Composite Repair Methods for Steel Pipes

by

Dr. Ozden O. Ochoa, Professor
Department of Mechanical Engineering
Texas A&M University

Chris Alexander
Stress Engineering Services, Inc.

Final Project Report
Prepared for the Minerals Management Service
Under the MMS/OTRC Cooperative Research Agreement
1435-01-04-CA-35515
Task Order 39300
MMS Project Number 558

June, 2007

For more information contact:

Offshore Technology Research Center
Texas A&M University
1200 Mariner Drive
College Station, Texas 77845-3400
(979) 845-6000

or

Offshore Technology Research Center
The University of Texas at Austin
1 University Station C3700
Austin, Texas 78712-0318
(512) 471-6989

A National Science Foundation Graduated Engineering Research Center

TABLE OF CONTENTS

DEVELOPMENT OF GUIDELINES 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) operations 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 has been the primary focus of research efforts up to this point in time (1-5). [1] 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). 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 is defined in this document 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 the ASME 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

---

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

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 performs 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.

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 inspections 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 to consider 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 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. It is noted that the composite repair systems maybe exposed to fire and open flames. This can be mitigated by additives in the resin and external fire retardant coatings for fire. In areas where exposure to fire is possible, it is important that this be done. Even if the composite repair system does not catch fire, exposure to elevated temperatures will result in loss of strength which could result in failure of the repair, possibly leading to catastrophic failure of the repaired piping.

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 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 is intended 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 to 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, selected regions of the repair should be inspected for possible delamination.
5. If the repair has been painted to protect against 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

Due to 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 the area of splash zone. 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. This full scale test program evaluated four different composite repair systems. The program incorporated 8.625-inch x 0.406-inch, Grade X46 pipe test samples that were fitted with simulated corrosion by machining. The program involved destructively testing three samples repaired by each respective composite repair system. The three tests included a burst test (increasing pressure to failure), a tension to failure test (pressure 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).

It should be recognized that 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. 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 repair systems relative to loading conditions associated with offshore risers. In using composite materials to reinforce damaged and corroded risers, it is critical to integrate a design methodology that assesses 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 has been demonstrated in this presentation, 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

REFERENCES

1. Pipeline Safety: Gas and Hazardous Liquid pipeline Repair, Federal Register, Vol. 64, No. 66, Wednesday, April 7, 1999, Proposed Rules, Department of Transportation, Research and Special Programs Administration, Docket No. RSPA-98-4733, Notice 1.
2. Fawley, N. C., *Development of Fiberglass Composite Systems for Natural Gas Pipeline Service*, Final Report prepared for the Gas Research Institute, GRI-95/0072, March 1994.
3. Stephens, D. R. and Kilinski, T. J., *Field Validation of Composite Repair of Gas Transmission Pipelines*, Final Report to the Gas Research Institute, Chicago, Illinois, GRI-98/0032, April 1998.
4. Kuhlman, C. J., Lindholm, U. S., Stephens, D. R., Kilinski, T. J., and Francini, R. B., *Long-Term Reliability of Gas Pipeline Repairs by Reinforced Composites*, Final Report to the Gas Research Institute, Chicago, Illinois, GRI-95/0071, December 1995.
5. Block, N., and Kishel, J., *Clock Spring® Reinforcement of Elbow Fittings*, Topical Report prepared for the Gas Research Institute, GRI-93/0346, December 1995.
6. Alexander, C. R., Pitts, D. A., *Evaluation of the Aquawrap™ System in Repairing Mechanically-damaged Pipes*, report prepared for Air Logistics Corporation, Azusa, California, September 2005.
7. Alexander, C.R., Wilson, F.D., *Recent Test Results and Field Experience with Armor Plate® Pipe Wrap Repairing Corroded and Mechanically-Damaged Pipes*, 2000 Pigging Conference, Houston, Texas, February 2000.
8. Pipeline Safety: Gas and Hazardous Liquid pipeline Repair, Federal Register, Vol. 64, No. 239, Tuesday, December 14, 1999, Rules and Regulations, Department of Transportation, Research and Special Programs Administration, Docket No. RSPA-98-4733; Amdt. 192-88; 195-68 (Effective date: January 13, 2000).
9. American Society of Mechanical Engineers, *Manual for Determining the Remaining Strength of Corroded Pipelines*, ASME B31G-1991, New York, New York, 1991 edition.
10. American Society of Mechanical Engineers, *Gas Transmission and Distribution Piping Systems*, ASME B31.8, New York, New York, 2003 edition.
11. American Society of Mechanical Engineers, *Liquid Transportation System for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia and Alcohols*, ASME B31.4, New York, New York, 2003 edition.
12. *PCC-2-2006 Repair of Pressure Equipment and Piping Standard*, ASME, New York, New York, 2006 edition.
13. Personal communication with Mr. Paul Moise of Armor Plate, Inc., September 2006.

Appendix A - Recommended Tests

Recommended Tests

The following 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 manufacturer.

- 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

Repair of Risers Using Composite Materials Workshop

by

Dr. Ozden O. Ochoa, Professor
Department of Mechanical Engineering
Texas A&M University

Chris Alexander
Stress Engineering Services, Inc.

Workshop Proceedings
Prepared for the Minerals Management Service
Under the MMS/OTRC Cooperative Research Agreement
1435-01-04-CA-35515
Task Order 39300
MMS Project Number 558

March 29, 2007

For more information contact:

Offshore Technology Research Center
Texas A&M University
1200 Mariner Drive
College Station, Texas 77845-3400
(979) 845-6000

or

Offshore Technology Research Center
The University of Texas at Austin
1 University Station C3700
Austin, Texas 78712-0318
(512) 471-6989

A National Science Foundation Graduated Engineering Research Center

Table of Contents

Repair of Risers Using Composite Materials Workshop

O. O. Ochoa, Texas A&M University
C. Alexander, Stress Engineering Services, Inc.

Executive Summary

Background and Objectives

This one day workshop shared the results of an MMS sponsored research project at OTRC focused on developing guidelines to assist regulators, operators, and manufacturers in using composite technology to repair steel risers and tubulars.

Glass reinforced polymer systems have been routinely used to repair corrosion damaged onshore pipelines in the last two decades. These repair systems restore hoop strength. However in addition to internal pressure, offshore risers and pipelines are subject to tension and bending loads, and thus require an extension of repair performance to address combined loading.

The objective of the workshop was to introduce and discuss a recommended repair approach and metrics that addressed:

i. Design and development
ii. Installation and implementation
iii. Operation and maintenance

The workshop presentations and discussions highlighted the assessment of existing technology as well as development of new composite repair systems for future deep water considerations.

Workshop Organization

The workshop was initiated and sponsored by OTRC/MMS as a required task outlined in MMS Project 558 "Composite Repair Methods for Steel Pipes". The workshop was hosted by Stress Engineering Services, Inc., 13800 Westfair East Drive, Houston, TX 77041 and carried out by Chris Alexander, Principal, Stress Engineering, and Dr. Ozden Ochoa, Texas A&M University.

The one-day workshop was held March 29, 2007 and was well attended. The 34 participants represented a wide range of perspectives and experience. The workshop agenda and list of workshop participants are shown in Appendix A.

The morning session included the following presentations:

- Dr. E. G. Ward, OTRC – Dr. Ward's presentation covered OTRC background with extended emphasis on advanced materials research as shown in Appendix B.
- Lori Medley, MMS – Ms. Medley spoke briefly concerning the Gulf of Mexico's anticipation of the workshop and project results
- Dr. Ozden Ochoa, TAMU – Dr. Ochoa's presentation covered the possibilities of using composites in offshore applications as shown in Appendix C.
- Chris Alexander, Stress Engineering Services, Inc. – Mr. Alexander's presentation covered the fundamentals of composite repair and outlined recent test results. Chris' presentation also included discussions of the four team joint industry project conducted at Stress Engineering. Brent Vyvial, Stress Engineering, assisted Mr. Alexander with the discussion of the JIP test procedures and results. The full presentation is shown in Appendix D.

The afternoon session included a tour of the Mohr Engineering test facility and provided an opportunity for workshop participants to view the test samples of the JIP participants as well as interact with representatives from the four companies which participated in the JIP. Following the tour, Chris Alexander passed out a survey to workshop participants asking for feedback from the participants concerning their status and desire for the use of composites for pipeline/riser repair within their companies. An open discussion followed where technology/information gaps were identified so that a path forward for future work could be developed.

Recommendations

Based on a review of current industry practices and recognizing the potential role that composite materials will serve in the future of repairing offshore risers and pipelines, the following recommendations are provided. It should be noted that before industry-wide acceptance of this repair technology occurs, additional investigations are required. Addressing issues such as long-term performance is necessary to ensure that this technology functions as intended in restoring the serviceability to damaged offshore risers and pipelines.

1. It is necessary to develop definitive design guidelines in terms of allowable strains for both the reinforced steel and composite materials. The design document must take into account all modes of loading typical for offshore risers including internal pressure, tension, and bending. A limit state design methodology is recommended. Satisfying only the requirements for hoop strength is not sufficient. Additionally, design requirements should take into account reductions in strength and stiffness as functions of time and other environmental factors such as environmental exposure.

2. Performance testing is required to prove the viability of composite repair technology. While analysis can serve as the basis for the design, each composite

system used to repair risers and pipelines must be tested to establish performance capabilities.

3. Quality control of installation methods and materials is required. Personnel who are actually installing the repair materials must be trained and certified by the manufacturer or a representative party. Documentation must exist to ensure that minimum quality standards are maintained.

4. The composite repair system must be evaluated as part of an overall comprehensive testing program. Testing must be in accordance with industry norms and third party verification is encouraged.

5. To ensure long-term performance, a major focus of the overall testing program should involve assessing potential degradation mechanisms. This is especially important in offshore service where the test program should assess changes in strength as a function of time under loaded conditions. Demonstration of short-term strength is necessary, but not sufficient to establish long-term performance.

Acknowledgements

This workshop was an element of an Offshore Technology Research Center Project funded by the Minerals Management Service. Their sponsorship is gratefully acknowledged.

Special thanks to Stress Engineering Services, Inc. for hosting the workshop and for coordinating the tour at neighboring Mohr Engineering.

Thank you to the four Joint Industry Project participants for allowing workshop participants to view samples of their test results:

Air Logistics Corporation
Mr. Franz Worth
925 North Todd Avenue
Azusa, CA 91702
Phone: 626-633-0294
E-mail: fworth@airlog.com

Armor Plate, Inc.
Mr. Tony Wilson, President
P.O. Box 5625
Pasadena, Texas 77508-5625
Phone: (281) 487-2023
E-mail: twilson@armorplateonline.com

Comptek Structural Composites
Mr. Jim Lockwood, CEO
1966 13th Street, Suite 280
Boulder, Colorado 80302
Phone: 720-304-6882
Email: jlockwood@comptekcomposites.com

Pipe Wrap LLC
Ms. Gen Withers, CEO
P.O. Box 270190
Houston TX 77277-0190
Phone: 713-365-0881
Fax: 713-463-4459
Email: gwithers@piperepair.net

Appendix A

Workshop Agenda

8:30 – 8:45	Check-in and breakfast
8:45 – 9:00	Welcome and introductions (SES and OTRC)
9:00 – 9:15	Regulation perspectives and need for guidelines (MMS)
9:15 – 9:45	Use of composite materials in offshore applications (TAMU)
9:45 – 10:30	Fundamentals of composite repairs (SES)
10:30 – 10:45	Break
10:45 – 11:30	Discussions on Four Team Joint Industry Project (JIP) and introduction of composite repair companies (SES)
11:30 – 12:15	Lunch break
12:15 – 1:30	Tour of Mohr Engineering test facility and viewing of composite repair test samples from JIP program
1:30 – 2:15	Open group discussion on guideline development (OTRC/SES)
2:15 – 2:30	Closing remarks

Workshop Participants

Name	***Affiliation***
Chris Alexander	Stress Engineering Services, Inc.
Lawrence Borski	Williams Gas Pipe
Jaime Buitrago	ExxonMobil Upstream Research Co.
Robert Campbell	ExxonMobil Upstream Research Co.
Zai Chang	Chevron
Gautam Chaudhury	BP
Ronald Douglas	Williams Gas Pipe
Ronald Joseph	Williams Gas Pipe
King Lo	Shell International Exploration and Production Inc.
James Lockwood	Comptek Structural Composites
Xiaohua Lu	Technip USA
Theron C. McLaren	US DOT PHMSA
Fraser McMaster	Chevron ETC
Darryl McVeay	ExxonMobil
Lori Medley	Minerals Management Service

Paul Moise	Armor Plate Inc.
Aravind Nair	MCS
Debbie Oakes	Offshore Technology Research Center
Ozden Ochoa	Texas A&M University
Philippe Remacle	Total E&P USA, Inc.
George Ross	Stress Engineering Services, Inc.
Ron Scrivner	Stress Engineering Services, Inc.
Jim Souza	Pipe Wrap
Brent Vyvial	Stress Engineering Services, Inc.
Tom Walsh	Shell
E. G. Ward	Offshore Technology Research Center
David Weaver	Topcoar Offshore
Tony Wilson	Armor Plate Inc.
Gen Withers	Pipe Wrap
Franz Worth	Air Logistics Corp.
Jack Wu	KBR
Qing Yu	American Bureau of Shipping
Lee Zickefoose	Pipe Wrap

Appendix C – Workshop Presentations

Offshore Technology Research Center

A World Leader in Offshore Technology, Research,
Education and Testing

OTRC Core Mission

To provide technology, expertise, and services needed for the development of drilling, production, and transportation systems that enable the safe and economically viable exploitation of hydrocarbon resources in deep and ultra-deep water

Offshore Technology Research Center

Partnership:

