repair** – it is important as part of these guidelines to establish what constitutes an acceptable repair. External corrosion associated with general material loss and dents and scratches are covered as part of this guideline. It should be noted that whatever defect is repaired, applicable design and fitness for service codes should be referenced to ensure that the repair of inappropriate defects does not occur. <u>This guideline does not encourage or endorse the repair of leaking defects.</u>
7. **Environmental and operating factors** – the design of the composite repair should properly address all potential environmental and operating factors. Examples include UV exposure, wet/dry conditions, elevated temperatures and temperature extremes, long-term exposure to sea water, and potential for exposure to aggressive chemicals.
8. **Susceptibility to damage** – although perhaps more related to discussions on operations and maintenance, the design process should consider the effects of external damage and how a particular system can not only withstands damage, but also how the system can be repaired if necessary. Part of this process involves assessing damage tolerance before issues arise in the field.

INSTALLATION AND IMPLEMENTATION

The successes and failures in using composite materials to repair pipelines in the field have largely been related to issues associated with installation and implementation. When the repair systems are installed correctly according to the manufacturer's recommendations, they typically perform as designed. However, when improper installation techniques are used, the likelihood for inadequate performance is significantly increased. This section of the guideline has been developed to help manufacturers develop appropriate installation techniques, as well as providing for operators and regulators key points of interest to monitor during the installation of repairs.

Provided below is a list of important topics associated with the installation of composite repair systems offshore.

1. **Documentation** – it is important that manufacturers have documentation available for operators and regulators that covers the following subject matters:
    a. Material performance data including MSDS sheets
    b. Details on design basis and testing program
    c. Quality control procedures including material traceability and tracking
    d. Installation procedures with details as appropriate including minimum cure times
    e. Forms for detailing specific elements of the repair procedure and how the repair conforms with manufacturer's recommendations
2. **Installation procedures** – to ensure quality installation, it is important that installation procedures be developed so that each repair is performed consistently and in a manner that meets certain workmanship standards. Additionally, the procedures should provide details on what to do when untoward conditions occur during installation. An example includes what to do when a resin does not cure in the appropriate time period.
3. **Assessing quality of installation** – this has historically been the primary problem with field installation of composites. When failures have occurred, they most often involve the improper allocation of resin and also using resins that fail to cure. When either of these conditions exists, the performance of the repair will not meet minimum requirements. Operators and regulators should ensure that the resins have been properly installed and that curing has occurred as specified by the manufacturer.

OPERATIONS AND MAINTENANCE

Unlike buried pipelines where repairs are largely unseen, offshore repairs are exposed to the elements including weather, sea conditions, and the possibility for impact with outside forces. For this reason, it is recommended that periodic inspection of the repairs be made when possible. Provided below are examples of some facets of the repairs that should be inspected:

1. Inspecting for external damage associated with impact.
2. Looking at the ends of the repair to assess the possibility for moisture ingression.
3. Evaluating if any loads have been applied to the repair that exceed the original design values (this is especially important in hurricane conditions).
4. On a periodic basis, select regions of the repair should be inspected for possible delamination.
5. If the repair has been painted to protect exposure from UV light, inspection should ensure that no exposed surfaces exist.
6. Operators should document inspection efforts as part of a formal fitness for purpose inspection program.
7. If sub-standard conditions are found to exist, the composite system should be repaired (if possible), or replaced if remediation options do not exist.

CONCLUSIONS

Because of the complex loads associated with repairing risers, the offshore industry has been cautious and methodical in accepting the use of composite materials as a means for reinforcing corroded and damaged risers. It is possible, under the right conditions, that composite materials can be used to repair offshore risers. In order for this to take place, the user must have a clear understanding of the loads imparted to the riser and be technically confident that the selected composite materials can provide an adequate level of reinforcement. The fundamental objective of this effort has been demonstrated in the four-team JIP program conducted by Stress Engineering Services, Inc.

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Appendix A - Recommended Tests

The follow list comprises tests that should be considered as part of the development of any composite repair system. The test results should be documented and preferably performed by a third-party test lab. As noted, some tests referenced use the appropriate ASTM designation. Test results should include the following, preferably in a single document that can be provided upon request by the manufacture.

Tensile Strength per ASTM D3039
Tensile Modulus per ASTM D3039
Compressive Strength of Filler Materials per ASTM C579
Shear Strength per ASTM D5379-05
Shear Modulus per ASTM D5379-05
Shear Failure Strain per ASTM D5379-05
Thermal Expansion per ASTM E 831
Glass Transition per ASTM D660
Poisson's Ratio per ASTM D3039
Barcol Hardness per ASTM D2583
Flexural Modulus per ASTM D790
Hydrostatic Burst Test per ASTM G42-95
Cathodic Disbondment per ASTM G 95-87
Abrasion Resistance
Lap Shear Adhesive Test per ASTM 3163 (surface preparation per ASTM 2093)
Cathodic Disbondment per ASTM G42
Pull-Off Adhesion per ASTM D454
Impact Resistance per ASTM G14

In addition to the above tests, for repair of risers it is recommended that a specific test program be designed that includes the following loads:
1. Internal pressure
2. Axial tension
3. Bending

The test program should ensure that the composite repair system reduces strains in the repaired section of the steel test pipe to below a specified level.

Additionally, it is critical that the composite repair system demonstrate adequate long-term performance for the intended design life.

Appendix B – Workshop Proceedings

(this information not included in dissertation for brevity)

Appendix C – Workshop Presentations

(this information not included in dissertation for brevity)

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