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Design of an Optimized Composite Repair System for Offshore Risers Using Integrated Analysis and Testing Techniques

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Abstract

Composite systems are a generally-accepted method for repairing corroded and mechanically-damaged onshore pipelines. The pipeline industry has arrived at this point after more than 15 years of research and investigation. Because the primary method of loading for onshore pipelines is in the circumferential direction due to internal pressure, most composite systems have been designed and developed to provide hoop strength reinforcement. On the other hand, offshore pipes (especially risers), unlike onshore pipelines, can experience significant tension and bending loads. As a result, there is a need to evaluate the current state of the art in terms of assessing the use of composite materials in repairing offshore pipelines and risers.

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

Introduction

At the core of proving the worthiness of composite repair systems is full-scale testing, where damage is recreated and loading is generated to simulate actual real-world loading conditions. These real-world conditions include, but are not limited to, static and cyclic internal pressure, axial tension and bending loads, and exposure to environmental conditions. These efforts are essential to establish the long-term viability of composite repair systems. As the pipeline industry continues to expand the use of composite materials beyond repairing corrosion, full-scale validation becomes even more important.

The purpose of this paper is to provide a high-level overview of recent testing and analysis to evaluate the performance of composite repair systems, including testing methods, results, and implications. The following assessments are discussed in this paper:

- Pressure cycle testing of corroded pipes
- Composite reinforcement (inter-layer strain distribution), including discussion on long-term design including ASME PCC-2 philosophy
- Wrinkle bend tension testing and composite reinforcement
- Upcoming research programs
  - Girth weld study (tension and bending)
  - Subsea composite reinforcement of corroded pipes (pressure, tension, and bending)

Also included is a discussion on performing a risk analysis for composite repair using the elements included in Paragraph 1.3 of ASME PCC-2 Part 4. Finally, a Closing Comments section provides comments for the reader in relation to how composite materials can and will be used to ensure the long-term integrity of identified pipeline anomalies.

Testing Efforts

This section of the paper provides details on prior and ongoing studies developed to evaluate the performance of composite materials. One of techniques employed by the authors involves the use of strain gages installed on the damage test pipes beneath the composite reinforcement. The reason for acquiring strain measurements beneath the composite materials is to evaluate the level of reinforcement that they provide, with a specific interest in determining if the strain in the pipe remains within an acceptable level. Although there is no designated “acceptable” strain level in a composite reinforced pipe section, it is possible to utilize strain measurements to assess the long-term viability and performance of the repair. Fundamentally, the success of a composite repair is related to its ability to ensure that the damaged section of pipe is able to function per its required service conditions.

In addition to evaluating the integrity of the reinforced pipe material via strain gages installed on the pipe, it is also possible to measure strains within the composite material itself. The benefit associated with this technique is that the stress in the composite material can be measured, which can then be compared to an allowable design stress. In contrast to the absence of strain limits for composite-reinforced steel, there are allowable design stresses (and strains) for composite materials based on the requirements designated in ASME PCC-2, *Repair of Pressure Equipment and Piping*. For purposes of this discussion, the stress limit will correspond to the long-term design stress designated in ASME PCC-2.

Pressure cycle testing of corroded pipes. While burst testing test pipes having simulated corrosion is the backbone of any composite assessment program, an equally important testing effort involves pressure cycling. Over the course of several years, pressure cycle testing was conducted on 12.75-inch x 0.375-inch, Grade X42 pipe samples having 75% deep corrosion that were pressure cycled with a range equal to 36% SMYS. Refer to the schematic provided in **Figure 1** for details on the test sample. As of the current time, eight different composite repair systems have been tested. Fatigue life results are provided below for the tested systems, with the minimum and maximum values noted.

- E-glass system: 19,411 cycles to failure (MIN)
- E-glass system: 32,848 cycles to failure
- E-glass system: 129,406 cycles to failure
- E-glass system: 140,164 cycles to failure
- E-glass system: 165,127 cycles to failure
- Carbon system (Pipe #1): 212,888 cycles to failure
- Carbon system (Pipe #2): 256,344 cycles to failure
- Carbon system (Pipe #3): 202,903 cycles to failure
- E-glass system: 259,537 cycles to failure
- Carbon system (Pipe #4): 532,776 cycles (run out, no failure)
- Hybrid steel/E-glass system: 767,816 cycles to failure (MAX)

Figure 2 and **Figure 3** show hoop strain as functions of cyclic pressure and cycle number for one of the corroded fatigue test samples (the E-glass system that achieved 259,537 cycles to failure), respectively. Of particular note in **Figure 3** is the change in strain range and maximum strain that occur as functions of cycle number. As observed, the maximum strain increases with increasing cycle number, while the strain range remains relatively constant over the period of measurement, which for this case happened to be almost 100,000 cycles.

The tests associated with this particular effort are critically important for evaluating the overall integrity of composite repair systems. To convert the above fatigue failure data into a meaningful design condition, it is recommended that the experimental data be divided by a value between 10 and 20. For the system having minimum performance, the design fatigue life at 36% SMYS ranges between 1,000 and 2,000 cycles (i.e. approximately 20,000 cycles to failure divided by 10 or 20), while for the maximum fatigue life the design fatigue life is between 38,000 and 76,000 cycles. In terms of applying these results to an actual pipeline, once the number of annual pressure cycles is obtained for a given system the calculation is relatively simple. For example, if a liquid pipeline experienced 2,000 cycles at a pressure range of 36% SMYS, the design life for the 38,000 cycle condition is 19 years.

Composite reinforcement (inter-layer strain distribution). When designing a composite repair system for long-term service, it is essential that the magnitude of stresses in the composite material not exceed a designated level (i.e. long-term design stress). ASME PCC-2 provides a means for determining the long-term design stress based on using results from either 1,000 hour or 10,000 hour pressurized pipe samples. Until relatively recently there has been no attempt to actually quantify at a designated pressure level, the hoop stresses in the composite material of a repair used to reinforce a corroded section of the pipe.

