STRESS ENGINEERING SERVICES INC.

an employee-owned company

Results of the Long-Term Subsea 10,000hr Testing

Final Report

Prepared for:

Bureau of Safety and Environmental Enforcement / Pipeline and Hazardous Materials Safety Administration

Houston, Texas

2 November 2017

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"THE RESEARCH PROJECT OUTCOME DID NOT CONCLUDE AS A HIGHLY INFLUENTIAL OR INFLUENTIAL CATEGORY. THEREFORE, BSEE WOULD NOT CONDUCT A PEER REVIEW FOR THIS RESEARCH."

Executive Summary

Stress Engineering Services, Inc. (SES) was contracted by the Bureau of Safety and Environmental Enforcement (BSEE) and the Pipeline and Hazardous Materials Safety Administration (PHMSA) to perform a study evaluating the use of composite repair systems for reinforcing offshore pipelines and risers. This study also provided further assessments to validate their use onshore for reinforcing high pressure gas and liquid transmission pipelines. As part of the study, SES conducted a series tests using pipe samples that were reinforced using composite repair systems. These tests were intended to recreate environmental and loading conditions that would be encountered during offshore operations. The activities completed as a part of this study are listed below:

- Simulated subsea installation and curing of composite repairs
- Examination of the effects of improper installation
- Composite repair inspection
- 10,000-hr pressure hold in simulated seawater conditions
- 90-day UV exposure
- Cyclic thermal loading
- Cyclic pressure testing
- Pressure-to-failure (burst) testing
- Axial tension and bending testing

The tasks listed above were completed using pipe samples fabricated from 12.75-inch OD x 0.375-inch, Gr. X42 pipe. Each of these samples contained a 6-inch x 8-inch region of simulated corrosion machined to a depth equal to 75% of the pipe's wall thickness. The repair options assessed were commercially available composite systems.

The project was divided into two primary phases, a 10,000-hr pressure hold in simulated seawater conditions and simulated field test conditions conducted following the 10,000-hr pressure hold. The simulated field tests included the 90-day UV exposure, cyclic thermal loading, cyclic pressure, burst, axial tension, and bending tests.

Three composite repair manufacturers participated in the offshore study; Manufacturer A, B, and C. All repair installations were performed underwater on samples that were used for the tests mentioned above. In addition to the standard installations completed by each manufacturer, an installation was completed in which a defect was intentionally introduced to the composite repair. This sample was subjected to the same testing as the repairs with no intentional defects.

Results from both phases of testing are summarized below.

10,000-hour Test Results

1. Five samples from each of the three manufacturers (15 total samples) were submerged in a simulated subsea environment for 10,000-hours while an internal pressure of 72% SMYS was maintained (+/- 15%). A salinity of 32 parts per thousand (ppt) was targeted for the 10,000-hr hold.

2. All samples tested survived the 10,000-hour pressure hold without failure.

3. Following completion of the 10,000-hour pressure hold, the samples were removed from the simulated subsea environment for continued testing.

Post-10,000-hour Test Results

1. After removal from the 10,000-hour hold period, the samples were subjected to a 90 day UV exposure and a series of 12 thermal cycles. The thermal cycles had a temperature range of approximately 100 °F with a maximum temperature of approximately 130 °F.

2. Following completion of the thermal cycling, the samples were pressure cycled at internal pressures of 890 psi to 1,780 psi (36% SMYS to 72% SMYS) prior to additional testing. A runout target of 25,000 cycles was set for the tension and bending samples. All other samples had a runout target of 50,000 cycles. The table below summarizes the results of the pre-cycling.

Sample Designation	Manufacturer A	Manufacturer B	Manufacturer C
Burst	**Failed after 17,411 cycles**	**Survived**	**Survived**
Fatigue	**Failed after 31,547 cycles**	**Survived**	**Survived**
Tension	**Failed after 3,678 cycles**	**Survived**	**Survived**
Bending	**Survived**	**Survived**	**Survived**
Delamination	**Failed after 23,237 cycles**	**Failed after 42,223 cycles**	**Survived**

3. Two reinforced samples were burst tested along with one unreinforced sample. All reinforced samples tested achieved failure pressures at least twice that of the unreinforced sample. The location of failure for Manufacturer A's sample was in the base pipe outside of the repair, while failure of the Manufacturer C's sample occurred in the simulated corrosion region within the composite reinforced region.

	Unreinforced	Manufacturer A	Manufacturer B	Manufacturer C
Failure Pressure (psi)	1,681	N/A	4,037	3,615
Failure Location	Simulated Corrosion	N/A	Base Pipe Outside of Repair	Simulated Corrosion

4. Two reinforced samples and one unreinforced sample were fatigue tested (cyclic internal pressure to failure) following pre-cycling. The unreinforced sample was unable to complete one cycle to 72% SMYS while the reinforced samples completed 130,960 and 250,000 cycles respectively.

5. Three samples completed tension-to-failure testing, including the Manufacturer C's delamination sample. All three samples had tensile failure loads in excess of 600 kips (1 kip = 1,000 lbf) and all failures were located underneath the repair in the simulated corrosion region. The results provided in the table below are the loads applied by the frame at the time of failure and do not include pressure end load (PEL).

Sample	Maximum Tensile Load (kip)
Manufacturer B - Tension	604.7
Manufacturer C - Tension	620.0
Manufacturer C - Delamination	635.0

6. Three samples completed bending-to-failure testing; one sample from each respective manufacturer. Each of the samples were pressured to an internal pressure equal to 72% SMYS, which was maintained while bending moments were applied. The maximum bending moments for each sample are provided in the table below and occurred with the simulated corrosion region loaded in compression. All failures occurred at bending moments in excess of 260 kip-ft (1 kip = 1,000 lbf).

Sample	Maximum Bending Moment (kip·ft)
Manufacturer A	264.6
Manufacturer B	262.4
Manufacturer C	278.4

The testing performed in this study was focused on reinforcement of external corrosion. Further investigation would be warranted prior to using these systems to reinforce other types of anomalies, including planar flaws.

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1. Introduction

Stress Engineering Services, Inc. (SES) was contracted by the Bureau of Safety and Environmental Enforcement and the Pipeline and Hazardous Materials Safety Administration (BSEE and PHMSA, respectively) to conduct a comprehensive study evaluating the use of composite repair systems in reinforcing offshore pipelines and risers. This study also provides further assessments that could validate their use onshore for reinforcing high pressure gas and liquid transmission pipelines. This program is under Contract No. E15PC00003 and includes the below areas of study. The findings from each of these areas will be used to develop a *Guideline Document for the Reinforcement of Offshore Piping, Risers, and Pipelines Using Composite Materials*.

- Composite Repair Gap Analysis and State-of-the-Art Assessment - **Completed**
- Plastic Pipe Insert Technology Report - **Completed**
- Inter-layer Strain Corrosion and Dent Testing - **Completed**
- Effects of Pressure during Installation - **Completed**
- Long-Term Subsea 10,000hr Test Program – **Subject of this Report**

This report presents the test results from the Long-Term Subsea 10,000hr Test Program completed as a part of the study described above. The purpose of this test program was to evaluate composite repair systems when subjected to several types of subsea exposure tests including long-term, 10,000 hour exposure to a simulated seawater environment, UV exposure, thermal cycling, and pressure cycling. Following the exposure tests, the surviving repaired samples completed several full-scale tests designed to represent loading conditions likely to be experienced by a composite repair providing structural reinforcement offshore. Three composite repair manufacturers participated in the Long-Term Subsea 10,000hr Testing: Manufacturer A, B, and C. Each manufacturer repaired five samples for the test program (15 samples total).

The following report details the test procedure and results of the Long-Term Subsea 10,000hr Test Program. Section 2 of the report outlines the scope of the exposure and full-scale tests included in this program. Section 3 reviews the test sample preparation, instrumentation, and composite repair installation. Inspections of the installed composite repairs were also performed as part of this study. The pre-10,000hr hold inspection report is included in Section 4 along with the procedure and results of the exposure tests. Section 5 covers the test procedure and results of the full-scale burst, fatigue, tension, bending, and delamination tests respectively. The post-10,000hr hold inspection is also included in this section. The report concludes with discussion of the study results in Section 6: Findings and Conclusions.

2. Test Program Scope

The Long-Term Subsea 10,000hr Test Program includes a comprehensive set of exposure tests designed to subject composite reinforced pipe samples to conditions simulating the in-service effects of a subsea environment. The exposure testing included the following phases:

- 10,000hr exposure to simulated seawater environment
  - Internal pressure maintained between 60% and 80% of the specified minimum yield stress (SMYS) during the 10,000hr exposure
- 90-day UV exposure
- Thermal cycling
  - Twelve (12) thermal cycles with temperature range of ≈100 °F
- Pressure cycling
  - 50,000 or 25,000 pressure cycles, depending on the sample, at a pressure range of 36% to 72% SMYS

Five samples were prepared for each of the three participating manufactures. All samples were subjected to the above exposure tests, and the surviving samples were used in the below full-scale tests to simulate potential loading conditions in a subsea application.

- Burst test
- Fatigue (cycles to failure) test
  - Continuation of exposure pressure cycles
- Tension test
  - Tension to failure with internal pressure
- Bending test
  - Four-point bend test to failure with internal pressure
- Tension Test of Improper Repair Installation (Delamination)

3. Sample Preparation and Composite Repair Installation

The repair installations took place at SES's Waller Test Facility in Waller, Texas in January of 2016. The following sections cover the sample preparation, instrumentation, and composite repair installation.

3.1 Sample Preparation and Instrumentation

SES fabricated 15 test samples from 12.75-inch OD x 0.375-inch WT, Grade X42 pipe with a 75% deep, 6-inch x 8-inch simulated corrosion defect in the center as shown in Figure 3-1. The samples were sandblasted to near white metal (NACE #2) prior to the composite repair installations. SES installed hoop and axial oriented weldable strain gages at five locations along the sample as illustrated in Figure 3-2 (10 gages total per sample). Three of the gage locations were located in the simulated corrosion defect (locations 1, 2, and 3), one outside the repair on the base pipe (location 4), and one 90° from the corrosion defect under the composite repair (location 5). Weldable strain gages were selected for this test program due to the harsh testing environment. Figure 3-3 provides an example of the hoop and axial oriented weldable strain gages at locations 1, 2, and 3 in the simulated corrosion defect.

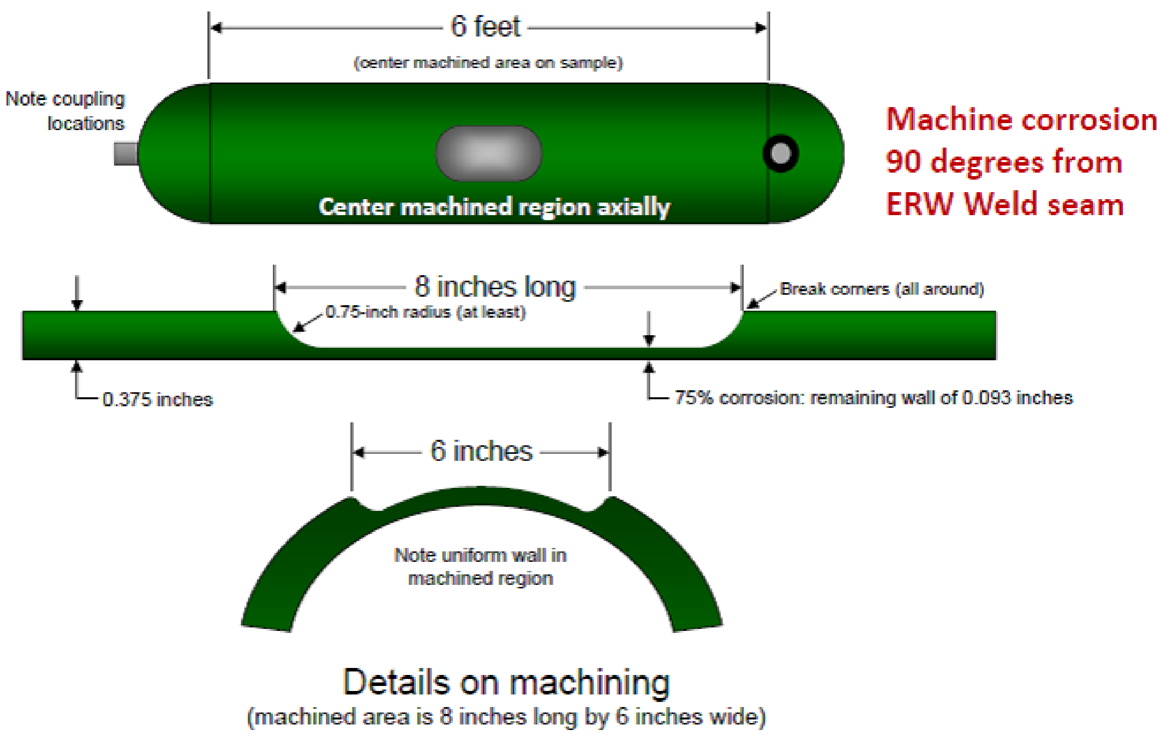

Figure 3-1: Schematic of 12.75-inch OD x 0.375-inch WT, Grade X42 pipe samples with a 75%, 6-inch x 8-inch simulated corrosion defect

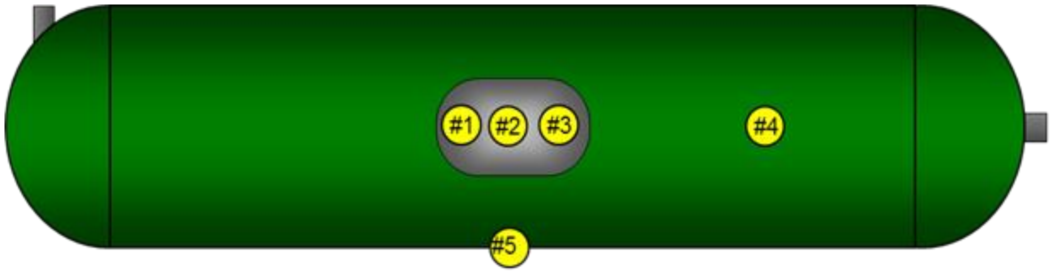

Figure 3-2: Schematic of sample strain gage locations (two weldable strain gages per location)

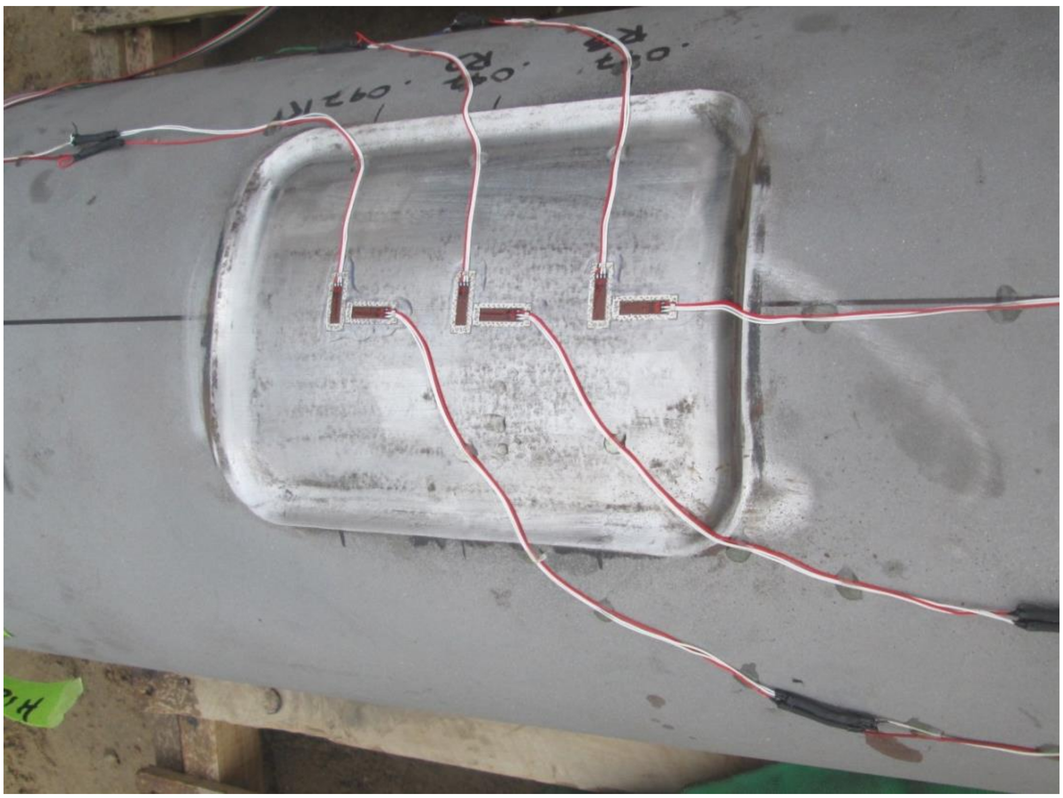

Figure 3-3: Example photograph of strain gage locations 1, 2, and 3 in simulated corrosion defect

The 15 test samples were fabricated from three joints of pipe. Material testing was performed on a ring of material removed from each pipe joint. The chemistry, tensile results, and Charpy v-notch (CVN) impact test results are summarized in Table 3-1 through Table 3-3. The original reports for the material testing are provided in Appendix A. These properties are in the range expected for 12.75-inch OD x 0.375-inch WT, Grade X42 material (API 5L).

Table 3-1: Sample chemical analysis results

Element	Composition (%)		
	Joint 1	Joint 2	Joint 3
Carbon	0.16	0.16	0.16
Manganese	0.79	0.79	0.78
Phosphorus	0.016	0.015	0.016
Sulfur	0.004	0.004	0.004
Silicon	0.02	0.02	0.02
Chromium	0.01	0.01	0.01
Nickel	<0.01	<0.01	<0.01
Molybdenum	<0.01	<0.01	<0.01
Copper	0.01	0.01	0.01
Aluminum	0.03	0.03	0.03
Vanadium	<0.01	<0.01	<0.01
Titanium	<0.01	<0.01	<0.01
Niobium	<0.01	<0.01	<0.01
Boron	<0.001	<0.001	<0.001

Table 3-2: Sample tensile test results

Joint	Location	Yield Strength[1] (psi)	Tensile Strength (psi)	Elongation (%)
1	Pipe body	49,500	70,700	44.2
2		50,500	70,200	43.6
3		49,000	70,700	43.4

[1] YS at 0.5% total extension.

Table 3-3: Sample CVN impact test results

Sample	Absorbed Energy (ft-lb)	Percent Shear (%)
Joint 1	58	100
	61	100
	62	100
Average	***60.3***	***100***
Joint 2	65	100
	58	100
	64	100
Average	***62.3***	***100***
Joint 3	64	100
	66	100
	65	100
Average	***65***	***100***

Transverse, 70°F, ¾ size CVN 90° from the weld

3.2 Composite Repair Installation

The three composite repair manufactures listed below participated in this study. Also listed below are abbreviations for each manufacturer used throughout this report.

- Manufacturer A (A)
- Manufacturer B (B)
- Manufacturer C (C)

Each manufacturer repaired five samples for the test program (15 samples total). The samples were designated by the manufacturer, test type, joint number, and sample number. The nomenclature for the samples was as follows:

- Offshore Study – OFF
- Manufacturer – A, B, C
- Test type – B (Burst), F (Fatigue), T (Tension), BE (Bending), DL (Delamination)
- Joint Number – J1, J2, or J3
- Sample Number – 1 (Burst), 2 (Fatigue), 3 (Tension), 4 (Bending), 5 (Delamination)

For example, the sample titled OFF-B-F-J2-2 represents Offshore Study, Manufacturer C, Fatigue, Joint #2, Sample 2.

Prior to the composite repair installation the pipe samples were filled with water and a bio-scavenger (after strain gages were applied). The samples were then submerged in a simulated sea water trough for the repair installation. All installations took place with the pipe samples fully submerged to simulate a subsea installation. Example photographs of each manufacturer's repair process are shown in Figure 3-4 through Figure 3-6. Additional photographs of the repair installations are included in Appendix B. The repaired samples were stored in saltwater tanks until fully cured.

Figure 3-4: Representative photograph during installation of Manufacturer A's repair.

Figure 3-5: Representative photograph during installation of Manufacturer C's repair.

Figure 3-6: Representative photograph during installation of Manufacturer B's repair.

One of the five repairs from each manufacture was installed with artificial delaminations between the first layer of the composite wrap and the steel substrate. The purpose of the delamination sample was to evaluate the effects of improper or poor installation of the composite. SES created the delaminations using 6-inch wide high-temperature Teflon tape illustrated in Figure 3-7 and Figure 3-8. The tape was oriented axially along the pipe every 90° started at the corrosion defect, and covered approximately 60% of the steel pipe surface. The composite repair was then wrapped over the artificial delaminations. The delamination samples that survived the exposure testing completed an axial tension test.

Figure 3-7: Example of artificial delaminations on Manufacturer B's sample (1 of 2)

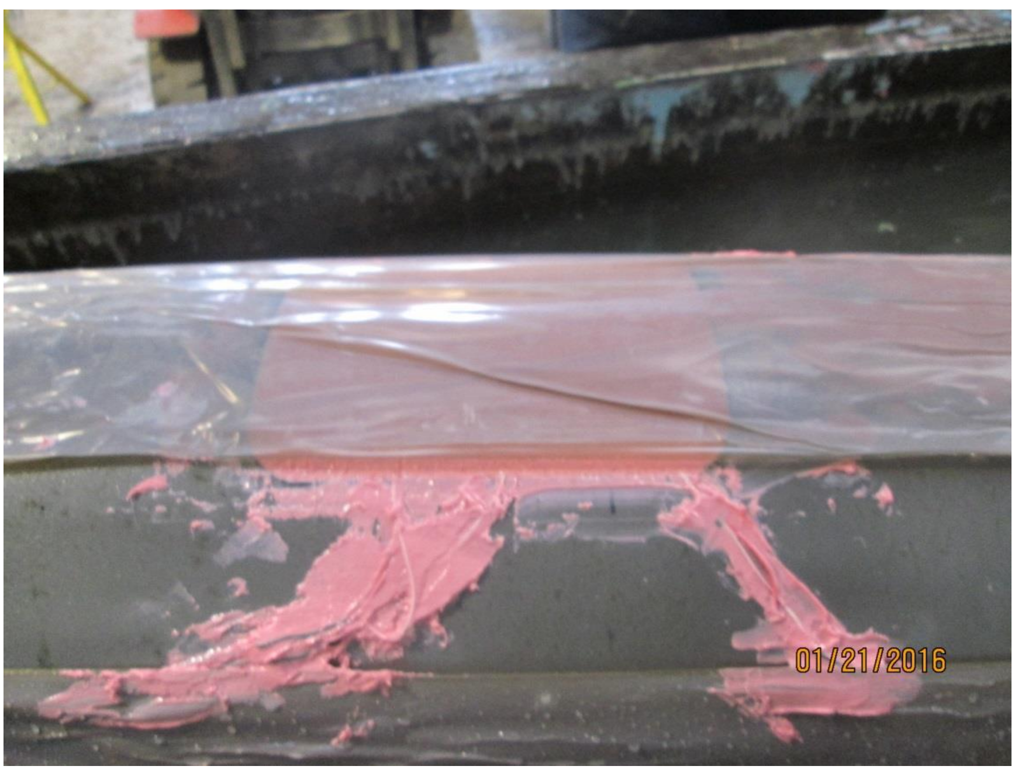

Figure 3-8: Example of artificial delaminations on Manufacturer B's sample (2 of 2)

3.3 Pre-Test Composite Repair Inspection

SES contracted Sonomatic to inspect samples for all three repair systems prior to beginning the 10,000hr study. Four total samples were inspected by Sonomatic; the delamination sample from each manufacturer and Manufacturer A's fatigue sample. The pre-10,000hr hold inspections were not successful due to the inability of the technology to inspect composite repairs with the thickness of those found in the offshore study. None of the installed delaminations or simulated corrosion defects were located in any of the samples and no usable information was provided for Manufacturer A's fatigue sample. Further discussion on the inspection technique and the full results are provided Sonomatic's report located in Appendix C.

4. Exposure Tests

The exposure tests of the offshore repair samples took place at SES's Waller Test Facility from April 22nd, 2016 through August 8th, 2017. The exposure tests were intended to subject the composite repairs to conditions simulating the in-service effects of a subsea environment for an extended period of time prior to the full-scale tests. The exposure tests included the following:

- 10,000hr exposure to simulated seawater environment
- 90-day UV exposure
- Thermal cycling
- Pressure cycling

The sections below detail the test procedure and results of each exposure test. Calibration certificates for instrumentation used in test are available in Appendix F.

4.1 10,000 Hour Simulated Seawater Exposure

The purpose of the 10,000hr seawater exposure was to simulate an extended in-service subsea environment where the composite repairs were exposed to saltwater while subjected to internal pressure. This was the first exposure test following the installation of the composite repairs and took place from April 22, 2016 through May 14th, 2017 (10,000 hours ≈ 1.15 years). Before installing the samples in the saltwater bath, the exposed steel pipe of each sample was wrapped with a wax tape coating, and the five samples from each manufactured were stacked in groups. The samples were then installed in the saltwater bath and connected to a common pressure line as shown in Figure 4-1 and Figure 4-2. The test procedure for the 10,000 hour simulated seawater exposure test was as follows:

1. Installed samples in the saltwater pool and performed leak check at 500 psi.
2. Filled tank and adjusted salinity to 32 parts per thousand (ppt).
3. Increased pressure in samples to 72% SMYS (1,780 psi) and held for 10,000 hours
    a. Recorded pressure every 6 hours
    b. Maintained pressure between 1,500 psig and 2,000 psig
    c. Maintained tank salinity between 29 and 32 ppt.
    d. Checked sample pressure and pool salinity daily.
4. If leak occurred in a sample at any point during testing, isolated the sample stack and removed the leaking sample from the system.

Figure 4-1: Samples submerged in simulated seawater envionemnt

Figure 4-2: Simulated saltwater exposure tank at SES – Waller Test Facility

All 15 samples survived the 10,000hr salt water exposure tests without leaking. As shown in Figure 4-3, the internal pressure was maintained between 1,500 psi and 2,000 psi during the 10,000 hours. All samples were connected to a common pressure line and pressure transducer. The weldable strain gages installed under the composite repairs were not monitored during the pressure hold. Figure 4-4 is a photograph of the 15 samples following the pressure hold and draining of the saltwater bath.

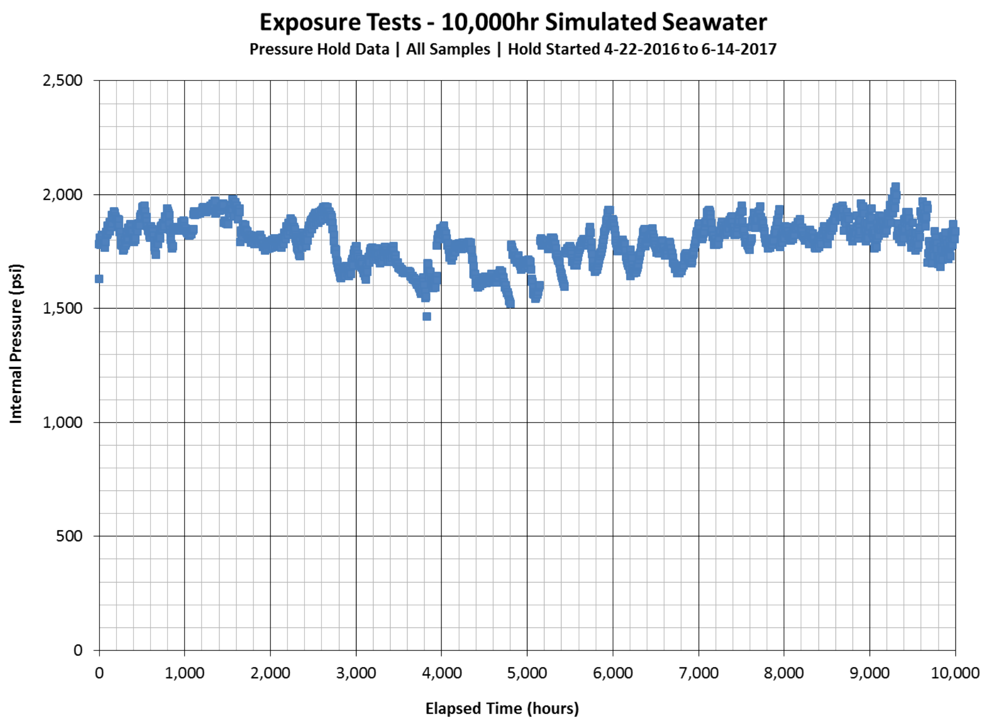

Figure 4-3: Pressure vs. time plot for all samples during 10,000hr pressure hold

Figure 4-4: Photograph of samples after completion of 10,000 hour hold.

