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EVALUATING THE USE OF COMPOSITE MATERIALS IN REINFORCING OFFSHORE RISERS USING FULL-SCALE TESTING METHODS

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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 several composite repair manufacturers was undertaken to assess 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. 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.

PROGRAM OVERVIEW

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

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

Product A – this system uses an E-glass fiber system in a water-activated urethane matrix. The fiber cloth is a balanced plain-weave with orthogonal fibers aligned at 0 and 90 degrees relative to the axis of the pipe . During installation, the cloth was oriented either axially or circumferentially to achieve the desired level of reinforcement.

Product B – this system uses an E-glass fiber system in a water-activated urethane matrix. The cloth for this system also uses a balanced weave. This particular repair incorporated an epoxy filler material in the corroded region, as opposed to placing composite material in this region of the repair. All of the other manufacturers chose to install fibers in the corroded region. During installation, the cloth was oriented either axially of circumferentially to achieve the desired level of reinforcement. Due to issues encountered during testing with uncured resins, no results are presented for this system.

Product C – this system uses a carbon fiber system in an epoxy matrix. The cloth is a stitched fabric with uniaxial fibers. During installation, the fibers were aligned at 0 and 90 degrees relative to the axis of the pipe to achieve the desired level of reinforcement.

Product D – this system uses an E-glass fiber system in an epoxy matrix. The cloth has fibers that are oriented at 0, 90, and +/- 45 degrees. Additionally, a layer of chopped strand fibers is sprayed on the underside of the cloth. During installation, the cloth was oriented either axially of circumferentially to achieve the desired level of reinforcement.

Because of the lack of available performance data on composite repairs subject to tension and bending loads, the need for integrating these load types was identified. Additionally, discussions with participating manufacturers focused on the need to ensure that their repair systems would be designed in a manner that could provide adequate reinforcement in terms of both bonding to the pipe and providing sufficient bending strength to reinforce the corroded section of pipe. Fundamentally, bonding to the pipe involves shear strength of the adhesive (or resin used in fabricating the composite) as well as available shear area. In other words, even with a strong adhesive, shear failure is possible if there is an inadequate bonding area.

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

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

TECHNICAL DETAILS OF THE TEST PROGRAM

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

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

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

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

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

Pressure-only Test

The purpose of this test type was to assess the performance of the composite repair in providing hoop strength. Figure 1 is a schematic showing the unrepaired sample geometry. An axisymmetric groove was machined in the center of the 8-ft long sample to simulate corrosion. It is recognized that actual corrosion never possesses the uniformity of the simulated corrosion; however, fo testing this geometry is acceptable. Prior to installation of the repair, bi-axial strain gage rosettes were installed on the samples to measure hoop and axial strains. Figure 2 shows the location of the strain gages. Nine strain gages were placed on the steel pipe and three were placed on the outside surface of the repair once it had been installed. The design pressure of the given test sample is 2,887 psi based on the API RP 1111 design basis [1].

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

Pressure-tension Test

The next series of tests involved a sample similar to the pressure only sample; however, the focus was on axial tension capacity. In this test, pressure was held constant (2,887 psi based on the API RP 111 design basis), while axial tension was increased to the point of failure. Figure 3 shows the schematic for this test, which is identical to the pressure only test except that instead of elliptical dome caps, 7-1/2 inch diameter STUB ACME threaded end caps were used to interface with the tension load frame. As with the pressure only sample, strain gages were installed on the tension-pressure sample at the same locations shown in Figure 4. API RP 1111 was used to determine that the limit an axial tension loads was 145 kips.

Prior to testing, details on the importance of having adequate repair length were provided to each of the manufacturers. If a sufficient reinforcing length is not available, during tension loading premature failure of the repair will ensue because of the inability of the repair to remain attached to the pipe. As a point of reference, consider an axial length of the repair spanning 18 inches on each side of the 24 inch long corrosion section (60 inches total repair length). If an adhesive lap shear strength of 1,000 psi exists (a conservative estimate considering the performance of most epoxy adhesive systems [2]), a tensile capacity of approximately 490 kips exists prior to failure of the adhesive bond between the steel pipe and composite material (this tension loads significantly exceeds the design axial tension load of 145 kips). For the nominal pipe wall of the test samples, this results in an axial stress of 44.5 ksi. Samples were taken to failure by increasing the axial tension in the sample to the point where failure in the corroded region occurred. The indication of failure was when pressure in the sample could no longer be maintained.