This section of the paper provides the reader with data acquired from two different composite repair test samples. Strain gages were installed within the composite repair system (i.e. on layers as they were installed around the pipe) to measure strains within the repair. This approach reduces the guesswork associated with trying to determine actual stresses in the composite material during pressurization of the pipe. For composite materials, and purposes of this discussion, stress is the product of strain and elastic modulus for the composite. It is necessary to measured via mechanical testing the elastic modulus in order for this calculation to be made. It is the authors' opinion that this type of testing is essential to ensure that composite materials are not overstressed. Without measurements of these types there is no assurance that the repair materials are not overstressed, as overstressing could lead to failure of the material. Equally important, when composite reinforcement materials are overstressed their ability to provide the required reinforcement to damaged sections of pipe is reduced.

Tests were conducted on two different composite repair systems, both of which used E-glass fibers. The objectives in testing were two-fold. The first was to determine the actual distribution of strain in the layers of the composite reinforcement; specifically, determining which layers carried the greatest percentage of the load. The second objective was to measure the maximum strain in the composite material for comparison to the ASME PCC-2 long-term design stress (determine by a 1,000 hour test for both of the tested systems).

Figure 4 and **Figure 5** plot hoop strain in the composite materials at 72% SMYS for Systems #1 and #2 as a function of radial position, respectively. **Figure 6** plots hoop stress as a function of internal pressure using data collected during testing for System #2. Included in this plot are average hoop strain data collected for 12 composite repair systems participating in the Pipeline Research Council International, Inc. (PRCI) MATR-3-4 long-term composite reinforcement study.

Table 1 presents a summary of data for both systems measured at 72% SMYS, along with a comparison of the measured stresses to the respective long-term design stresses.

Table 1 – Comparison of Measured Stresses to PCC-2 Design Stresses

Stress Value	Calculation Variable	System #1 (t_{comp} = 0.76 inches)	System #2 (t_{comp} = 0.63 inches)
Mean Tensile Stress (based on short-term tensile testing)	A	51,700 psi	72,088 psi
Long-term Design Stress, S_{lt} (based on PCC-2 Appendix V testing)	B	20,369 psi	23,836 psi
Allowable Stress (based on short-term tensile testing)	C	10,184 psi	11,918 psi
Maximum stress in composite (based on measured strain values)	D	4,806 psi	9,438 psi
Maximum measured strain in steel (75% corroded region)		2,976 με	3,125 με
Resulting Design Margins			
Mean Tensile Stress vs. Allowable Stress (A/C)		5.1	6.0
Mean Tensile Stress vs. Maximum Stress (A/D)		10.8	7.6
Usage factor (percentage of allowable, D/C)		47%	79%

Note: 10,000 microstrain (με) equals 1 percent strain.

As a point of reference in referencing the pressure cycle data previously discussed, System #1 achieved 140,164 cycles to failure, while Sample #2 was cycled 259,537 times before a failure occurred. Also, both of these systems ensured that strains in the corroded region

One of the most important observations made in reviewing the data presented in **Table 1** is the relatively large design margin that exists for both systems, especially in relation to the short-term tensile strength. When comparing the measured stresses in System #1 and #2, the ratios of mean tensile strength to maximum stress for the composite materials are 10.8 and 7.6, respectively. If we consider the average stresses in the composite based on the strain gage results, as opposed to the maximum stress that is reported in **Table 1**, the design margins are even larger. The significance of these design margins should not be understated. In order for a composite material to provide long-term reinforcement, it is essential that stresses in the composite material and reinforced steel are kept to a minimum. Hoop strains in the pipe beneath the repair were limited to approximately 0.3 percent when the test sample was pressurized to 72% SMYS.

Wrinkle bend tension testing and composite reinforcement. It is recognized throughout the transmission pipeline industry that failures in wrinkle bends have occurred. While identifying the causes and contributors to wrinkle bend failures are the subjects of several ongoing studies, in 2010 six full-scale tests were conducted to evaluate the performance of wrinkle bends, including the assessment of composite materials (3 sets with each set having one reinforced and one unreinforced test sample). **Figure 7** and **Figure 8** are photographs showing the test set-up and composite installation, respectively.

Of the three sets of tests that were performed, results are presented in this paper for one set of wrinkle bends fabricated from 26-inch x 0.313-inch, Grade X52 pipe material. The test effort included the installation of strain gages near the wrinkle bends to monitor strain during testing. Internal pressure was held constant, while axial tension loads were increased until failure occurred in the pipe material or a plastic collapse condition (i.e. unbounded displacements with minimum increases in loading) was observed via the strain gage readings. Prior to testing, SES contracted services to measure the geometry using an optical mapping tool (results not included in this paper). One of the test samples was reinforced using Armor Plate® Pipe Wrap, while the other sample was tested without reinforcement. Of particular note in this study was corrosion that was present near the wrinkle bends. Although difficult to measure due to the presence of the wrinkles, pitting on the order of 30% of the pipe's nominal wall was detected in both the unreinforced and reinforced test samples. The wrinkle bend severity ratios, h/L, were measured to be 0.123 and 0.137 for the unreinforced and reinforced samples, respectively.

During the test, an internal pressure of 900 psi was applied to the sample and held constant while an axial tension load was applied to the samples. The unrepaired sample failed by leaking at a combined load of 1,527 kips, while the repaired sample failed by rupture at a combined load of 1,815 kips. The unrepaired sample developed a leak in the corroded region near a wrinkle bend.

Figure 9 plots axial strain as a function of axial tension loading. Provided below are several noteworthy observations made in reviewing the data plotted in **Figure 9** that was generated during the course of this study.

- At an axial stress of 36% SMYS (455 kips), the following strains were measured (where 10,000 microstrain, $\mu\varepsilon$, equals 1% strain):
  - Base pipe without wrinkle bend (calculated): 593 $\mu\varepsilon$
  - Unreinforced wrinkle bend (h/L = 0.123): -3,508 $\mu\varepsilon$
  - Reinforced wrinkle bend (h/L = 0.137): -1,611 $\mu\varepsilon$
- While the reduction in strain provided by the composite material is critically important, it should also be noted that the composite material increased the ultimate load capacity of the pipe having wrinkle bends. Corrosion pitting in both samples was on the order of 30%, yet the composite-reinforced sample increased the tensile capacity to achieve a stress level in the base pipe on the order 71 ksi (i.e. 1,815 kips / [$\pi\cdot$ 26 inches x 0.313 inches]). This stress level is in excess of the minimum tensile strength of the Grade X52 pipe material (i.e. 66 ksi) assuming that no corrosion is present.
- Because the fractures that typically develop in wrinkle bends are circumferentially-oriented, any composite reinforcement must be able to provide significant levels of axial reinforcement. The Armor Plate® Pipe Wrap system uses E-glass material with a tensile strength and elastic modulus of 72 ksi and 4.4 Msi. To be effective, 50% of the composite material was oriented in the axial direction. One reason for the success of this particular system, as demonstrated in this particular test program, are the relatively high strength and stiffness values.
- The length of the composite repair is extremely important. As part of the composite design, calculations should be made to ensure that the calculated product of the repair area (π x *pipe diameter* x *repair length*) and the adhesives' lap shear strength are sufficient. Any repair where axial reinforcement is required should consider this issue, including the reinforcement of wrinkle bends and girth welds.