4.2 Post-10,000 Hour Hold Composite Repair Inspection

SES contracted BIS Salamis to inspect the fatigue and delamination samples for all three repair systems. In most cases, BIS Salamis identified the machined simulated corrosion and the simulated delamination. BIS Salamis reported that some indications could be non-relevant based on size and a low amplitude signal, especially the ones that likely correspond to the simulated corrosion. The full report provided by BIS Salamis is attached in Appendix D.

4.3 UV Exposure

The UV exposure began while the samples were completing the final hours of the 10,000hr pressure hold in May of 2017. Up to that point, a pool cover had protected the samples from UV light. The tank cover was removed to begin the UV exposure. After completion of the 10,000hr hold, the samples were removed from the simulated seawater tank and left outside to complete the 90 days of UV exposure (Figure 4-5). The samples were not under pressure during the UV exposure.

Figure 4-5: Photograph of samples after cleaning with pressurized water in preparation for the 90 day UV exposure.

4.4 Thermal Cycling

The thermal cycling took place midway through the 90 days of UV exposure. The 15 samples were placed inside the insulated box shown in Figure 4-6 and thermally cycled using a forced air heating/cooling unit. Twelve (12) cycles were completed with a change in temperature of approximately 100 °F. Thermocouples placed on samples spaced throughout the box monitored and recorded temperature. The samples were not pressurized. The test procedure for the thermal cycles was as follows:

1. Installed samples in insulated box and connected thermocouples.
2. Active heating/cooling unit for thermal cycles with the following set-points.
   a. Low temperature range 30°F to 10°F
   b. High temperature range 110°F to 130°F
   c. Total of 12 cycles
3. Deactivated the heating/cooling unit following completion of the thermal cycles and allowed the samples to reach room temperature.
4. Moved samples outside to complete UV exposure testing.

Figure 4-6: Photograph of insulated wooden box.

Figure 4-7 displays a plot of the average sample temperature vs. elapsed time for the 12 thermal cycles. The two temperature lags following the cycle peaks at 64 hours and 112 hours were due to compressor shutdowns meant to protect the heating/cooling equipment. The samples were removed from the insulated box following the thermal cycles and placed outside to complete the UV exposure.

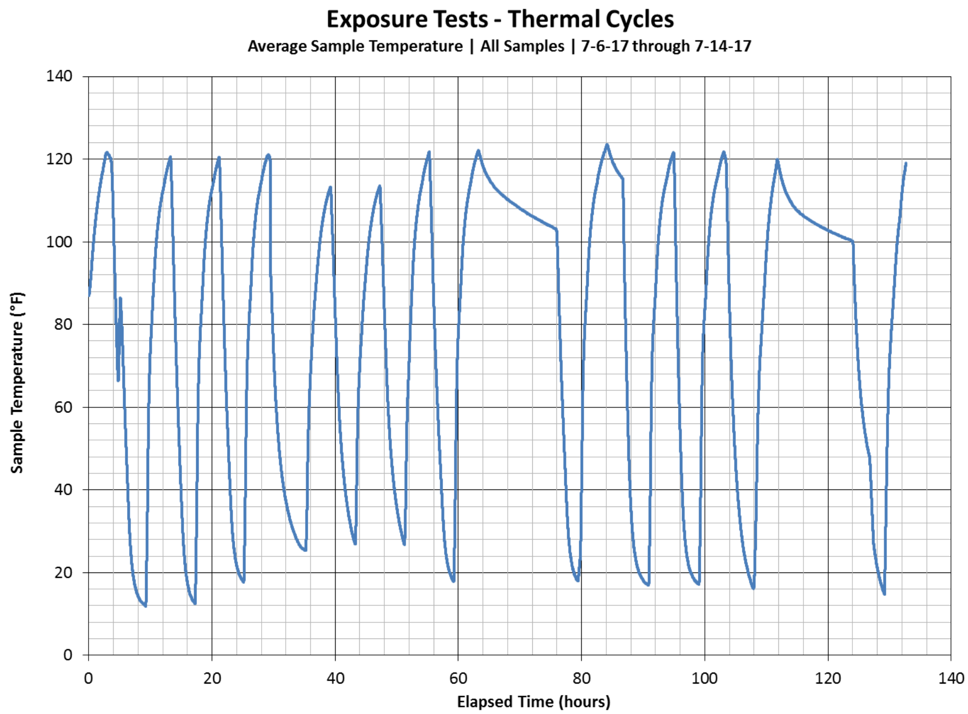

Figure 4-7: Temperature vs. elapsed time plot during thermal cycling.

4.5 Pressure Pre-Cycling

The final exposure test was the pressure pre-cycling which was completed following the UV exposure. The original pre-cycling scope required 50,000 pressure cycles at a pressure range of 36% to 72% SMYS (890 psi to 1,780 psi). An initial sample failure after approximately 31,500 cycles prompted a reduction in cycle count for the six samples designated for bending and tension to increase the likelihood of survival for the full-scale tests. The test procedure for the pre-cycling was as follows:

1. Installed samples in SES pressure cycle facility.
2. Pressure cycled samples between 36% and 72% SMYS (890 psi to 1,780 psi)
    a. 50,000 cycles for burst, fatigue, and delamination samples.
    b. 25,000 cycles for tension and bending samples.
3. If failure occurred at any point during testing, the failure was photographed and the cycle count recorded.

Figure 4-8 illustrates a typical data snapshot of internal pressure vs. elapsed time during the pre-cycling. The data snapshot includes two full pressure cycles for sample OFF-A-BE-J1-4. The max and min pressures for the full 25,000 pre-cycles for this sample are included in Figure 4-9. Similar plots for the other samples that survived the pre-cycling are included in Figure through Figure of Appendix E. The pressure vs. cycle count plots of some samples are the same since samples were cycled simultaneously using shared pressure lines.

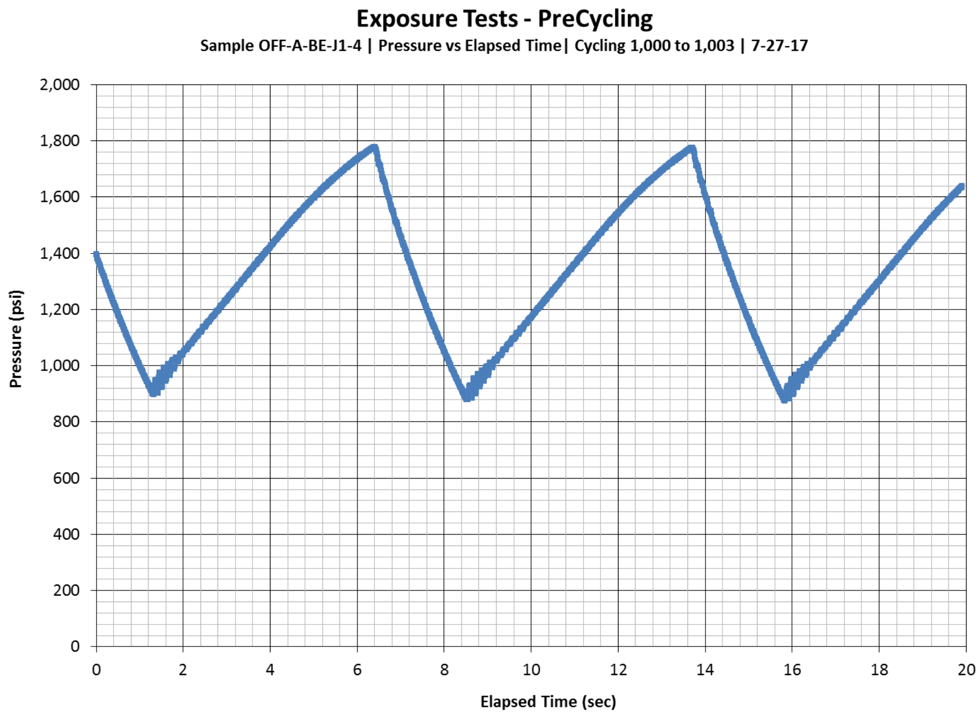

Figure 4-8: Representative pressure vs. elapsed time for sample OFF-A-BE-J1-4 (Manufacturer A's bending sample) for cycles 1,000 to 1,003

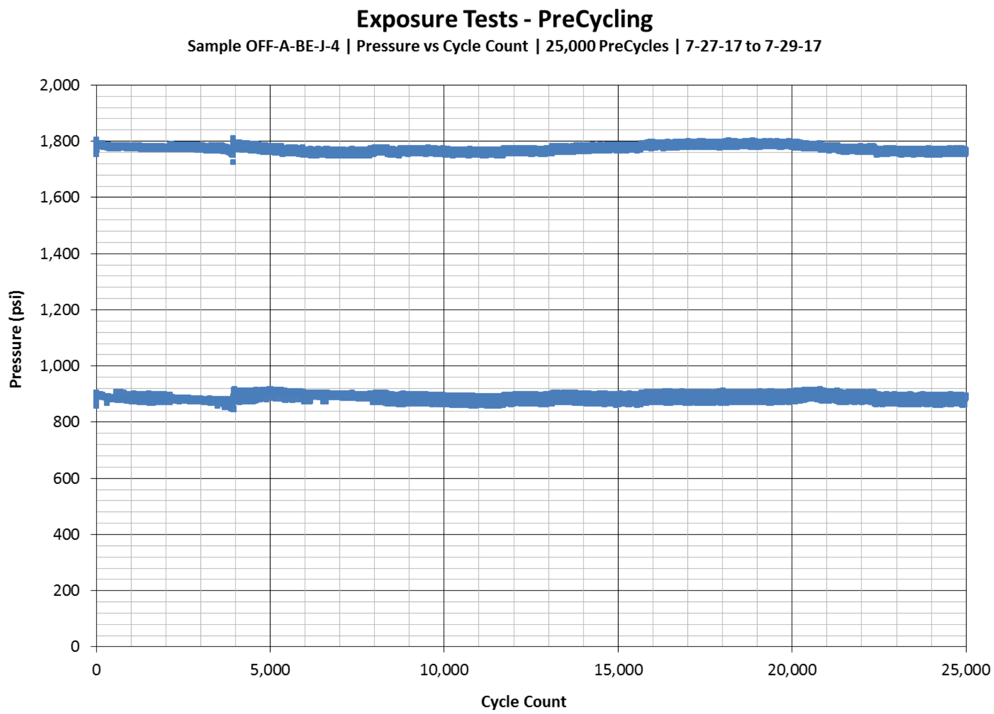

Figure 4-9: Max/min pressure vs. cycle count for 25,000 pre-cycles of sample OFF-A-BE-J1-4 (Manufacturer A's bending sample)

An attempt was made to pre-cycle an unreinforced sample, using the test procedure described above, to serve as a baseline case for the reinforced samples. The unreinforced sample failed prior to completing the first pressure cycle and achieved a maximum pressure of 1,553 psi.

At the start of the pre-cycling exposure test, all 15 samples had survived the previous exposure tests and could maintain an internal pressure of 72% SMYS (1,780 psi). The pre-cycling test caused failures in five of the samples. Table 4-1 displays a summary of the samples that survived the pre-cycling, and those that failed (including the cycles to failure). As seen in Table 4-1, four out of the five Manufacturer A's samples failed along with Manufacturer B's delamination sample. Recall the delamination sample included intentional defects between the steel substrate and first layer of the composite. The five samples failed in a similar manner by developing a through-wall crack in the simulated corrosion region that leaked through the outer edge of the composite as highlighted in Figure 4-10.

Table 4-1: Summary of Surviving Samples during Pre-Cycling

Sample	Manufacturer A	Manufacturer B	Manufacturer C
Burst	Failed after 17,411 cycles	Survived	Survived
Fatigue	Failed after 31,547 cycles	Survived	Survived
Tension	Failed after 3,678 cycles	Survived	Survived
Bending	Survived	Survived	Survived
Delamination	Failed after 23,237 cycles	Failed after 42,223 cycles	Survived

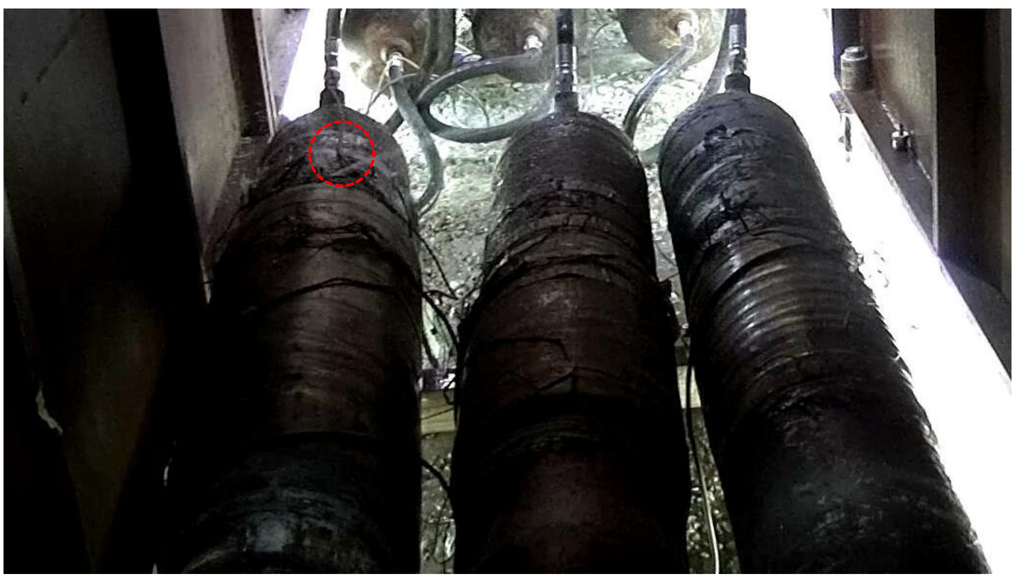

Figure 4-10: Photograph of failure (circled) during cycling of Manufacturer A's Tension sample.

The lowest number of pre-cycles to failure was 3,678 for Manufacturer A's tension sample. It is important to remember that an unreinforced 12.75-in OD x 0.375-inch WT, Grade X42 sample with the same 75% corrosion defect will burst well below the max cycle pressure of 72% SMYS (1,780 psi). Even this sample with a low cycle count provided reinforcement to the corroded region. The 10 samples that survived the exposure tests went on to complete the full-scale tests.

5. Full-Scale Testing

The full-scale tests took place at SES's Waller Test Facility from July 31st through September 9th, 2017, following completion of the exposure tests. The following full-scale tests were included in the program:

- Burst
- Cyclic Fatigue
- Tension (including delamination samples)
- Bending

The purpose of the full-scale testing was to simulate potential loading conditions an offshore composite repair might encounter in service. Together, these tests provide a means to evaluate the composite repair system's overall performance following the simulated exposure. The sections below detail the test procedure and results of each full-scale test. Calibration certificates for instrumentation used in the tests are available in Appendix F.

5.1 Burst Tests

The two reinforced samples listed below survived the exposure tests and were burst tested. Manufacturer A's burst sample (OFF-A-B-J1-1) failed during the pre-cycling exposure test at 17,411 cycles. SES also burst tested an unreinforced sample with the 75% corrosion defect for a baseline comparison to the reinforced samples.

- Manufacturer B – Sample Number OFF-B-B-J1-1
- Manufacturer C – Sample Number OFF-C-B-J1-1
- Unreinforced 75% Corrosion Sample

5.1.1 Burst Test Instrumentation and Procedure

Three additional biaxial strain gages were added to each burst test sample. This included the following locations:

- One biaxial strain gage on the base pipe halfway between the repair edge and sample endcap.
- Two biaxial strain gages on the composite surface at 0° and 90°.

The 0° strain gage was located over the simulated corrosion defect. Strain measurements were also recorded from the surviving weldable strain gages installed in Section 3.1. Data from these gages was limited as many were damaged during the exposure tests. Following installation of the strain gages, the samples were installed in a pressure pit for the burst test. Figure 5-1 provides an example of a burst sample (Manufacturer C) prior to the burst test. The procedure for the burst test was as follows:

1. Installed burst sample in test pit and photographed.

2. Pressurized samples to failure with 2 minute holds at the following pressures (pressure rate approximately 10 psi per second).

    a. 890 psi (36% SMYS)

    b. 1780 psi (72% SMYS)

    c. 2470 psi (100% SMYS)

3. Following failure, noted burst pressure and photographed failure surface.

Figure 5-1: Manufacturer C's burst sample (OFF-C-B-J1-1) installed in test pit prior to burst test

5.1.2 Manufacturer B's Burst Test Results

Manufacturer B's burst sample (OFF-B-B-J1-1) reached a maximum pressure of 4,037 psi (163% SMYS) before failure occurred outside of the repair in the base pipe (Figure 5-2). There was no visible damage to the outer surface of Manufacturer B's repair following the test. Figure 5-3 displays the internal pressure vs. elapsed time for the burst test. The three (3) hold points at 36%, 72%, and 100% SMYS are visible in the plot. The hoop strain measurements in Figure 5-4 indicate significant deformation in the base pipe and corrosion region during the test (corrosion region gage 2H was the only operable gage during the burst of this sample). The gages on the outside of the composite repair measured little in the way of hoop strain during the test.

Figure 5-2: Manufacturer B's burst sample post-test – failure outside the composite

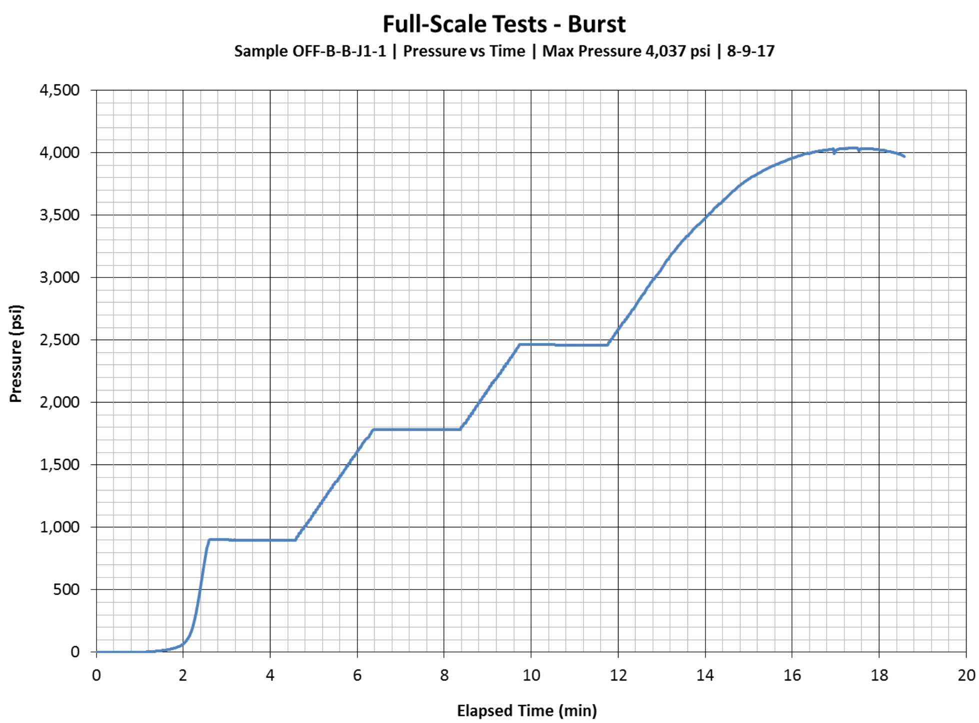

Figure 5-3: Internal pressure vs. elapsed time for Manufacturer B's burst sample (OFF-B-B-J1-1)

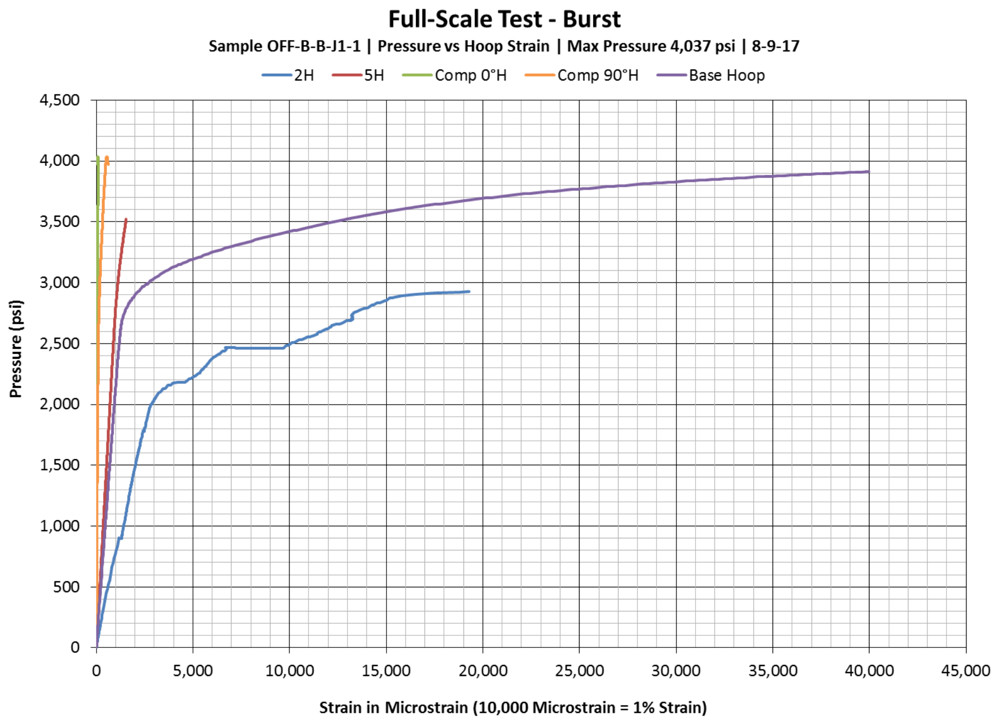

Figure 5-4: Internal pressure vs. hoop strains in corrosion region, base pipe, and on outer layer of composite repair for Manufacturer B's burst sample (OFF-B-B-J1-1)

5.1.3 Manufacturer C's Burst Test Results

The Manufacturer C's burst sample (OFF-C-B-J1-1) reached a maximum pressure of 3,615 psi (146% SMYS) before failure occur in the simulated corrosion defect as shown in Figure 5-5. Figure 5-6 displays a plot for the internal pressure vs. elapsed time during the burst. Similar to Manufacturer B's sample, the hoop strain measurements in Figure 5-7 also indicated deformation in the base pipe with little change on the surface of the composite repair. No gages in the simulated defect were operable during the burst.

Figure 5-5: Manufacturer C's burst sample post-test – failure in simulated corrosion region

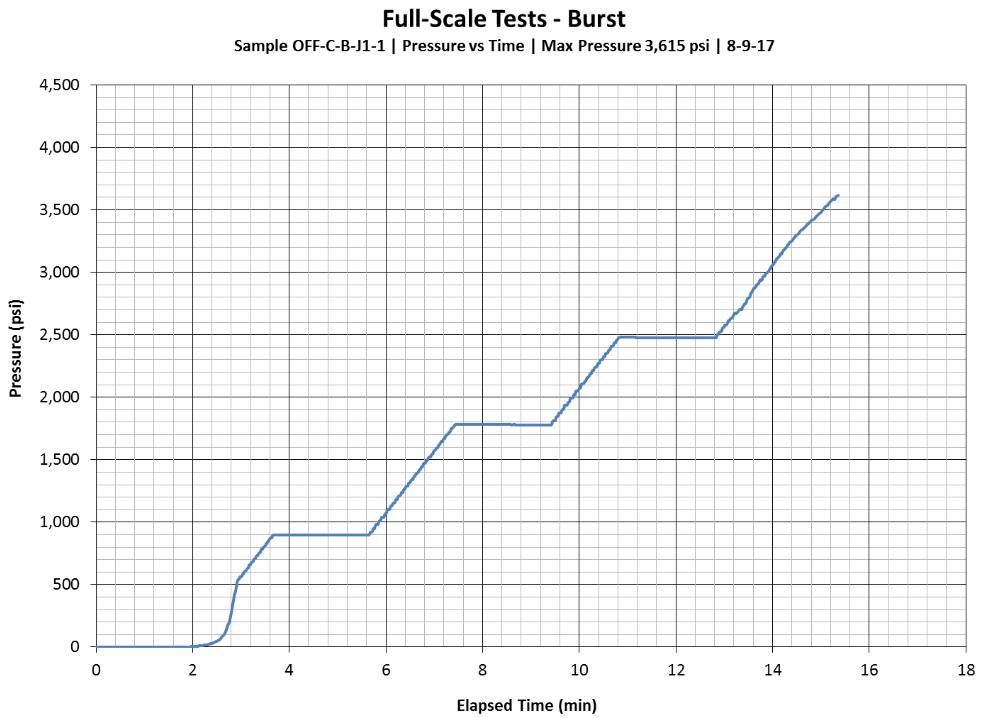

Figure 5-6: Internal pressure vs. elapsed time for Manufacturer C's burst sample (OFF-C-B-J1-1)

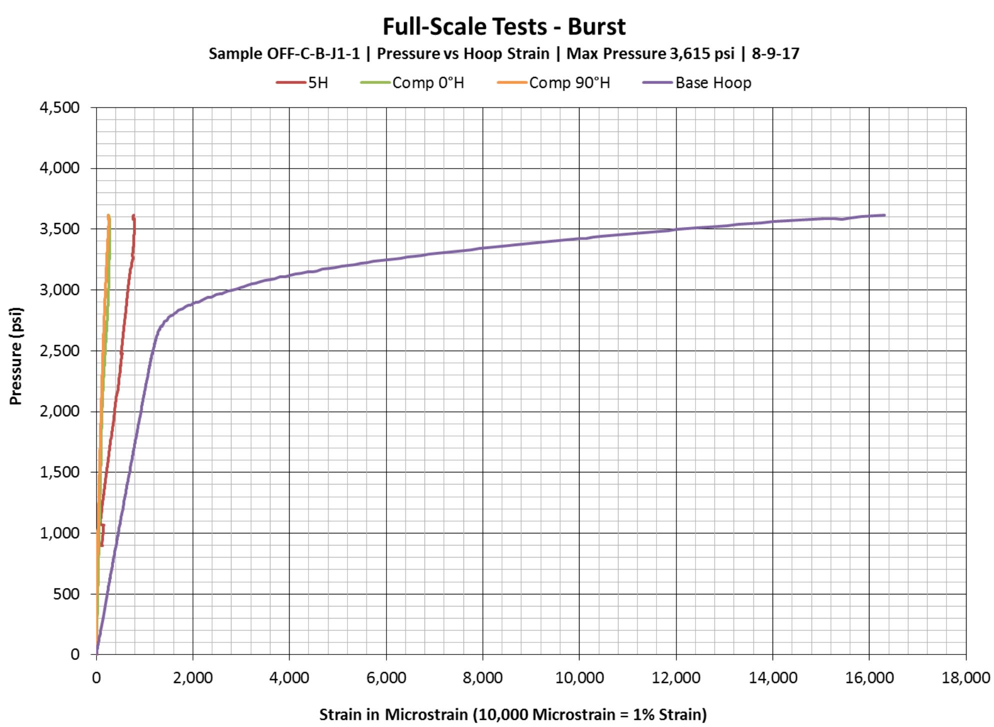

Figure 5-7: Internal pressure vs. hoop strains in corrosion region, base pipe, and on outer layer of composite repair for Manufacturer C's burst sample (OFF-C-B-J1-1)

5.1.4 Unreinforced Burst Test Results

The 75% corrosion unreinforced sample burst at a pressure of 1,681 psi (68% SMYS) in the corrosion region. This sample did not reach the second hold point of 72% SMYS. A strain gage installed in the corrosion region indicated yielding occurred at just over 600 psi.