Pressure-tension-bending Test

This test combined all three load types: internal pressure, tension, and bending. The variable load of interest in this round of testing was bending. During testing, internal pressure and tension were held constant at 2,887 psi and 145 kips, respectively. Bending loads were applied using a four-point bend configuration as shown in Figure 4.

Holding pressure and tension constant, the bending load was increased by incrementally increasing the force applied by the two hydraulic rams. Due to safety concerns, testing was terminated once significant plastic flow in the reinforced corrosion area occurred and axial strain in the unreinforced region of the pipe outside of the repair approached 10,000 microstrain (1.0% strain). This also corresponded to the point where load was transferred from the steel to the composite material as observed by the strain gages positioned beneath the reinforcement.

Figure 5 shows the location of the strain gages placed on the pressure-tension-bend samples. As with the other two tests, nine strain gages were installed on the pipe and three were installed on the outside surface of the composite repair after curing had taken place. Figure 6 shows the load frame used for the bend tests. This load frame has an axial tension capacity of 1 million lbs and can apply bending loads up to 750 kip-feet.

TEST RESULTS

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

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

Pressure-only Test

Results for the pressure-only test are provided in Figure 7. This phase of testing represents the initial benchmark of the test. To a certain extent, it presents the most basic test as it only addresses the performance of the repair in reinforcing hoop strength.

In reviewing the test data in Figure 7, there are several noteworthy points.

- In limit state design, one must address the limit state, or the maximum capacity a structure can withstand. Although fundamentally this involves failure, more practically it involves assessing the load at which unbounded displacements (or strains) occur. In pressure vessel design, this condition is known as the collapse load. The strain gage results presented in Figure 7 show the pressure at which unbounded displacements occur, typically near 2000 microstrain (or 0.2 percent strain). The unbounded condition occurs when minimum increases in load (i.e. internal pressure) results in disproportionate increases in hoop strain.
- The post-yield slope in the strain-strain curves observed for each of the repair systems is the result of reinforcement being provided to the corroded region of the steel pipe. This occurs once plasticity initiates in the steel and load is transferred to the reinforcing composite material. This bi-linear stress-strain curve is typical for structures reinforced using composite materials subject to hoop tensile loading [3, 4, and 5].
- The unrepaired sample failed at a pressure of 3,694 psi. Failures in the test samples prepared using Products A, C, and D occurred in the steel away from the repaired region. Figure 8 shows the failure in the Product C repaired sample outside of the repaired region in the base pipe. This failure was typical for the repaired samples. The failure pressures for the four repaired samples are listed below.
    - Unrepaired – 3,694 psi
    - Product A – 6,921 psi
    - Product B – data not reported
    - Product C – 7,502 psi
    - Product D – 7,641 psi
- The strain gage results provide measurements of the strains in the pipe during pressurization. The measurements of greatest significance are those that that demonstrate behavior once yielding initiates in the steel and the point at which load is transferred from the steel into the composite material. This latter observation is the best indicator for determining how much reinforcement is provided by the composite material. Product C provides the greatest continuous reinforcement, while Product A provides similar results up to 2,500 microstrain (0.25 percent strain). As noted, Product D did not provide the same level of strain reduction beneath the repair as the other two systems.

Pressure-tension Test

Results for the pressure-tension test are provided in Figure 9. This phase of testing primarily assessed the lap shear strength of the adhesive that bonded the composite reinforcement to the steel pipe. This failure condition was anticipated prior to testing and was the basis for the minimum repair length of 60 inches. Several noteworthy observations are made in reviewing the test data presented in Figure 9.