Upcoming research programs The backbone of knowledge that has been acquired over the past decade is the result of significant financial sponsorship contributions provided by the pipeline operators (primarily via the Pipeline Research Council International, Inc.) and the composite manufacturers. Since 2006 more than $5 million have been invested in the assessment and evaluation of composite repair materials via full-scale testing programs. In coordination with prior research efforts, several upcoming programs are being sponsored by PRCI and the composite repair manufacturers. A brief discussion on each program is provided below.

Girth weld study (tension and bending) This program, known as PRCI MATR-3-7, is being co-sponsored by PRCI and five composite manufacturers. The purpose of this program is to evaluate the use of composite materials to reinforce pipelines having vintage girth welds that do not meet workmanship criteria. **Figure 10** provides the geometry for girth weld test samples, including the location of the installed strain gages. Listed below are the companies participating in the current study:

- Armor Plate
  - E-glass system
  - Carbon System
- Air Logistics
- Citadel
- Pipe Wrap, LLC
- Western Specialties

The purpose of this program is to shore up knowledge gaps associated with the following subjects:
- Design to account for adhesive shear strength
- Effects of composite stiffness (i.e. modulus and thickness)
- Design to account for bending loads
- Reduction in pipe strain due to reinforcement.

Full-scale destructive testing will be conducted involving the following sample types:
- Girth weld subjected to pressure and tension loads (unreinforced)
- Girth weld subjected to pressure, tension, and bending loads (unreinforced)
- Girth weld subjected to pressure and tension loads (reinforced)
- Girth weld subjected to pressure and tension loads (reinforced with reduced bonding area where packing tape is installed on the outside surface of the pipe to simulate areas of reduced bonding)
- Girth weld subjected to pressure, tension, and bending loads (reinforced)

This program was completed in December 2011. Preliminary results demonstrated that several of the tested systems provided significant reinforcement to the pipe samples having defective girth welds, including one sample where the pipe actually pulled apart outside of the repair as shown in **Figure 11**.

Subsea composite reinforcement of corroded pipes (pressure, tension, and bending) Like the MATR-3-7 girth weld study, another program (PRCI MATR-3-6) is underway to evaluate the performance of composite materials in reinforcing corroded subsea pipelines and risers. However, one element integrated into this particular study involves evaluating the long-term performance of composite repair systems in a seawater environment. Test samples will be placed in a seawater test facility for 10,000 hours and then removed for destructive testing. **Figure 12** is a schematic diagram showing the proposed test facility. In this program the repaired test samples will be pressurized for the duration of the 10,000 hour period, with periodic pressure cycling. The composite repairs will be performed underwater.

Listed below are the companies participating in the current study:
- Armor Plate
  - E-glass system
  - Carbon System
- Air Logistics
- Neptune Research
- Walker Technical Resources

Risk Analysis

As more sophisticated methods are being employed by pipeline operators in managing integrity, performing risk analyses has become an important part of the process. The use of composite materials has become an important part of many company's integrity management programs, so a discussion on conducting a proper risk analysis is warranted. Actually conducting a risk analysis has occurred on a limited basis based on the authors' experience, although the ASME PCC-2 provides a comprehensive list of items that can be used. Guidelines are provided in Paragraph 1.3 of Article 4.1 of ASME PCC-2 for performing a risk analysis on a composite repair. Provided below is the text from this document.

> An assessment of the risks associated with the defect and repair method shall be completed in line with the relevant industry best practice. When applying a Repair System in accordance with this Article the following items shall be considered:
>
> (a) assessment of the nature and location of the defects
> (b) design and operating conditions for the pipe and contents (including pressure, temperature, sizes, and combinations thereof)
> (c) repair life (see para. 1.4)
> (d) geometry of the pipe being repaired
> (e) hazards associated with system service
> (f) the availability of the personnel with the necessary skills
> (g) the ease with which it is practicable to execute surface preparation operations
> (h) performance under upset and major incident situations including impact, abrasion, fire, explosion, collision, and environmental loading
> (i) failure modes
> (j) inspectability
> (k) the Repair System materials

> The information and data describing any hazards shall be included in the method statement (para.4.4) to be used on site.
>
> The application of these Repair Systems will typically change the mode of failure from rupture to a leak; the consequences of failure will therefore be reduced. A repair applied in accordance with this Article will also reduce the probability of failure.

As noted in (c) above, Paragraph 1.4 is referenced; the associated text is provided below.

> The repair life is the useful service period of the Repair System, as defined by the design assessment. This may be limited by the defect type and service conditions (e.g., internal corrosion). The repair life will depend on the Repair System.

Also referenced in Paragraph 1.3 is Paragraph 4.4, *Method Statements*. Listed below are the tasks covered by this particular method statements.

- ¶ 4.4.1 Health and Safety
- ¶ 4.4.2 Repair Design
- ¶ 4.4.3 Repair Application
- ¶ 4.4.4 Quality Assurance
- ¶ 4.4.5 Environmental

The intent in conducting a risk analysis based on the guidelines provided in ASME PCC-2 is to provide operators with pertinent information related to each item to ensure that an optimum repair solution is developed. For those areas where a greater perceived risk is identified, measures should be taken to either minimize this risk, or eliminate it altogether.

An extension of the risk analysis effort involves the execution of a Failure Modes and Effects Analysis (FMEA). An in-depth discussion on performing an FMEA is outside the scope of this study; however, provided a formal definition of FMEA is provided as follow.