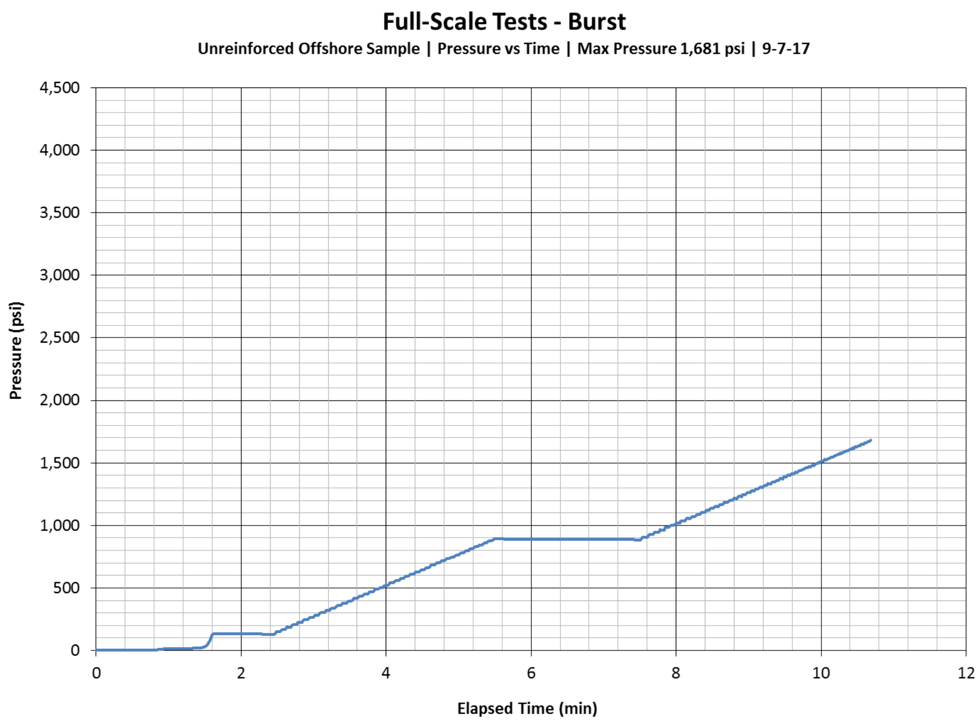

Figure 5-8: Internal pressure vs. elapsed time for unreinforced sample with 75% corrosion defect

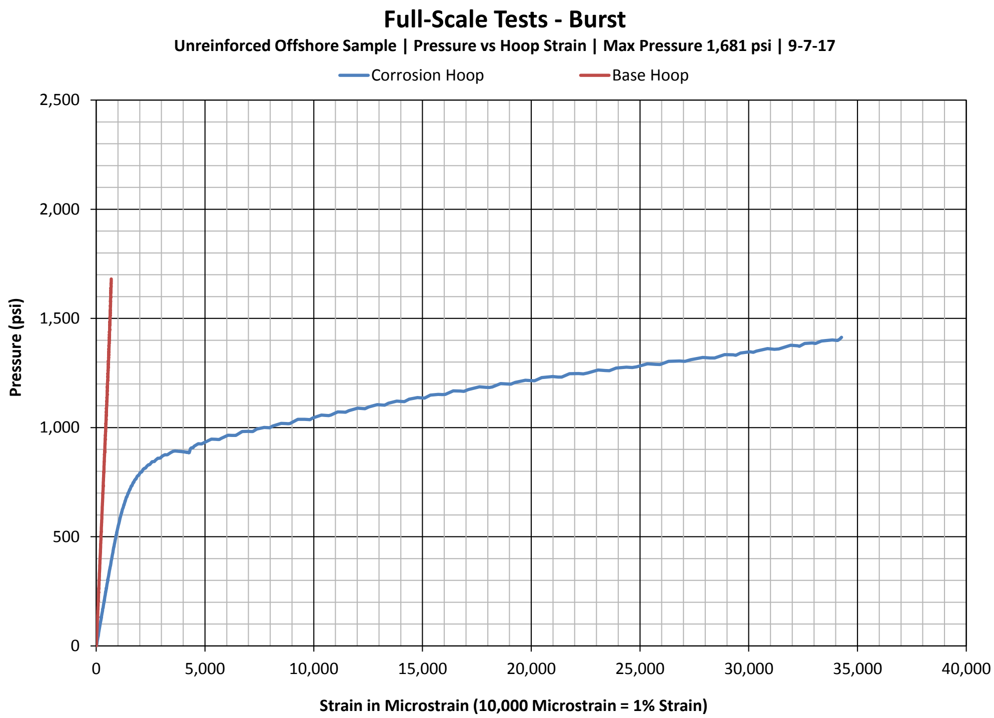

Figure 5-9: Internal pressure vs. hoop strain for unreinforced sample with 75% corrosion defect

5.1.5 Burst Test Summary

The burst test results indicated that the composite repairs successfully reinforced the corrosion defect even after surviving multiple exposure tests. Table 5-1 summarizes the burst test results. Both Manufacturer B and C's samples far surpassed the burst pressure of an unreinforced pipe with the same corrosion defect. Note the unreinforced sample was not subjected to any of the exposure tests.

Table 5-1: Burst testing results summary

Sample	Failure Pressure (psi)
Unreinforced	1,681
Manufacturer B	4,037
Manufacturer C	3,615

5.2 Fatigue Tests

The full-scale fatigue tests were an extension of the pre-cycling exposure test in Section 4.5. Samples that survived the 50,000 pre-cycles continued to cycle into the fatigue test. The two samples that survived the pre-cycling are listed below. The following section details the procedure and results of the fatigue test.

- Manufacturer B – Sample Number - OFF-B-F-J1-2

- Manufacturer C – Sample Number OFF-C-F-J3-2

5.2.1 Fatigue Test Procedure

The full-scale fatigue test used the same pressure cycle range as the pre-cycling exposure test, and the total number of pressure cycles included the 50,000 pre-cycles. The procedure for the fatigue test was as follows:

1. Installed samples in SES pressure cycle facility.
2. Pressure cycled samples between 36% and 72% SMYS (890 psi to 1,780 psi)
    a. If sample did not fail after 250,000 cycles, stopped test (sample runout).
3. If failure occurred at any point during testing, the failure was photographed and the cycle count recorded.

5.2.2 Fatigue Test Results Summary

Table 5-2 summarizes the cycles to failure for each fatigue sample. Manufacturer A's sample which failed after 31,547 cycles during the exposure pre-cycles is also included in the table. Manufacturer B's sample failed after 130,960 cycles, and Manufacturer C's sample reached the runout target of 250,000 cycles without failure. Note that these cycle counts include the 50,000 exposure test pre-cycles. For example, Manufacturer C's sample completed 50,000 pre-cycles and then an additional 200,000 cycles before reaching runout.

The results in Table 5-2 demonstrate that the composite repairs were successful in reinforcing the corrosion defects in an aggressive cycling environment even after the exposure tests. From Figure 5-8, an unreinforced sample would not have reached the peak cycle pressure of 72% SMYS (1,780 psi) before failure.

Table 5-2: Fatigue test results summary

Sample	Cycles to Failure
Manufacturer A	31,547
Manufacturer B	130,960
Manufacturer C	250,000*
Unreinforced	0^+

*Sample reached runout without failure
$^+$Sample failed in first cycle prior to maximum pressure

5.3 Tension Tests

Tension samples from Manufacturer B and C survived the exposure tests prior to full-scale testing. The three delamination samples were also designated for tension testing, but Manufacturer C's delamination sample was the only sample that survived the exposure testing. A list of tension samples with sample numbers is provided below. Since the samples were tested with internal pressure, a pressure end load (PEL) was also acting on the sample (i.e., internal pressure times inside cross-sectional area). Two summary tables are provided in this section; one that provides only the maximum frame load at the time of failure (Table 5-3) and one that includes frame load plus the calculated PEL based on the internal pressure (Table 5-4). Results reported in this section and the provided data plots reference the frame load and do not include the PEL. The remainder of this section details the additional instrumentation for the tension samples, the tension test procedure, and results for the tension and delamination samples.

- Manufacturer B – Sample Number OFF-B-T-J2-3
- Manufacturer C – Sample Number OFF-C-T-J3-3
- Manufacturer C Delamination – Sample Number OFF-C-DL-J3-5

5.3.1 Tension Test Instrumentation and Procedure

In addition to the weldable strain gages installed prior to the exposure tests (Section 3.1), 12 additional biaxial strain gages were installed on the base pipe and composite repair. Figure 5-10 illustrates the locations of the additional strain gages which included:

- Eight biaxial strain gages installed halfway between the composite repair and endcap on both sides of the repair every 90°.
- Four biaxial strain gages installed on the composite surface every 90°.

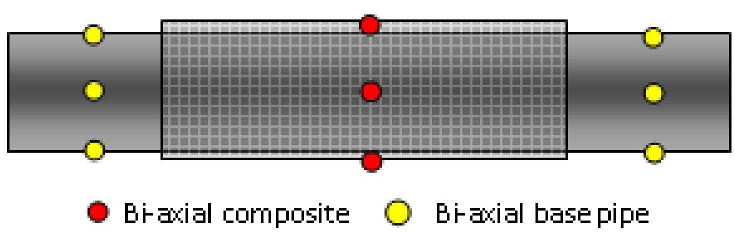

Figure 5-10: Additional biaxial strain gages installed on tension samples

Endcaps were welded to the ends of the pipe to allow for internal pressurization and interface with SES's 1-million pound load frame. An internal pressure of 1,780 psi resulted in a pressure end load of 201.3 kips. Figure 5-11 and Figure 5-12 are examples of Manufacturer B's (OFF-B-T-J2-3) and Manufacturer C's (OFF-C-T-J3-3) tension samples respectively installed in the load frame prior to testing. The procedure for the tension and delamination samples was as follows:

1. Pressurized sample to 1,780 psi (72% SMYS)
    a. Maintained pressure between 1,770 and 1,790 psi through test
2. Increased applied tension to +200 kips (65% SMYS with PEL) at a load rate of 25 kips per minute.

   a. Maintained the load for a 15 minute hold period.

3. Increased applied tension to +470 kips (110% SMYS with PEL) at a load rate of 25 kips per minute.

   a. Maintained the load for a 15 minute hold period.

4. Increased tension load to +620 kips (135% SMYS with PEL) at a load rate of 25 kips per minute.

   a. Maintained the load for a 15 minute hold period.

5. Continued to increase tensile load until failure occurred. Failure was defined as loss of internal pressure or gross plastic deformation.

6. Following failure, noted the failure load and photographed failure location and/or visible damage to the composite repair.

Figure 5-11: Manufacturer B's tension sample (OFF-B-T-J2-3) installed in 1-million pound load frame

Figure 5-12: Manufacturer C's tension sample (OFF-C-T-J3-3) installed in 1-million pound load frame

5.3.2 Manufacturer B's Tension Sample

Manufacturer B's sample reached a maximum applied tensile load of 604.7 kips as shown in Figure 5-13 before failure. Failure occurred when the sample was no longer able to maintain the internal pressure, and a leak path developed from the corrosion defect to the edge of the repair. SES inspected the repair following the failure, but there was no other visible damage.

Strain measurements in Figure 5-14 indicate that the base pipe to either side of the repair had begun to plastically deform and reached a maximum axial strain of 4,700 to 4,800 microstrain before failure in the corrosion defect. It should be noted that the base pipe axial strains in Figure 5-14 are the average of the four strain gages installed per side. Manufacturer B's sample had three operable axial gages in the corrosion defect that indicated a significant increase in strain after an applied load of 350 kips. A maximum axial strain of 559 microstrain was measured on the outer layer of the composite. This is not insubstantial for Manufacturer B's carbon fiber repair and indicates that load was being transferred throughout the composite.

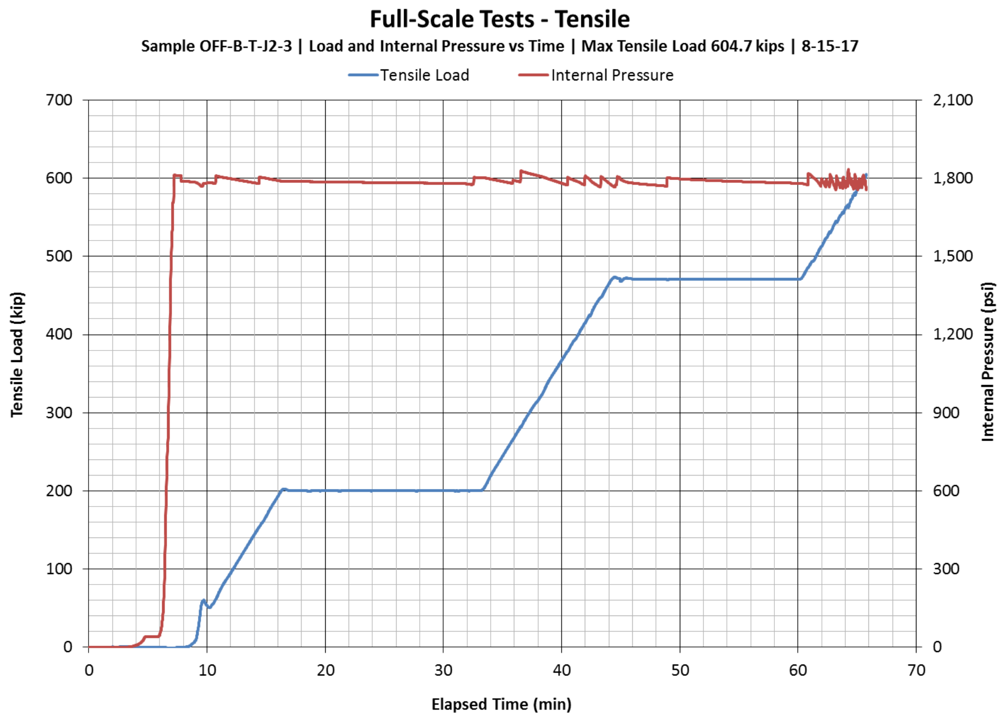

Figure 5-13: Load and internal pressure vs. elapsed time for Manufacturer B's tensile sample (OFF-B-T-J2-3)

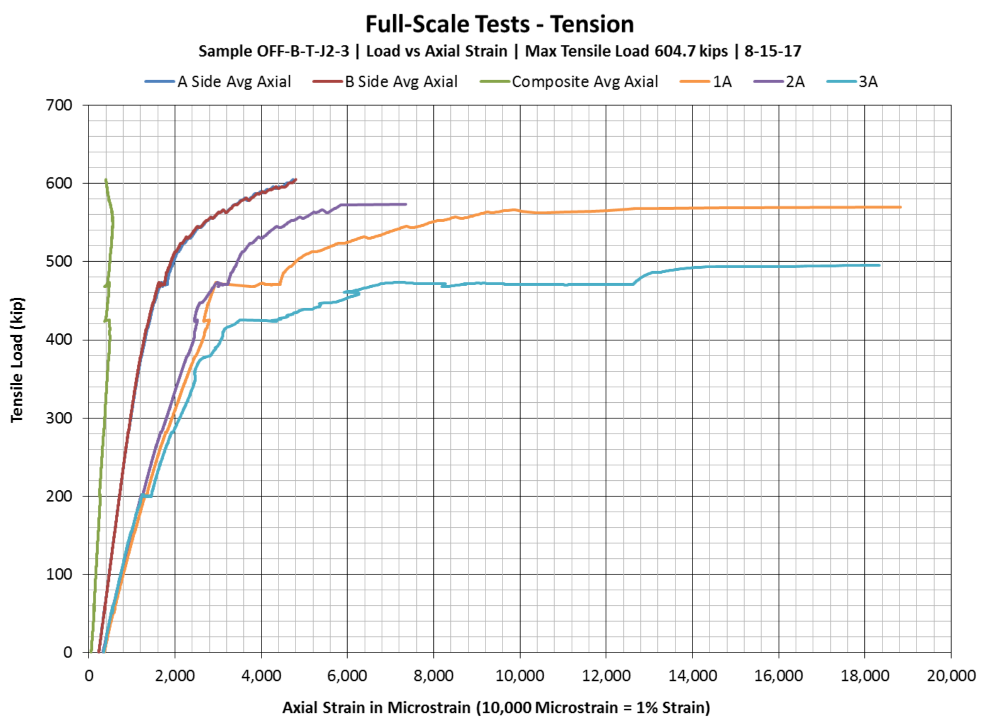

Figure 5-14: Tensile load vs axial strain for Manufacturer B's tensile sample (OFF-B-T-J2-3)

5.3.3 Manufacturer C's Tension Sample

Manufacturer C's sample reached a maximum applied tensile load of 620.0 kips as shown in Figure 5-15 before failure. The failure occurred before the five minute hold at 620 kips began. The sample was no longer able to maintain pressure at this load and a leak path developed from the corrosion defect to the edge of the repair. Post-test examination of the repair revealed cracks near the edge of the repair as shown in Figure 5-17.

The strain measurements in Figure 5-16 indicate plastic deformation in the base pipe on both sides of the repair which reached nearly 8,000 microstrain in the axial orientation before the failure. Manufacturer C's sample also had three operable axial strain gages in the corrosion defect at the start of the test. Gage 3A reached a maximum axial strain of 9,000 microstrain at an applied load of just over 510 kip before the gage failed. The axial strain on the surface of the composite remained near zero during the test.

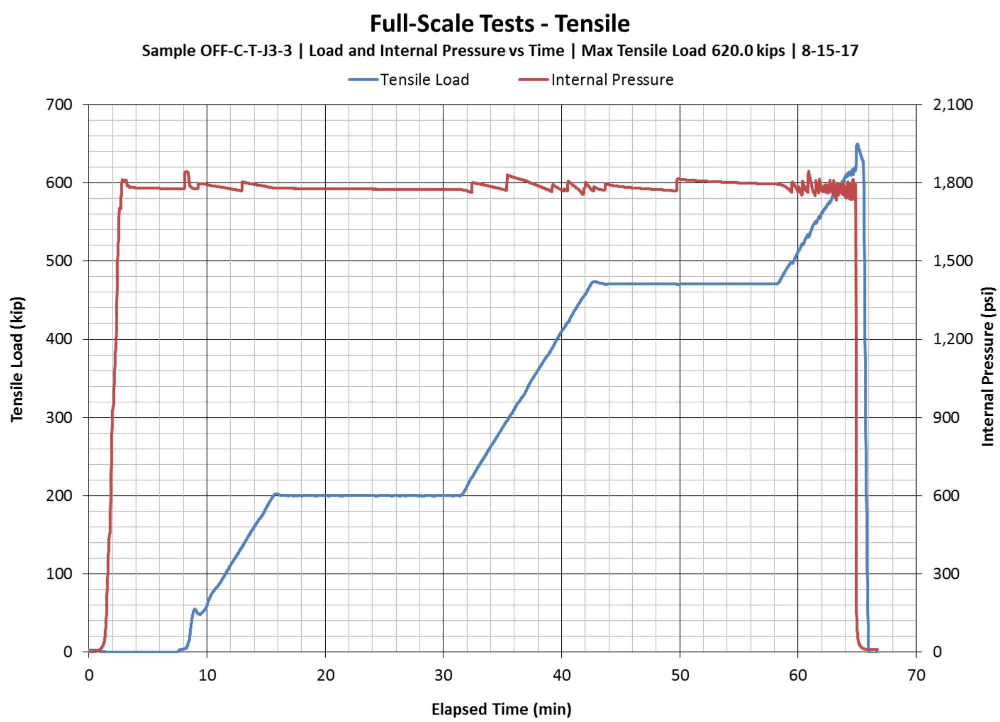

Figure 5-15: Load and internal pressure vs. elapsed time for Manufacturer C's tensile sample (OFF-C-T-J3-3)

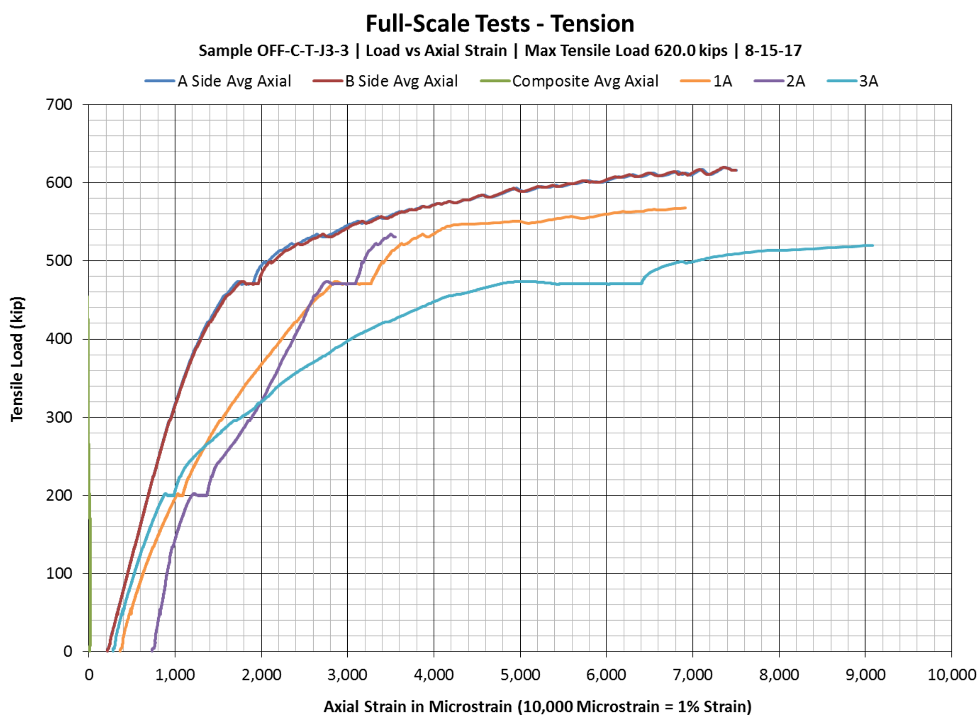

Figure 5-16: Tensile load vs axial strain for Manufacturer C's tensile sample (OFF-C-T-J3-3)

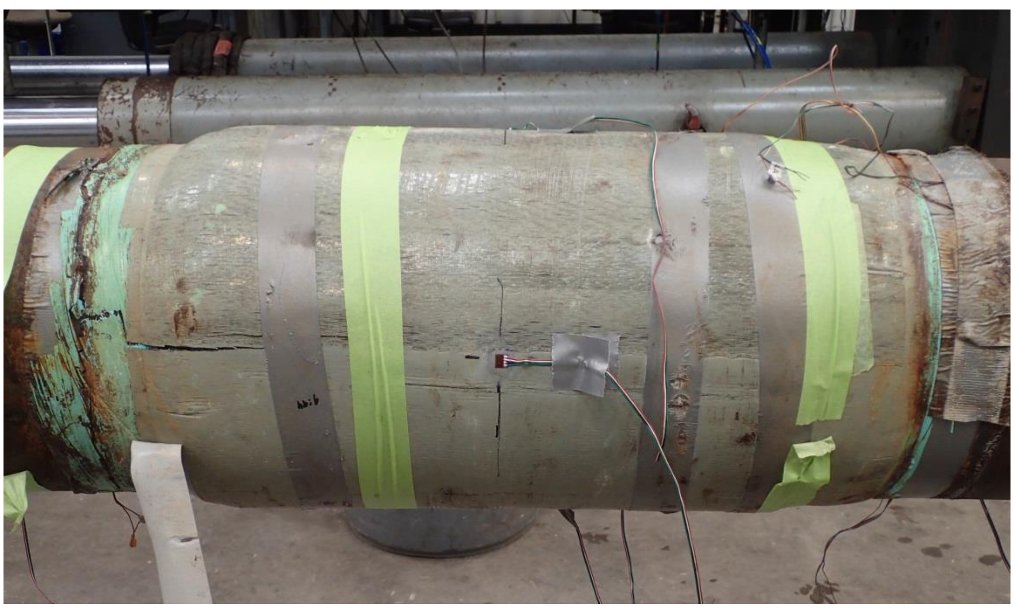

Figure 5-17: Manufacturer C's tensile sample (OFF-C-T-J3-3) post test with cracks near edges

5.3.4 Manufacturer C's Delamination Sample

Manufacturer C's delamination sample (OFF-C-DL-J3-5) was the only delamination sample to survive the exposure tests. As previously discussed in Section 3.2, several artificial delaminations were introduced into the sample to simulate improper or poor installation techniques. Four layers of high temperature

Teflon tape were placed between the steel substrate and first layer of the composite every 90°. These delaminations covered approximate 60% of the pipe surface.

The test results in Figure 5-18 indicate that the delaminations had little effect on the repair's tensile test performance. Manufacturer C's delamination sample reached a maximum applied tensile load of 635.0 kips, which was slightly higher than the previous Manufacturer C tensile sample with no delaminations. The drop in load in Figure 5-18 was to repair a leak in a pressure line and does not represent a failure of the sample. Similar to the previous tests, failure occurred when a leak path developed in the simulated corrosion region under the composite repair.

Axial strain measurements in Figure 5-19 indicate the base pipe in this sample reached nearly 10,000 microstrain before failure. The one operable axial strain gage in the corrosion defect reached over 8,000 microstrain before it became inoperable at an applied load of 490 kips. Similar to the previous Manufacturer C tension sample, there was little to no increase in axial strain on the outer surface of the repair. This Manufacturer C repair also exhibited cracks in the repair post-test as shown in Figure 5-20.