- Product C shows the greatest axial rigidity of all the repair systems. The basis for this observation is that Product C was fabricated using carbon fibers, with a large percentage of fibers being oriented axially. Products A and D show similar levels of reinforcement up to 200 kips, while after this point Product D shows greater reinforcement.
- The following tension failure data were recorded.
    - Unrepaired sample – 317 kips
    - Product A – 492 kips
    - Product B – data not reported
    - Product C – 562 kips
    - Product D – 579 kips

Figure 10 provides several photos showing the post-failure surface of the pressure-tension sample for Product D. As shown, the inner steel in the corroded region failed due to tensile overload. The adhesive at the interface between the composite and steel is used to transfer load into the composite material. At some point during loading, the strength in this bond is exceeded and the composite is no longer able to carry the tensile load. As shown in Figure 10 (lower right hand side photo), the composite material remains intact.

Pressure-tension-bending Test

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

Results for the pressure-tension-bending test are provided in Figure 11. There are several noteworthy observations in reviewing the plotted data.

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

- In assessing the relative performance of the composite systems, the objective of the repair is to reduce the strain in the corroded steel during bend testing, as well as provided reinforcement in the circumferential and axial directions due to internal pressure and axial tension loads, respectively. As noted in Figure 11, at some point the strain gage results appear to stop changing with increasing load (plotted lines trend vertical). It is at this point that gross plastic deformation, as recorded by the strain gages, occurs outside of the reinforced region and that deflection is occurring primarily in areas outside the composite reinforcement. The sooner this transformation takes place, the more effective the repair is in reinforcing the corroded region.
- Another option for assessing the relative performance of the composite repair systems is to determine the applied bending moment at a specified strain value. If the strain limit is 0.20 percent, the following bending forces and moments are extracted. This method is a better assessment of the relative performance of the repair systems. It should be noted that the unreinforced sample did not include internal pressure during bend testing as failure would have occurred at a lower bending load.
    - Unrepaired sample – 30 kips (87.5 kip-feet)
    - Product A – 26 kips (75.8 kip-feet)
    - Product B – data not reported
    - Product C – 70 kips (204.2 kip-feet)
    - Product D – 40 kips (116.7 kip-feet)

Figure 12 is a photograph of the Product C repair in the load frame prior to bend testing.

GENERAL OBSERVATIONS

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

Specifically, the following average design margins were calculated for all of the repair systems. These were calculated by dividing the failure load by the specified design loads listed in Table 1. For example, the design margin for Product A considering internal pressure is calculated by dividing its burst pressure of 6,921 psi by the design pressure of 2,887 psi, or 2.40.

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

As seen with values listed previously based on the Table 1 test data, the tested composite reinforcement systems possess an adequate safety margin for their intended service conditions relatively to the ASME design standards [6 and 7].

CONCLUSIONS

In using composite materials to reinforce damaged and corroded risers, it is critical to integrate design methodologies that assess strain in the reinforced steel. This is especially important in offshore design as risers in the splash zone are subjected to combined loads including internal pressure, axial tension, and bending loads, as compared to onshore repairs that primarily involve restoration of hoop strength.

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

The primary purpose of the state of the art assessment and associated JIP study was to identify and confirm the critical elements required for an effective composite repair. Other benefits were also derived in the execution of the program, including the development of guidelines for industry and regulators and providing the manufacturers with the opportunity to assess their given repair systems subject to loading conditions associated with offshore risers.

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Table 1 – Summary of test results relative to design conditions

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

Notes:

1. The unrepaired bending sample did not include internal pressure at the time of testing. The decision to run this test without internal pressure was based on safety concerns and recognizing the possibility for failure at relatively low bending loads due to large strains.
2. The ratio of average failure loads for the repaired samples to the unrepaired sample for the internal pressure and tension load samples are 2.0 and 1.72, respectively.
3. The unrepaired sample exhibited failure loads exceeding the specified Design Load for both the pressure and tension tests.