Texas A&M University

The University of Texas at Austin

OTRC History

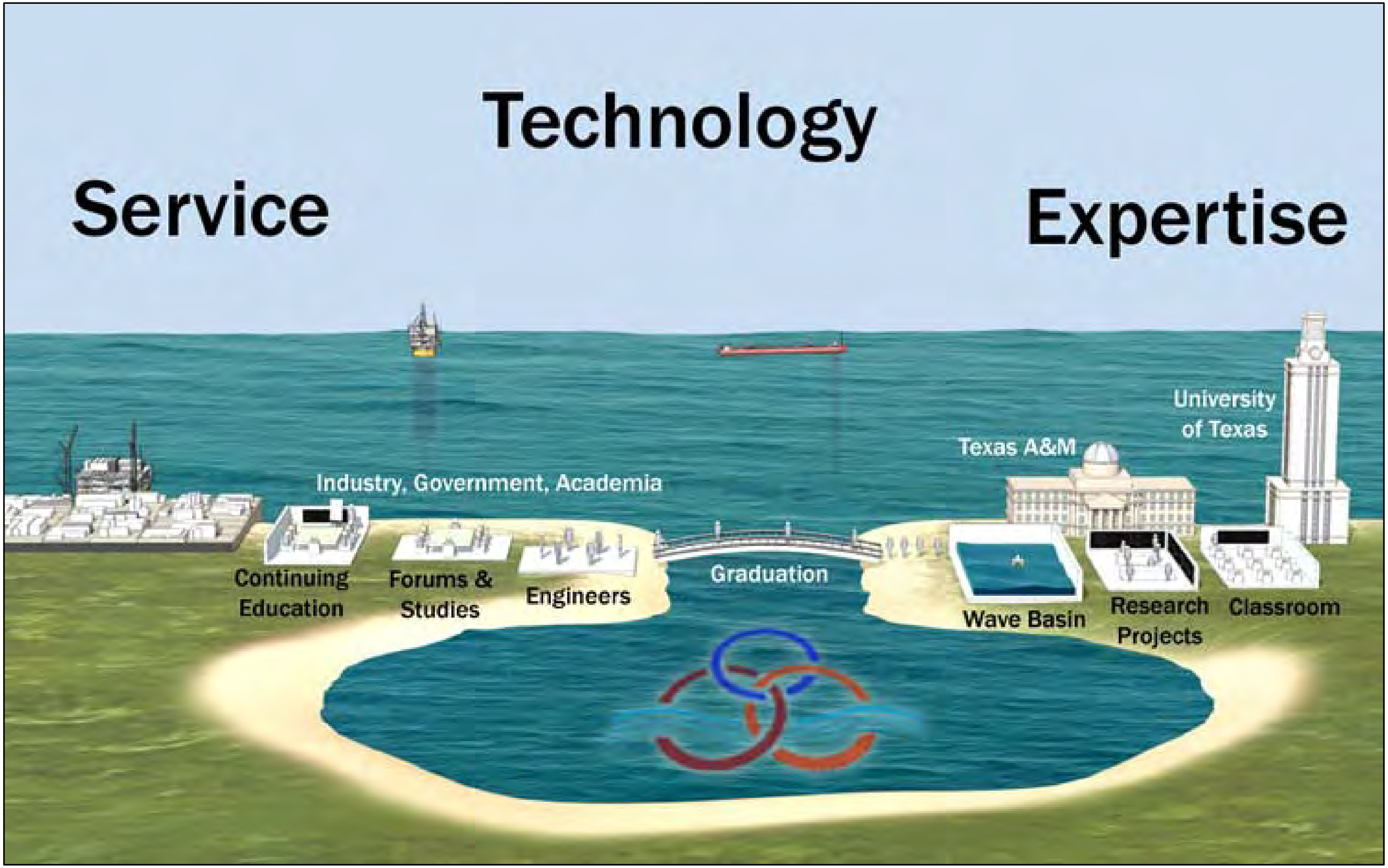
1988 - 1998

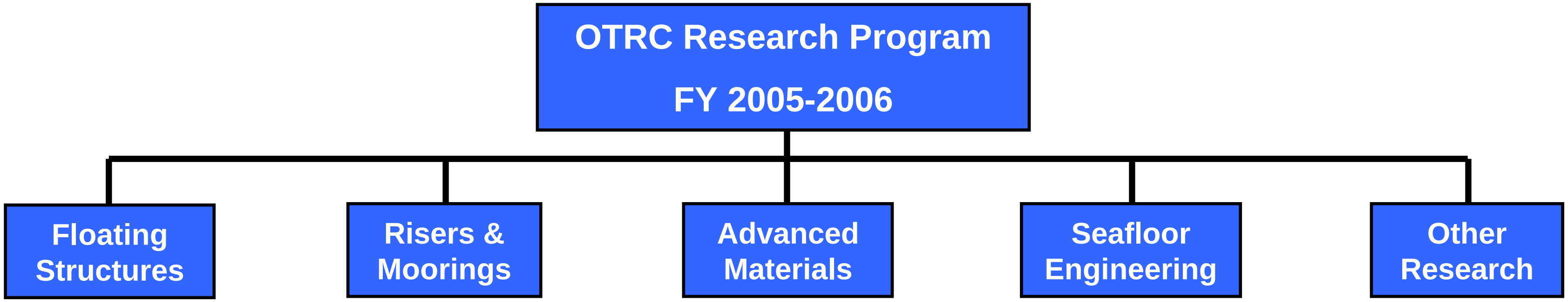
- established as National Science Foundation (NSF) Engineering Research Center (ERC)
- focus on technology for Gulf of Mexico out to 1,000 m water depth
- cutting edge research on tension leg platform (TLP) and spar technology

1999 - Present

- graduated NSF ERC
- cooperative agreement with Minerals Management Service
- broadening of interest to global, ultra-deep & remote

OTRC Mission




OTRC Research Program
FY 2005-2006
Floating Structures
Risers & Moorings
Advanced Materials
Seafloor Engineering
Other Research

OTRC Research Program

FY 2005-2006

Floating Structures | **Risers & Moorings** | **Advanced Materials** | **Seafloor Engineering** | **Other Research**

Composite Drilling Riser (NIST)

Coiled Tubing

Qualifying New Technologies for DW Development Workshop

NDE Evaluation Methods for Offshore Composites Workshop

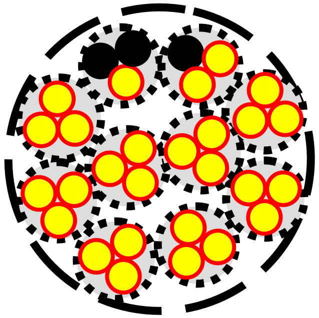
Polyester Mooring Line Damage Model

Polyester Rope Large Scale Experiments JIP

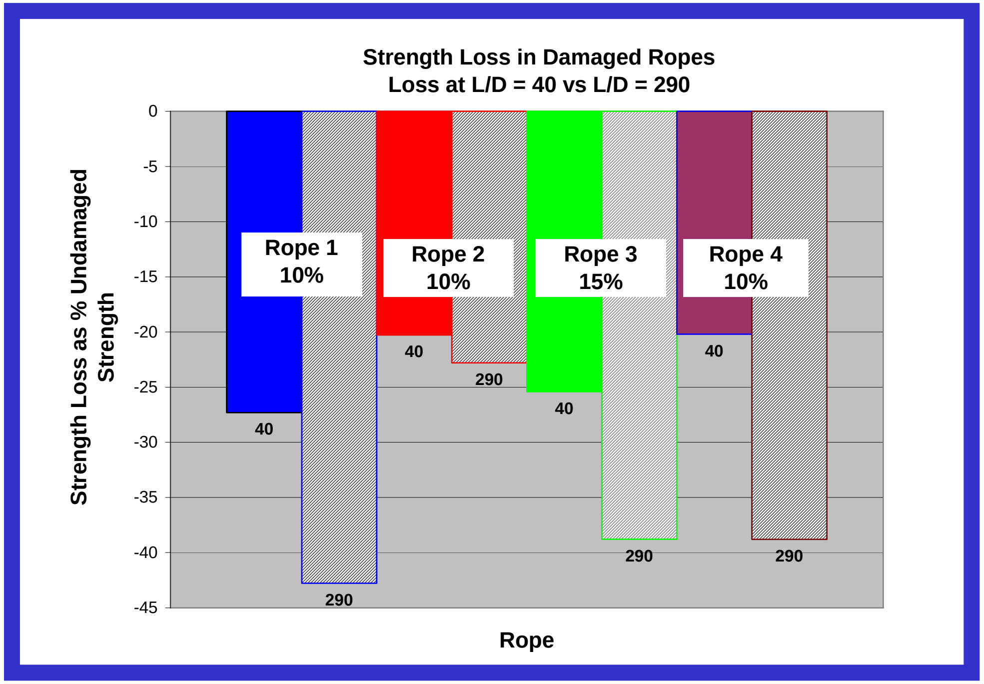
CRA for Composite & Steel Prod. Risers

Composite Riser Experience & Design Guidance

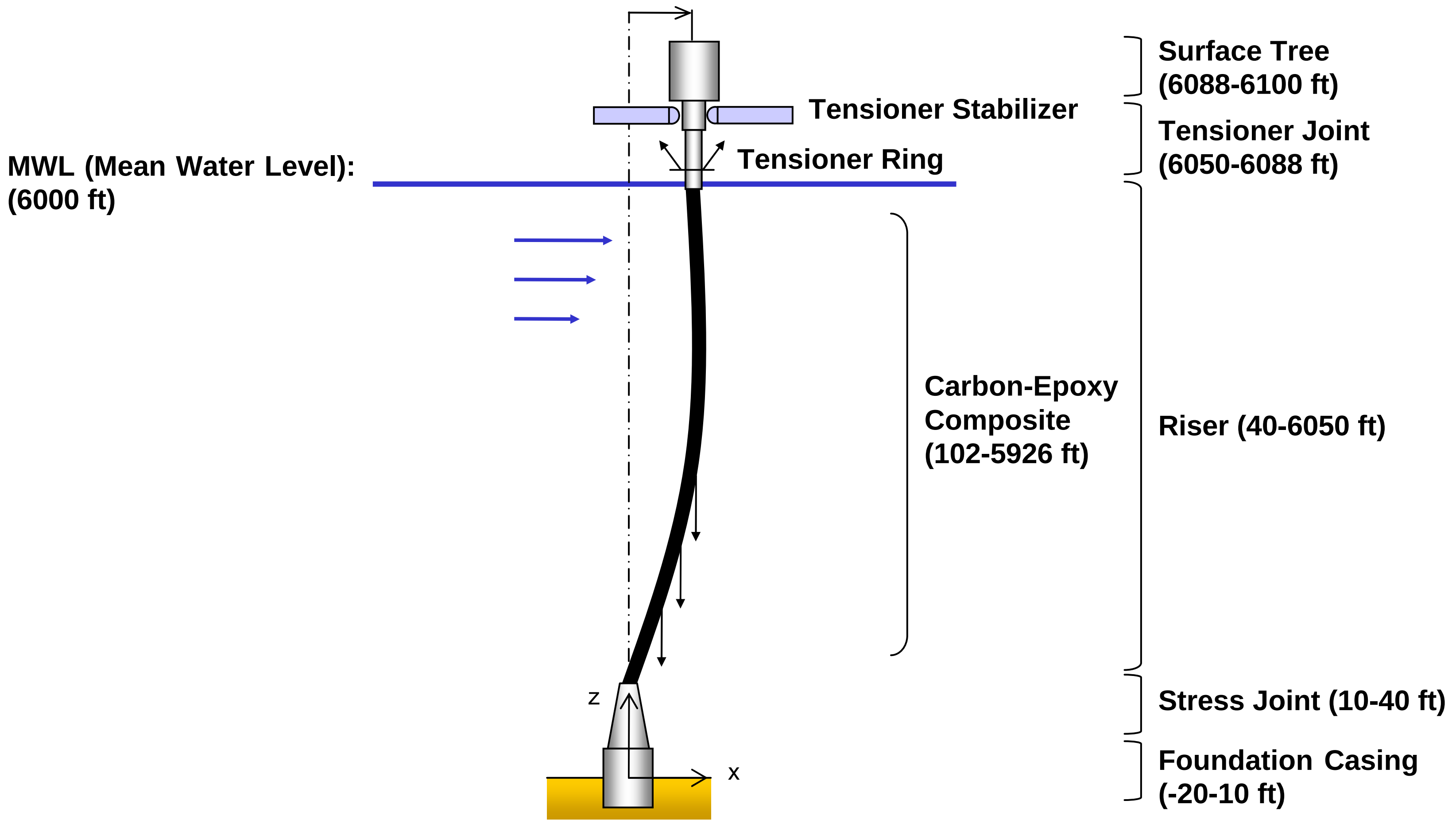
Use of Composite Materials to Repair Pipelines