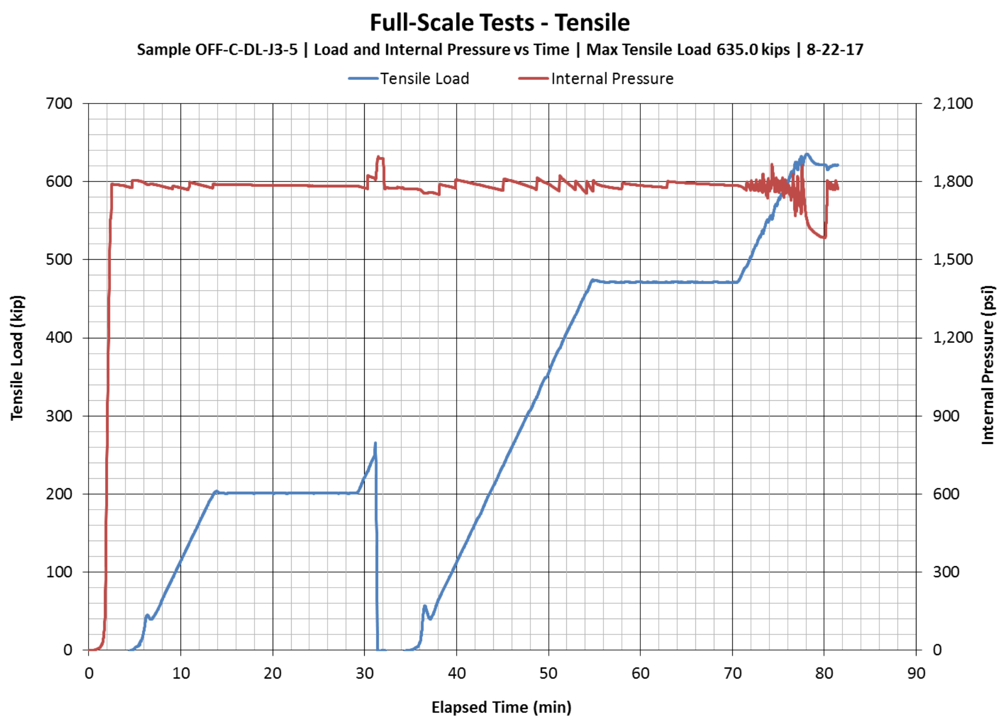

Figure 5-18: Load and internal pressure vs. elapsed time for Manufacturer C's delamination sample (OFF-C-DL-J3-5)

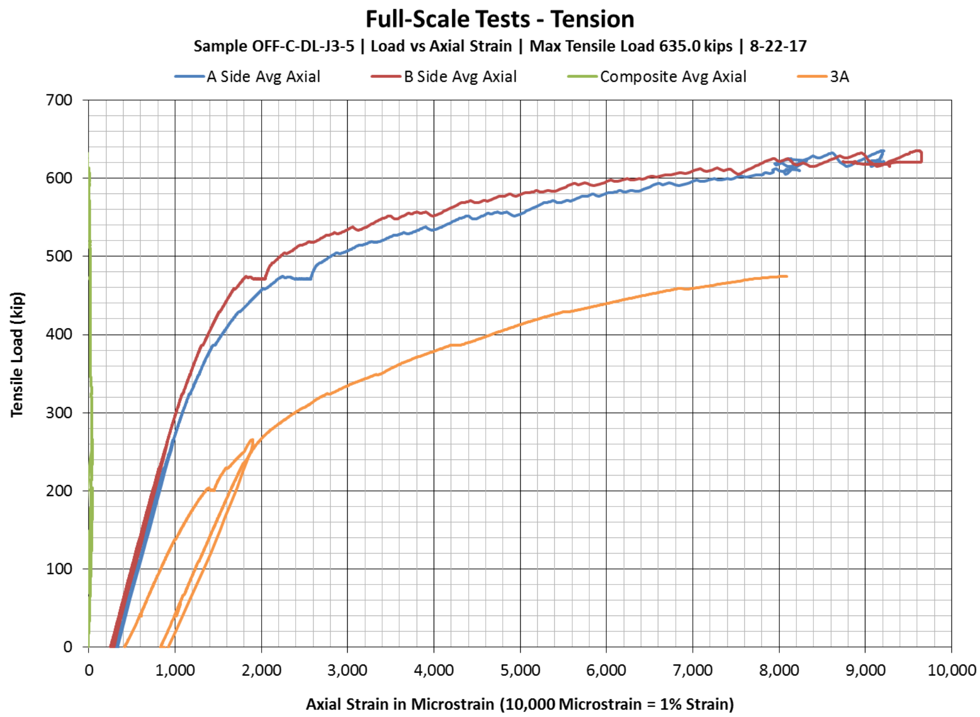

Figure 5-19: Tensile load vs axial strain for Manufacturer C's delamination sample (OFF-C-DL-J3-3)

Figure 5-20: Manufacturer C's delamination sample (OFF-C-DL-J3-5) post test with large crack in composite repair

5.3.5 Tensile Test Summary

The tensile test results indicated that the composite repairs successfully reinforced the corrosion defect in tensile loading after surviving the exposure tests. Table 5-3 summarizes the maximum tensile load for each sample; showing the frame load at the time of failure. Axial strain results showed that the base pipe of each sample plastically deformed before failure occurred in the corrosion defect. Interestingly, Manufacturer C's delamination sample reached the highest tensile load even with the introduction of artificial delaminations in the repair.

Table 5-3: Tensile and Delamination Testing Results Summary (Frame Load at Failure Only)

Sample	Maximum Tensile Load (kip)
Manufacturer B - Tension	604.7
Manufacturer C - Tension	620.0
Manufacturer C - Delamination	635.0

Table 5-4: Tensile and Delamination Testing Results Summary (PEL Included)

Sample	Maximum Tensile Load (kip)
Manufacturer B - Tension	806.0
Manufacturer C - Tension	821.3
Manufacturer C - Delamination	836.3

5.4 Bending Tests

Bending samples from all three manufactures survived the exposure tests and completed full-scale testing. A list of the samples with their designations is provided below. The following sections detail the additional instrumentation for the bend samples, the bend test procedure, and results for the bend tests.

- Manufacturer A – Sample Number OFF-A-BE-J2-4
- Manufacturer B – Sample Number OFF-B-BE-J2-4
- Manufacturer C – Sample Number OFF-C-BE-J1-4

5.4.1 Bend Test Instrumentation and Procedure

In preparation for the bend tests, the endcaps from exposure testing were removed and 7.5-foot pup extensions added to each end of the sample. The additional length was required for the four-point bend fixture. Six (6) additional bi-axial strain gages were installed on each sample in the below locations. These were monitored in addition to the weldable gages that survived exposure testing (see Section 3.1).

- Two biaxial strain gages to either side of the composite repair at 0° and 180° and 6-inches from the pup extension weld (4 total).

- Two biaxial strain gages installed on the surface of the composite at 0° and 180°.

Seven displacement transducers were installed along the length of the sample to measure the sample curvature during the tests. Figure 5-21 illustrates the additional instrumentation and dimensions for the bend test. Two calibrated, 200-kip hydraulic cylinders applied the forces for the four-point bending. Calibration certificates for the hydraulic cylinders, pressure transducers, and displacement transducers are provided in Appendix F. An example of the final test setup is shown below in Figure 5-22 (Manufacturer A's bend sample).

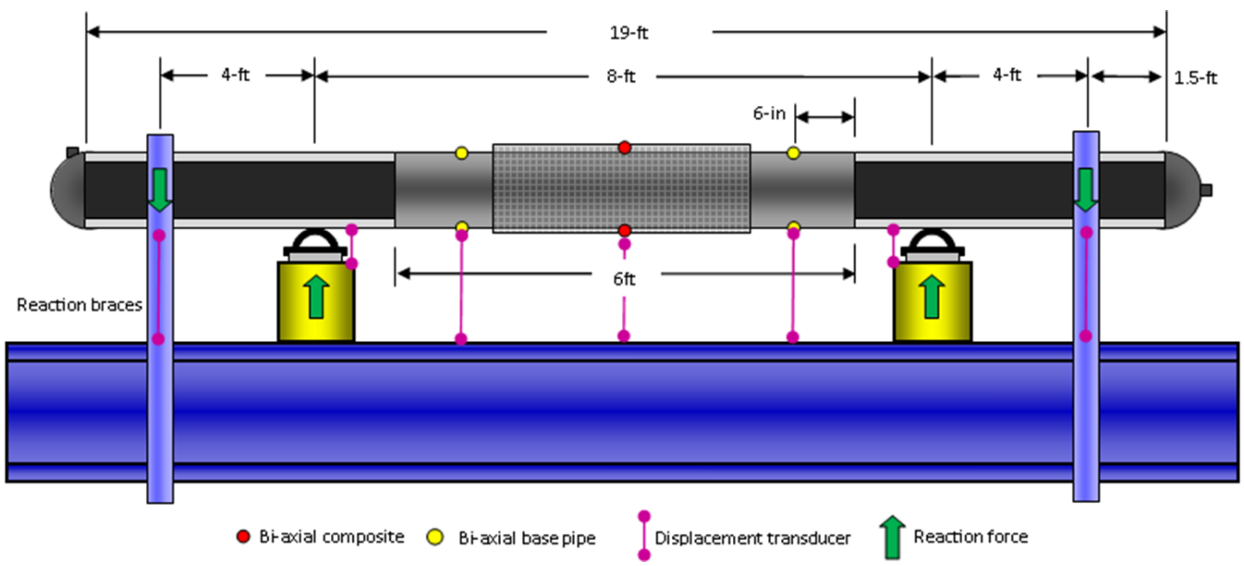

Figure 5-21: Bend frame instrumentation and spacing

Figure 5-22: Manufacturer A's bending sample (OFF-A-BE-J2-4) installed in four-point load frame pre-test

The bend test took place in two phases in order to test the corrosion defect in both tension and compression. SES's four-point bend fixture places samples into negative curvature with 0° (top of sample) in tension and 180° (bottom of sample) in compression. The bend samples started the first phase of the test with the corrosion defect in tension. After the sample was loaded to the predicted yield of the base pipe, the bending moment was removed and the sample rotated 180°. The test was completed by increasing the bending moment until the sample failed. The specifics of the procedure were as follows:

1. Placed sample in four-point bend frame with corrosion defect at 0° (in tension during bending).
2. Pressurized sample to 1,780 psi (72% SMYS).
    a. Maintained pressure between 1,770 and 1,790 psi through test.
3. Increased bending moment to 125 ft·kips (corrosion in tension)
    a. If internal corrosion reached 10,000 με, held for 5 minutes and then continued.
4. Held for 15 minutes.
5. Reduced moment and pressure to 0 ft·kips and 0 psi, respectively.
6. Rotated sample 180° (placed defect in compression during bending).
7. Pressurized sample to 1,780 psi (72% SMYS).
    b. Maintained pressure between 1,770 and 1,790 psi through test.
8. Increased bending moment to 125 ft·kips or (corrosion in compression).
    c. Monitored corrosion strains, if internal corrosion reached 10,000 με, held for 5 minutes and then continued.
9. Held for 15 minutes.
10. Continued to increase bending moment until loss of internal pressure or gross plastic deformation.

5.4.2 Manufacturer A's Bending Sample

Manufacturer A's bending sample survived the first phase of testing to a maximum bending moment of 125 ft·kips with the defect in tension as shown in Figure 5-23. The axial strains in the base pipe and corrosion defect were similar to those observed in Manufacturer B and C's samples (Figure 5-24). After the sample was rotated to place the corrosion defect in compression, the sample failed at a bending moment of 264.6 ft·kips (Figure 5-25). The base pipe axial strains in Figure 5-26 for Manufacturer A's sample were slightly lower than the other bending samples at just over 5,000 microstrain (0.5% strain).

Similar to Manufacturer C's sample, failure occurred at the corrosion defect which ruptured through the composite repair as pictured in Figure 5-5-27.

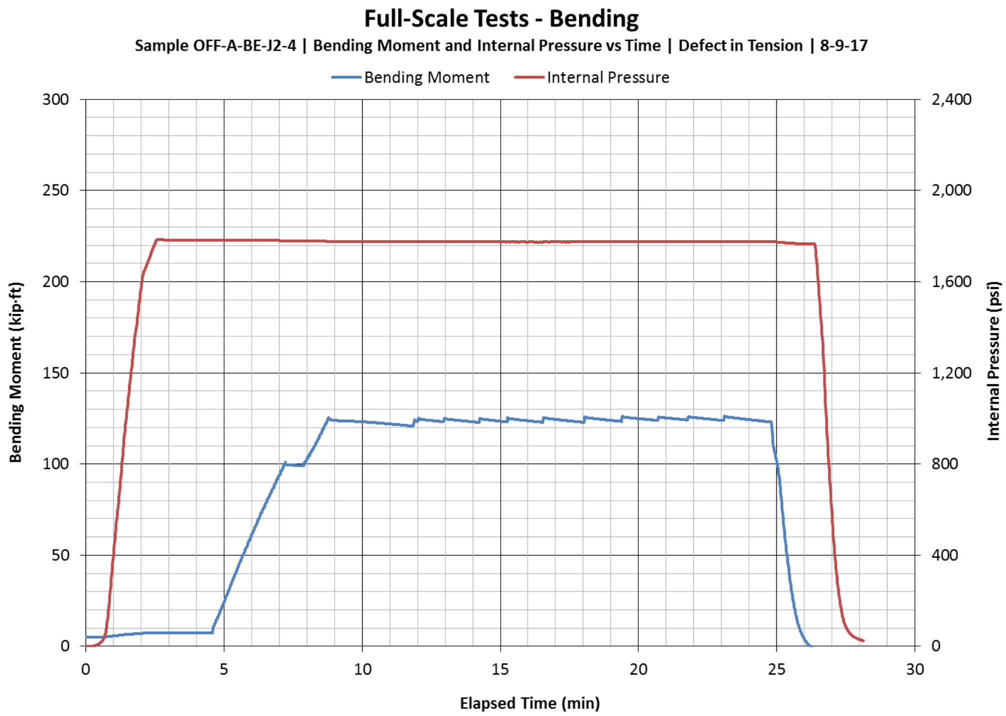

Figure 5-23: Manufacturer A's bending sample (OFF-A-BE-J2-4) moment and internal pressure vs. elapsed time with corrosion defect in tension

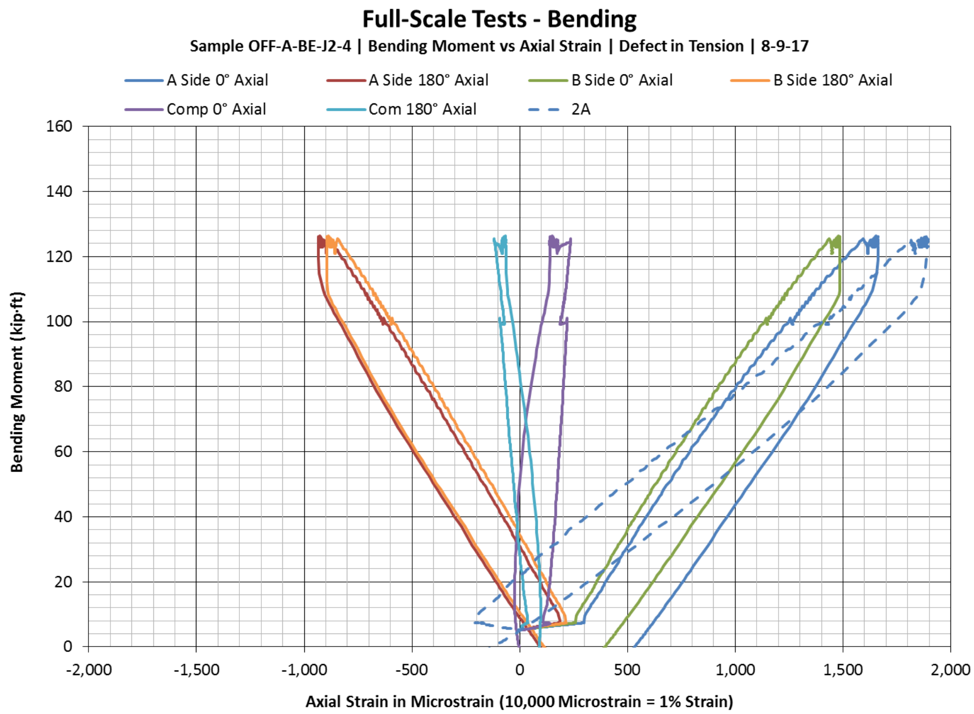

Figure 5-24: Manufacturer A's bending sample (OFF-A-BE-J2-4) moment vs. axial strain with corrosion defect in tension

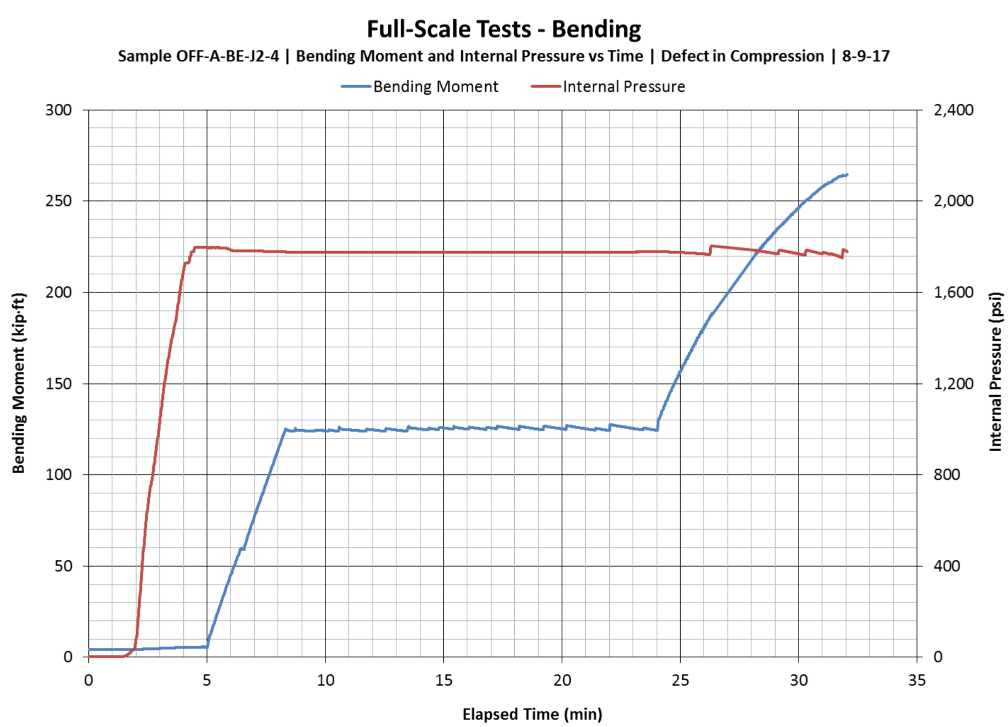

Figure 5-25: Manufacturer A's bending sample (OFF-A-BE-J2-4) moment and internal pressure vs. elapsed time with corrosion defect in compression

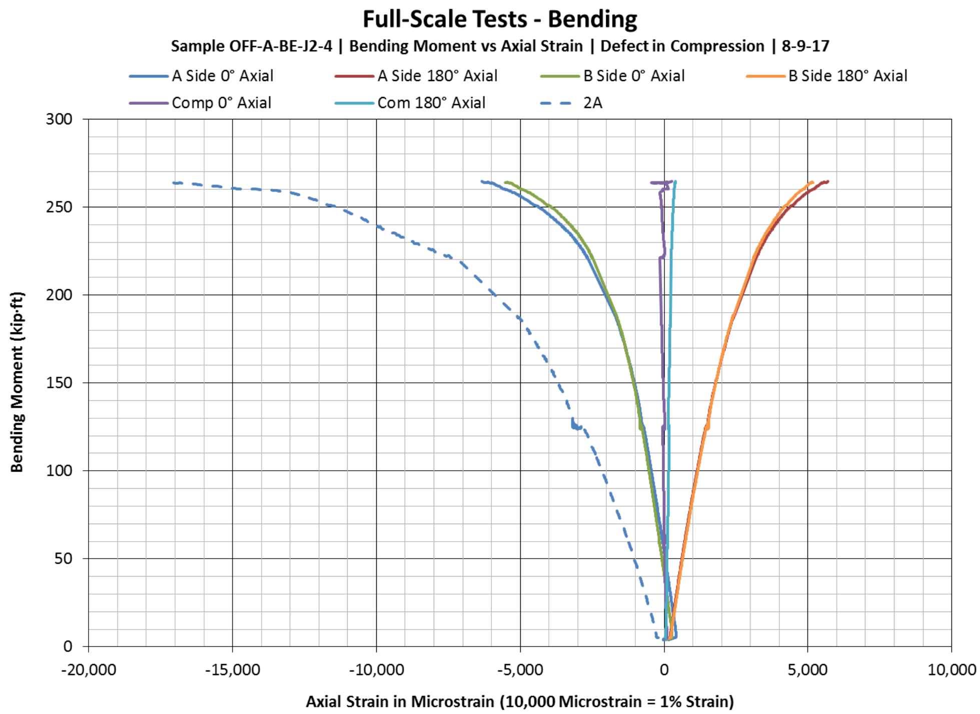

Figure 5-26: Manufacturer A's bending sample (OFF-A-BE-J2-4) moment vs. axial strain with corrosion defect in compression

Figure 5-5-27: Failure at the corrosion defect in Manufacturer A's bending sample (OFF-A-BE-J1-4)

5.4.3 Manufacturer B's Bending Sample

Manufacturer B's bending sample completed the first phase the bend test without failure (defect in tension) as shown in Figure 5-28. The bending moment and internal pressure both remained stable during the 15 minute pressure hold. Figure 5-29 indicates the maximum axial strains in the base pipe were under 1,500 microstrain at 125ft·kips. Figure 5-29 does not include any of the weldable strain gages installed under the composite repair as none survived the exposure testing. After the bending moment was removed, Manufacturer B's sample was rotated so the corrosion defect was in compressed.

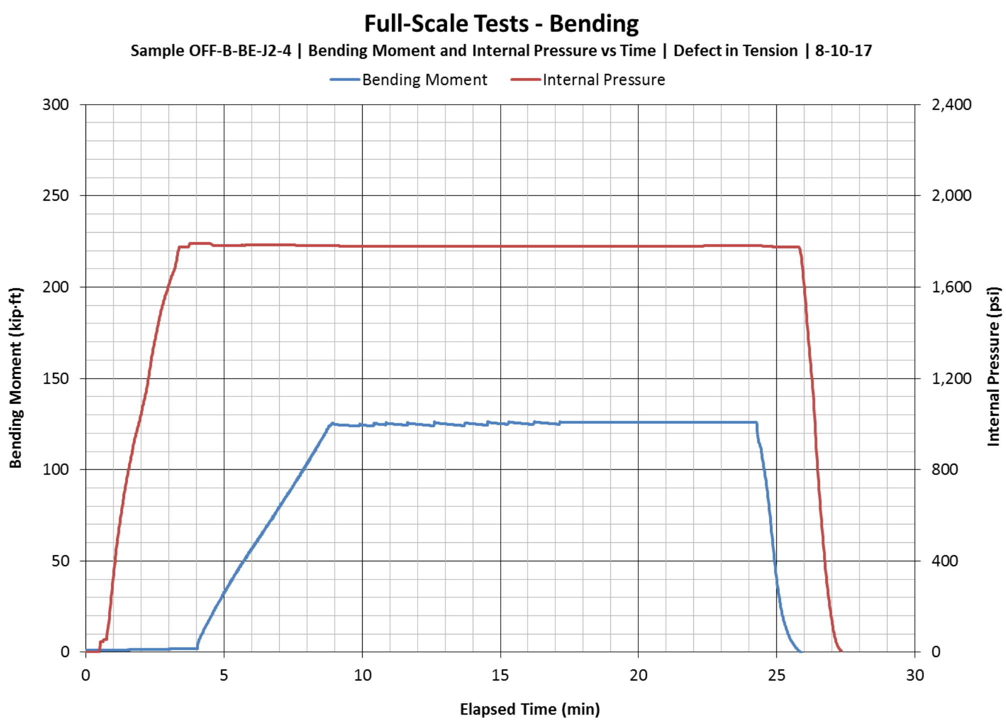

Figure 5-28: Manufacturer B's bending sample (OFF-B-BE-J2-4) moment and internal pressure vs. elapsed time with corrosion defect in tension

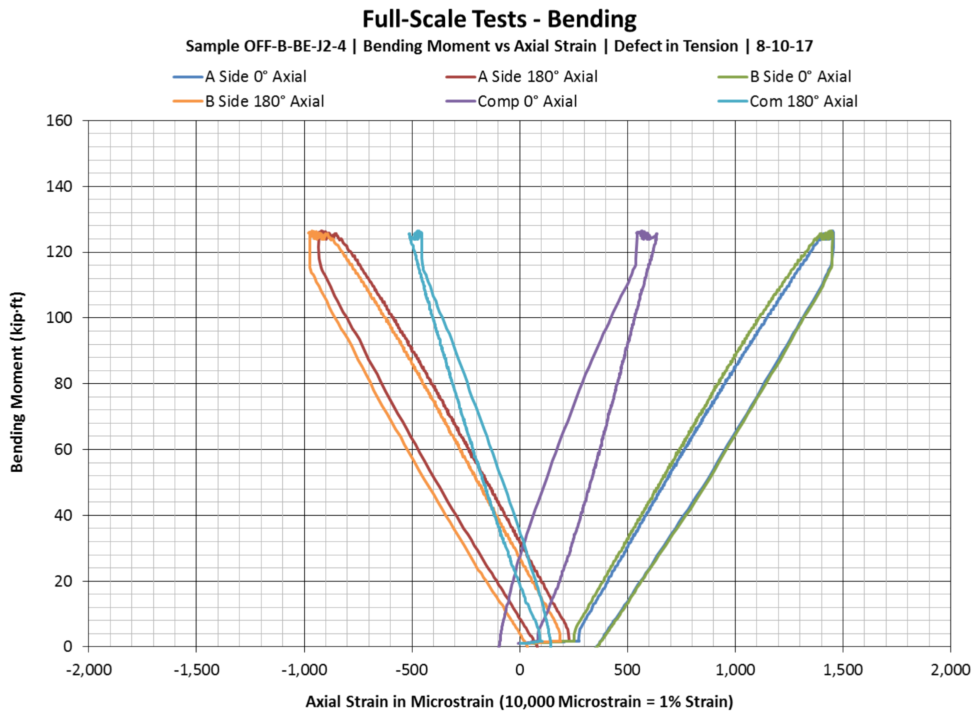

Figure 5-29: Manufacturer B's bending sample (OFF-B-BE-J2-4) moment vs. axial strain with corrosion defect in tension

Manufacturer B's sample failed at a bending moment of 262.4 kip·ft with the defect in compression as shown in Figure 5-30. Beyond a load of 175 ft·kips, the internal pressure was difficult to maintain due to deformation in the base pipe. This deformation is confirmed by the base pipe axial strains in Figure 5-31 (note the 0° location is now in compression since the sample was rotated). The maximum axial strain in the composite was 1,230 microstrain (0.12% strain). The maximum axial strain in the base pipe was approximately 11,900 (1.19% strain) at the time of failure. Failure occurred by a loss of internal pressure when a leak path developed from the corrosion defect to the edge of the repair. Figure 5-32 is Manufacturer B's sample post-test after the bending moment was removed. The sample experienced permanent deformation and exhibited a visible curvature following the bend test.