> A failure modes and effects analysis (FMEA) is a procedure in product development and operations management for analysis of potential failure modes within a system for classification by the severity and likelihood of the failures. A successful FMEA activity helps a team to identify potential failure modes based on past experience with similar products or processes, enabling the team to design those failures out of the system with the minimum of effort and resource expenditure, thereby reducing development time and costs. It is widely used in manufacturing industries in various phases of the product life cycle and is now increasingly finding use in the service industry. Failure modes are any errors or defects in a process, design, or item, especially those that affect the customer, and can be potential or actual. Effects analysis refers to studying the consequences of those failures.[1]

By conducting an FMEA, a user of composite repair materials is in a position to actually quantify the risk associated with a given installation. Quantifying risk is achieved by assigning to each identified risk a numerical value associated with the occurrence, severity, and likelihood of detection. The product of these three numbers is known as the Risk Priority Number (RPN). Provided in **Table 2** is a *Failure Modes and Effects Analysis* Worksheet that includes the factors of interest and their associated risk factors. As an example, the authors have provided a list of RPNs based on an assessment conduced for an operator in evaluating the repair of a given corrosion defect in a process piping facility. The following FMEA risk ranking was determined as presented by the data in **Table 2**. Included in the following list are the calculated RPN values; the product of the Occurrence, Severity, and Detection values: (RPN = O x S x D).

- Adhesive bond failure RPN = 360
- Insufficient number of axial fibers RPN = 200
- Composite degradation due to high temperatures RPN = 108
- Outer layer degradation RPN = 60
- Composite material thickness insufficient RPN = 54

As seen in the above listing, the adhesive bond failure is the primary concern for this particular installation. As a result, the operator was encouraged to take all steps necessary and reasonable to achieve the best bond possible. This example provides a clear demonstration in how operators and composite manufacturers can work together to minimize risk by determining the

[1] Information obtained from http://en.wikipedia.org/wiki/Failure_mode_and_effects_analysis

steps required to design and install an optimized composite repair system. The benefit in conducting the FMEA is that the Risk Priority Numbers help determine the order of focus and concern, thus reducing a subjective-based decision making that might result.

Closing Comments

The use of composite materials has had a profound impact on the integrity management programs of most pipeline companies. Early efforts dating back to the mid-1990s focused on using composite materials for the repair of corrosion defects; however, over time the use of composite materials has evolved into the reinforcement of pipeline anomalies/features including dents, girth welds, wrinkle bends, branch connections, and seam weld defects. The key to achieving confidence in the composite repair solution has been the use of full-scale destructive testing, in conjunction with designing repairs using sound engineering principles based on design documents like ASME PCC-2.

This paper has provided for the reader an overview of recent activities associated with the assessment of composite repair solutions. As new composite materials are brought to market, and improved confidence in composite performance is achieved, it is envisioned that greater uses of composite materials for repairing damaged high pressure transmission pipelines using full-scale testing will occur.

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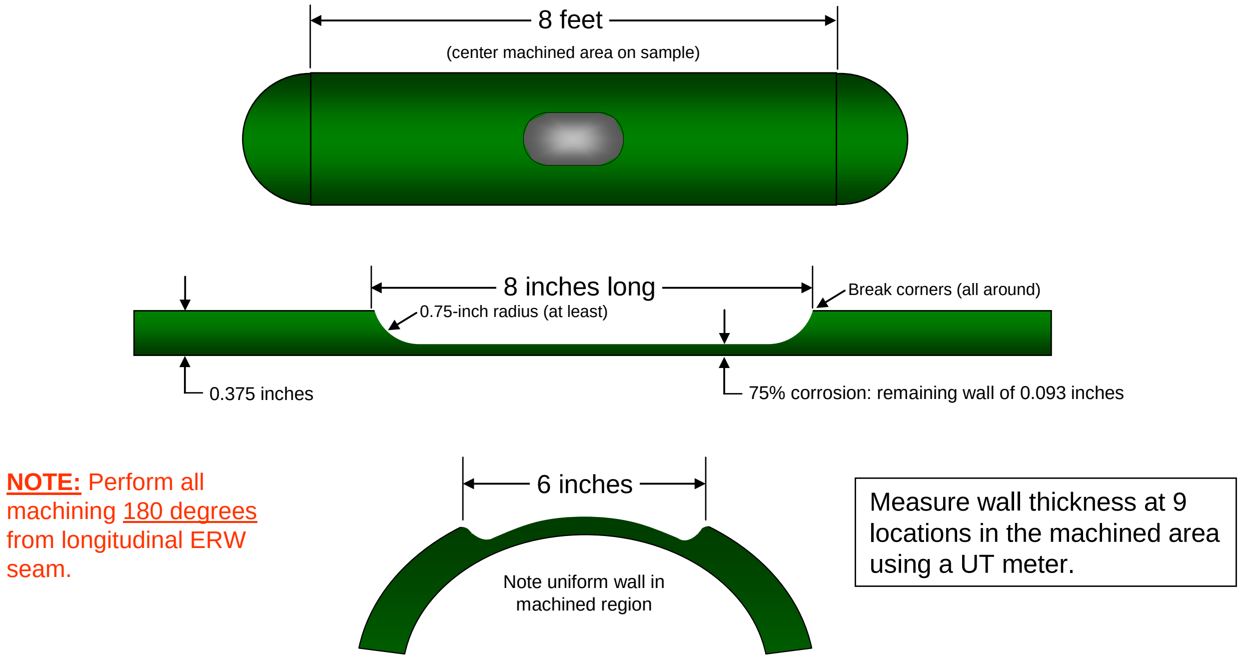
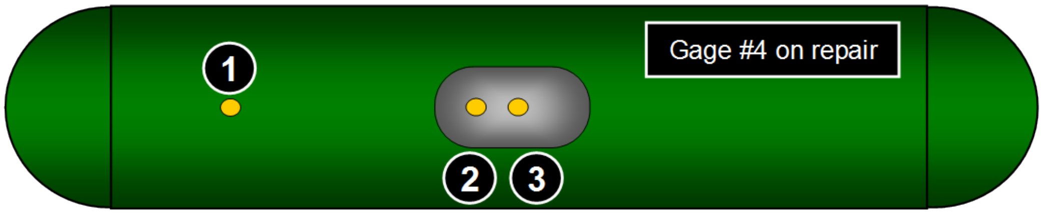
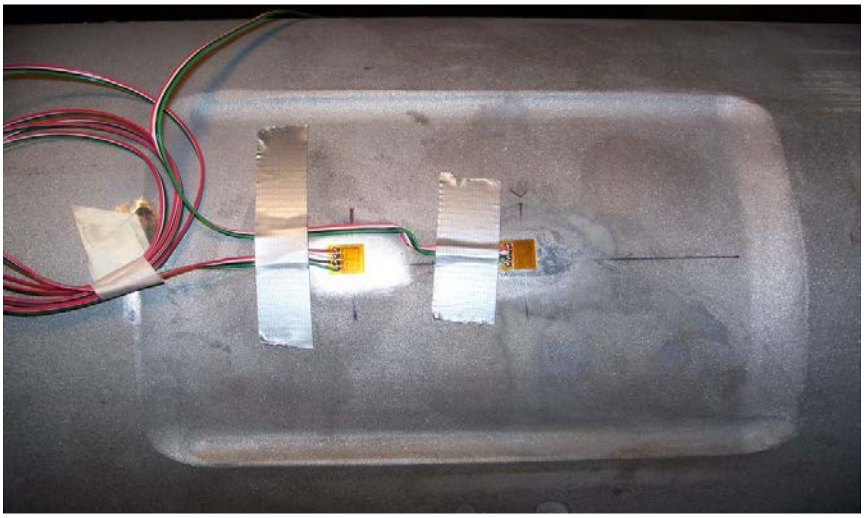