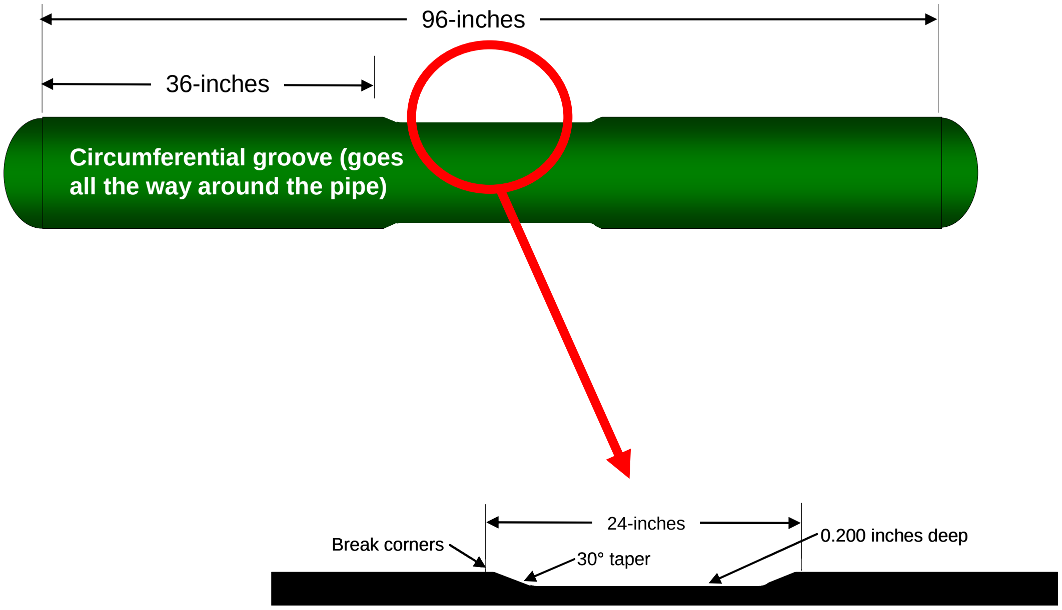

Figure 1 – Schematic diagram showing pressure only test sample

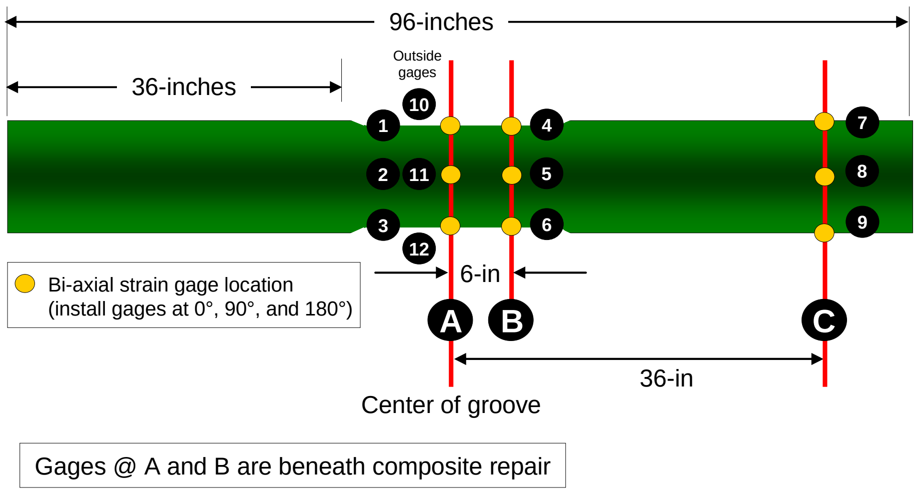

Figure 2 – Location of strain gages on the pressure and pressure/tension samples