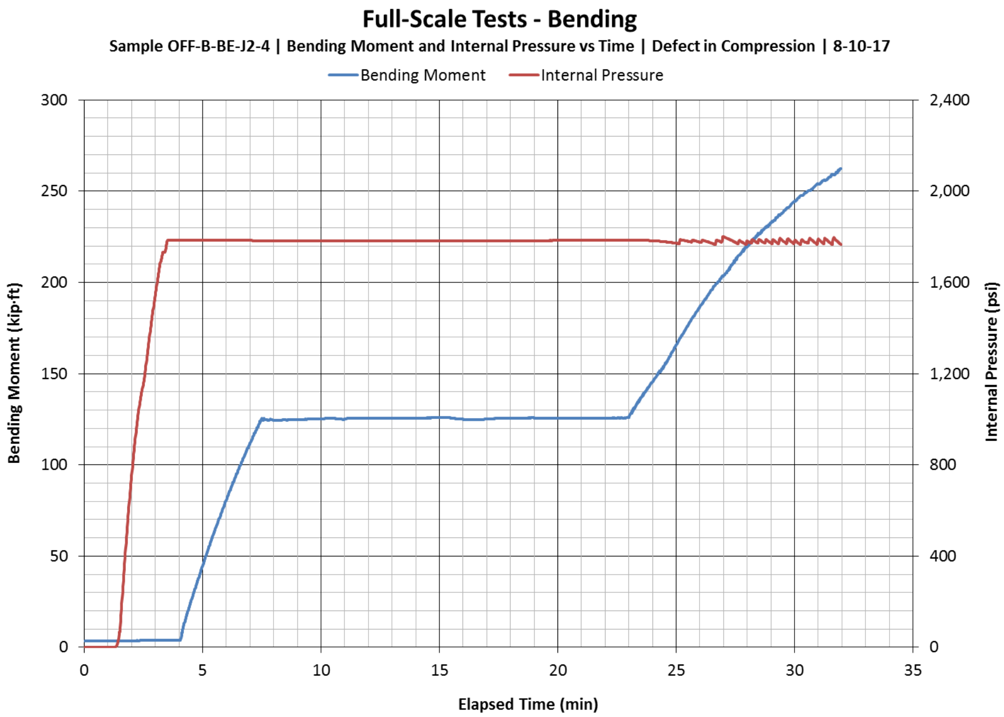

Figure 5-30: Manufacturer B's bending sample (OFF-B-BE-J2-4) moment and internal pressure vs. elapsed time with corrosion defect in compression

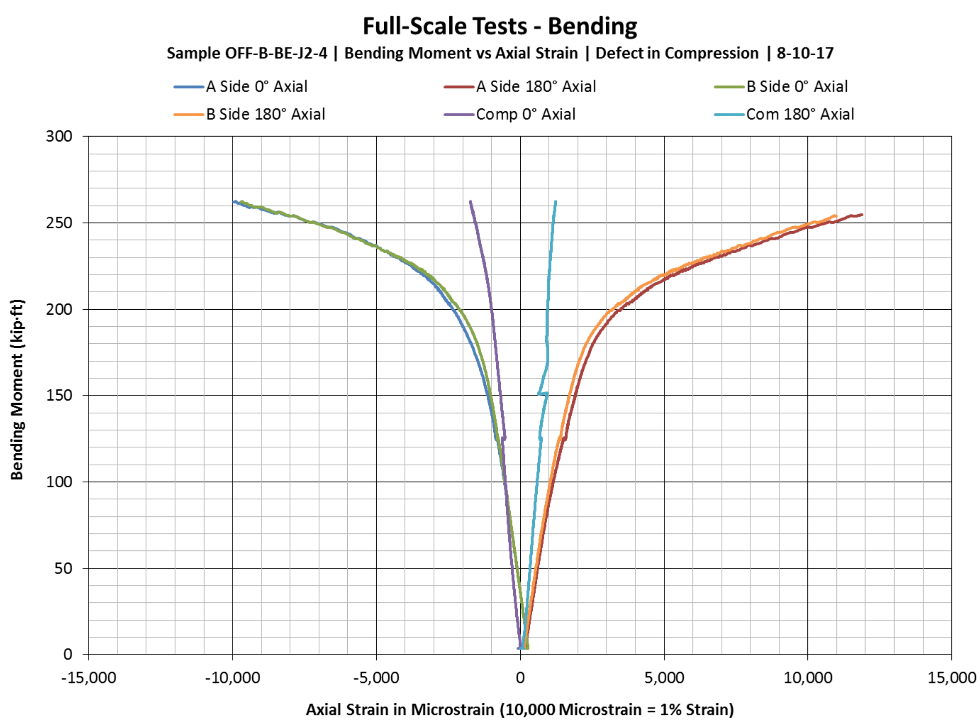

Figure 5-31: Manufacturer B's bending sample (OFF-B-BE-J2-4) moment vs. axial strain with corrosion defect in compression

Figure 5-32: Permanent shape of Manufacturer B's bending sample (OFF-B-BE-J2-4) post-test (no bending load applied to sample at time of photograph)

5.4.4 Manufacturer C's Bending Sample

Manufacturer C's sample also successfully completed the first phase of the bend test with the defect in tension. Figure 5-33 displays the bending moment and internal pressure vs. elapsed time for this phase of the test. The base pipe axial strains in Figure 5-34 are similar to those observed in Manufacturer B's sample. Three weldable axial strain gages in the corrosion defect were still functioning after the exposure tests and are included in Figure 5-34. The 3A axial gage in the corrosion defect recorded the highest defect axial strain of 3,100 microstrain during the bend test. After completing the first phase of the bend test with the corrosion defect in tension, the sample was rotated 180° to place the defect in compression for the second phase of the test.

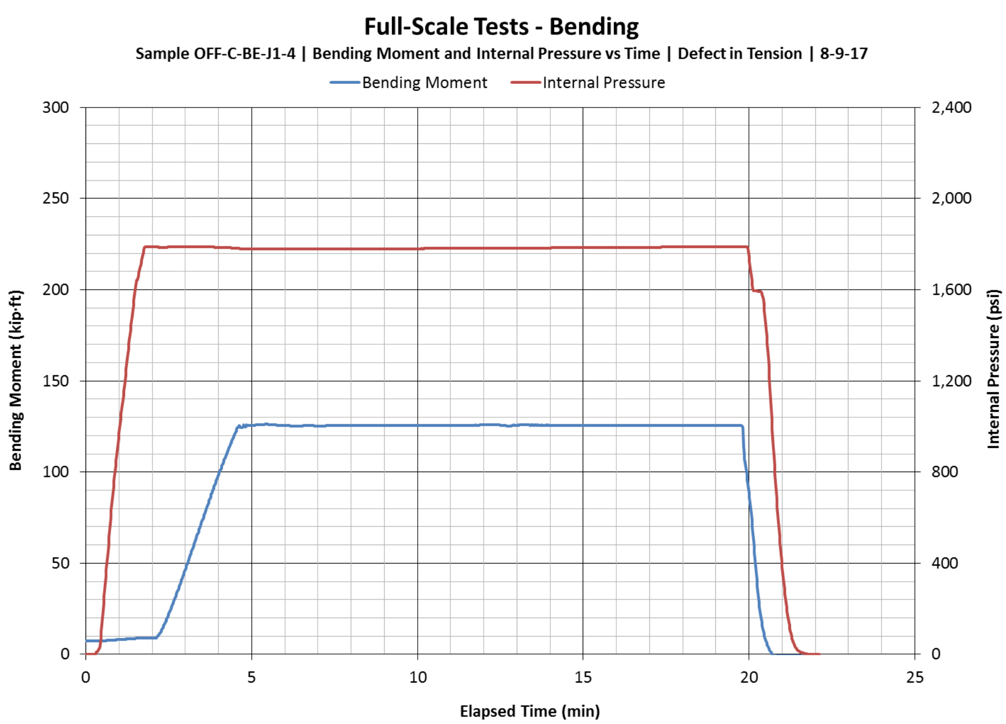

Figure 5-33: Manufacturer C's bending sample (OFF-C-BE-J1-4) moment and internal pressure vs. elapsed time with corrosion defect in tension

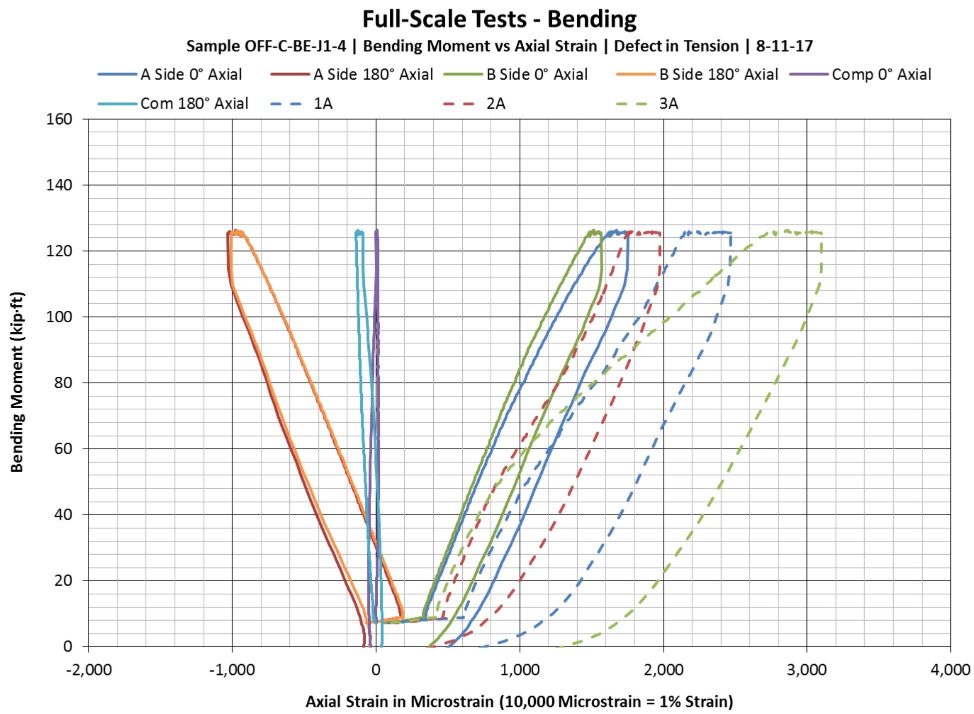

Figure 5-34: Manufacturer C's bending sample (OFF-C-BE-J1-4) moment vs. axial strain with corrosion defect in tension

With the corrosion in compression, Manufacturer C's sample reached a bending moment of 278.4 kip·ft as shown in Figure 5-35 before failure occurred at the corrosion defect. Similar to Manufacturer B's sample, the sample began to deform near the end of the test and it became difficult to maintain the internal pressure. Figure 5-36 indicates that the axial strains in the base pipe ranged from 10,000 to 20,000 microstrain (1% to 2% strain) prior to failure. The strains on the outer surface of the composite repair during the test were low (under 300 microstrain) which indicates the majority of the load was carried by the inner layers of the repair. The permanent shape of Manufacturer C's sample after failure and removal the bending moment is shown in Figure 5-37. Unlike Manufacturer B's sample that developed a leak at the edge of the repair at failure, the corrosion defect in Manufacturer C's sample ruptured through the composite as illustrated in Figure 5-38.

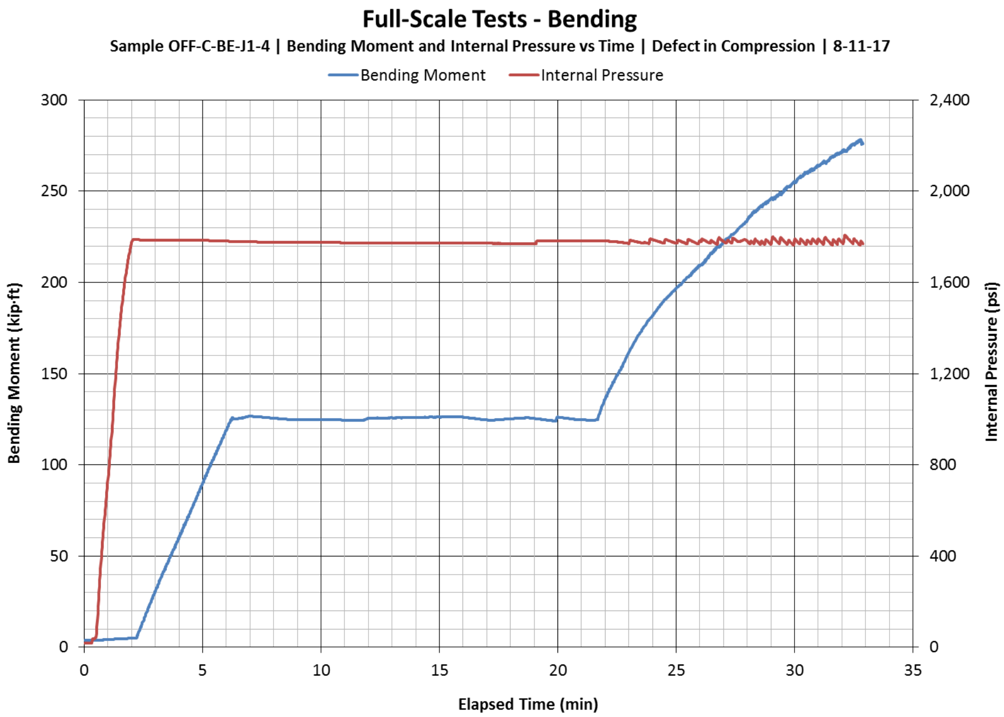

Figure 5-35: Manufacturer C's bending sample (OFF-C-BE-J1-4) moment and internal pressure vs. elapsed time with corrosion defect in compression

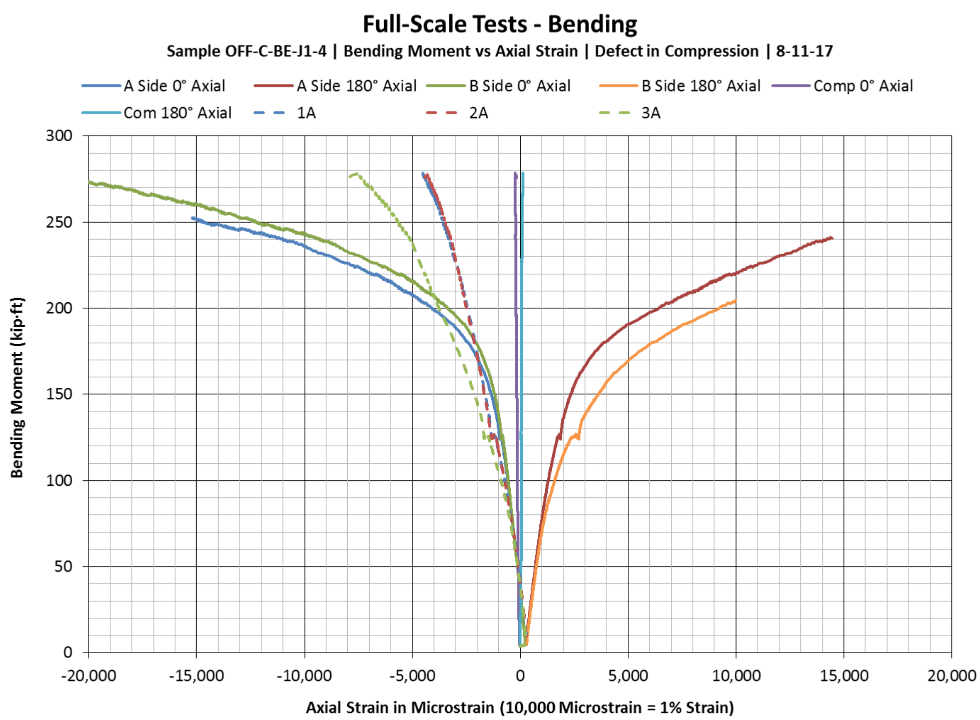

Figure 5-36: Manufacturer C's bending sample (OFF-C-BE-J1-4) moment vs. axial strain with corrosion defect in compression

Figure 5-37: Permanent shape of Manufacturer C's bending sample (OFF-C-BE-J1-4) post-test (no bending load applied to sample at time of photograph)

Figure 5-38: Failure at the corrosion defect in Manufacturer C's bending sample (OFF-C-BE-J1-4)

5.4.5 Bending Test Summary

The four-point bend test was the only full-scale test to include a sample from each manufacturer. Table 5-5 summarizes the maximum bending moments from the three samples. It is clear that all three reached a similar maximum value (corrosion defect in compression). All three samples experienced permanent deformation of the base pipe surrounding the repair before failure of the repair itself. The results indicate that the composite repairs were successful in reinforcing the simulated 75% wall loss corrosion defect in both tensile and compressive loadings.

Table 5-5: Bending testing results summary

Sample	Maximum Bending Moment (kip·ft)
Manufacturer A	264.6
Manufacturer B	262.4
Manufacturer C	278.4

6. Findings and Conclusions

The exposure and full-scale testing phases of the offshore composite repair study produced a significant amount of information on the performance of composite repairs in simulated offshore conditions. Three manufacturers participated in both the exposure and full-scale phases of the study and produced results that can be divided into two categories; those that are manufacturer specific and those that can be applied more generally to the use of composite repairs for offshore applications. The sections below discuss these findings, highlight manufacturer specific and general composite conclusions from the study, and offer brief recommendations for future work.

6.1 Manufacturer Specific Discussion

The results of the offshore study highlight the unique aspects of each composite repair manufacturer and show that variations in performance exist. Many of these differences can likely be attributed to the individual design of the composite repairs and proprietary materials used. This means qualification of individual composite repair systems needs to be completed by manufacturers before they can confidently be approved as offshore structural reinforcements. Conclusions for each manufacturer are provided below.

6.1.1 Discussion of Manufacturer A's results

All five of Manufacturer A's samples completed the 10,000-hr pressure hold in simulated subsea conditions. The samples also completed the 90 day UV exposure and thermal cycling with no obvious degradation to the composite repairs. Differences in performance from the other composite repairs began to appear during the pre-cycling exposure test. The earliest Manufacturer A failure occurred at a cycle count of just over 3,500 pressure cycles. This was significantly lower than the next closest failure for the other manufacturers, which occurred at over 42,000 cycles. Following the initial failure, Manufacturer A repairs failed at cycle counts ranging from approximately 17,000 cycles to over 31,000 cycles. One sample (bending) achieved its designated runout target of 25,000 cycles.

Following pre-cycling, the Manufacturer A sample that was subjected to full-scale bend testing performed similarly to samples from the other manufacturers and achieved the second highest maximum bending moment (264.6 kip-ft). The sample maintained an internal pressure of 1,780 psi throughout the bend test which indicates that sufficient reinforcement was being provided by the composite in the hoop direction. The sample also provided axial reinforcement, as the ultimate failure was near the expected failure of nominal base pipe with no simulated corrosion.

A summary of the conclusions are below:

- Four out of five repairs failed during the pre-cycling portion of the exposure testing phase.
- No obvious signs of degradation or damage to the composite were observed following the 10,000 hour pressure hold.

- The sample that survived pre-cycling and was full-scale tested achieved the second highest maximum moment during bend testing.
- The performance of the repairs points to a failure mechanism related to an epoxy/resin used by Manufacturer A or installation techniques while performing the repairs.
- Despite the pressure cycling failures during the exposure test, all pre-cycling results were significant improvements from the unreinforced sample.

6.1.2 Discussion of Manufacturer B's results

All five of Manufacturer B's samples completed the 10,000hr pressure hold in simulated subsea conditions. The samples also completed the 90 day UV exposure and thermal cycling with no obvious degradation to the composite repairs. Four of the five Manufacturer B samples were able to complete the pre-cycling exposure testing. The only Manufacturer B failure during pre-cycling (delamination) occurred at a cycle count of just over 42,000 pressure cycles. Following the completion of pre-cycling, the surviving four Manufacturer B samples completed full-scale bending, tension, burst, and fatigue testing.

The Manufacturer B burst sample had the highest failure pressure (4,037 psi) of the samples tested and ruptured in the base pipe outside of the simulated corrosion region. The fatigue sample completed over 130,000 pressure cycles (including the 50,000 pre-cycles) prior to failure. These results are a significant improvement upon the unreinforced samples which failed at a pressure of 1,681 psi during burst testing and did not complete one cycle during fatigue testing. The performance of the Manufacturer B samples show that sufficient hoop reinforcement was provided by the Manufacturer B repairs.

Strain gage results from the tension sample do not point to significant reinforcement being provided by the composite repair. Axial strains in the simulated corrosion region are consistently greater than those recorded in the base pipe outside the repair. This is not necessarily an indication of damage due to exposure testing, but could reflect the design of the composite repair itself. Achieving the test pressure of 72% SMYS shows that adequate reinforcement was provided in the hoop direction, but the tension test requires substantial reinforcement in the axial direction. Although it appears that the composite is not providing a significant amount of reinforcement, it is clear that there is load transfer to the composite due to the correlation between composite axial strain and increasing axial load during testing (Figure 6-2).

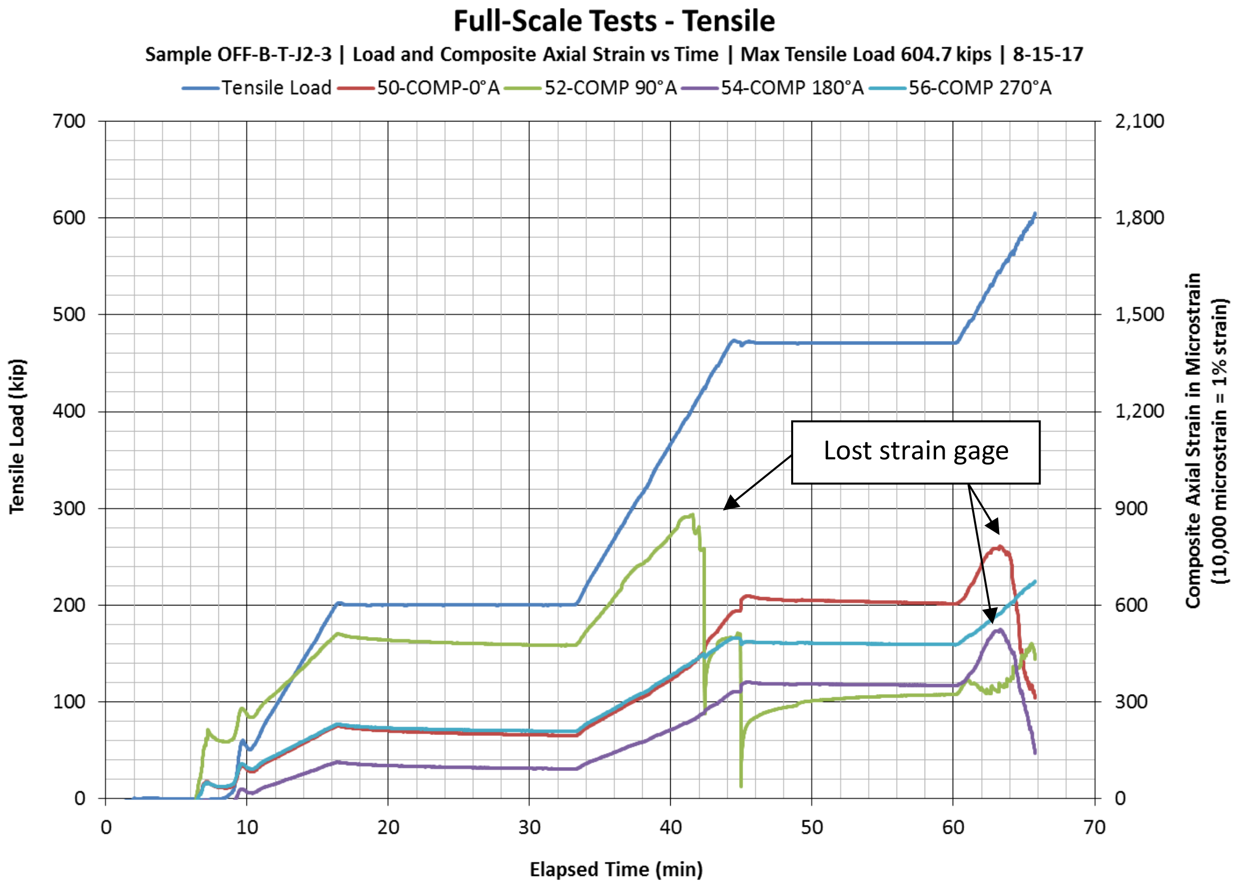

Figure 6-1: Plot of axial load and composite axial strain vs elapsed time during tension test

The bend test results show that the composite provided reinforcement to the simulated corrosion defect following completion of the exposure testing. The composite repair reinforced the simulated corrosion region such that it achieved bending moments near what would be expected of the nominal base pipe. Failure in the simulated corrosion region occurred following significant deformation of the base pipe outside of the repair.

A summary of the conclusions are below:

- Four out of five repairs survived exposure testing. The only sample that did not survive was the intentional delamination sample.
- No obvious signs of degradation or damage to the composite were observed following the 10,000 hour pressure hold.
- Manufacturer B's full-scale bend testing results indicate that reinforcement was being provided to the simulated corrosion region even after the exposure tests had been completed.

- The results of fatigue and burst testing showed significant improvement from those observed during unreinforced testing.

6.1.3 Discussion of Manufacturer C's results

The results of Manufacturer C's testing were very similar to Manufacturer B's samples. All five of Manufacturer C's samples completed the 10,000-hr pressure hold in simulated subsea conditions as well as the 90 day UV exposure and thermal cycling with no obvious degradation to the composite repairs. All five Manufacturer C samples were also completed the pre-cycling exposure testing. Following the completion of pre-cycling, the surviving five Manufacturer C samples completed full-scale bending, tension (including delamination sample), burst, and fatigue testing.

Manufacturer C's burst sample failed at a pressure of 3,615 psi in the simulated corrosion region underneath the repair. The fatigue sample was able to achieve the runout target of 250,000 pressure cycles (including the 50,000 pre-cycles) without failing. Similar to Manufacturer B's full-scale testing, the strain gage results from the tension sample do not point to significant reinforcement being provided by the composite repair. Axial strains in the simulated corrosion region are consistently greater than those recorded in the base pipe outside of the repair. Again, this is not necessarily an indication of damage due to exposure testing, but could reflect the design of the composite repair itself. Like Manufacturer B's tension sample, achieving the test pressure of 72% SMYS shows that adequate reinforcement was provided in the hoop direction. Of note with the Manufacturer C's samples is the higher failure load for the delamination sample than the designated tension sample. This could be another indication that the failure load is driven more by the ultimate capacity of the pipe sample with the simulated corrosion defect and is not being significantly increased by the composite reinforcement.

Manufacturer C's bend test sample was able to achieve the highest maximum failure load of all samples tested (278.4 kips). Although failure of the bend sample consisted of rupture in the simulated corrosion region, this only occurred after significant deformation of the base pipe outside of the repair. Like Manufacturer A and C samples, failure occurred at a maximum load near what would be expected of the nominal base pipe.

- All five samples survived exposure testing, including the intentional delamination sample.
- Manufacturer C's fatigue sample achieved the runout condition of 250,000 cycles at a cyclic pressure range of 36 – 72% SMYS.
- The delamination sample had the highest failure load during tension testing when compared to the other samples.
- Manufacturer C's bend sample achieved the highest maximum bend load of the samples tested.
- Failures tended to occur in the composite repair.

6.2 Observations on the Use of Composite Repairs for Offshore Applications

In addition to the manufacturer specific conclusions discussed in the previous section, there are also conclusions from the study that can be applied more generally to the composite repairs tested. These conclusions are discussed in this section.

Although the composite repairs tested in this study displayed a range of results during pre-cycling and full-scale testing, all reinforced samples were able to survive the initial 10,000hr hold period in simulated subsea conditions. Additionally, all samples were able to complete the remaining exposure testing and achieve some number of pre-cycles from 36 – 72% SMYS. This is significant when compared to the performance of an unreinforced sample that had not completed exposure testing. The unreinforced sample was unable to complete a single pressure cycle.

Five of the 15 samples failed during the pre-cycling portion of exposure testing. Of these five samples, four were from the same manufacturer. The fifth sample that failed was the delamination sample from a different manufacture and had intentional defects in the repair.

Full-scale testing showed that all samples tested were able to provide sufficient reinforcement to prevent the simulated corrosion defect from failing at internal pressures equal to 72% SMYS. Additionally, all bend tests reinforced the simulated corrosion defect such that ultimate failure was near that expected of nominal base pipe with no simulated corrosion. This indicates that following a rigorous set of exposure tests, all repairs were able to provide reinforcement to the simulated corrosion defect in the hoop direction and increase the ultimate capacity of the pipe sample. This held true even for the delamination samples that had intentional defects introduced in the repairs.