Details on machining
(machined area is 8 inches long by 6 inches wide)



Location of strain gages installed on the test sample



Photograph of strain gages installed in the machined corrosion region

Figure 1 – Layout for 75% corrosion in 12.75-inch x 0.375-inch, Grade X42 pipe

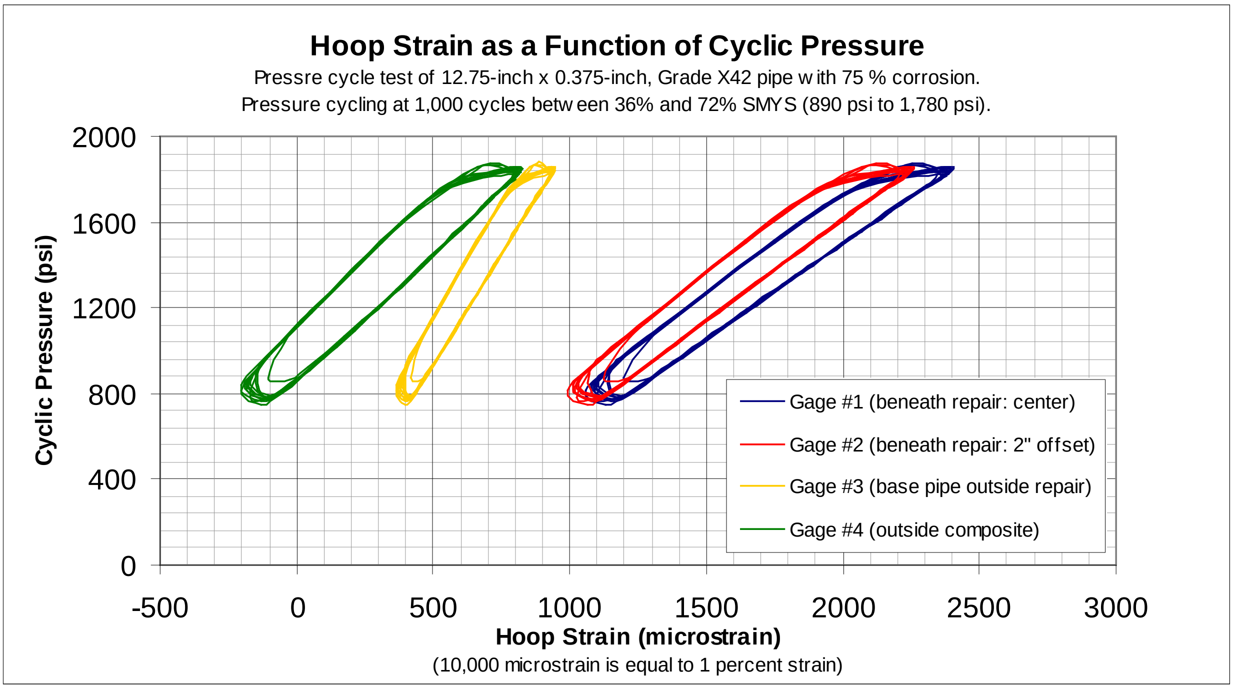


Figure 2 – Hoop strain as a function of cyclic pressure for corroded fatigue test sample

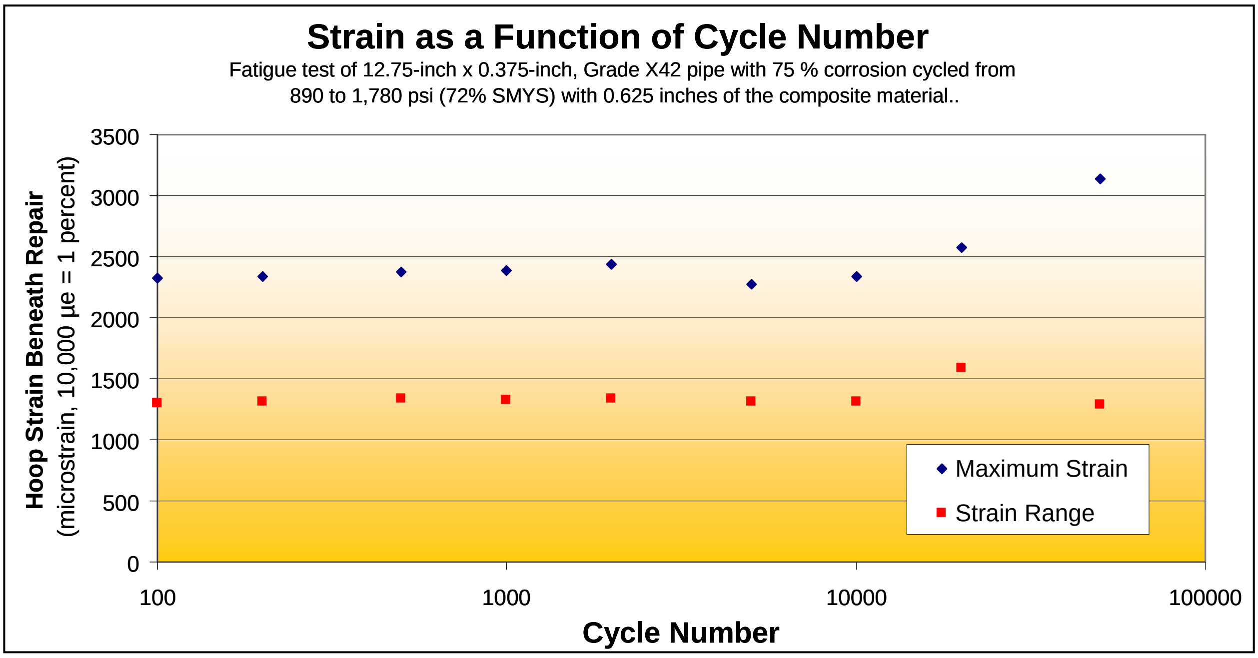


Figure 3 – Hoop strain as a function of cycle number for corroded fatigue test sample