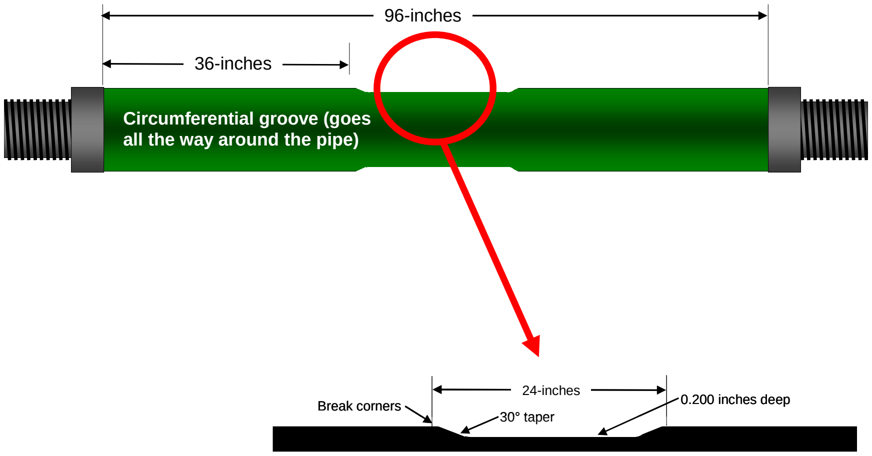

Figure 3 – Schematic diagram showing pressure-tension test sample

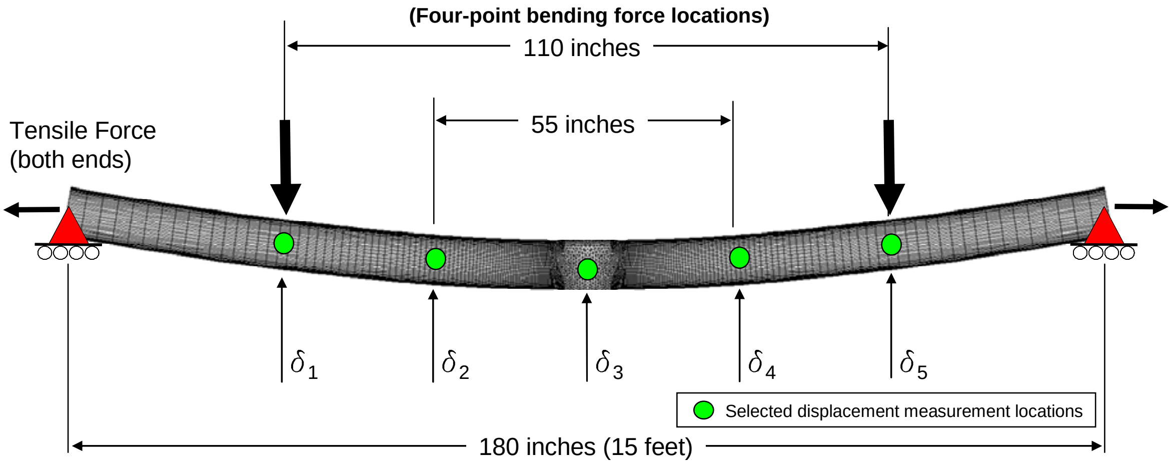

Figure 4 – Four point bending configuration for pressure-tension-bend testing