Although each repair system was able to demonstrate some level of reinforcement following the 10,000hr exposure test, the range of performances indicate that systems should be qualified through exposure testing prior to offshore or subsea use. This could take the form of sub-scale exposure testing of an epoxy / resin and / or installation and should be completed prior to certification for an offshore installation. A sub-scale test could serve as an initial threshold to identify systems that are not suited to extended exposure to a saltwater environment. Installation techniques should also be verified as part of the protocol for offshore / subsea qualification.

An additional objective of the study was to gauge the effectiveness of composite repair inspection technology and assess its readiness level for use as an integrity management tool for composite repair systems. The technologies used in this study demonstrated mixed success in identifying the simulated corrosion defects and anomalies within the composite repairs themselves. The pre-10,000hr hold inspection technology was unable to provide any meaningful inspection results. This was attributed to the thickness of the composite repairs. The post-10,000hr hold technology identified the simulated corrosion regions and anomalies within the repairs. Based on the results of this study, additional verification would be required to confidently use a composite repair inspection technology as part of an integrity management program.

6.3 Future Work and Recommendations

A substantial amount of information was collected during this study on the performance of composite reinforcement systems when subjected to conditions simulating the in-service effects of offshore and subsea environments. Although this study is a good starting point, there continue to be several opportunities remaining for additional investigation. This future work and recommendations section serves to highlight some of these items.

The first recommendation is to use this study as a foundation and continue collecting data on the long-term performance of composite repairs in subsea environments. While 10,000hrs is considered long-term in the realm of laboratory studies, it is likely a fraction of the time many composite repairs will spend in offshore environments experiencing similar conditions tested in this program. Continued investigations into the performance of composite repairs when subjected to multiple years of offshore / subsea conditions will only give further confidence to their suitability for offshore use. This could take the form of additional full-scale tests with increased simulated subsea hold periods or accelerated aging tests that could simulate environmental damage to the composite in a more condensed period of time.

Accelerated aging and environmental compatibility testing should be part of any qualification program used to certify a particular composite repair system for offshore use. This is especially important if the installations will be made underwater, as they were in this study. Qualification testing should focus on the composite formulation that will be used for offshore and subsea applications to verify that no compatibility issues are present.

Additionally, there are several aspects of subsea environments that were not considered in this study, including temperature and external hydrostatic pressure. If repairs are to be installed below the water surface, the installation and operating temperatures could potentially be cooler than the ambient temperature in this study, which would impact curing of the composite repair. An opportunity for future investigation would be determining if immediate loading or pressurization has an impact on the performance of composite repairs installed subsea. The temperature and hydrostatic pressure of the external environment should be taken into account for this type of study.

In the more distant future, it may become necessary to investigate the application of composite repairs remotely; for instance using a remote operated vehicle (ROV) for subsea installations. These installations will likely introduce new complexities and potential for defects that will need to be addressed from a performance standpoint. At least initial thought should be given to how these installations could be qualified as the pace of technology will dictate that they be considered.

Finally, inspections performed as part of an integrity management program will be integral to accepting composite repairs for use in offshore / subsea applications. The mixed results from this study show that future work should continue to identify the state of this technology and give concrete evidence of their capabilities. This will allow end users to more appropriately utilize the results of composite repair inspections and approach the inspection process with realistic expectations. An additional aspect of this future work is identifying what types of repair anomalies are injurious and the threshold at which the anomalies affect either the short-term or long-term performance of the repair.

Appendix A: Mechanical and Chemical Test Report

BL

BRYAN LABORATORY, INC.

METALLURGICAL CONSULTATION - INSPECTION - TESTING
ANALYTICAL SERVICES - FAILURE ANALYSIS
6919 ALMEDA ROAD (77021)
P. O. BOX 300366
HOUSTON, TX 77230-0366
TELEPHONE 713/747-7470 800/922-7470 FAX 713/747-7477

REPORT

Lab. No. B1L5-1286 **December 4, 2015**

ON: Steel Pipe

TO: Stress Engineering Services, Inc.
13610 Westland East Blvd.
Houston, Texas 77041-1101
Attention: Dr. Chris Alexander

IDENTITY: Project Number 1461125-OFFSHORE; Three samples identified as 12-3/4" O.D., 0.375" W.T., welded, marked Joint 1, Joint 2 and Joint 3

CHEMICAL ANALYSIS

Sample	-	Joint 1	Joint 2	Joint 3
Carbon, %	-	0.16	0.16	0.16
Manganese, %	-	0.79	0.79	0.78
Phosphorus, %	-	0.016	0.015	0.016
Sulfur, %	-	0.004	0.004	0.004
Silicon, %	-	0.02	0.02	0.02
Chromium, %	-	0.01	0.01	0.01
Nickel, %	-	<0.01	<0.01	<0.01
Molybdenum, %	-	<0.01	<0.01	<0.01
Copper, %	-	0.01	0.01	0.01
Aluminum, %	-	0.03	0.03	0.03
Vanadium, %	-	<0.01	<0.01	<0.01
Titanium, %	-	<0.01	<0.01	<0.01
Niobium, %	-	<0.01	<0.01	<0.01
Boron, %	-	<0.001	0.001	<0.001

TENSION TESTS

Specimens - Transverse, 1-1/2" wide reduced sections, 180° from the weld

Sample	-	Joint 1	Joint 2	Joint 3
Yield Strength*, psi	-	49,500	50,500	49,000
Tensile Strength, psi	-	70,700	70,200	70,700
Elongation in 2", %	-	44.2	43.6	43.4

*At 0.5% total extension

IMPACT TESTS

Specimen Type - Transverse, 3/4 Size, Charpy V-notch, 90° from the weld

Test Temperature - 70°F

Sample Specimen		Absorbed Energy, ft·lb	Percent Shear
Joint 1 - 1	-	58	100
Joint 1 - 2	-	61	100
Joint 1 - 3	-	62	100
Joint 2 - 1	-	65	100
Joint 2 - 2	-	58	100
Joint 2 - 3	-	64	100
Joint 3 - 1	-	64	100
Joint 3 - 2	-	66	100
Joint 3 - 3	-	65	100

Respectfully submitted,
BRYAN LABORATORY, INC.

Signature on Original Only

Walter T. Bryan

1/cd

Appendix B: Subsea Composite Installations

Manufacturer A Installation

Figure B-1: Manufacturer A repair installation (1 of 4)

Figure B-2: Manufacturer A repair installation (2 of 4)

Figure B-3: Manufacturer A repair installation (3 of 4)

Figure B-4: Manufacturer A repair installation (4 of 4)

Manufacturer B Installation

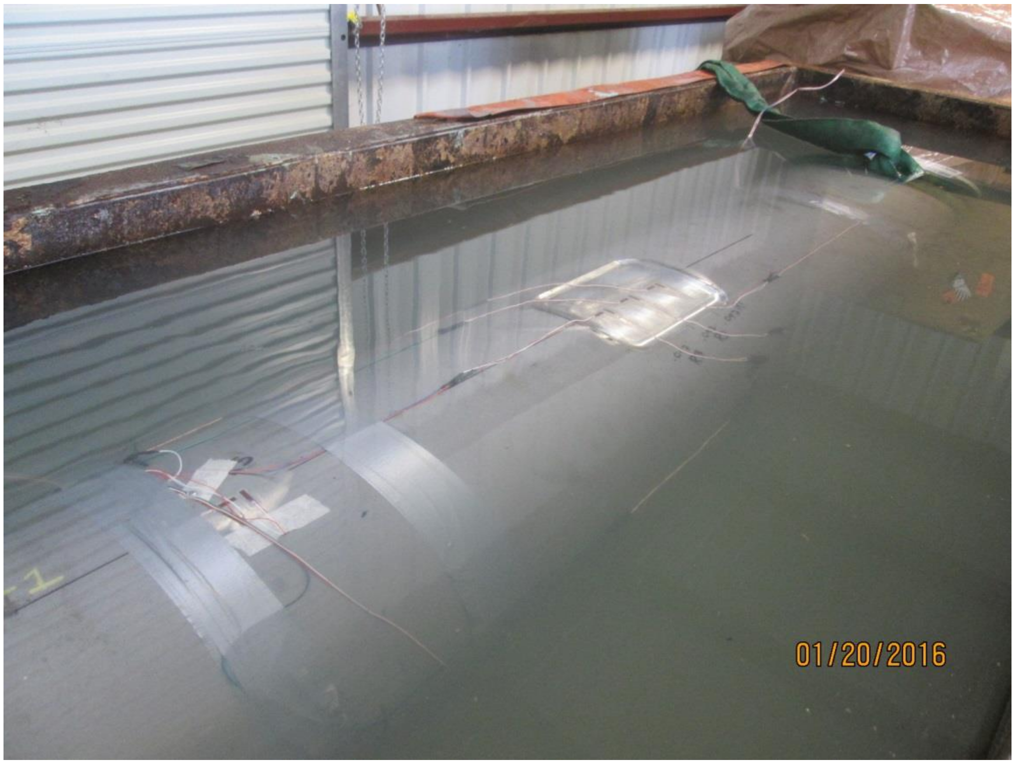

Figure B-5: Manufacturer B repair installation (1 of 4)

Figure B-6: Manufacturer B repair installation (2 of 4)

Figure B-7: Manufacturer B repair installation (3 of 4)

Figure B-8: Manufacturer B repair installation (4 of 4)

Manufacturer C Installation

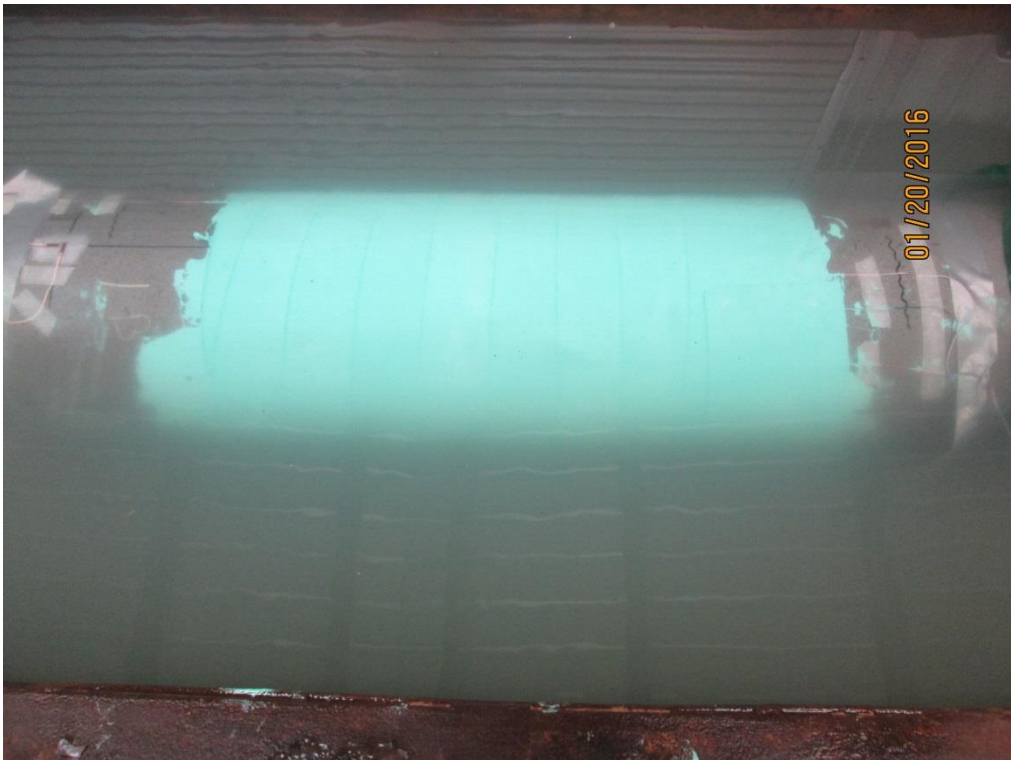

Figure B-9: Manufacturer C repair installation (1 of 4)

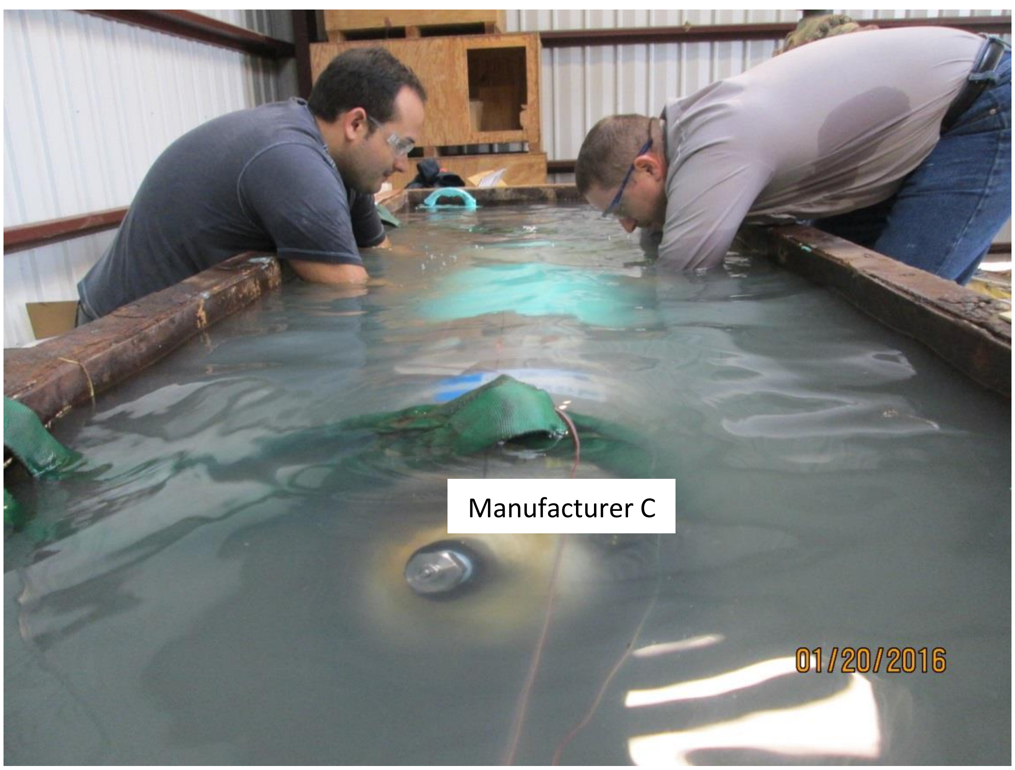

Figure B-10: Manufacturer C repair installation (2 of 4)

Figure B-11: Manufacturer C repair installation (3 of 4)

Figure B-12: Manufacturer C repair installation (4 of 4)

Appendix C: Sonomatic Composite Repair Inspection

Report

sonomatic®
innovative inspection technologies

DRS inspection feasibility study on subsea composite repairs

Report Produced for: Stress Engineering
Produced by: Alison Craigon
Report No.: C58678
Date: August 2017

Inspection Services Content For Internal Use					
Comment	Rev No.	Author	Completed date	Reviewer	Completed date
Initial	0.0	A Craigon	21/08/2017	M Stone	21/08/2017

For external Use		
Issue No.	Issuer	Date issued
1	E Cesan	23/08/2017

Title	DRS inspection feasibility study on subsea composite repairs
Customer	Stress Engineering
Customer reference	
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File Reference	
Report number	C58678

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Engineering Services Author	Alison Craigon		21/08/2017
Approved for Engineering Services by	Mark Stone		21/08/2017

Foreword

This document supersedes previous revisions.

Revision Control

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Revision history		
Issue	Date	Summary
1	21/08/2017	Initial

EXECUTIVE SUMMARY

Sonomatic was invited by Stress Engineering to evaluate the capabilities of their new ultrasonic inspection technique on four pipe samples wrapped with subsea composite repairs.

Existing ultrasonic corrosion mapping techniques utilise the travel time of high frequency signals reflected from the inner surface of the pipe. High frequencies are critical for accurate measurements but they are strongly attenuated in many coatings and are unable to penetrate composite repairs.

Dynamic Response Spectroscopy (DRS) was developed by Sonomatic to address the issue of ultrasonic attenuation in coatings. It utilises lower frequency ultrasound to penetrate coatings and induce the steel to vibrate at its natural frequencies. Advanced signal processing algorithms are used to extract these frequencies and convert them to wall thickness (WT) measurements.

This report presents the results of a DRS feasibility study conducted at Stress Engineering's facility in Waller, Texas in March 2016.

The DRS inspection was carried out using Sonomatic's automated Nautilus scanner with DRS attachment. The data was collected in 1 mm increments axially and 10 mm increments circumferentially, to create WT maps of the steel.

The table below summarises the results of the study.

Sample	Repair Type	Repair Thickness inches / mm	DRS Inspection Feasible?	Comment
A-DL-5	Glass Fiber	1.28 / 32.4	N	No signal evident from steel. Attenuation likely due to repair thickness*.
A-F-2	Glass Fiber	1.28 / 32.4	N	No signal evident from steel. Attenuation likely due to repair thickness*.
C-DL-J35	Glass Fiber	0.24 / 6.1	N	No signal evident from steel*. Repair thickness recorded incorrectly? Appears thicker in photos.
B-DL-J1-5	Carbon Fiber	0.38 / 9.5	N	Signal evident from steel in places. Not consistent enough for DRS to be considered a suitable inspection technique.*

*Thinner versions of these repairs may be suitable for DRS inspection.

TABLE OF CONTENTS

1 Introduction

Sonomatic was invited by Stress Engineering to evaluate the feasibility of utilising their Dynamic Response Spectroscopy (DRS) ultrasonic inspection technique to measure the steel wall thickness profiles of four pipe samples wrapped with subsea composite repairs.

Inspection of steel through composite repairs, such as Technowrap 2K (Figure 1), is a challenge for existing ultrasonic inspection methods which are based on the travel time of high frequency (4 – 15 MHz) ultrasonic signals. These high frequencies are critical for accurate thickness measurements but are more strongly attenuated than lower frequencies and are unable to penetrate composite repairs.

DRS is an innovative ultrasonic inspection technique developed by Sonomatic for corrosion mapping through challenging coatings where the conventional ultrasonic method is ineffective. Low frequency ultrasound (<1 MHz) penetrates the coating and excites the steel, causing it to vibrate at its natural frequencies. Using advanced signal processing algorithms, these frequencies are extracted from the returning signals and used to determine the steel wall thickness (WT) profile (Figure 2).

Further development of the DRS technique is underway to evaluate the integrity of composite repairs. Flaws such as disbondment from the steel or delamination between the layers contain small air pockets which block the transmission of ultrasound into the steel. DRS maps these flaws where the steel response signal is lost. Sonomatic is currently working with composite repair manufacturers to develop flaw acceptance criteria.

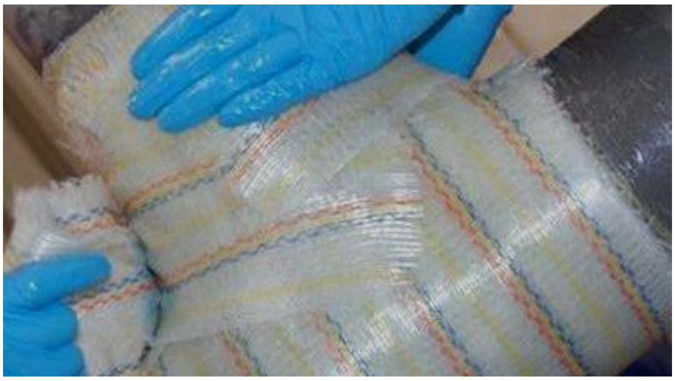


Figure 1. Application of a Technowrap 2K composite repair.

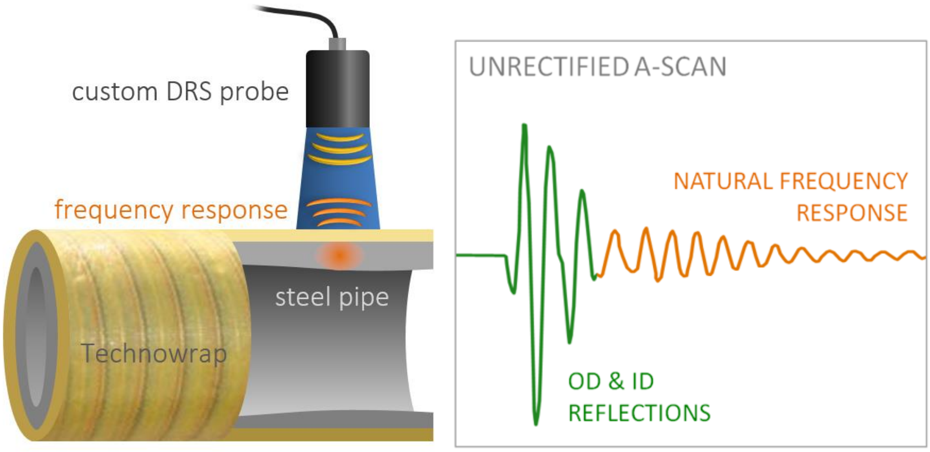


Figure 2. DRS inspection diagram. The orange part of the signal contains the natural vibration frequencies of the steel, which are used to determine its thickness profile.

2 Samples

The samples consisted of four 12” pipes with 0.375” (9.5 mm) nominal WT. A rectangular area, 6 x 8”, had been machined from the OD, as shown in Figure 3.

Sections 2.1 to 0 show the composite repairs. The areas inspected for this feasibility study are marked in blue on the diagrams.

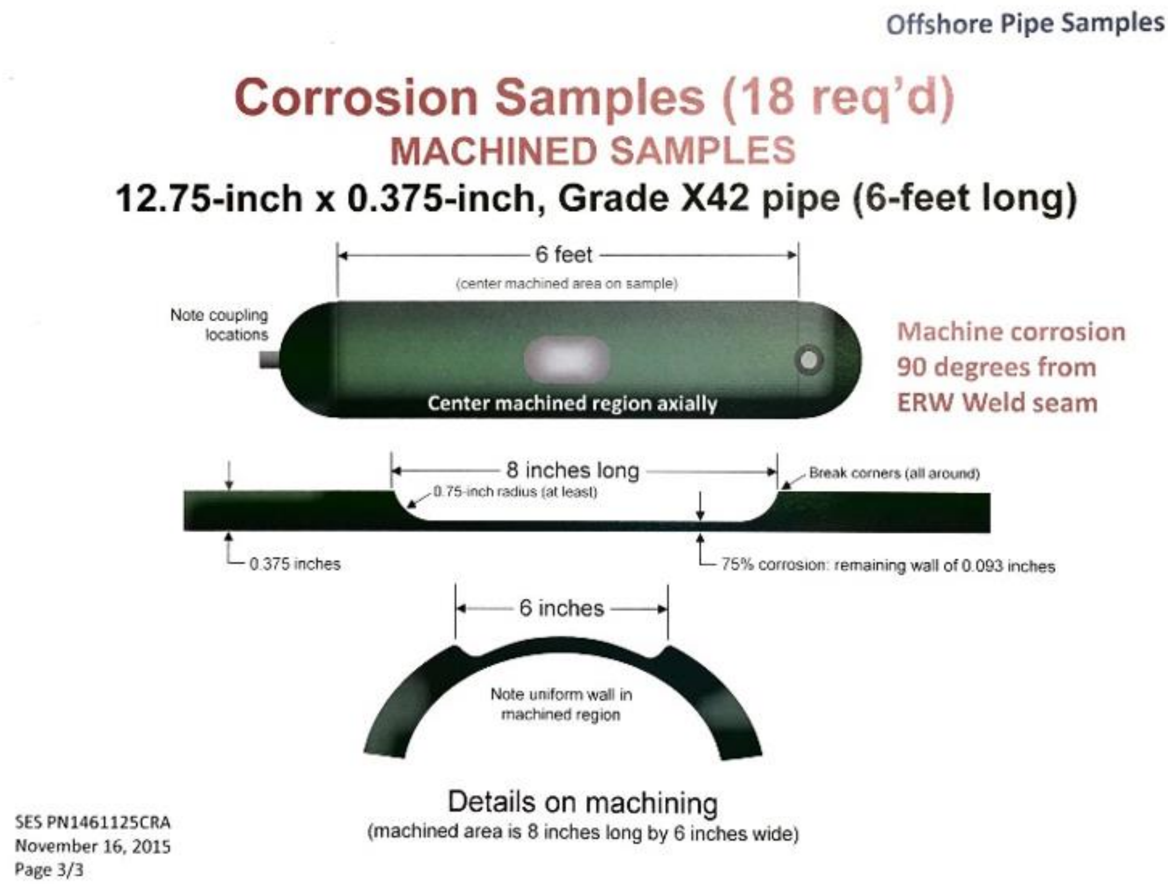
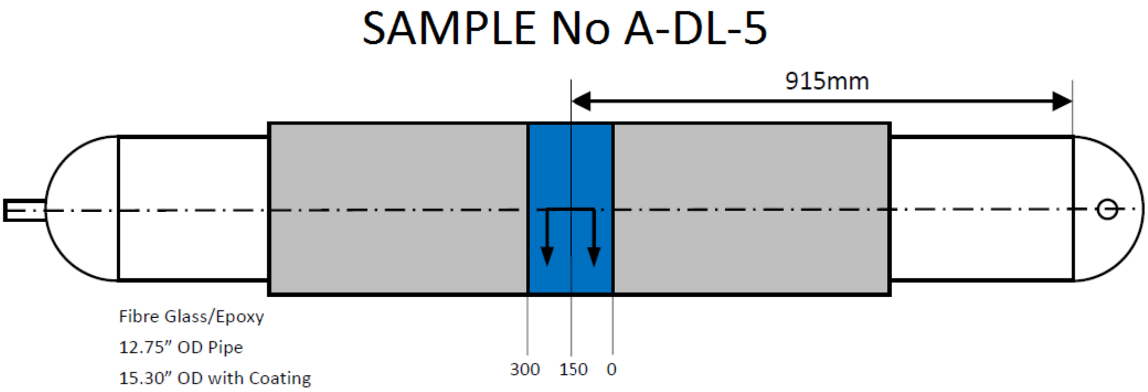
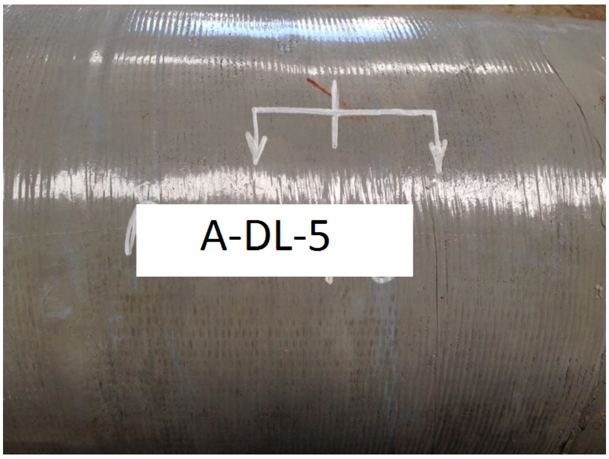


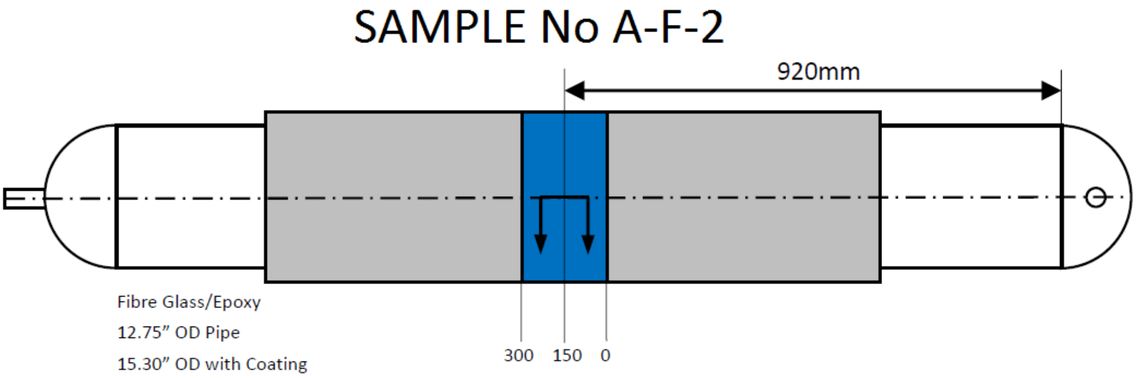
Figure 3. Diagram showing the design of the steel pipe samples prior to application of the composite repairs.