Strength of Damaged Polyester Rope



TLP Riser System Configuration



Composite Analysis

Large size of the structure

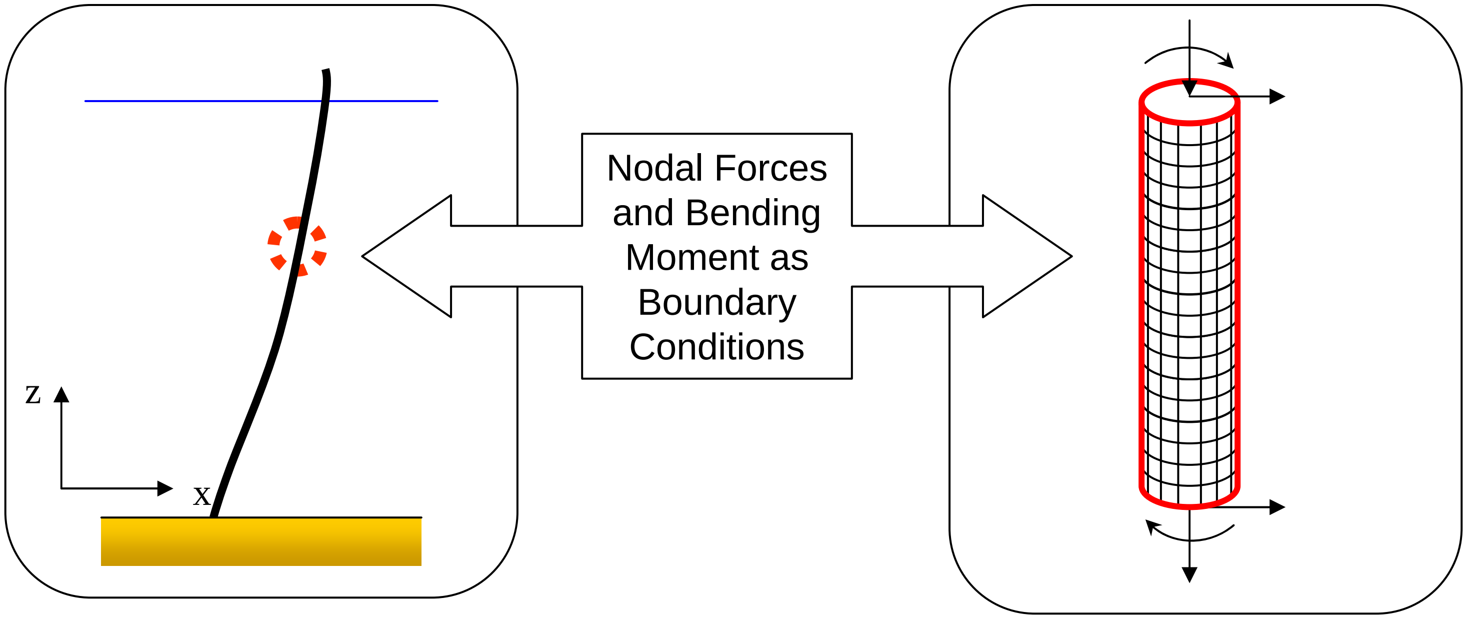
Beam Model

Effective Properties

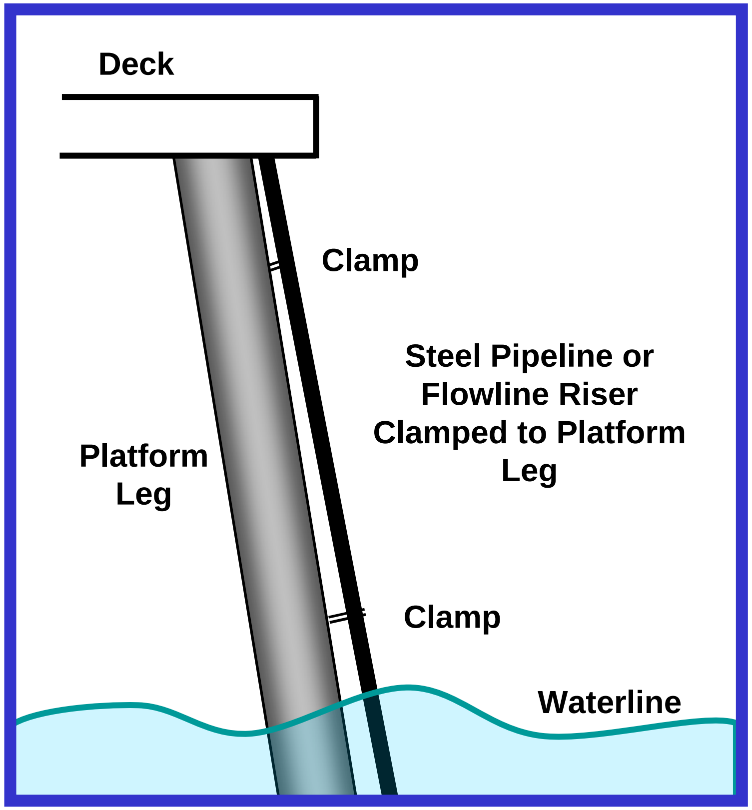
Complex Architecture of Composite

Shell Model

Lamina Properties

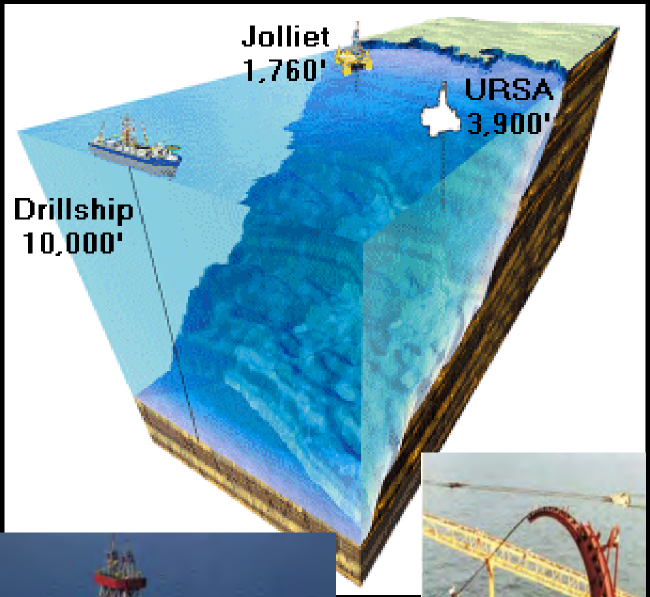


Composite Repairs of Steel Pipes



- Assess currently available composite repair systems for steel pipes
- Test a number of existing repair systems
- Provide practical and useful information to
  - (1) improve existing systems
  - (2) expand applicability these systems to more demanding repair scenarios

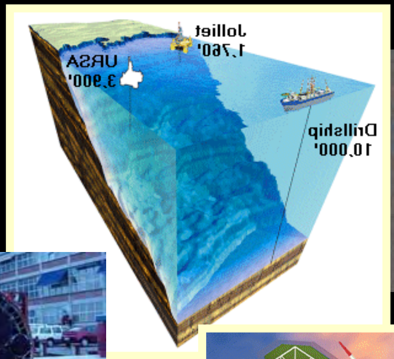
COMPOSITES IN OFFSHORE

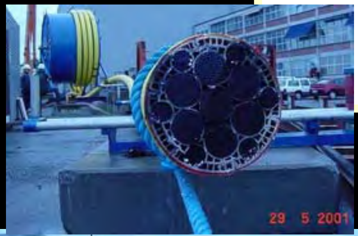


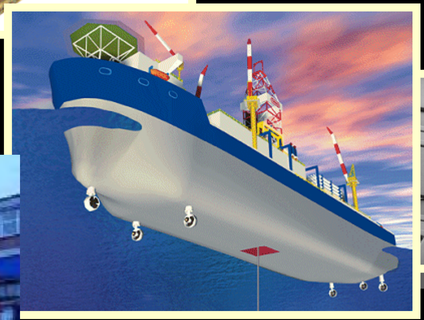
Dr. Ozden O. Ochoa

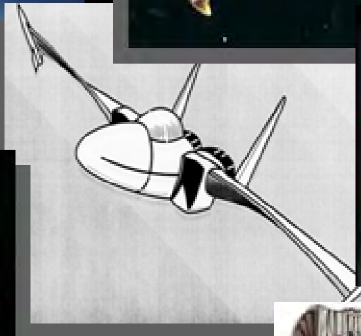
Offshore Technology Research Center
Texas A&M University
College Station, Texas

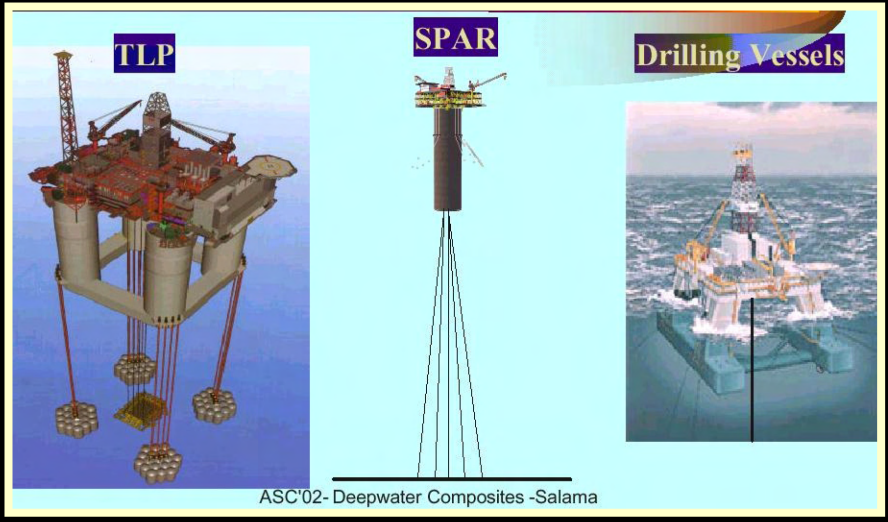
TODAY and BEYOND











RATIONALE

DEVELOP

Long Term Durability Philosophy

to incorporate physical and chemical material response into service life prediction

COUPONS

REDUCE SYSTEM CAPEX & OPEX!

RIGID TUBES

FLEXIBLE SYSTEMS

SYSTEM BENEFITS

- Provide
  - durability
  - dimensional stability
  - damage tolerance
- Accelerate innovative design
- Reduce development time and cost
- Enable flexible systems

MULTIPLE SCALES M^3

M^3icro

Multiple Constituents

Interfaces

Interphases

Processing
Manufacturing
Service

M^3eso

Coupled

Nonlinear

Time Dependent

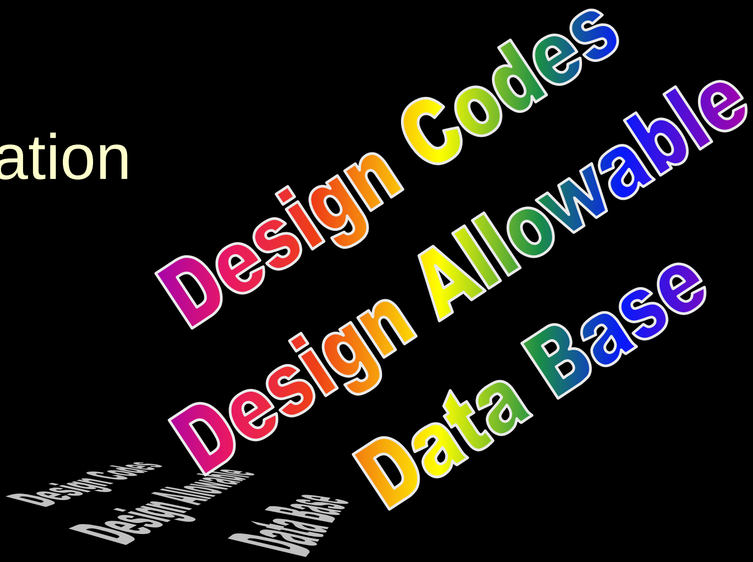
Integrated Analysis & Testing

Damage Mechanisms

M^3acro

CHALLENGES

- computational life prediction
- materials system design
- accelerated aging & correlation
- testing and NDE
- similitude
- intelligent processing
- certification
- zero environmental impact



REQUIREMENTS

- multidisciplinary optimization
  - processing
  - manufacturing
  - cost
  - performance
- environmentally acceptable materials
- low cost - high performance trade-off

APPROACH

- Establish engineering knowledge base
  - Interactive
  - Integrated
  - Instructive
- Champion insertion
  - Design-in properties
  - Optimize response

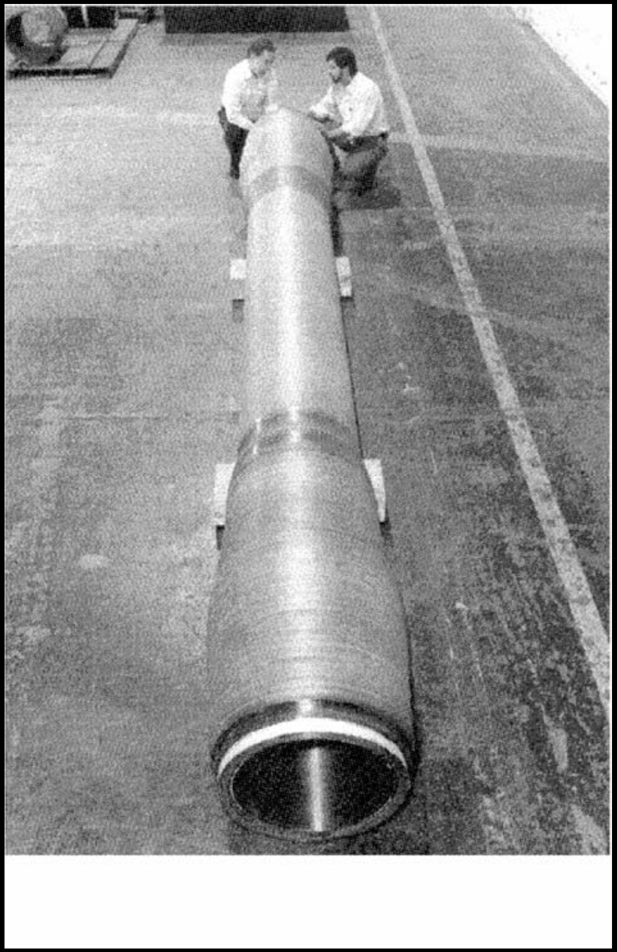
POSSIBILITIES..