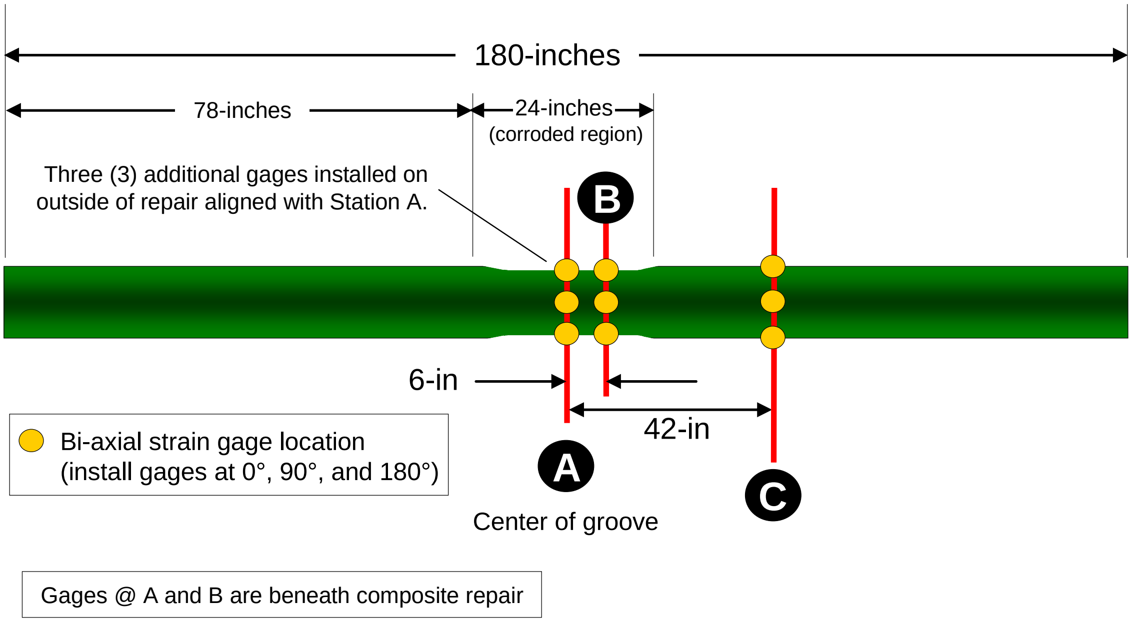

Figure 5 - Location of strain gages on the pressure-tension-bend samples

Figure 6 – Load frame used for pressure-tension-bend testing

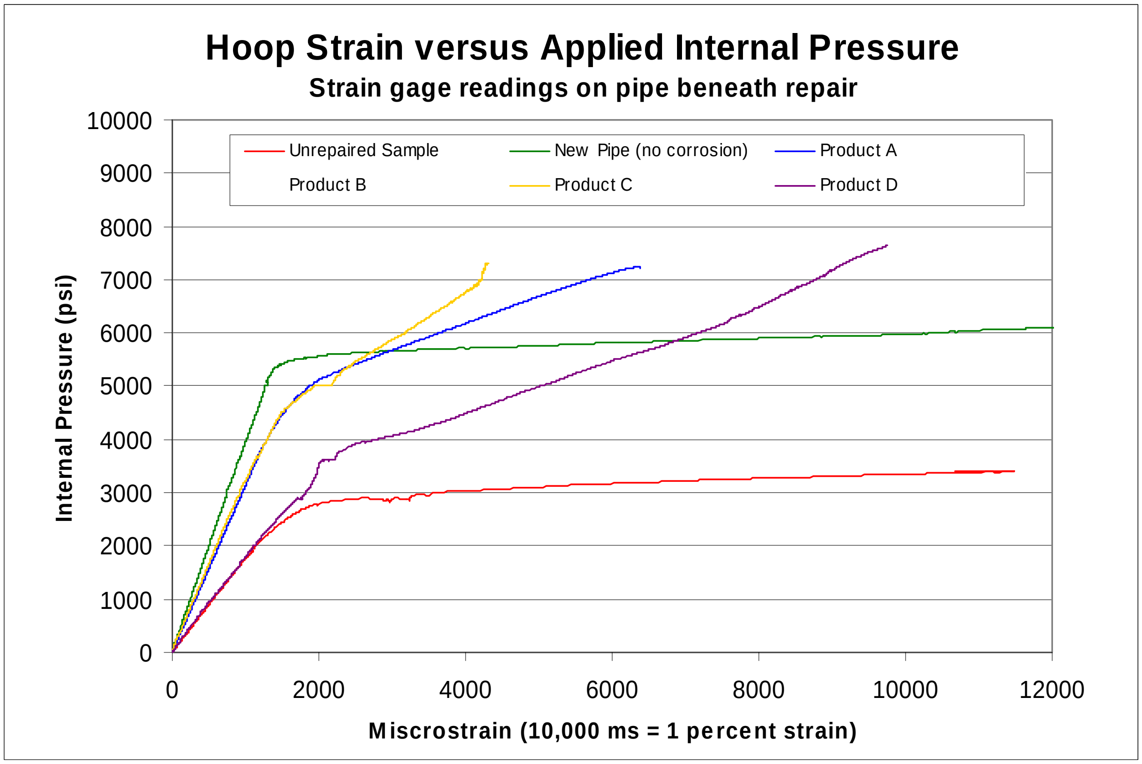