2.1 A-DL-5

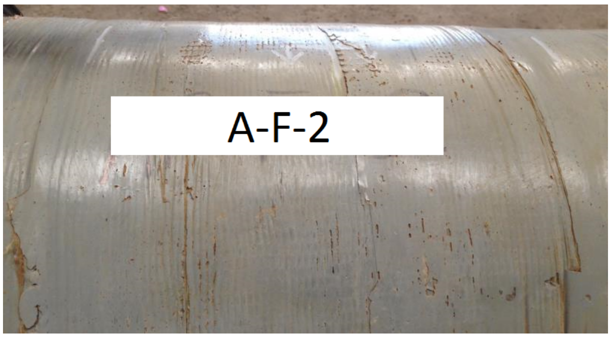

SAMPLE No A-DL-5
915mm
Fibre Glass/Epoxy
12.75" OD Pipe
15.30" OD with Coating
300
150
0


A-DL-5

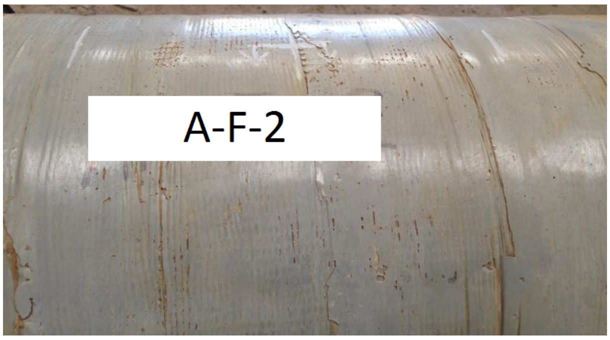
2.2 A-F-2



SAMPLE No A-F-2
920mm
Fibre Glass/Epoxy
12.75" OD Pipe
15.30" OD with Coating
300
150
0

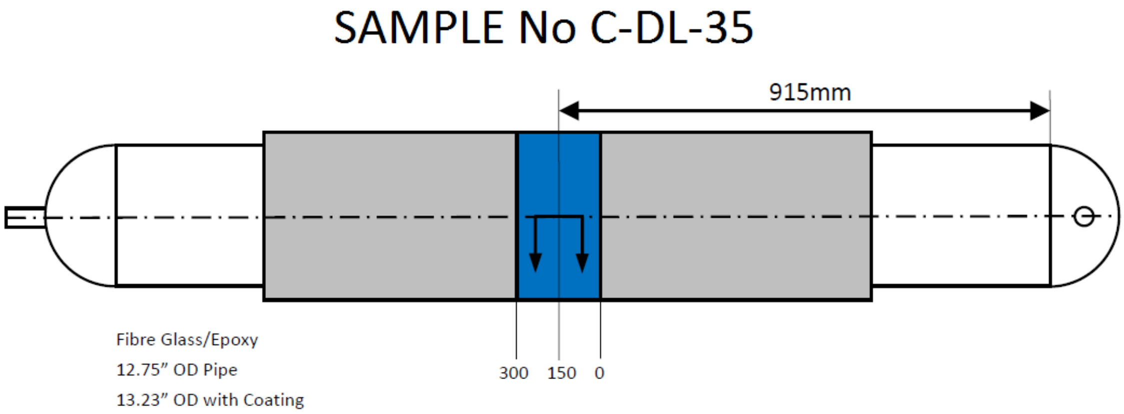


A-F-2

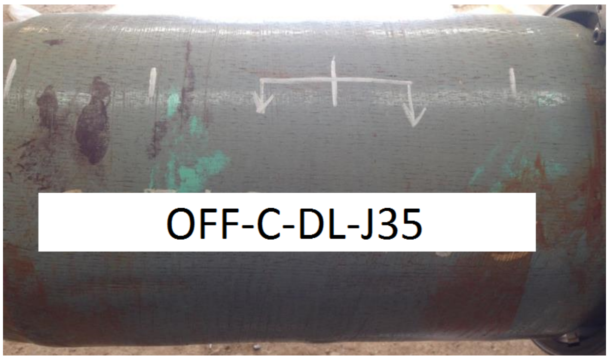


A-F-2

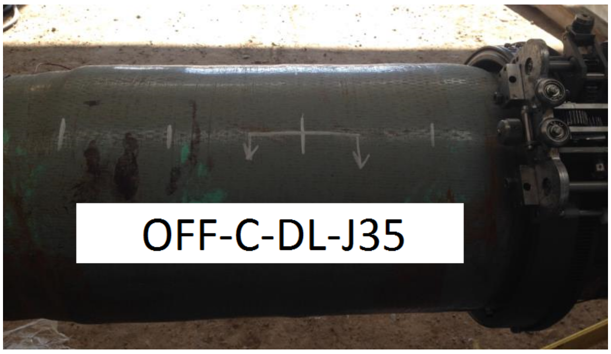
2.3 C-DL-J35



SAMPLE No C-DL-35
915mm
Fibre Glass/Epoxy
12.75" OD Pipe
13.23" OD with Coating
300
150
0



OFF-C-DL-J35

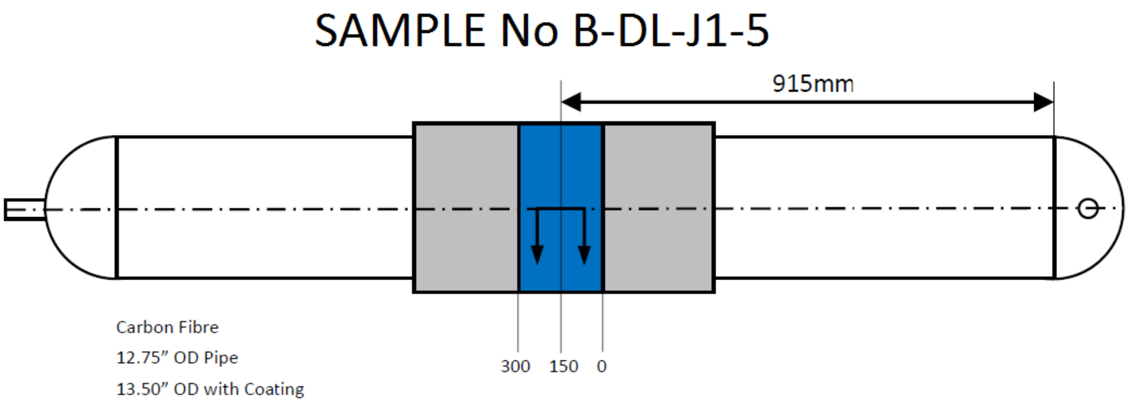


OFF-C-DL-J35

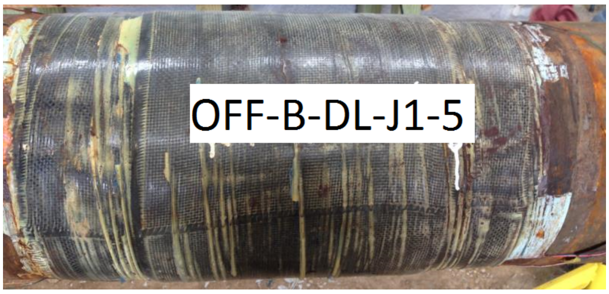
OFF-C-DL-J35

OFF-C-DL-J35

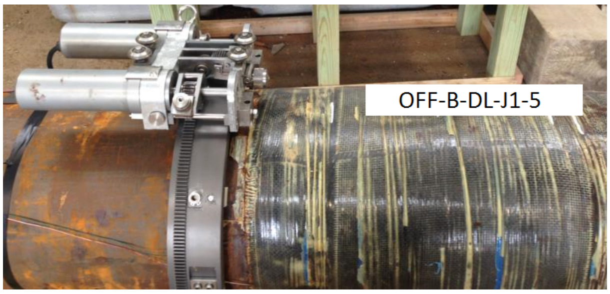
2.4 B-DL-J1-5



SAMPLE No B-DL-J1-5
915mm
Carbon Fibre
12.75" OD Pipe
13.50" OD with Coating
300
150
0



OFF-B-DL-J1-5



OFF-B-DL-J1-5

OFF-B-DL-5

OFF-B-DL-J1-5

3 Inspection

The feasibility study was conducted in March 2016 at the Stress Engineering facility in Waller, Texas, where the samples were immersed in a tank to simulate a subsea inspection.

The inspection was carried out using an automated Nautilus scanning system, which collected data in 1 mm increments axially and 10 mm increments circumferentially. The scans were then processed to evaluate the signal quality and create maps of the steel WT.

4 Results

The results of the DRS feasibility study are presented in Table 1 and Figure 4.

No signals were seen from the steel for three of the samples. Steel WT measurements were possible for the fourth sample, B-DL-J1-5, but only in small areas due to the inherent variability of the repair composition and thickness. DRS is therefore not a suitable inspection technique for subsea composite repairs of these particular designs.

DRS has been successfully used on other composite repair products to evaluate the integrity of the repair and measure the steel WT; some examples are presented in Appendix 2. Extensive trials on a range of composite repairs have shown that the maximum repair thickness for DRS inspection is in the region of 12 mm, although this limit varies depending on the specific repair product and quality of application.

It should be noted that for repairs suitable for DRS inspection, a loss of signal from the steel indicates a flaw in the composite (such as a delamination), as shown in Figure 5 and Figure 6. However, for repairs such as those evaluated in this study, it is not possible to identify delaminations as they are indistinguishable from the loss of signal due to attenuation in the thick composite.

Table 1. Summary of inspection results.

Sample	Repair Type	Repair Thickness inches / mm	DRS Inspection Feasible?	Comment
A-DL-5	Glass Fiber	1.28 / 32.4	N	No signal evident from steel. Attenuation likely due to repair thickness.
A-F-2	Glass Fiber	1.28 / 32.4	N	No signal evident from steel. Attenuation likely due to repair thickness.
C-DL-J35	Glass Fiber	0.24 / 6.1	N	No signal evident from steel. Repair thickness recorded incorrectly? Appears thicker in photos.
B-DL-J1-5	Carbon Fiber	0.38 / 9.5	N	Signal evident from steel in places (see Figure 4). Not consistent enough for DRS to be considered a suitable inspection technique.

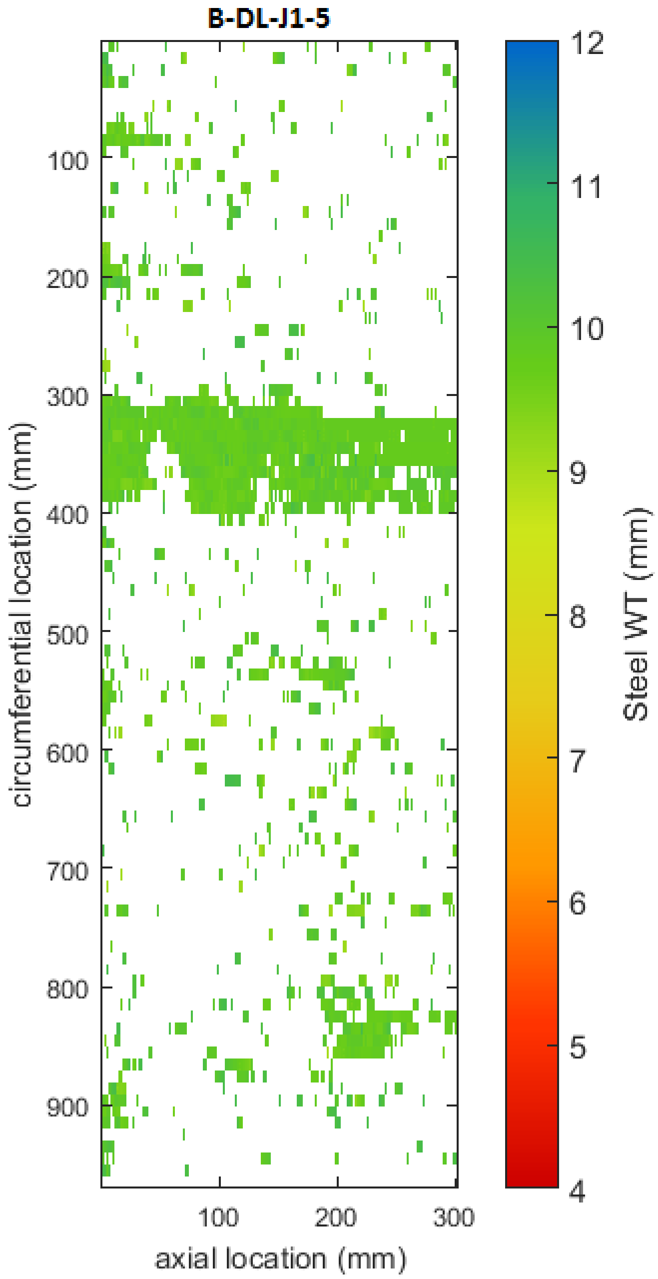


Figure 4. DRS map showing the steel WT where signals penetrated the composite. Although measurements were possible in some locations, the large areas of signal loss demonstrate that DRS is not a suitable inspection technique for this particular design.

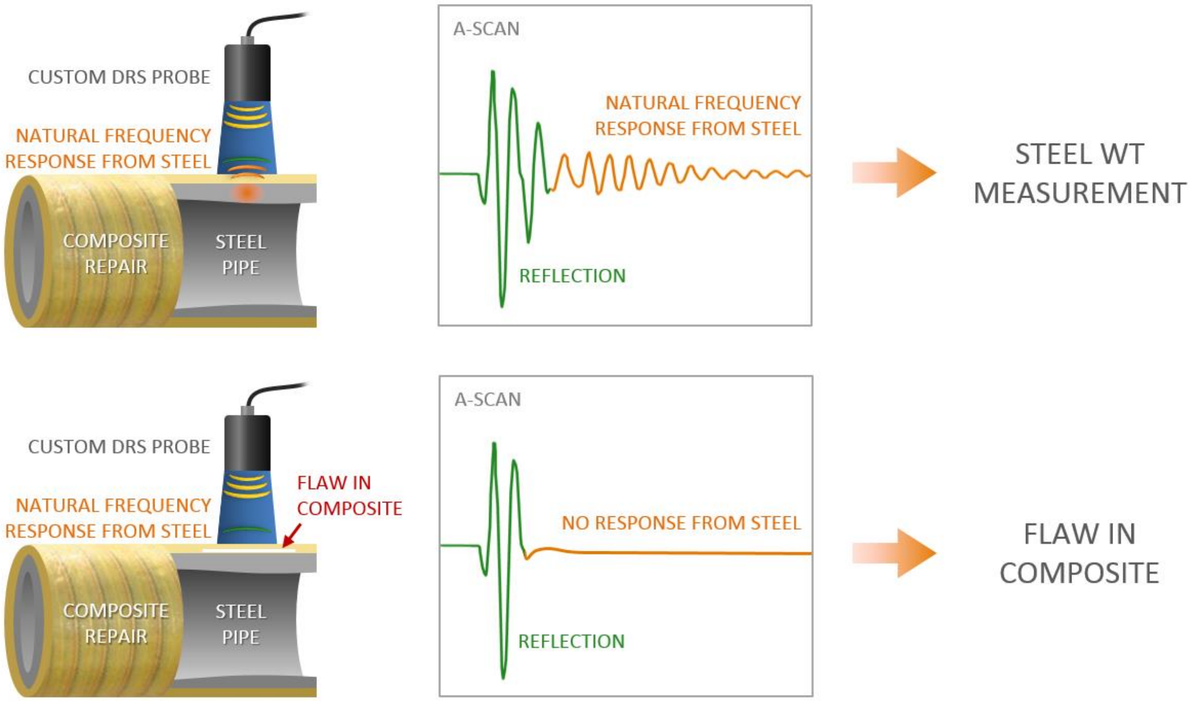


Figure 5. Diagram illustrating the effect of a flaw in the composite on the DRS signals.

Figure 6. DRS inspection of a blow-off test plate sample. Green shows the steel WT where the composite remains bonded, white shows where the DRS signals are lost due to delamination.

5 Summary

This feasibility study has shown that DRS is not a suitable inspection technique for subsea composite repairs of the designs tested. For three of the samples, the composite attenuates the DRS signals severely enough to prevent them reaching the steel. Hand-applied repairs such as these are inherently variable in composition and thickness, resulting in variable levels of attenuation. While the fourth sample shows small areas where measurements of the steel WT are possible, the large areas of signal loss demonstrate that DRS inspection is unsuitable for this repair also.

Extensive work on other composite repair products has shown that DRS is effective in evaluating the integrity of the repair and measuring the steel WT where the composite is up to 12 mm thick.

Appendix D: BIS Salamis Composite Repair Inspection

Bond-master Composite Test

Information ONLY Report

Test Report (6/28/17):

Technician's: Brady Guillory / Chris LaFleur

Equipment Used in Non-Destructive Test:

Unit: Bond-Master 1000e+

Probe Model: S-PC-P14

Probe s/n: P04252

Code / Spec: Information Only. No specification was provided

Calibration Standard: none available (Cal block with known reflector size and location was not generated for the testing of this piece)

Note: The use of a claibration block or reference standard would allow us a more precise way of measuring and distinguising between relevant & non-relevant indications.

Bond-master Composite Test

Information ONLY Report

Subsea Composite Test Sample # C-F-J3-2

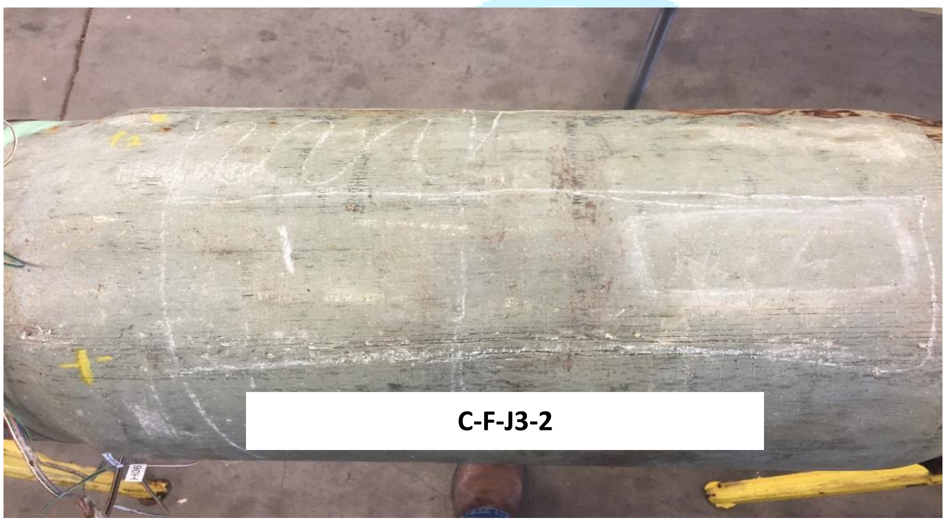
Test Results:

Relevant Indication # 1 (Between the 0 & 1 marker). Starting about 3" from nozzle end running 16"long

- Approximately 5" x 16"

Indication # 2 (All around the circumference of the wrap. From Nozzle end – Starting 2" to 3" from edge of wrap; 6" wide (radius)).

- Note these could be non–relevant indications based on the inconsistency of the readings and lower amplitude of the signals.

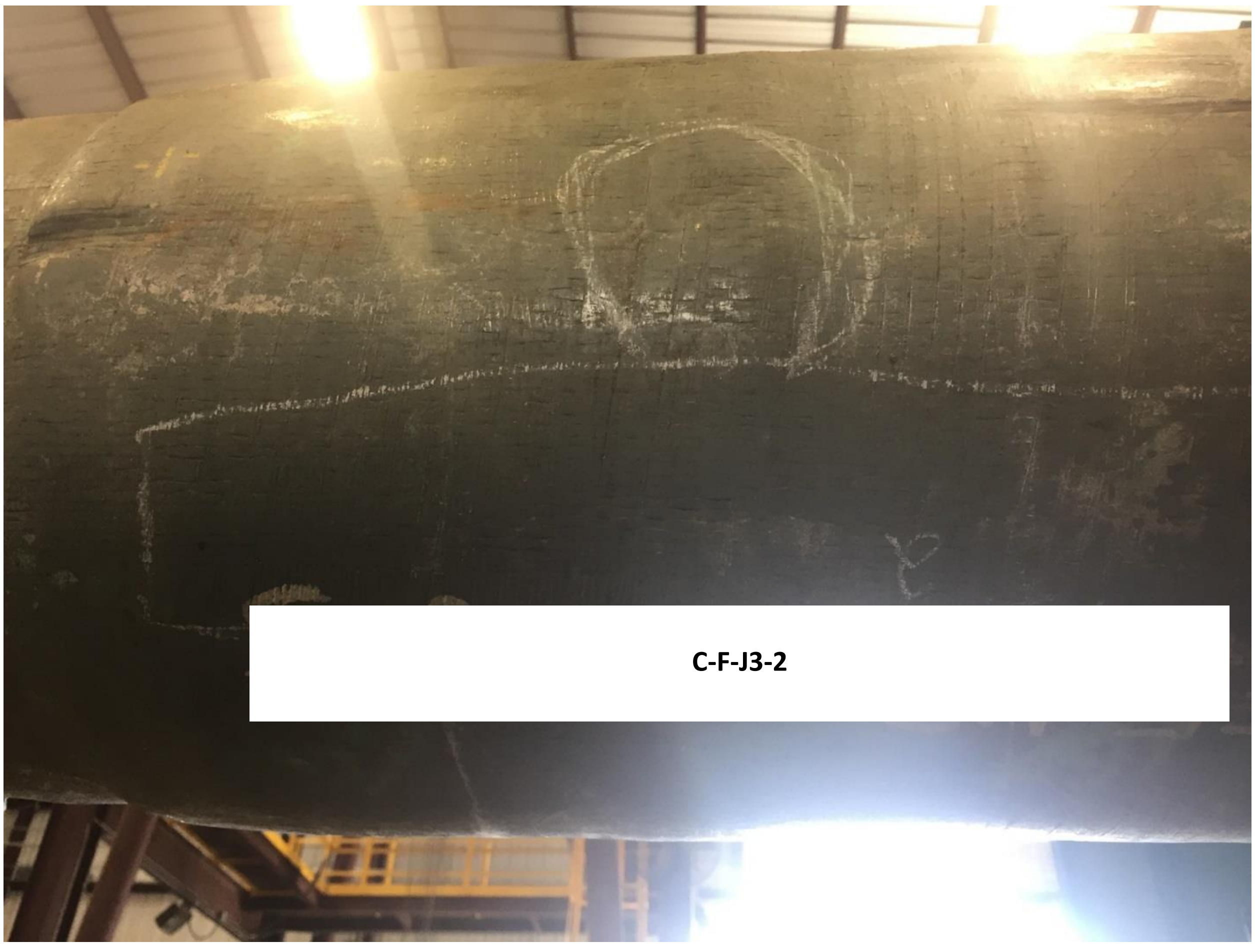


Subsea Composite Test Sample # C-F-J3-2

Test Results:

Relevant Indication # 2 (Between the 0 & 1 marker). Starting about 2” from nozzle end running 16”long

- Approximately 5” x 16”



Indication # 1 Starting about 2” from nozzle end running around the circumference of the wrap inconstantly

- Approximately 10” Long (axially) (Could be non-relevant)

Subsea Composite Test Sample # B-DL-J1-5

Test Results:

Relevant Indication # 2 (At the 0 marker / Nozzle). In middle of wrap

- Approximately 3" x 3"

Relevant Indication # 1 (at the 3 marker). In middle of wrap but closer to nozzle side

- Approximately 5" x 3"

Indication # 3 (between the 0 & 1 marker). In middle of wrap but closer to opposite of nozzle side. Could be non-relevant

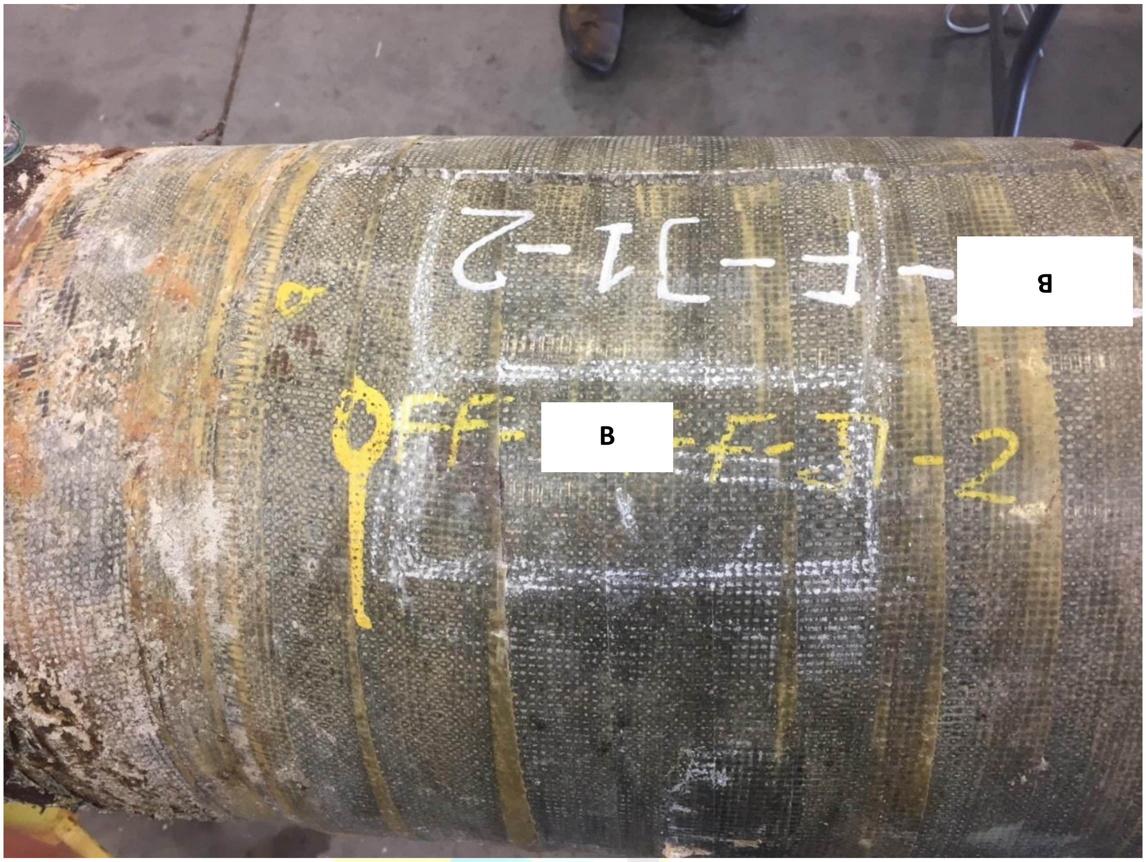
- Approximately 5" x 3"

Subsea Composite Test Sample # B-F-J1-2

Test Results:

Relevant Indication # 1 (At the 0 marker / Nozzle). 3” from edge of wrap closer to nozzle

- Approximately 8” x 6”


B
OFF
F-J1-2
B

Subsea Composite Test Sample # A-DL-5

Test Results:

Relevant Indication # 1 (At the 2 marker). Middle of wrap

- Approximately 17" long (axial) x 10" wide (radius)

Indication # 2 (At the 1 marker). 10" from nozzle end of wrap.