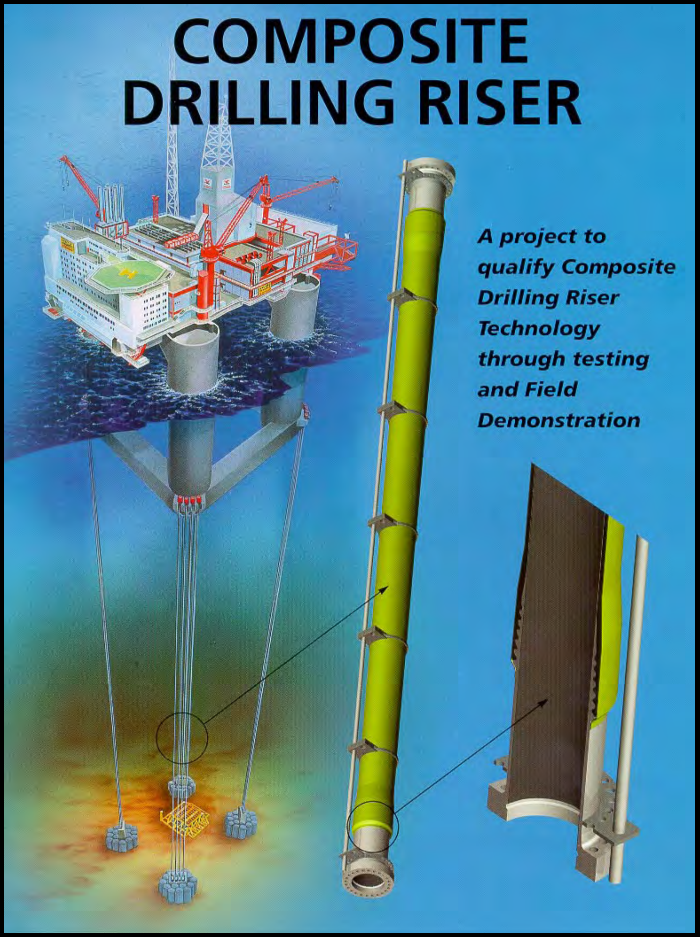
RISERS
TENDONS
MOORINGS
FLOW LINES

←

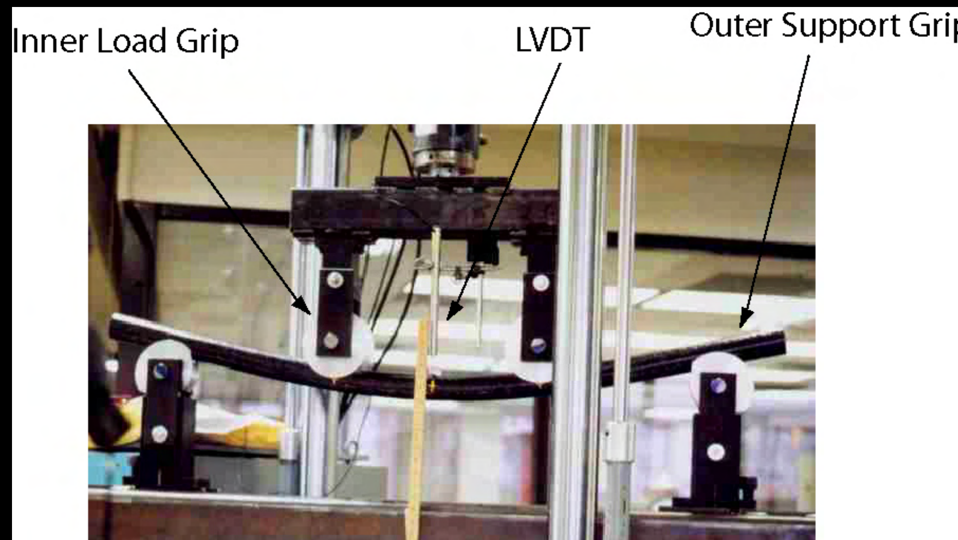
Thermoplastic Liner
Composite Strength Member
  Polymer Resin
  Continuous Fiber
Composite Damage Tolerance Layer
Thermoplastic Sleeve

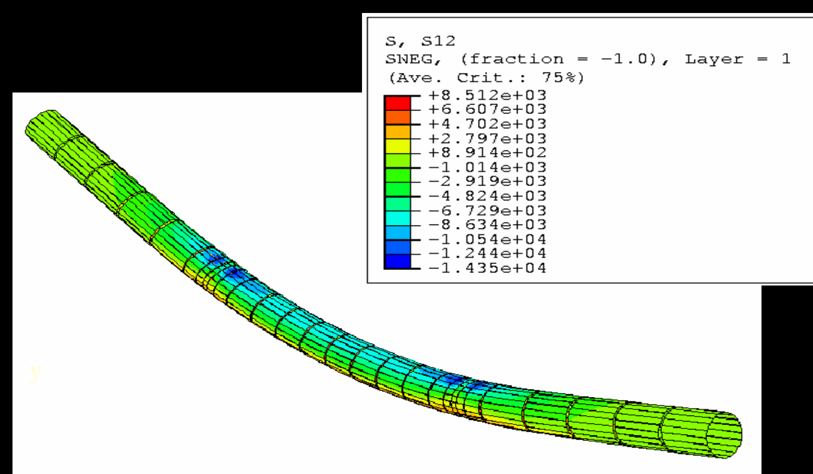
COMPOSITE DRILLING RISER



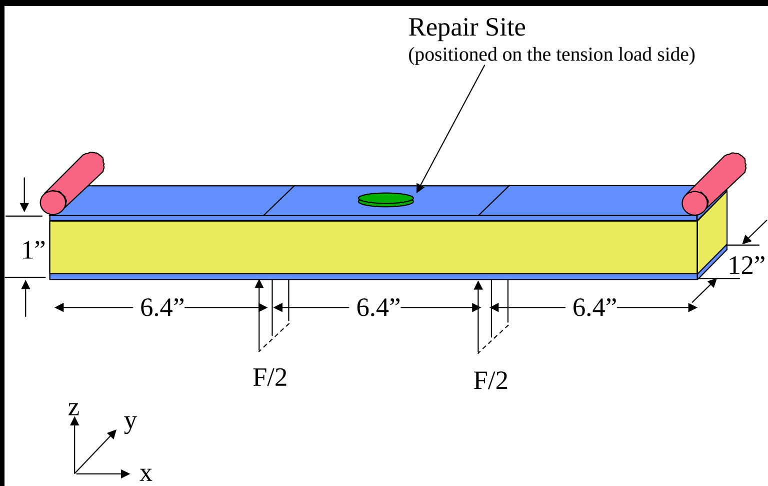


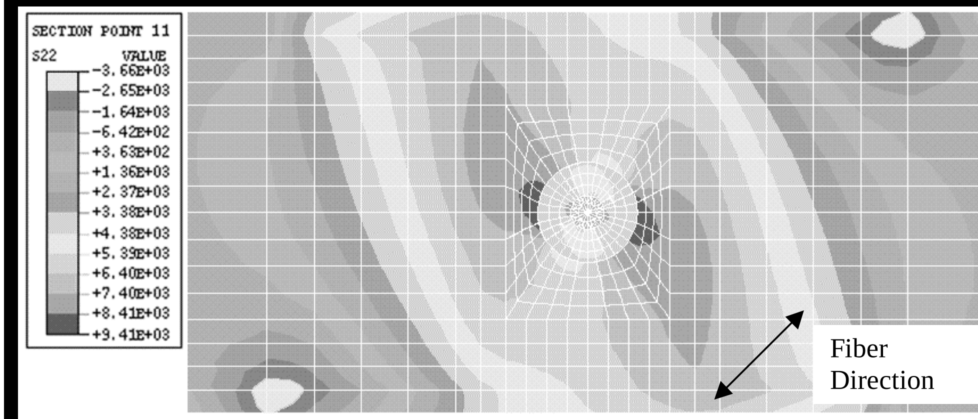
SPOOLABLE TUBULARS

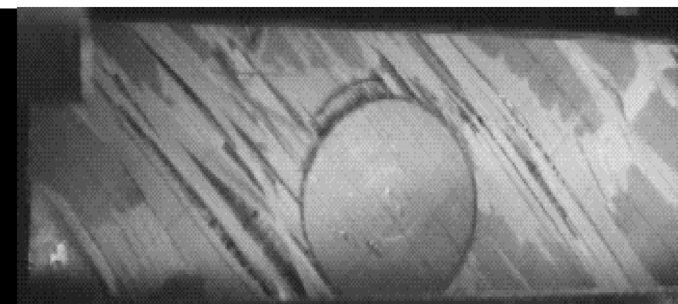


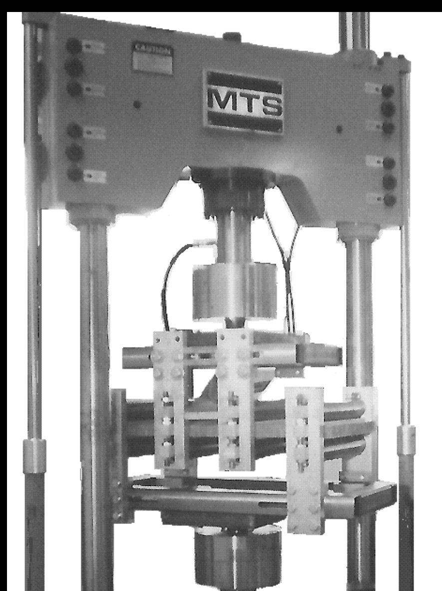


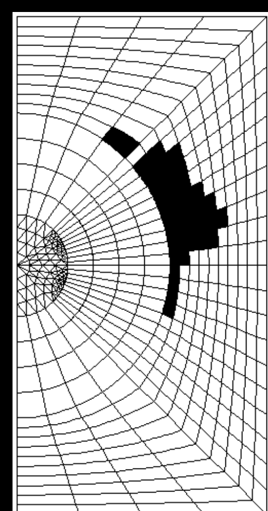
and REPAIR …Helicopter Blade

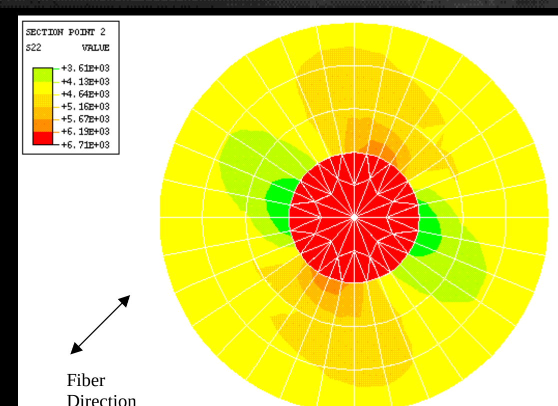












OTRC Reports Ochoa

Composite Repair Methods For Steel Pipes
US DOI Minerals Management Service, 2007

Composite Riser Experience & Design Guidance
US DOI Minerals Management Service, 2006

Comparative Risk Analysis of Composite Risers
US DOI – Mineral Management Service, 2005

Composite Spoolable Tubulars
US DOI Minerals Management Service, 2001

Composite Drilling Risers
NIST-ATP, 2000

Response and Reliability of Composite Risers
NSF Offshore Technology Research Center 1997-2002

Recent Publications

- Kim, W. K., Ochoa, O. O. & Miller, C. A., "Axial and Burst Analysis of Offshore Composite Risers," 20th Annual Technical Conference of the American Society for Composites, Philadelphia, PA, September 7-9, 2005.

- Kim, W. K. & Ochoa, O. O., "Damage Progression in Composite Production Riser under Combined Loads," 15th International Conference on Composite Materials, Durban, South Africa, June 27 - July 1, 2005.

- Ochoa, O. O. and Salama M. M., “Offshore Composites: Transition Barriers to an Enabling Technology”, J. of Composite Science and Technology, 20th Anniversary Issue, 2005

www.asc-composites.org

OTRC-MMS Workshop on Reinforcing Offshore Risers Using Composite Materials

Thursday, March 29, 2007

Hosted by

Stress Engineering Services, Inc.

Houston, Texas

Presentation Schedule

8:30 – 8:45	Check-in and breakfast
8:45 – 9:00	Welcome and introductions (SES and OTRC)
9:00 – 9:15	Regulatory perspectives and need for guidelines (MMS)
9:15 – 9:45	Use of composite materials in offshore applications (TAMU)
9:45 – 10:30	Fundamentals of composite repairs (SES)
10:30 – 10:45	Break
10:45 – 11:30	Discussions on Four Team Joint Industry Project (JIP) and introduction of composite repair companies (SES)
11:30 – 12:15	Lunch break
12:15 – 1:30	Tour of the Mohr Engineering test facility and viewing of the composite repair test samples from JIP program
1:30 – 2:15	Open group discussion on guideline development (OTRC/SES)
2:15 – 2:30	Closing remarks

Designated speakers

SES – Chris Alexander and Brent Vyvial
OTRC – Dr. Skip Ward
TAMU – Dr. Ozden Ochoa
MMS – Lori Medley

Welcome and Introduction

- Introduction of guests
- Facility information and layout
- Today’s objectives

Fundamentals of Composite Repairs

Presented by
Stress Engineering Services, Inc.

Chris Alexander
chris.alexander@stress.com

Today's Presentation

- Background in pipeline evaluation and repairs
- Examples of when composites can be used to repair pipelines
- Background on the major pipeline repair systems using composite materials
- U.S. government regulations
- Guidelines for repair using composites and test program elements
- Repair of dents and gouges (mechanical damage)
- Question & Answer Session

Stress Engineering Services, Inc.