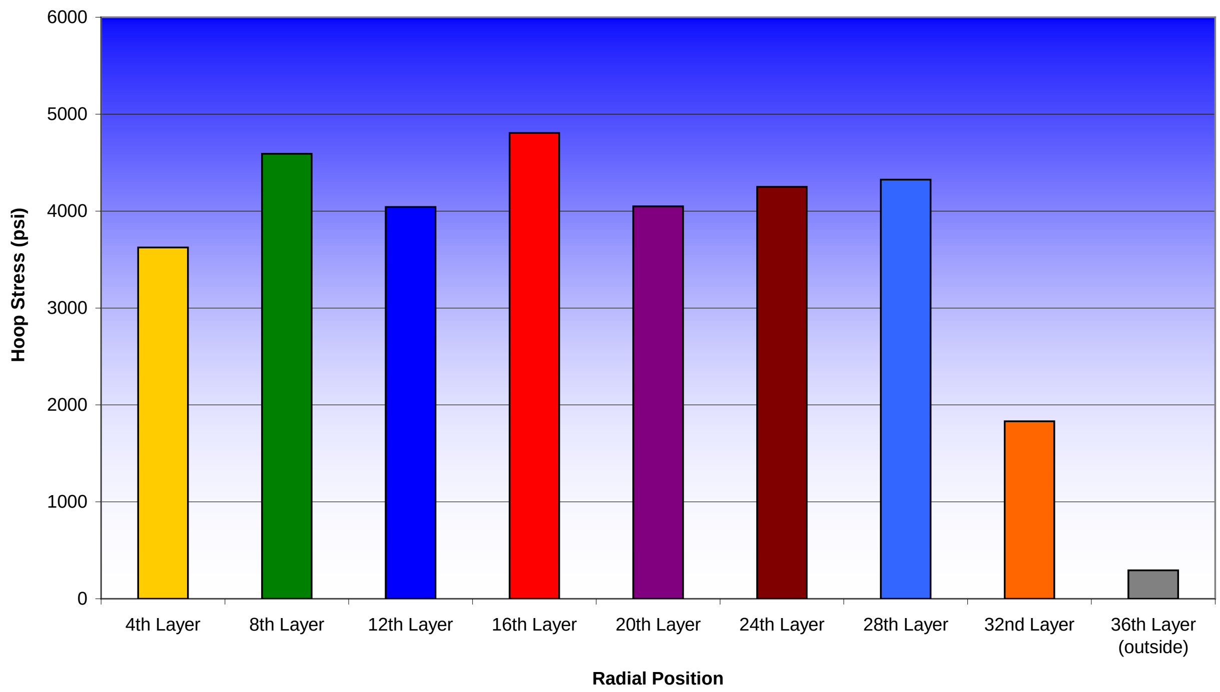


Figure 4 – Hoop Strain at 72% SMYS as a Function of Radial Position for System #1
(Hoop stress calculated as the product of the measured strain and the composite's elastic modulus)

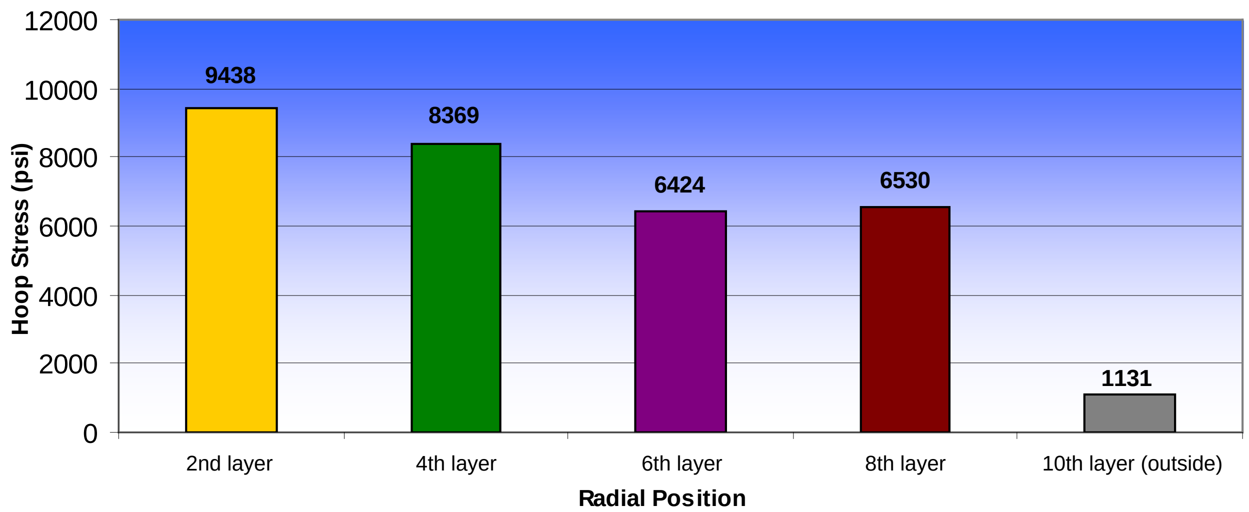


Figure 5 – Hoop Strain at 72% SMYS as a Function of Radial Position for System #2
(Hoop stress calculated as the product of the measured strain and the composite's elastic modulus)