Figure 7 – Test results from pressure-only testing

Figure 8 – Failure in burst sample using Product C

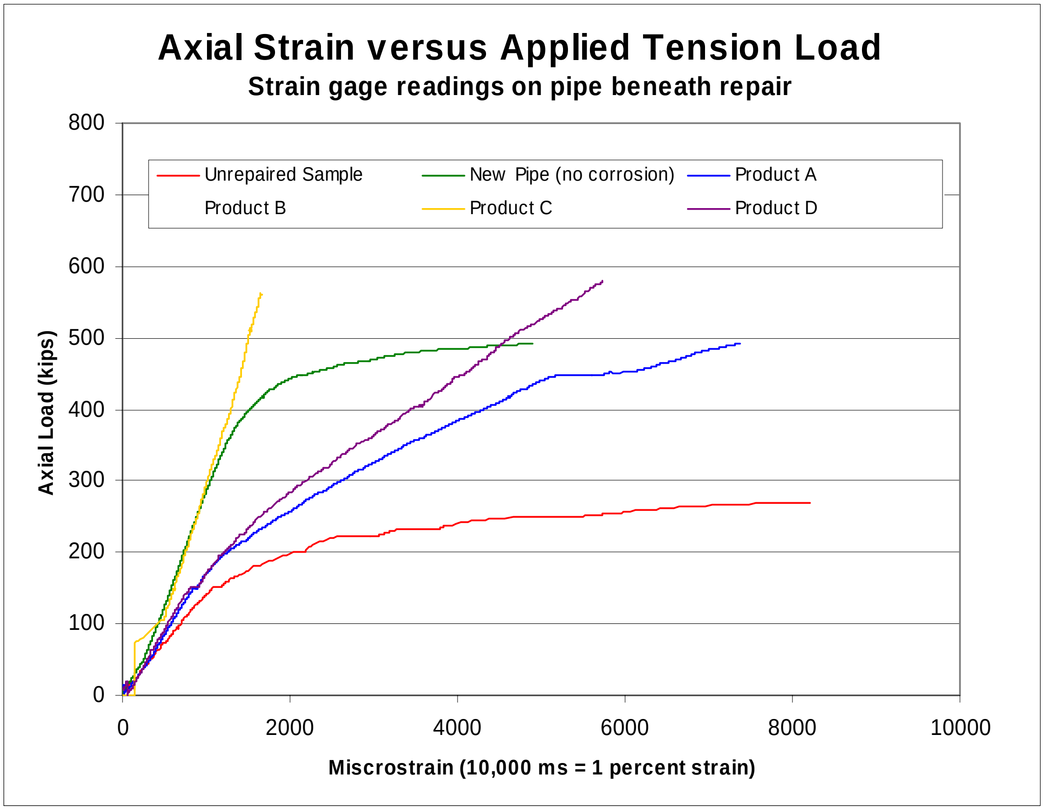

Figure 9 – Test results from pressure-tension testing

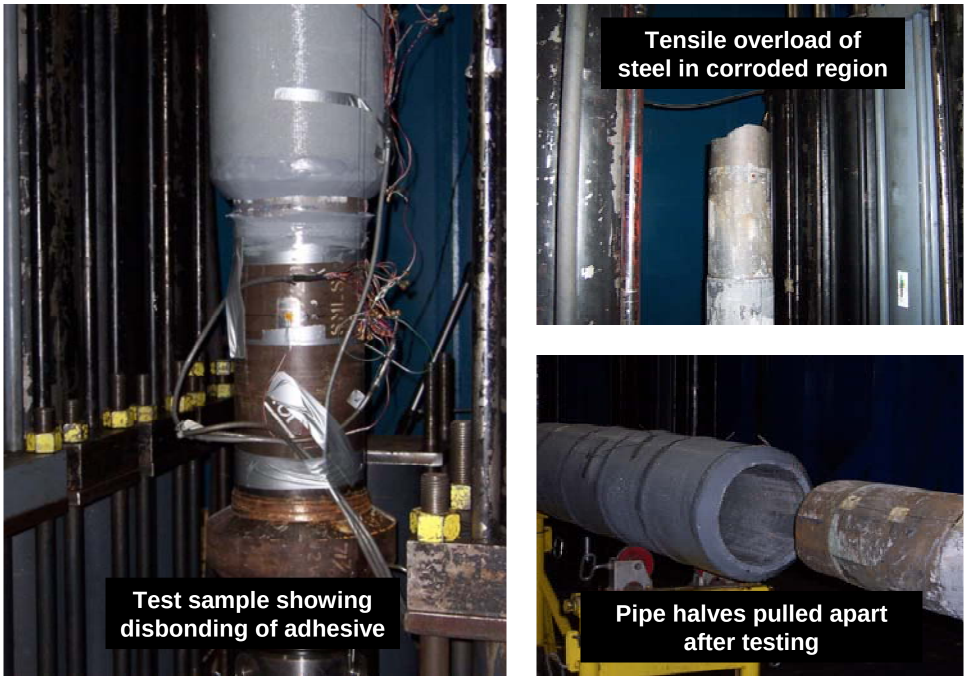