- Emphasis on both testing and analysis of pipeline systems
- Have been involved in testing and analysis of pipeline systems and products for 30 plus years
- Significant work in pipeline testing and analysis
  - Full-scale testing of pipeline including burst pressure and cyclic pressure (fatigue) of dented pipes
  - Studies associated with repair of mechanical damage via grinding relative to static and cyclic pressure loads
  - SES has evaluated/tested most of the major composite pipeline repair systems

Typical Aims of Pipeline Repair Methods

- Restore strength to damaged pipes
- Reduce strain in damaged areas of pipe
- Seal corroded area of pipe from further development of corrosion

Uses of Composite Materials
(repair and structural reinforcement)

- Metal wall loss (due to corrosion)
- Plain dents
- Mechanical damage (dents with a gouge)
- Re-rating pipeline system to achieve higher operating pressures
- Corrosion repair and replacement
  - Under insulation coating (UIC)
  - Wear-resistant coatings (e.g. saddles)
  - Underwater coatings

Types of Composite Repairs

(used to repair pipeline systems)

- Wet lay-up systems (e.g. Armor Plate Pipe Wrap, Aquawrap, Black Diamond, Comptek, and Pipe Wrap A+)
  - Monolithic
  - Can be applied to non-straight geometries
  - Versatility in range of epoxy products (e.g. underwater, high temperature, etc.)
- Layered systems (e.g. Clock Spring and PermaWrap)
  - First widely-used composite repair system
  - Layered repair system
  - Limited to repair of straight pipes

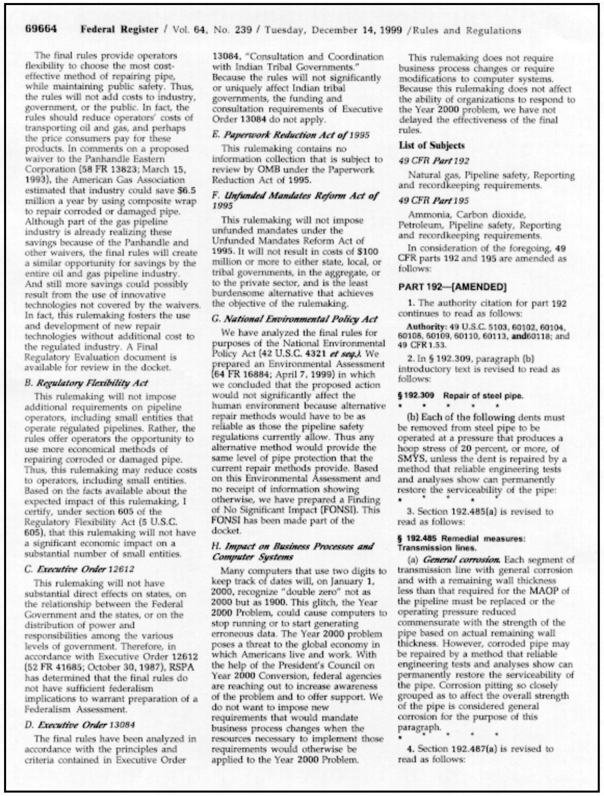
Government Regulations

(from the U.S. Department of Transportation)

On January 13, 2000, ***Pipeline Safety: Gas and Hazardous Liquid Pipeline Repair***, was issued by the RSPA of the Department of Transportation, went into effect.

According to this document, the requirement for repairing corroded and dents in pipelines is as follows,

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



69664 **Federal Register** / Vol. 64, No. 239 / Tuesday, December 14, 1999 / Rules and Regulations

The final rules provide operators flexibility to choose the most cost-effective method of repairing pipe, while maintaining public safety. Thus, the rules will not add costs to industry, government, or the public. In fact, the rules should reduce operators' costs of transporting oil and gas, and perhaps the price consumers pay for these products. In comments on a proposed waiver to the Panhandle Eastern Corporation (58 FR 13823; March 15, 1993), the American Gas Association estimated that industry could save $6.5 million a year by using composite wrap to repair corroded or damaged pipe. Although part of the gas pipeline industry is already realizing these savings because of the Panhandle and other waivers, the final rules will create a similar opportunity for savings by the entire oil and gas pipeline industry. And still more savings could possibly result from the use of innovative technologies not covered by the waivers. In fact, this rulemaking fosters the use and development of new repair technologies without additional cost to the regulated industry. A Final Regulatory Evaluation document is available for review in the docket.

B. ***Regulatory Flexibility Act***

This rulemaking will not impose additional requirements on pipeline operators, including small entities that operate regulated pipelines. Rather, the rules offer operators the opportunity to use more economical methods of repairing corroded or damaged pipe. Thus, this rulemaking may reduce costs to operators, including small entities. Based on the facts available about the expected impact of this rulemaking, I certify, under section 605 of the Regulatory Flexibility Act (5 U.S.C. 605), that this rulemaking will not have a significant economic impact on a substantial number of small entities.

C. ***Executive Order*** *12612*

This rulemaking will not have substantial direct effects on states, on the relationship between the Federal Government and the states, or on the distribution of power and responsibilities among the various levels of government. Therefore, in accordance with Executive Order 12612 (52 FR 41685; October 30, 1987), RSPA has determined that the final rules do not have sufficient federalism implications to warrant preparation of a Federalism Assessment.

D. ***Executive Order*** *13084*

The final rules have been analyzed in accordance with the principles and criteria contained in Executive Order 13084, "Consultation and Coordination with Indian Tribal Governments." Because the rules will not significantly or uniquely affect Indian tribal governments, the funding and consultation requirements of Executive Order 13084 do not apply.

E. ***Paperwork Reduction Act of*** *1995*

This rulemaking contains no information collection that is subject to review by OMB under the Paperwork Reduction Act of 1995.

F. ***Unfunded Mandates Reform Act of*** *1995*

This rulemaking will not impose unfunded mandates under the Unfunded Mandates Reform Act of 1995. It will not result in costs of $100 million or more to either state, local, or tribal governments, in the aggregate, or to the private sector, and is the least burdensome alternative that achieves the objective of the rulemaking.

G. ***National Environmental Policy Act***

We have analyzed the final rules for purposes of the National Environmental Policy Act (42 U.S.C. 4321 *et seq.*). We prepared an Environmental Assessment (64 FR 16884; April 7, 1999) in which we concluded that the proposed action would not significantly affect the human environment because alternative repair methods would have to be as reliable as those the pipeline safety regulations currently allow. Thus any alternative method would provide the same level of pipe protection that the current repair methods provide. Based on this Environmental Assessment and no receipt of information showing otherwise, we have prepared a Finding of No Significant Impact (FONSI). This FONSI has been made part of the docket.

H. ***Impact on Business Processes and Computer Systems***

Many computers that use two digits to keep track of dates will, on January 1, 2000, recognize "double zero" not as 2000 but as 1900. This glitch, the Year 2000 Problem, could cause computers to stop running or to start generating erroneous data. The Year 2000 problem poses a threat to the global economy in which Americans live and work. With the help of the President's Council on Year 2000 Conversion, federal agencies are reaching out to increase awareness of the problem and to offer support. We do not want to impose new requirements that would mandate business process changes when the resources necessary to implement those requirements would otherwise be applied to the Year 2000 Problem.

This rulemaking does not require business process changes or require modifications to computer systems. Because this rulemaking does not affect the ability of organizations to respond to the Year 2000 problem, we have not delayed the effectiveness of the final rules.

List of Subjects

49 CFR Part 192

Natural gas, Pipeline safety, Reporting and recordkeeping requirements.

49 CFR Part 195

Ammonia, Carbon dioxide, Petroleum, Pipeline safety, Reporting and recordkeeping requirements.

In consideration of the foregoing, 49 CFR parts 192 and 195 are amended as follows:

PART 192—[AMENDED]

1. The authority citation for part 192 continues to read as follows:

Authority: 49 U.S.C. 5103, 60102, 60104, 60108, 60109, 60110, 60113, and60118; and 49 CFR 1.53.

2. In § 192.309, paragraph (b) introductory text is revised to read as follows:

§ 192.309 Repair of steel pipe.

* * * * *

(b) Each of the following dents must be removed from steel pipe to be operated at a pressure that produces a hoop stress of 20 percent, or more, of SMYS, unless the dent is repaired by a method that reliable engineering tests and analyses show can permanently restore the serviceability of the pipe:

* * * * *

3. Section 192.485(a) is revised to read as follows:

§ 192.485 Remedial measures: Transmission lines.

(a) ***General corrosion.*** Each segment of transmission line with general corrosion and with a remaining wall thickness less than that required for the MAOP of the pipeline must be replaced or the operating pressure reduced commensurate with the strength of the pipe based on actual remaining wall thickness. However, corroded pipe may be repaired by a method that reliable engineering tests and analyses show can permanently restore the serviceability of the pipe. Corrosion pitting so closely grouped as to affect the overall strength of the pipe is considered general corrosion for the purpose of this paragraph.

* * * * *

4. Section 192.487(a) is revised to read as follows:

Page from the RSPA-98-4733 document

Guidelines for Evaluation of Composite Repair Methods

The **<u>basic fundamental issues</u>** for evaluating composite repair methods are as follows:

- Strength of the composite material
- Environmental effects (e.g. cathodic disbondment, temperature, acids and alkalines)
- Effects of pressure (both static and cyclic)
- Mechanics of load transfer from pipe to wrap
- <u>Long-term</u> performance issues
- Consistency in application and quality control in manufacturing

Elements of a Typical Testing & Analysis Program

- Corrosion repair (burst testing)
- Cyclic pressure effects on burst strength
- Repair of mechanical damage (static and cyclic)
- Load transfer analysis using strain gages and Finite Element Analysis (FEA)
- Tensile testing of composite materials
- Adhesive lap shear testing
- Effects of pressure at time of installation
- Long-term testing

Specific Technical Items
(discussed in today's presentation)

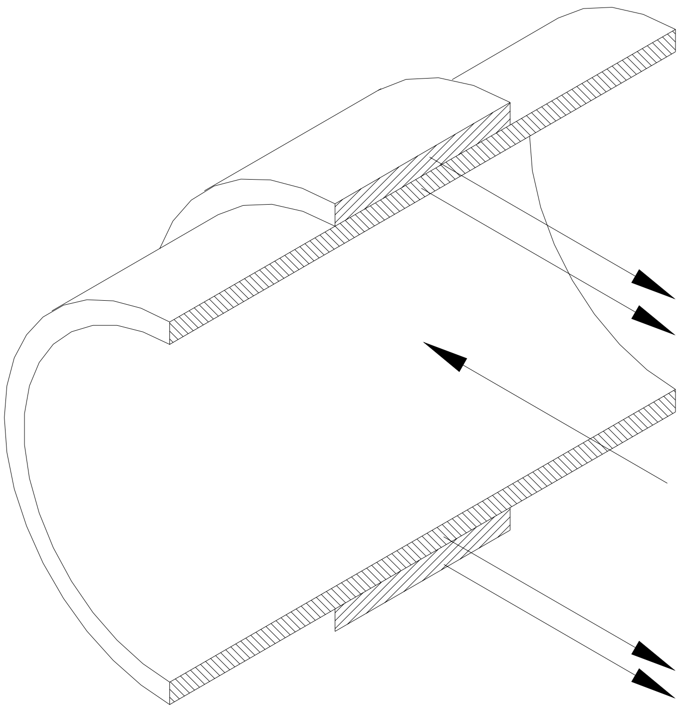
- Corrosion Repair and load transfer
- Repair of Pipe Fittings
- Repair of Mechanical Damage (dents with gouges)
- Discussion on Installation Concepts

CORROSION REPAIR

Load Sequence of Composite Repairs during Pressurization

- Pipe and wrap stressed as internal pressure increased (load distribution dependant upon relative stiffness of two components)
- Once yielding in corroded region occurs, local stiffness of pipe reduced and load transferred to wrap
- Final burst pressure governed by ultimate strengths of pipe and composite materials

Mechanics of Composite Repair Methods



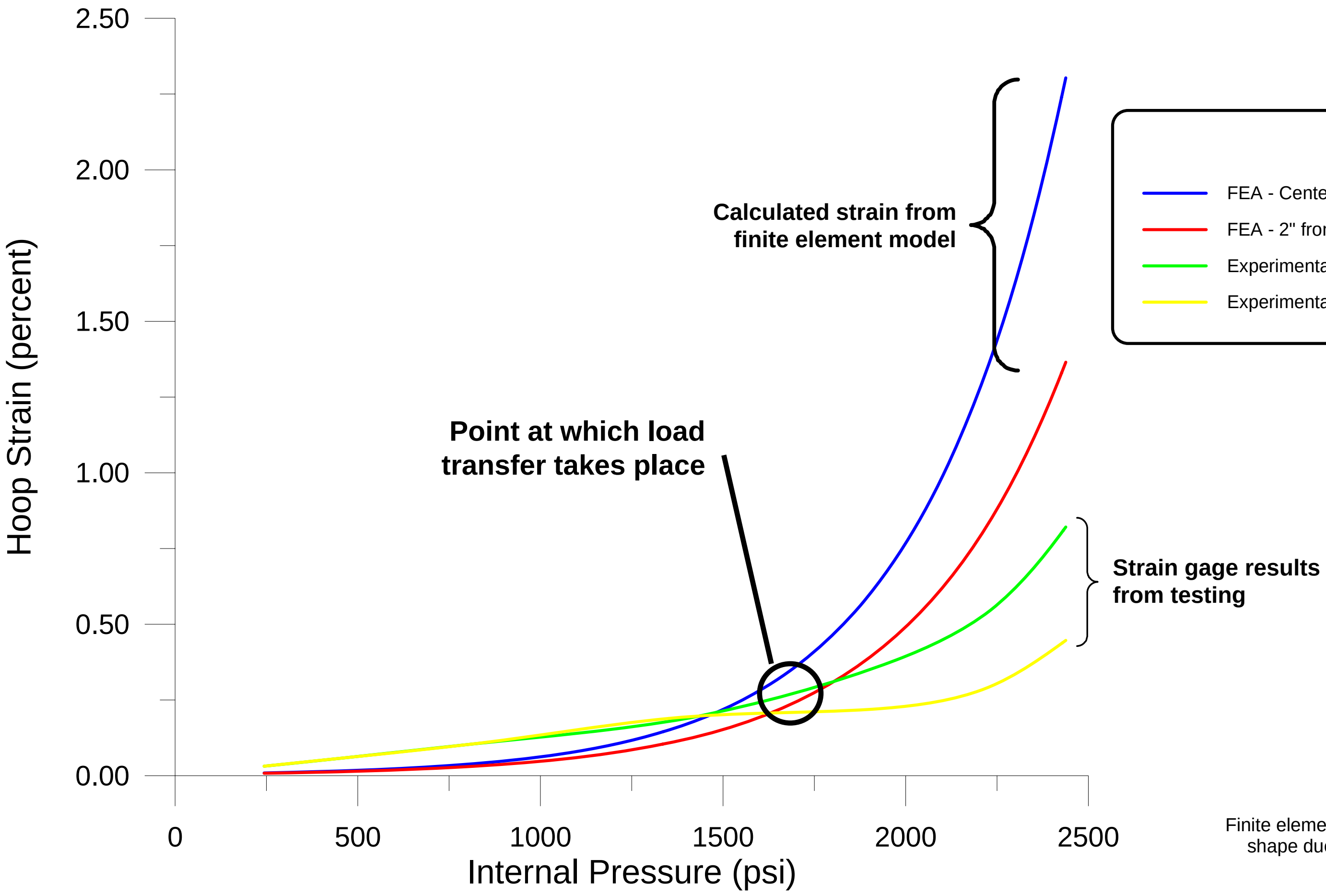
Equation defining burst pressure

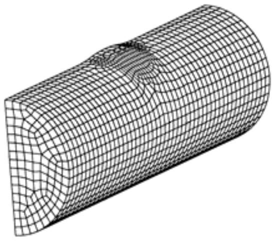
$$P_{burst} = \frac{\sigma_{ult_{pipe}} \cdot t_{pipe} + \sigma_{ult_{wrap}} \cdot t_{wrap}}{r_{inside}}$$

P = Internal pressure
σ = Material failure stress
t = Thickness of material
r = Radius of pipe

Note:
The above calculation is based on thin-wall shell theory and is not applicable for thick-walled pipes with diameter to wall thickness ratios less than 20.