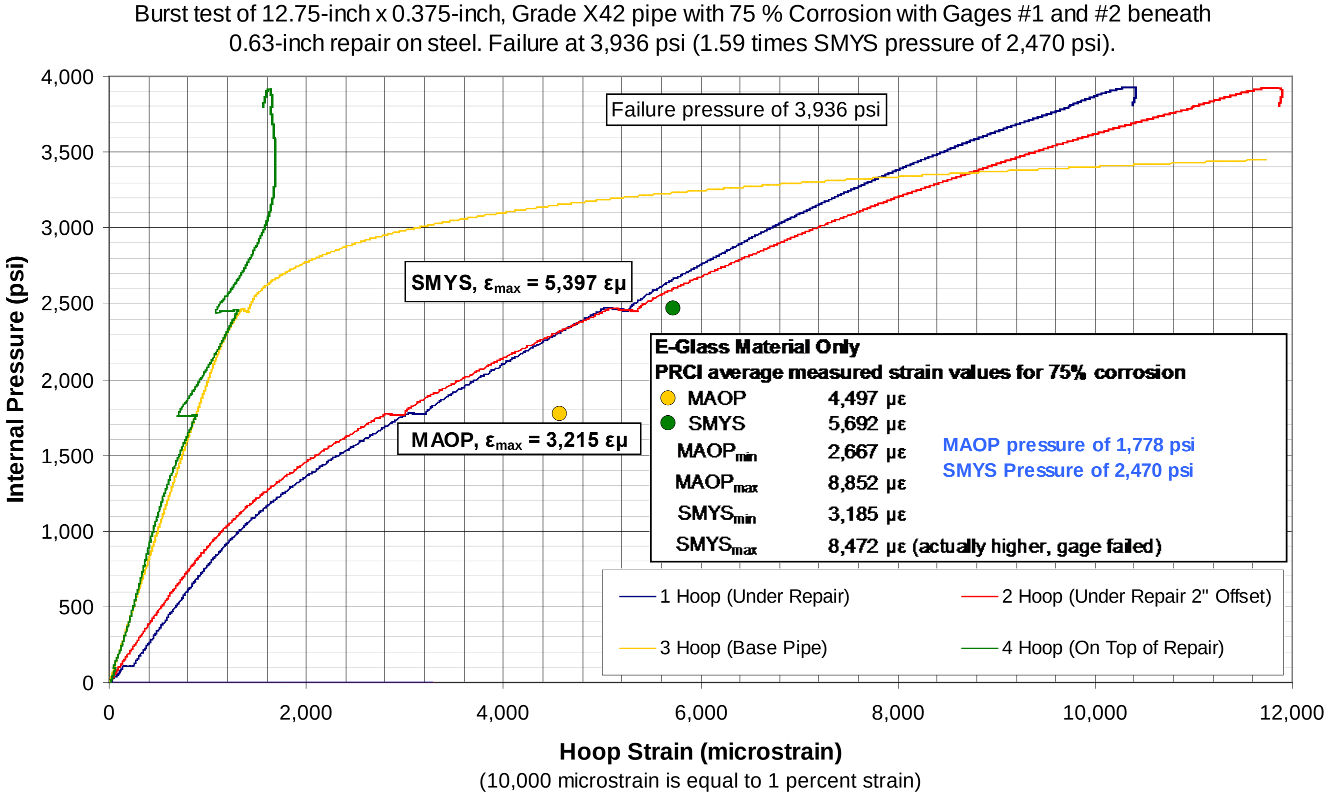


Figure 6 – Measurement of strain in 75% corroded region for System #2

Figure 7 – Photographs showing testing set-up for wrinkle bend testing

igure 8 – Photographs showing installation of composite materials on wrinkle bend samples

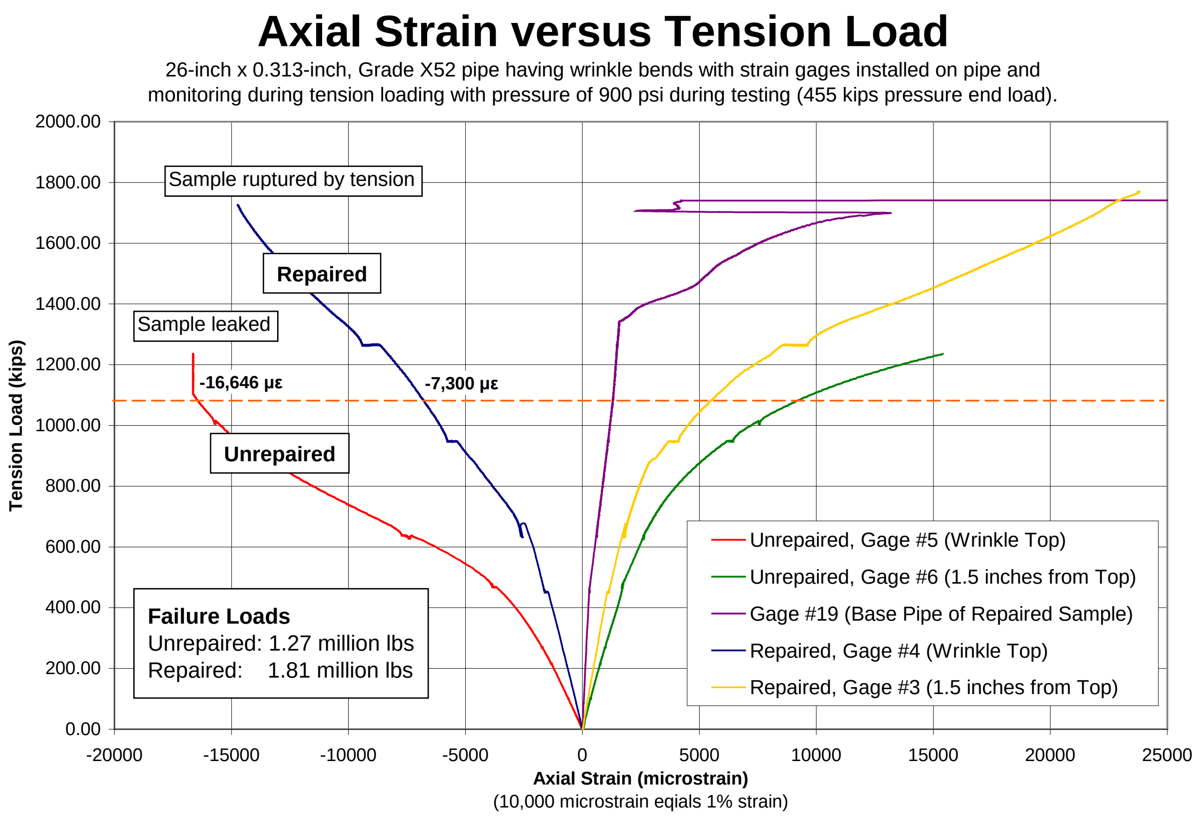


Figure 9 – Axial tension versus strain for the reinforced and unreinforced wrinkle bend test samples
(The *Tension Load* is the sum of tension loading from the load frame and the end load due to internal pressure)