Figure 10 – Post-failure photos of Product D pressure-tension test

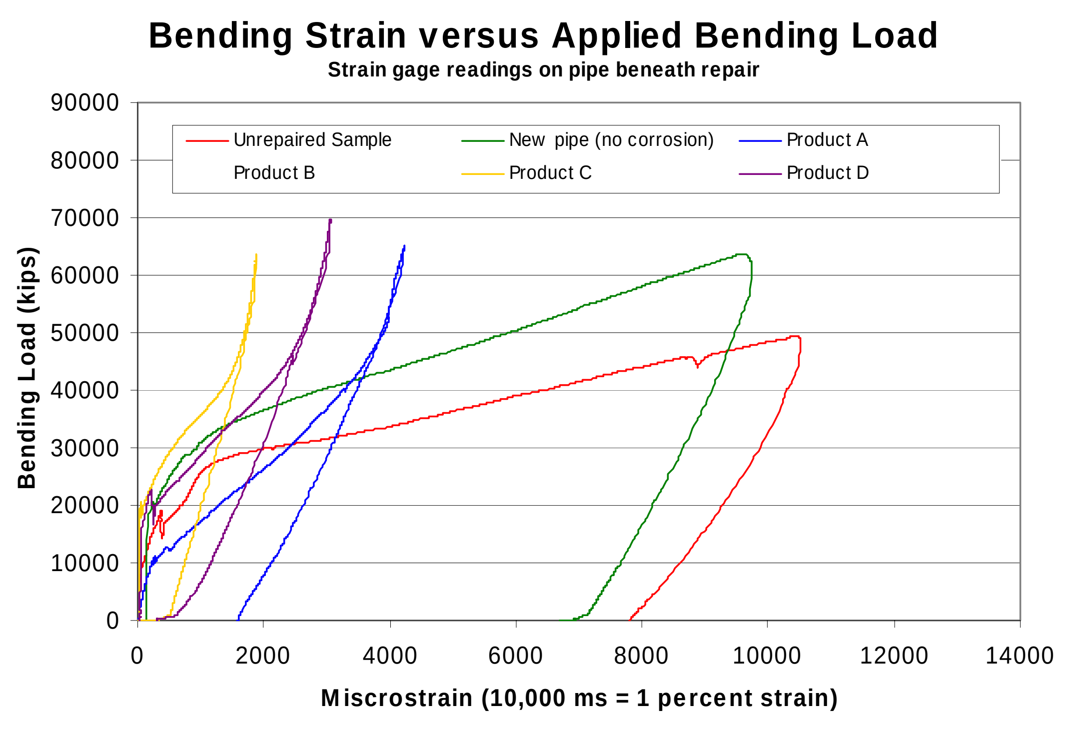

Figure 11 – Test results from pressure-tension-bending testing

Figure 12 – Photo showing Product C prior to bend testing