Pipe-to-Composite Load Transfer
(Hoop Strain During Pressurization)





Finite element model with displaced shape due to internal pressure

REPAIR OF PIPE FITTINGS

Repair of Pipe Fittings

6-in STD Elbow (50% corrosion)

Unrepaired:	4,532 psi
Repaired:	6,780 psi

6-in STD Tee (50% corrosion)

Unrepaired:	6,546 psi
Repaired:	7,500 psi

MECHANICAL DAMAGE

Defect Classification
(and associated failure modes)

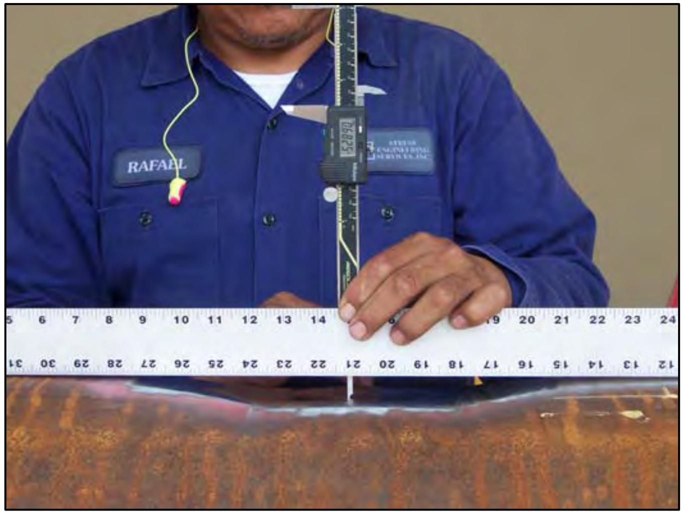
- Plain dents
- Gouges (no denting present)
- Mechanical damage (dents with gouges)
- Rock dents (constrained)
- Failure modes/methods
  - Rupture versus leak before break (K_{IC}, $\boldsymbol{\sigma}$, a)
  - Static burst versus fatigue failure (S-N relation)

Zone of Initiation/Propagation

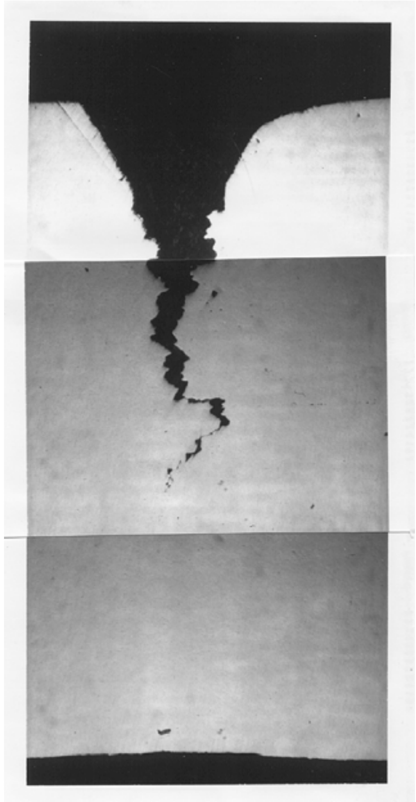
Verification of Crack Propagation

An initial gouge depth of 20% (a/t) propagated to a final crack depth that was 50% of the wall thickness when pressurized a <u>single cycle</u> to MAOP.

Photos from Dent Installation



Verification of Crack Propagation

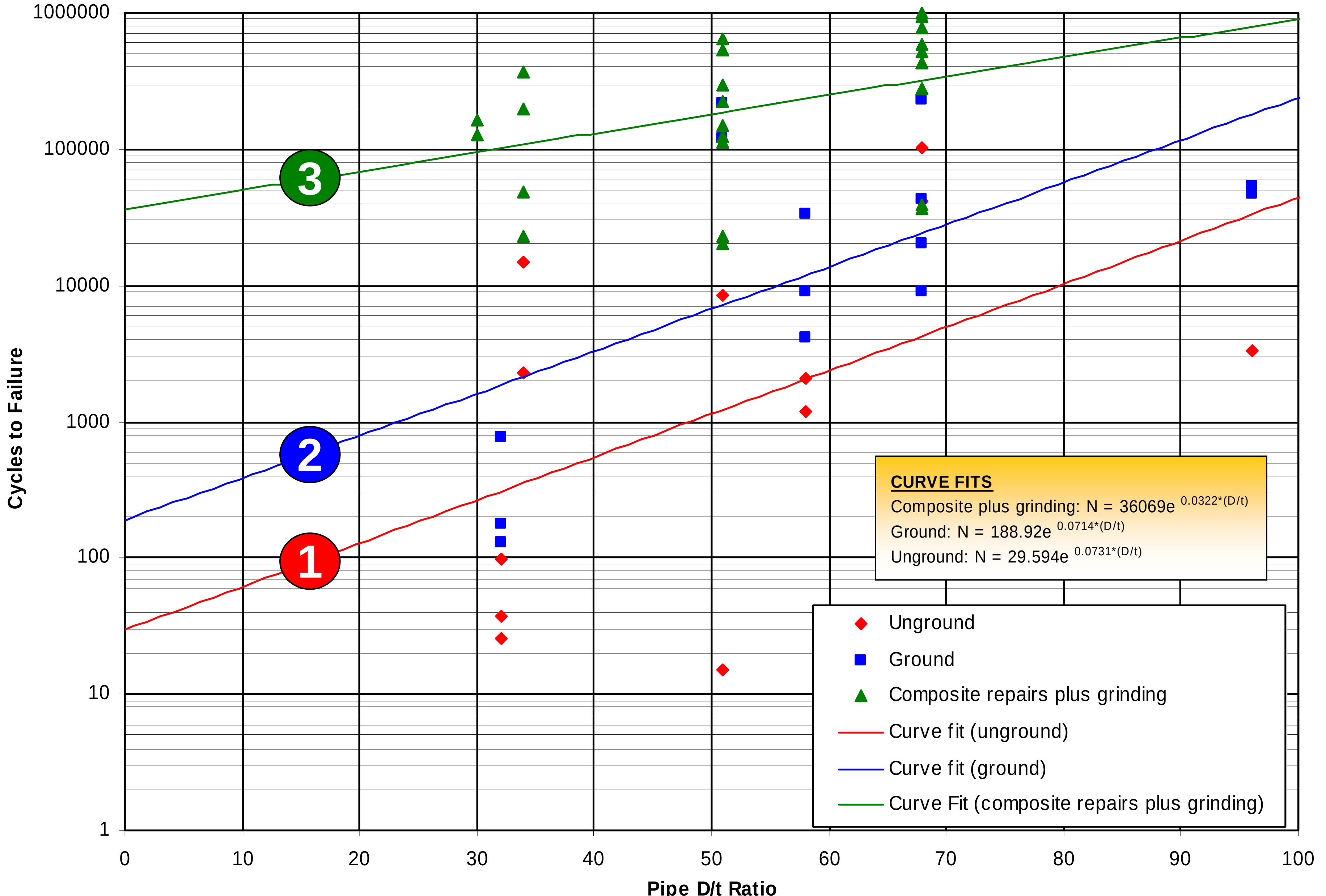


The gouge in *Sample P3C* (from PRCI Research project) developed a crack that propagated from an initial gouge depth of 20% (a/t) to a final crack depth that was 50% of the wall thickness

Mechanical Damage Repair

Cycles to Failure as a Function of D/t Ratio

Test results from pressure cycle fatigue tests performed on a range of pipe D/t ratios with a pressure range of 50% MAOP and initial dent depths of 15% and initial gouge depths of 15%.



MECHANICAL DAMAGE (Conclusions)

- Samples repaired by grinding had fatigue lives that were approximately 10 times those of *unrepaired dents and gouges*.
- Those defects that were repaired by grinding and composite* had fatigue lives that were approximately 1,000 times those of *unrepaired dents and gouges*.
- Slight improvements were obtained over the grinding/composite repair with the installation of the stainless steel clamp.

* - composite testing based on Armor Plate Pipe Wrap, Aquawrap, and Clock Spring

INSTALLATION AND APPLICATION TECHNIQUES

Steps in Pipeline Repair

- Locate damaged section(s)
- Assess severity of damage (e.g. corrosion, mechanical damage, etc.) and determine if repair is possible
- Calculate required number of wraps (if appropriate for respective repair type)
- Clean and prepare pipe (surface preparation critical)
- Install composite repair
- Allow repair to cure per manufacturer’s recommendations
- Restore pipeline environment (e.g. backfill and re-pressurize)

Observations on Current Composite Repair Methods

- For more than 10 years, the pipeline industry has been making repairs using composite materials
- A significant body of research exists addressing a variety of repair types
- It is the presenter's observation that the missing link with the composite repair systems is long-term test data (especially in terms of the adhesive/resin systems)
- New standards such as ASME's PCC-2 will set minimum design criteria, although the focus up to this point has been repair of onshore pipelines

Four Team Joint Industry Project

Presented by
Stress Engineering Services, Inc.

Brent Vyvial
brent.vyvial@stress.com

Chris Alexander
chris.alexander@stress.com

Overview of Presentation

- Current design needs for offshore riser repairs
- Joint Industry Project (JIP) test program
  - Elements of test program
  - Presentation of results
  - General observations
- Future developments
  - Additional analysis and testing work
  - Completing the guideline development for MMS
  - Addressing long-term performance issues

Current Design Needs
(Repair System Development)

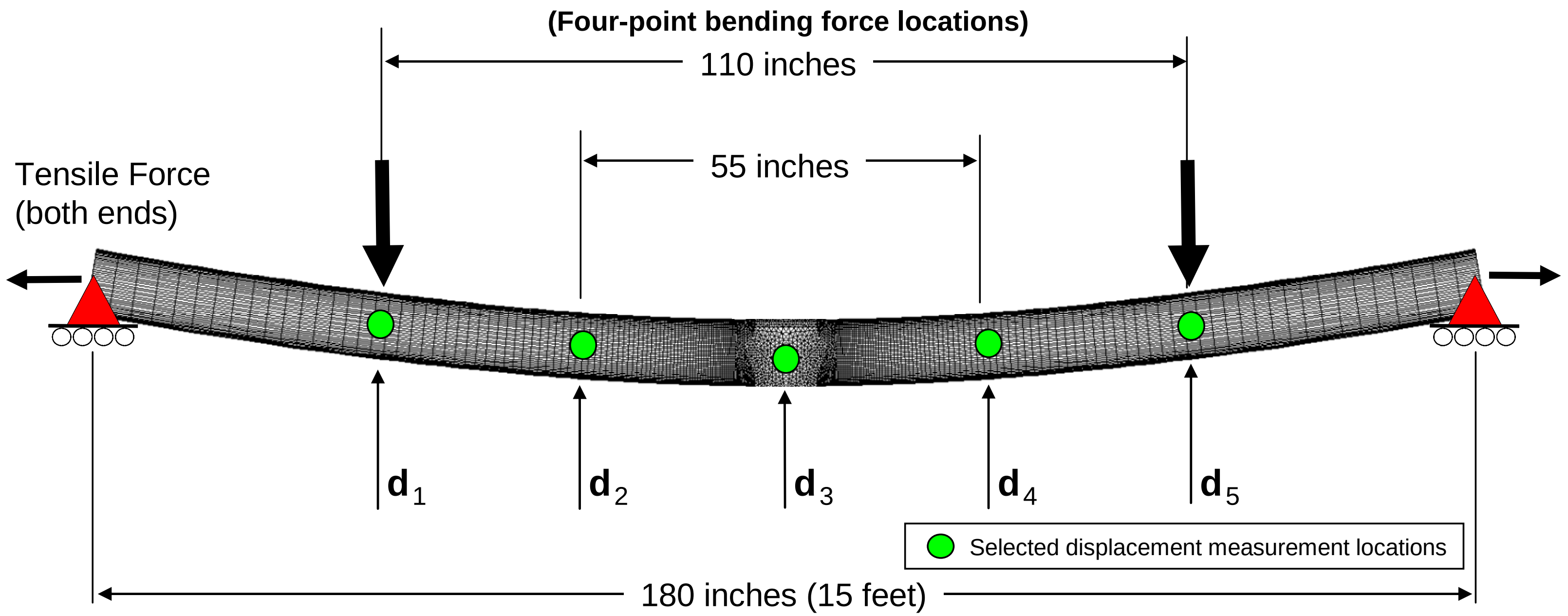
- Integrating riser loads
- Expected results for the different load requirements
  - Internal pressure
  - Axial tension
  - Bending
- Essential elements relative to design repair requirements
- Consider riser loads subject to appropriate design stress (or strain) limits
- Addressing and qualifying potential upset conditions

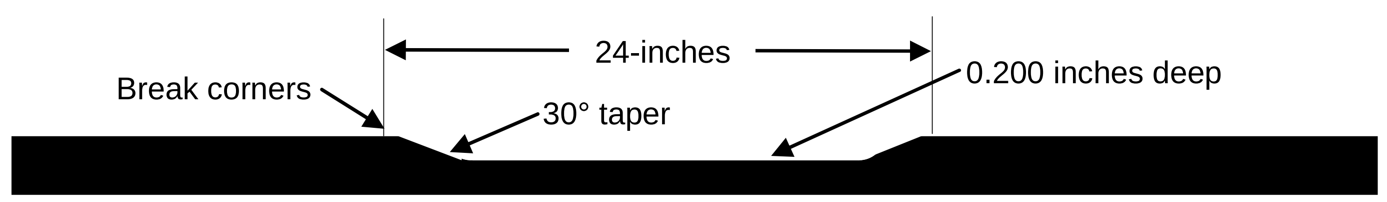
Testing Phase

- Full-scale testing using 8.625-in x 0.406-in, Grade X46 pipe (representative D/t ratio for risers)
- Three test samples integrating 50% corrosion
  - 8-ft long Internal **pressure** sample (see NOTE)
  - 8-ft long Pressure and **tension**
  - 15-ft long Pressure, tension, and **bending**
- Strain gages installed in corroded areas beneath repairs
- In testing limit analysis methods used to capture the lower bound plastic collapse load

NOTE: Test load variables shown in **BOLD RED** are the ones incrementally increased to capture the corresponding lower bound collapse load.