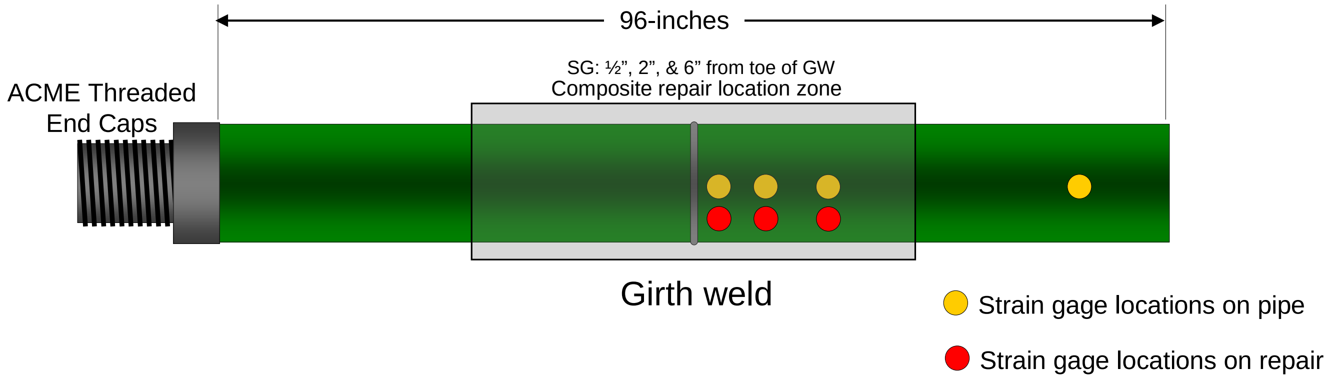


Figure 10 – Geometry for girth weld test samples

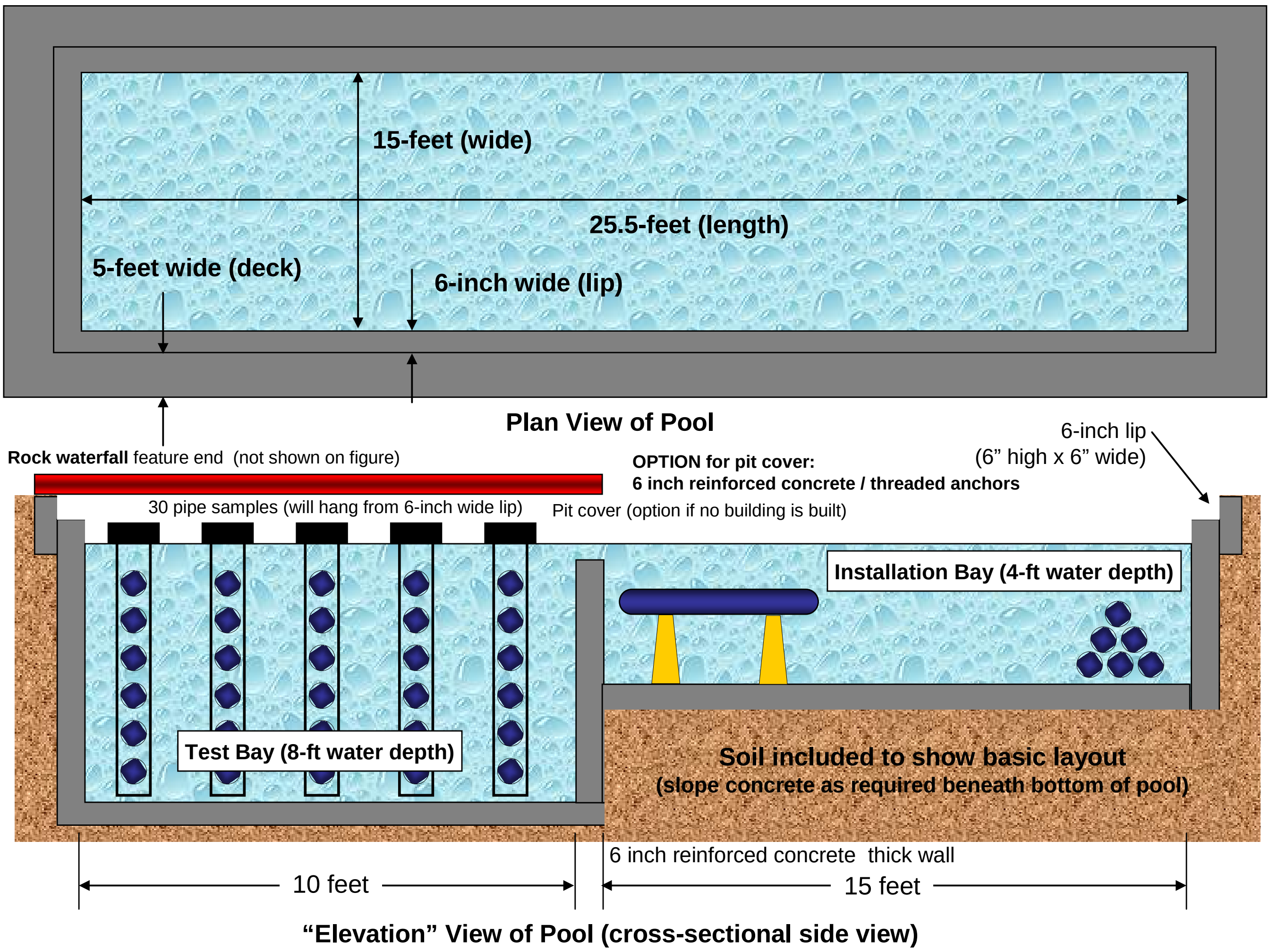


Figure 11 – Test set-up for the subsea composite study