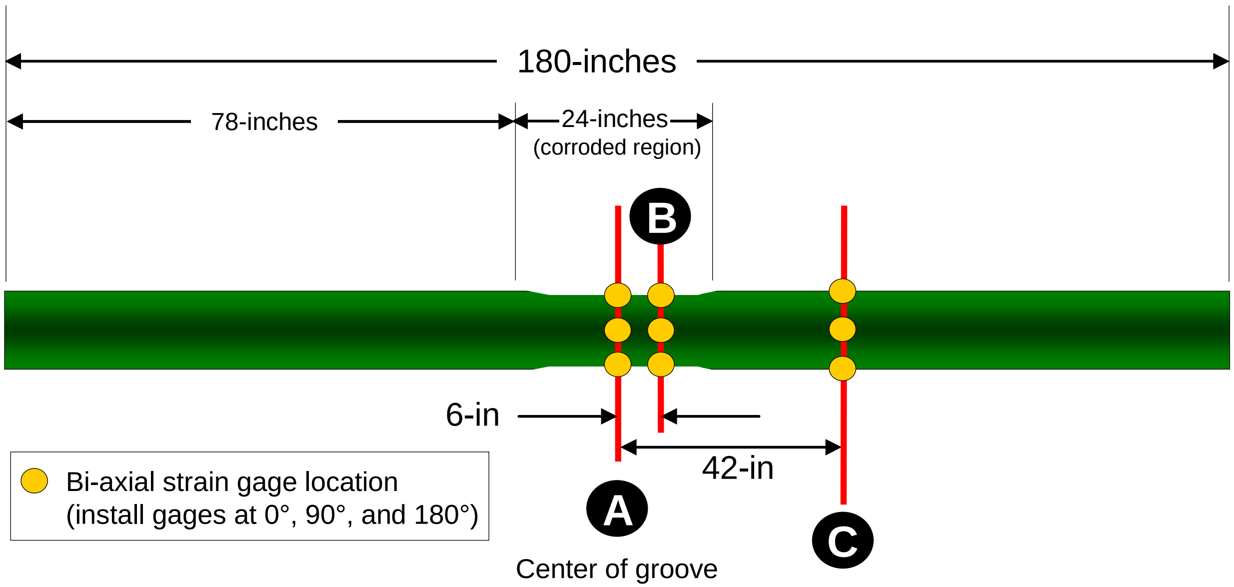
Testing Details
(Sample loading and defect configuration)



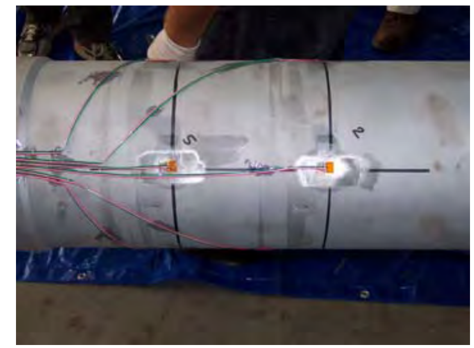


Simulated corrosion on outside surface of pipe (circumferential groove)

Testing Details
(Strain gage details – 12 per sample)



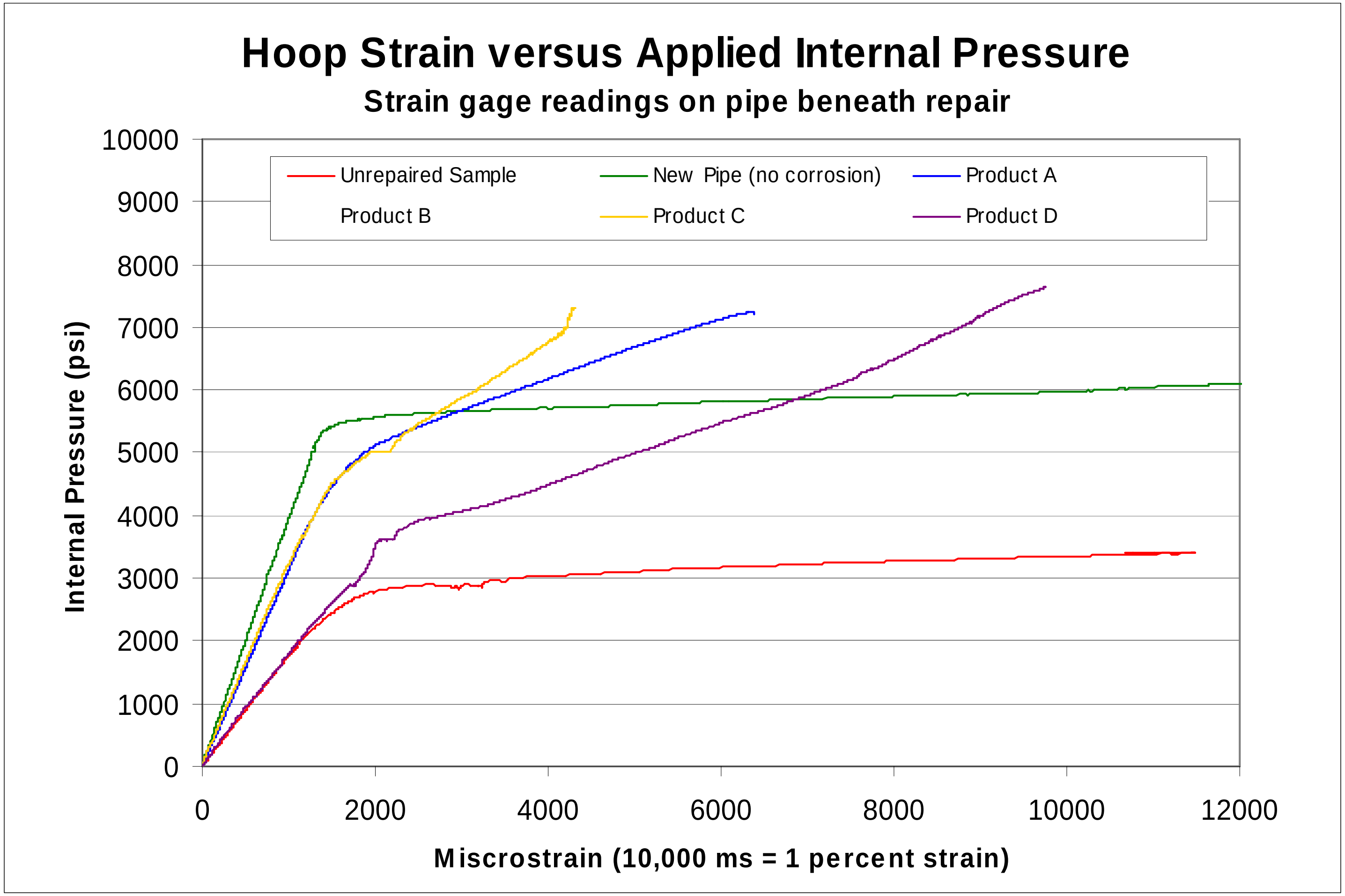
Gages @ A and B will be beneath composite repair



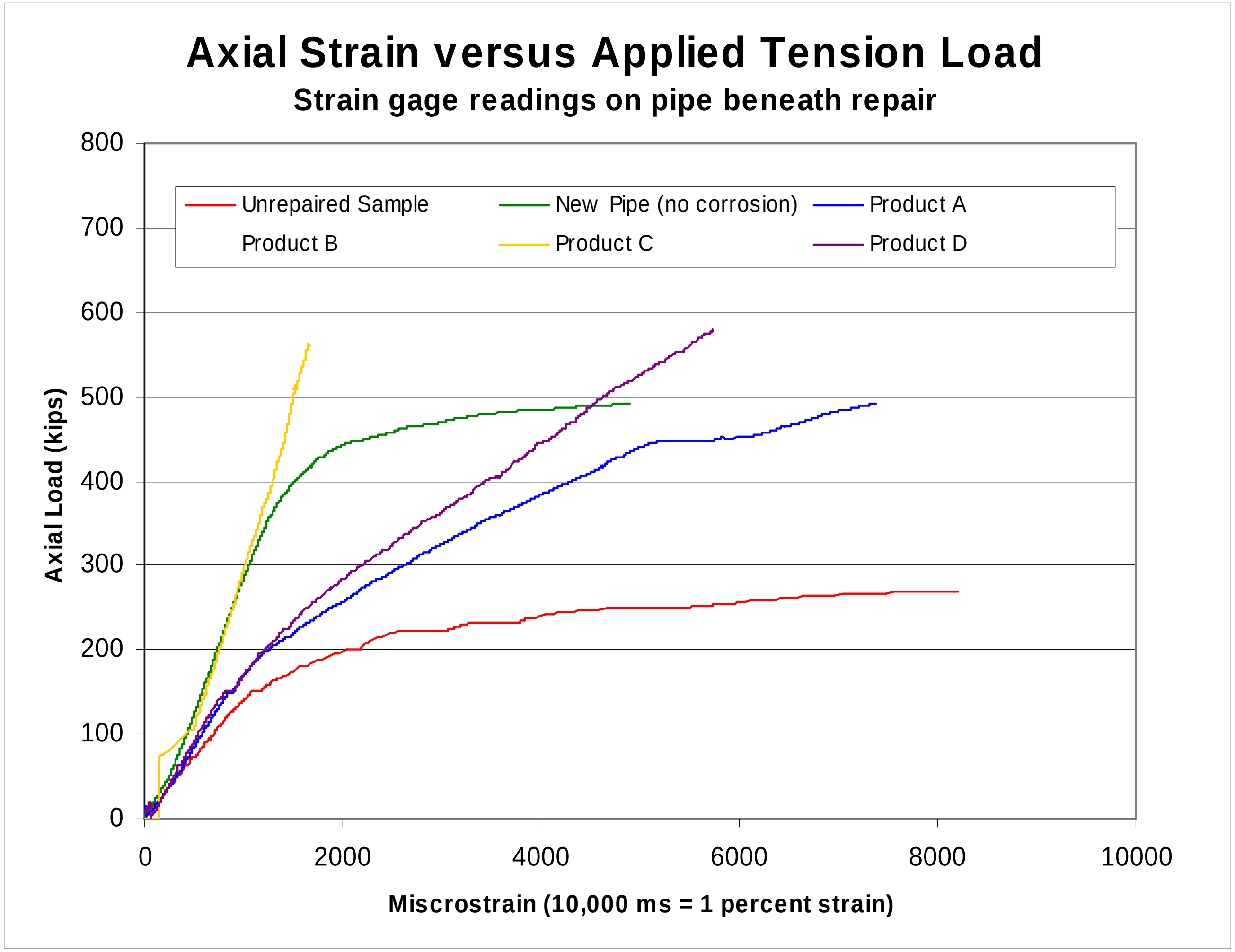
Four Repair Systems

- Product A
  - E-glass with water-activated urethane matrix
- Product B (test data not included)
  - E-glass with water activated urethane matrix
- Product C
  - Carbon with epoxy matrix
- Product D
  - E-glass with epoxy matrix

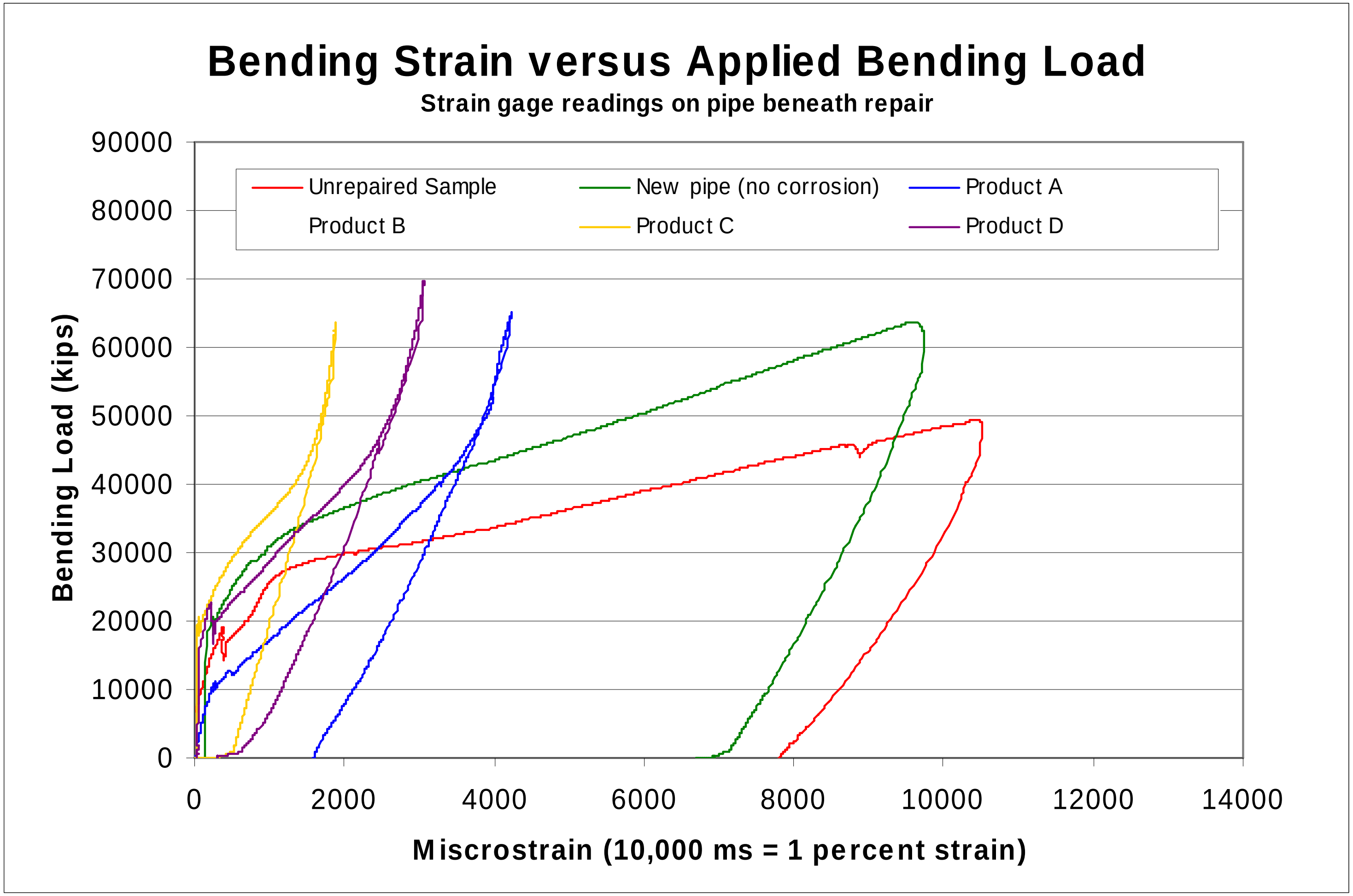
Test Results
(Burst pressure sample)



Test Results
(Tension loading sample)



Test Results
(Bending load sample)



General Comments on Testing

- This program integrated typical riser loads and was able to capture strain levels in pipe during testing
- Success criteria is rooted in the ability of the repair to reinforce the corroded region (i.e. reduce strain in the reinforced steel)
- Final consideration of success should consider
  - Quality control and consistency in application
  - Economics including efficiency of the repair process
  - Long-term performance

Analysis Phase

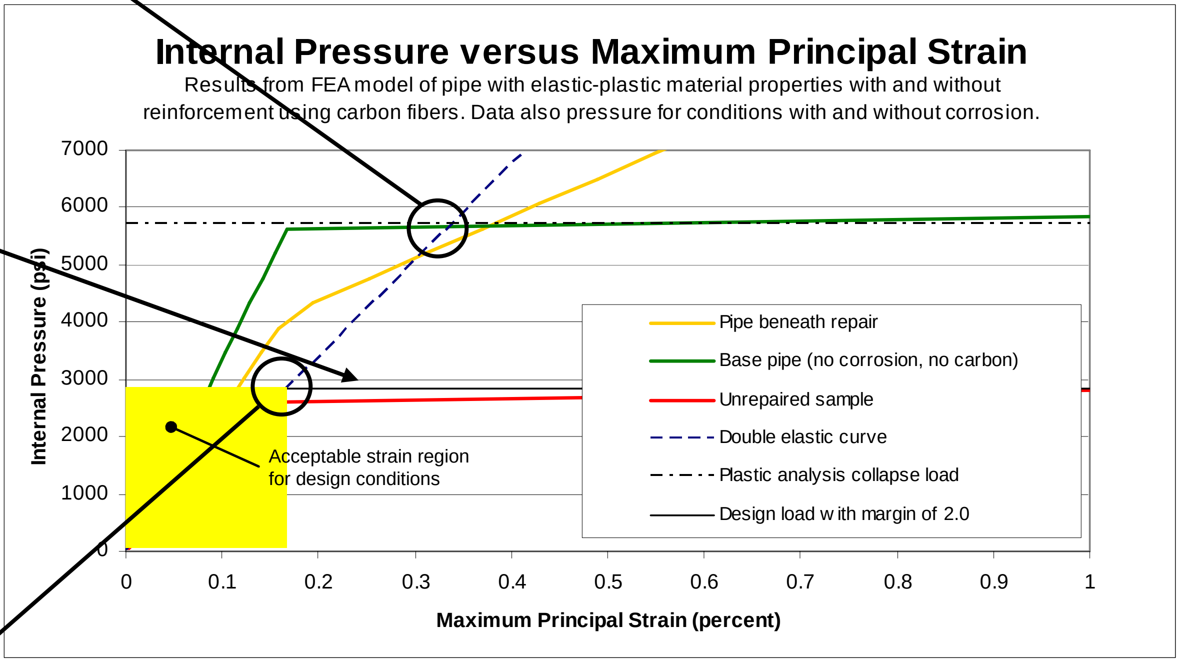
- Simulation of repair considering loads considered during testing phase
- Finite element analysis employing specific composite properties and elastic-plastic material properties for steel riser pipes
- Limit analysis methods used to capture the lower bound plastic collapse load and corresponding design load condition

Limit Analysis Methods
(Using the Double-Elastic Slope Technique)

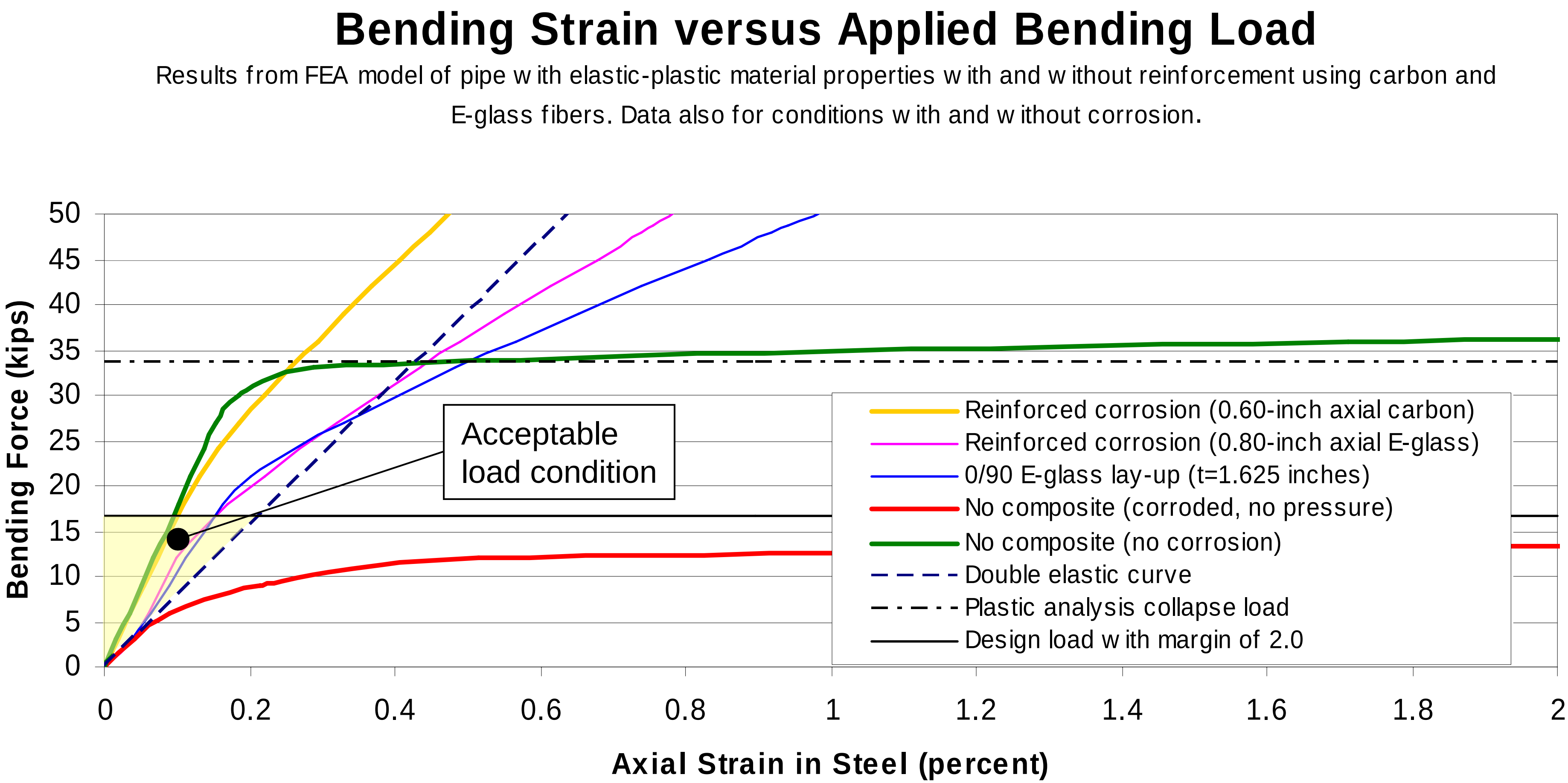
STEP #1
Determine the Limit Load for the Undamaged Riser: Using a finite element model for the uncorroded/undamaged state with elastic-plastic material properties, increase loading on the structure to the condition where unbounded displacements occur. This also corresponds to the intersection of the strain-deflection curve and the double elastic curve.

STEP #2
Calculate Design Load Using an Acceptable Design Margin: Using the calculated collapse load with an appropriate design margin (e.g. value of 2.0), calculate the design load. As long as the loads applied to a structure are less than this value, the structural integrity of the vessel is deemed acceptable.

STEP #3
Determine the Design Strain Limit: Using the results for the design load, the maximum acceptable design strain is defined as the intersection of the design load and the double elastic slope curve. As noted in this figure, the triangle created by this region is defined as the acceptable load-strain design region. The design strain limit is the maximum permitted strain that can occur in the corroded riser under the given loading conditions.



Limit Analysis Methods
(Design basis for pressure, tension, and bending)



Optimization Process
(including fiber type, orientation, and thickness)

Industrial Grade Carbon Material

carbon_005_h100.inp — **10 Msi Carbon: 0.200-in hoop | 0.005-in axial | 0.100-in hoop**

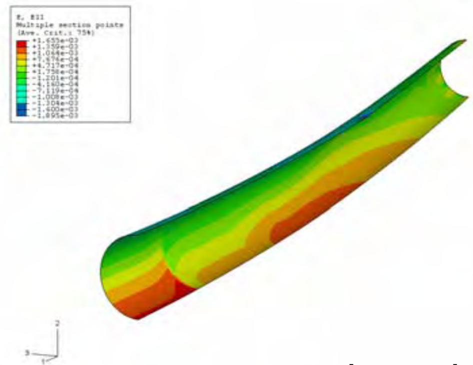
Layer	Material	Thickness	h/L	h/L (sum)	e11	e22
0	steel	0.2	0.396	0.000	0.512	
1	Carbon hoop	0.1	0.198	0.594	0.104	0.486
2	Carbon hoop	0.1	0.198	0.792	0.127	0.495
3	Carbon axial	0.005	0.010	0.802	0.500	0.140
4	Carbon hoop	0.1	0.198	1.000	0.152	0.505

carbon_200_h100.inp — **10 Msi Carbon: 0.200-in hoop | 0.200-in axial | 0.100-in hoop**

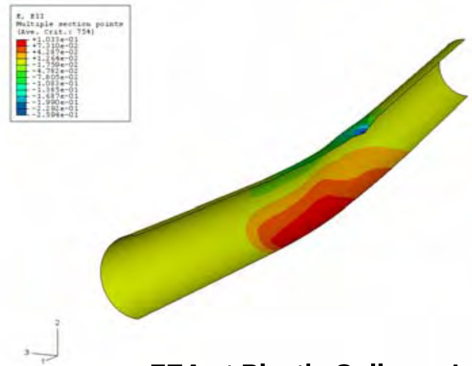
Layer	Material	Thickness	h/L	h/L (sum)	e11	e22
0	steel	0.2	0.396	0.000	0.188	
1	Carbon hoop	0.1	0.198	0.429	0.086	0.171
2	Carbon hoop	0.1	0.198	0.571	0.090	0.175
3	Carbon axial	0.1	0.198	0.714	0.178	0.093
4	Carbon axial	0.1	0.198	0.857	0.182	0.096
5	Carbon hoop	0.1	0.198	1.000	0.099	0.186

carbon_400_h100.inp — **10 Msi Carbon: 0.200-in hoop | 0.400-in axial | 0.100-in hoop**

Layer	Material	Thickness	h/L	h/L (sum)	e11	e22
0	steel	0.2	0.396	0.000	0.145	
1	Carbon hoop	0.1	0.198	0.333	0.089	0.125
2	Carbon hoop	0.1	0.198	0.444	0.088	0.128
3	Carbon axial	0.1	0.198	0.556	0.131	0.087
4	Carbon axial	0.1	0.198	0.667	0.134	0.087
5	Carbon axial	0.1	0.198	0.778	0.137	0.086
6	Carbon axial	0.1	0.198	0.889	0.139	0.085
7	Carbon hoop	0.1	0.198	1.000	0.084	0.142



FEA at Design Load



FEA at Plastic Collapse Load

Future Developments

- Developing a summary report that captures the results of the JIP test program
- Preparation of Composite Repair Guidelines for MMS that includes:
  - Observations from JIP study
  - Development of strain-based design criteria for steel
  - Limitations on composite design stresses in the absence of long-term stress rupture data (e.g. 40% UTS)
- A follow-on study is needed to establish repair criteria for offshore repair and should include a study of long-term performance

Overall Comments
(from Stress Engineering Services, Inc .)

- Today's workshop is the culmination of more than 10 years worth of research on composite materials used to repair pipelines
- Composite materials are currently being used offshore in the Gulf of Mexico and other regions around the world
- To be effective, composite repair systems must be designed to ensure (as a minimum):
  - Adequate reinforcement for the repaired steel
  - Long-term strength exists in the composite materials