- Approximately 3" x 3"
- Could be non-relevant based on size and lower amplitude

Subsea Composite Test Sample # A-F-2

Test Results:

Relevant Indication # 1 (At the 2 marker). Middle of wrap

- Approximately 9" long (axial) x 7" wide (radius)

Indication # 2 (Between the 3 marker & the 0 marker). Middle of wrap closer to nozzle

- Approximately 6” long (axial) x 4” wide (radius)
- Could be non-relevant based on size and lower amplitude

Appendix E: Pre-Cycling Data

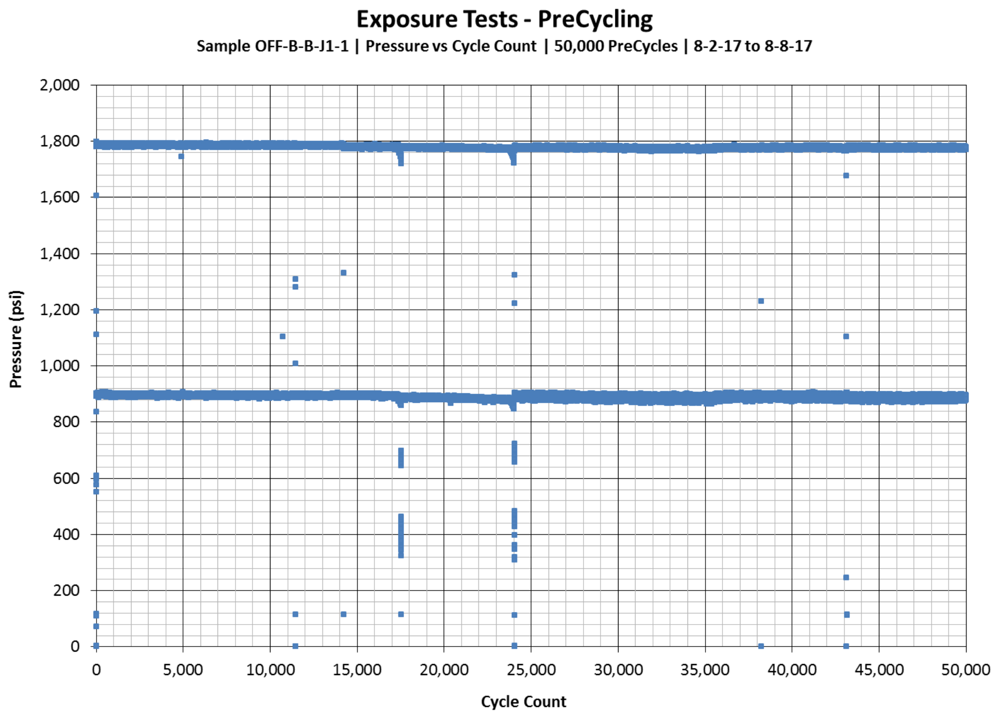


Figure E-1: Pressure vs. cycle count for 50,000 pre-cycles of sample OFF-B-B-J1-1 (Manufacturer B burst)

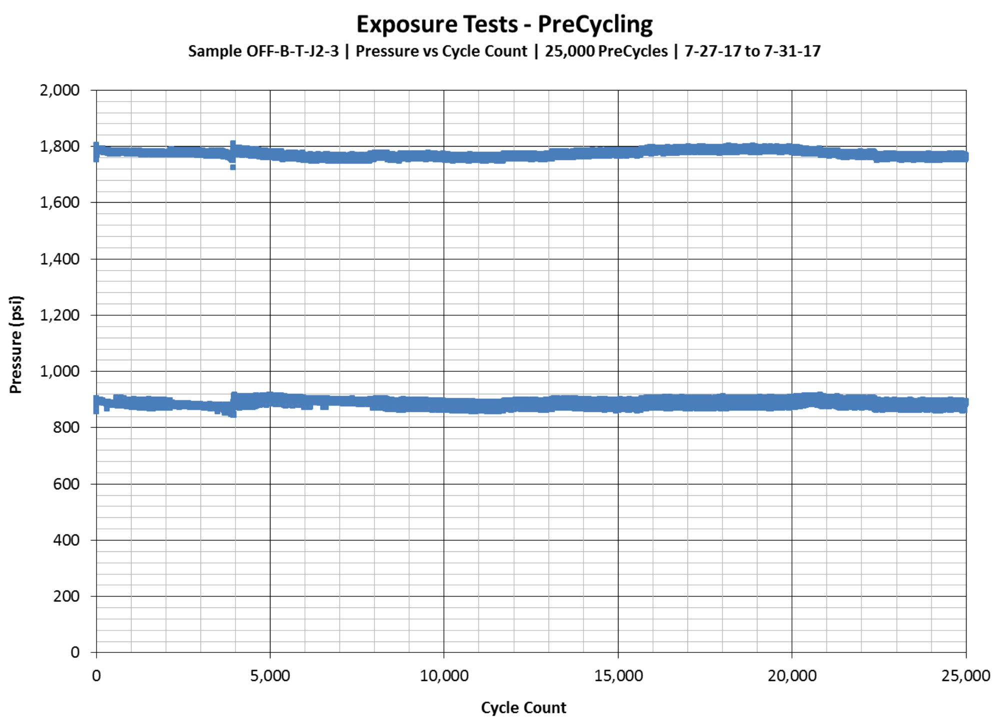


Figure E-2: Pressure vs. cycle count for 25,000 pre-cycles of sample OFF-B-T-J2-3 (Manufacturer B tension)

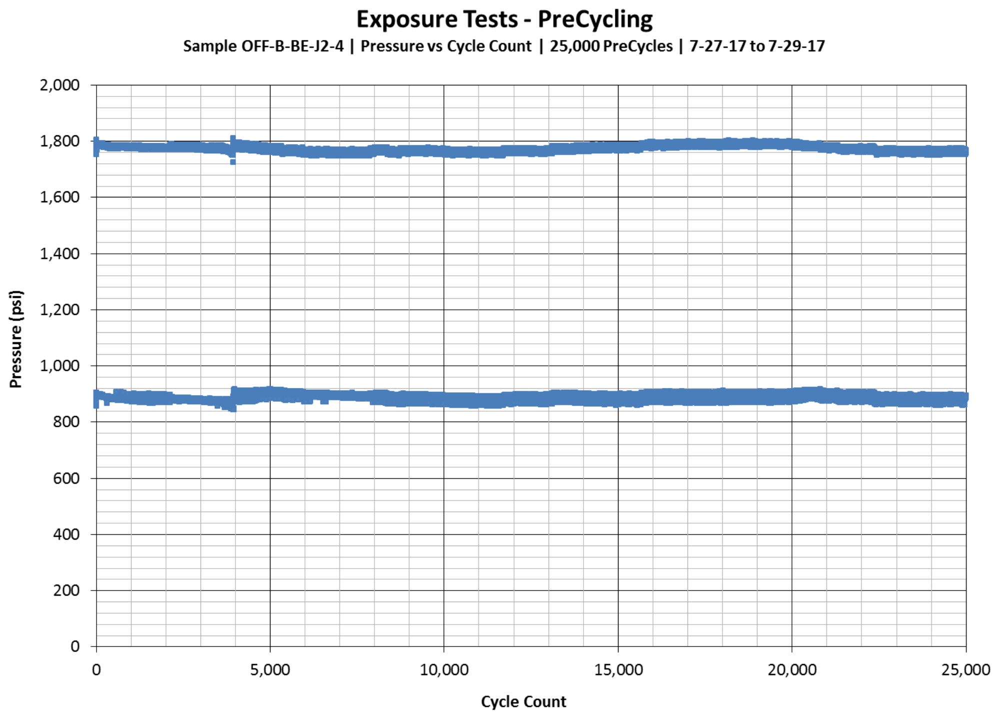


Figure E-3: Pressure vs. cycle count for 25,000 pre-cycles of sample OFF-B-BE-J2-4 (Manufacturer B bending)

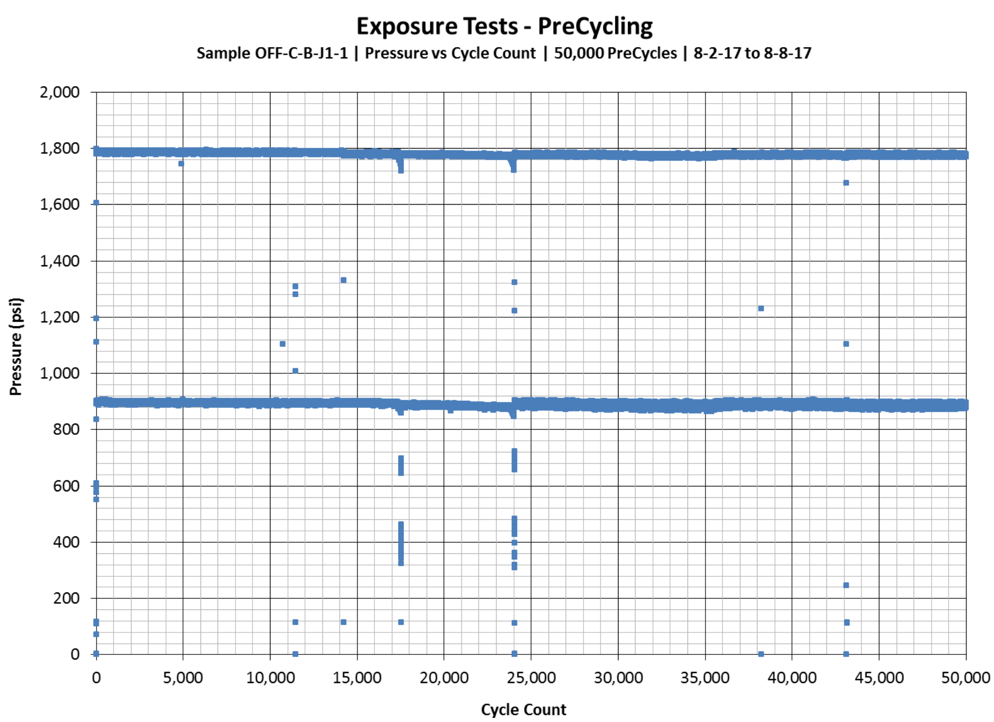


Figure E-4: Pressure vs. cycle count for 50,000 pre-cycles of sample OFF-C-B-J1-1 (Manufacturer C burst)

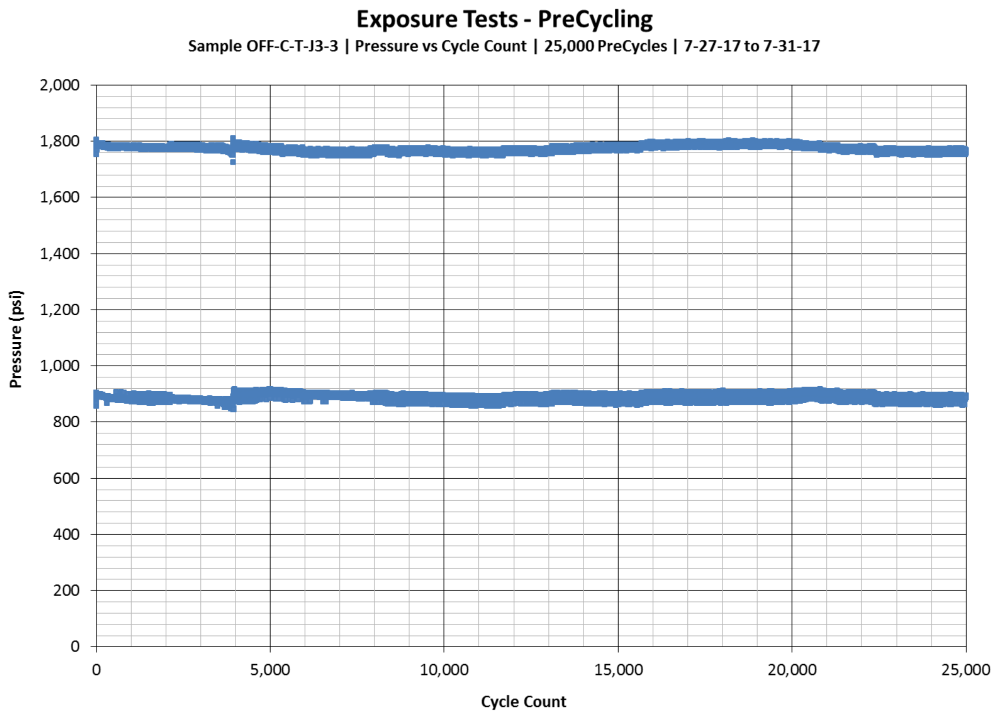


Figure E-5: Pressure vs. cycle count for 25,000 pre-cycles of sample OFF-C-T-J3-3 (Manufacturer C tension)

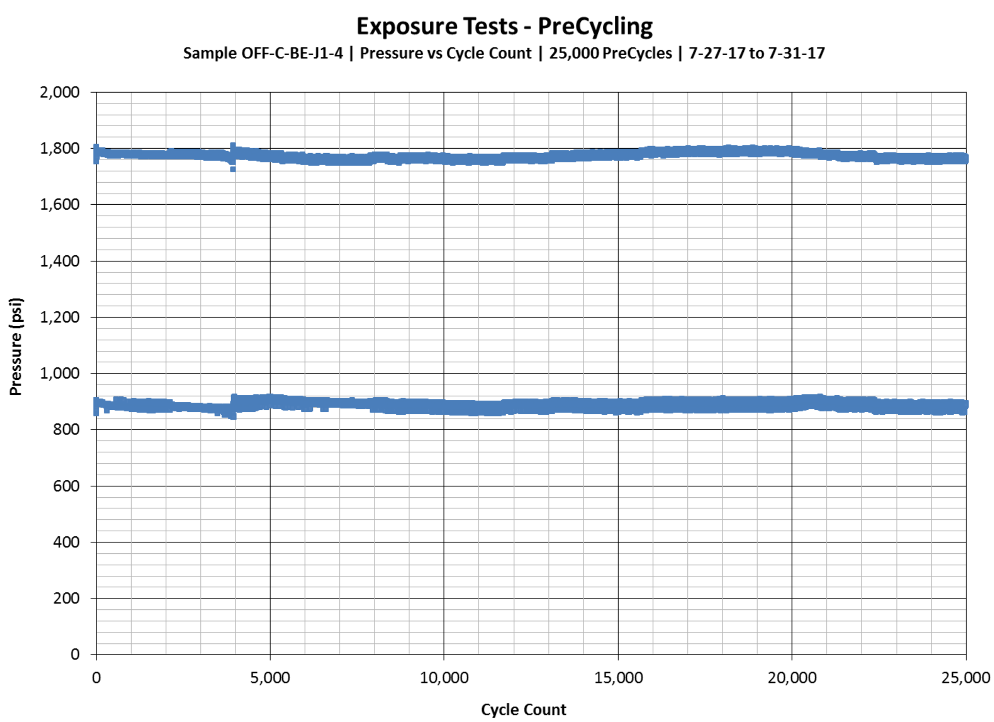


Figure E-6: Pressure vs. cycle count for 25,000 pre-cycles of sample OFF-C-BE-J1-4 (Manufacturer C bending)

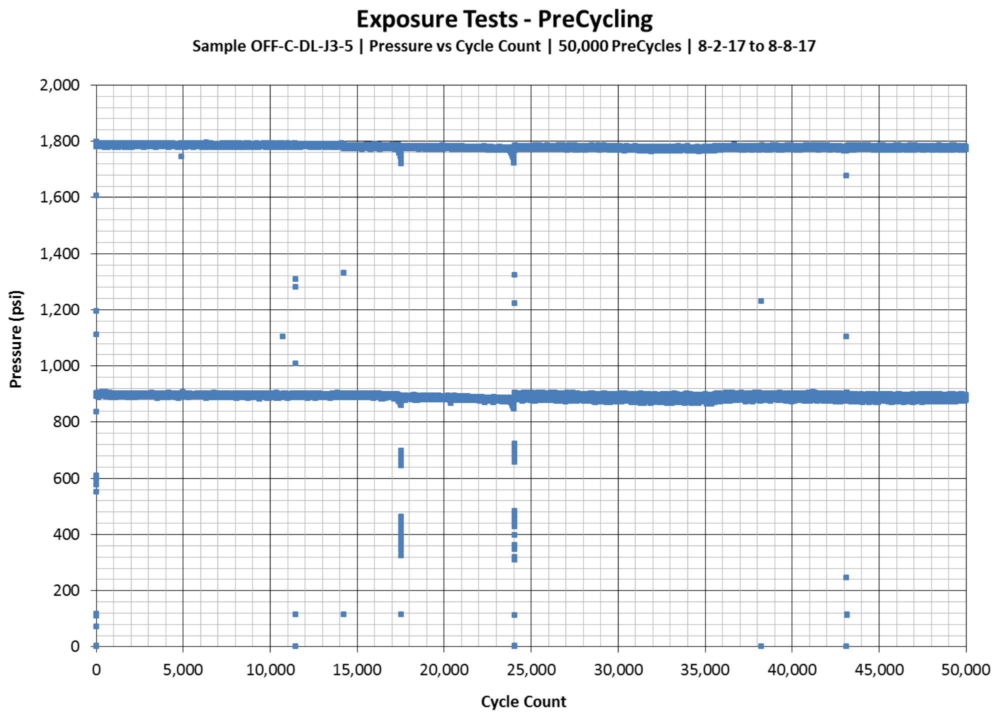


Figure E-7: Pressure vs. cycle count for 50,000 pre-cycles of sample OFF-C-DL-J3-5 (Manufacturer C delamination)

Appendix F: Calibration Sheets

Specialized Tech Services
28694 Denn Rd. Montgomery, Tx 77356
Phone - 713-515-3619

CALIBRATION CERTIFICATE

CUSTOMER: **Stress Engineering / Waller Division**

42403 Old Houston HWY

Transducer Make:	Delta Metrics	Transducer Model:	99-5864-0005
Transducer S/N:	108580	Transducer Range:	0 - 5000 psi
Reference and testing conditions:		979.312 gals	22°C +/- 1.5 deg
		Excitation:	5.053 volts

CALIBRATION READINGS (as found as left)

ACTUAL (psi)	READING 1 (mv)	CONVERTED (psi)	PERCENT ERROR % of FS
0	0.058	0	0.00
500	1.070	500	0.00
1000	2.083	1001	0.02
2000	4.107	2001	0.02
3000	6.130	3001	0.02
4000	8.152	4000	0.00
5000	10.173	4999	-0.02

All readings within manufacturer tolerance (+/- 0.5% F.S.)

CONVERSION FACTORS (Reading - Offset)*gain

Shunt Reading (millivolts)	Shunt Reading (psi)	Offset (millivolts)	Gain (psi/mv)
7.644	**3749**	0.058	494.20

Calibration performed per STS document PTC1001 and traceable to N.I.S.T.

Equipment used: Pressurements model M3800 SN:61205, Agilent model 34401A SN: MY47007060

Technician E. Wilson DATE: October 14, 2016

SIGNED: [signature] RECALL: October 14, 2017

Stress Engineering Services
13800 Westfair East Drive
Houston Texas 77041

Calibrated By: Stress Engineering Serivces, Inc.
13800 Westfair East Drive
Houston, Texas 77041

Enerpac - Daytronics 200T System Ram No: EP 001
Enerpac Hydraulic Ram Model: CLRG 20012
Crystal Digital Pressure Gauge Model: XP2i Serial: 471438
Nominal Rod Side Area: 19.685 SqIn

Calibration Date: 17 February 2017

Gage Pressure:	Observed Load, lbF	Equation Load, lbF	Error: Load, lbF	Error % of Rdg:
563	23,213	23,082	-131	-0.57%
1032	42,493	42,425	-68	-0.16%
1517	62,640	62,429	-211	-0.34%
2000	82,463	82,350	-113	-0.14%
2615	107,959	107,715	-244	-0.23%
3035	125,289	125,038	-251	-0.20%
3521	145,543	145,083	-460	-0.32%
4004	165,398	165,004	-394	-0.24%
4550	188,215	187,523	-692	-0.37%
5030	208,001	207,320	-681	-0.33%
6004	248,128	247,493	-635	-0.26%
7030	290,559	289,809	-750	-0.26%
8050	332,716	331,879	-837	-0.25%
9070	374,705	373,948	-757	-0.20%
9720	401,990	400,757	-1,233	-0.31%
513	21,239	21,019	-220	-1.03%
1018	42,123	41,848	-275	-0.65%
1532	62,906	63,047	141	0.22%
2155	88,531	88,743	212	0.24%
2600	106,609	107,096	487	0.46%
3000	123,341	123,594	253	0.21%
3550	145,811	146,279	468	0.32%
4030	165,668	166,076	408	0.25%
4508	185,071	185,791	720	0.39%
5048	207,124	208,063	939	0.45%
6040	248,246	248,977	731	0.29%
7029	289,188	289,768	580	0.20%
8046	331,183	331,714	531	0.16%
9050	372,691	373,123	432	0.12%
9755	401,881	402,200	319	0.08%
509	21,067	20,854	-213	-1.01%
1025	42,543	42,137	-406	-0.96%
1565	64,632	64,409	-223	-0.35%
2030	83,729	83,587	-142	-0.17%
2550	104,909	105,034	125	0.12%
3110	128,141	128,131	-10	-0.01%
3660	150,437	150,816	379	0.25%
4140	170,219	170,613	394	0.23%
4560	187,696	187,936	240	0.13%
5090	209,308	209,795	487	0.23%
6043	248,551	249,101	550	0.22%
7082	291,577	291,954	377	0.13%
8060	332,100	332,291	191	0.06%
9110	375,714	375,598	-116	-0.03%
9738	401,401	401,499	98	0.02%

Equation Load = Gage Pressure * Area + Intercept

Area: 41.244 SqIn

Intercept: -139 lbF

Roy C. Nash

Calibration Instrumentation:
HSI Load Cell 3335-006B

Stress Engineering Services
13800 Westfair East Drive
Houston Texas 77041

Calibrated By: Stress Engineering Serivces, Inc.
13800 Westfair East Drive
Houston, Texas 77041

Enerpac - Daytronics 200T System Ram No: EP 022
Enerpac Hydraulic Ram Model: CLRG 20012
Crystal Digital Pressure Gauge Model: XP2i Serial: 471438
Nominal Rod Side Area: 19.685 SqIn

Calibration Date: 17 February 2017

Gage Pressure:	Observed Load, lbF	Equation Load, lbF	Error: Load, lbF	Error % of Rdg:
515	21,129	21,114	-15	-0.07%
1022	42,221	42,021	-200	-0.47%
1500	61,759	61,732	-27	-0.04%
2000	82,390	82,350	-40	-0.05%
2540	104,530	104,618	88	0.08%
3037	125,094	125,112	18	0.01%
3507	144,474	144,493	19	0.01%
4040	166,338	166,472	134	0.08%
4515	185,919	186,060	141	0.08%
5080	209,435	209,358	-77	-0.04%
6018	248,056	248,038	-18	-0.01%
7080	291,939	291,831	-108	-0.04%
8050	332,042	331,830	-212	-0.06%
9070	374,609	373,891	-718	-0.19%
9717	400,525	400,571	46	0.01%
550	22,722	22,557	-165	-0.72%
1030	42,521	42,351	-170	-0.40%
1505	62,142	61,938	-204	-0.33%
2000	82,365	82,350	-15	-0.02%
2520	103,814	103,793	-21	-0.02%
3010	124,083	123,999	-84	-0.07%
3505	144,791	144,411	-380	-0.26%
4140	170,551	170,596	45	0.03%
4520	186,207	186,266	59	0.03%
5003	206,128	206,183	55	0.03%
6020	248,176	248,120	-56	-0.02%
7005	289,049	288,738	-311	-0.11%
8040	331,312	331,418	106	0.03%
9070	374,023	373,891	-132	-0.04%
9720	400,663	400,695	32	0.01%
548	22,422	22,475	53	0.24%
1050	43,120	43,176	56	0.13%
1550	63,630	63,794	164	0.26%
2100	86,436	86,474	38	0.04%
2538	104,880	104,535	-345	-0.33%
3080	126,681	126,885	204	0.16%
3540	145,599	145,854	255	0.18%
4055	166,800	167,091	291	0.17%
4570	188,093	188,328	235	0.12%
5030	206,984	207,296	312	0.15%
6054	249,169	249,522	353	0.14%
7097	292,288	292,532	244	0.08%
8022	330,573	330,675	102	0.03%
9020	371,718	371,829	111	0.03%
9708	400,065	400,200	135	0.03%

Equation Load = Gage Pressure * Area + Intercept

Area: 41.236 SqIn

Intercept: -123 lbF

Calibration Instrumentation:
HSI Load Cell 3335-006B

Roy C. Nash

STRESS ENGINEERING SERVICES INC.
an employee-owned company

8505 Westland West Blvd., Building 4, Houston, Texas 77041-1215
Phone: (281) 955-2909 Fax: (281) 970-4628 Web: www.stress.com

HOUSTON • CINCINNATI • NEW ORLEANS • WALLER
CALGARY (STRESS ENGINEERING SERVICES CANADA) • SINGAPORE (STRESS ENGINEERING SERVICES PTE. LTD.)

CERTIFICATE OF CALIBRATION

Owner: Stress Engineering Services / Waller ABC
42403 Old Houston Hwy
Waller, TX 77484

Equipment:

Transducer Make:	Tecsis	Transducer Model:	99-6228-0004
Transducer SN:	138268	Transducer Full Scale:	5000 psi

Calibration Equipment

Manufacturer	Model	Tracking Number	Calibration Due
Pressurements	M3860	61205	28-Jul-17
Agilent	34401a	MY47007060	14-Nov-17

Calibration Data ("As Left")

Excitation Voltage:	10.000 V	Ambient Temperature:	71.7 °F (+/- 1.5°F)
		Ambient Humidity:	44.1 %RH (+/- 1.5%)

Actual	Reading	Converted	Error
(psi)	(mV)	(psi)	(% of FS)
0	-0.098	-2	-0.04
500	2.905	499	-0.01
1000	5.907	1001	0.01
2000	11.905	2002	0.04
3000	17.895	3002	0.04
4000	23.877	4000	0.01
5000	29.851	4998	-0.05

All readings within tolerance (±0.25% Full Scale)

Converted = (Reading - Offset)*gain

Shunt Reading	Shunt Reading	Offset	Gain
ΔmV	ΔPSI	mV	psi/mV
24.090	**4021**	-0.087	166.94

The measurement standards used during calibration are traceable to NIST
Calibrations were performed per SES Document: L3-CAL-PR-006 rev. 1

Technician: Alejandro Galvan | Date: 3/15/2017

Signed: [signature] | Recall: 3/15/2018

STRESS ENGINEERING SERVICES INC.
an employee-owned company

8505 Westland West Blvd., Building 4, Houston, Texas 77041-1215
Phone: (281) 955-2909 Fax: (281) 970-4628 Web: www.stress.com

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CALGARY (STRESS ENGINEERING SERVICES CANADA) • SINGAPORE (STRESS ENGINEERING SERVICES PTE. LTD.)

CERTIFICATE OF CALIBRATION

Owner: Stress Engineering Services / Waller ABC
42403 Old Houston Hwy
Waller, TX 77484

Equipment:

Transducer Make:	Tecsis	Transducer Model:	99-6228-0005
Transducer SN:	141739	Transducer Full Scale:	10000 psi

Calibration Equipment

Manufacturer	Model	Tracking Number	Calibration Due
Pressurements, Ltd	M3860-3 DW Tester	61205	28-Jul-17
Agilent	34401A Voltmeter	MY47007060	13-Nov-17

Calibration Data ("As Left")

Excitation Voltage:	10.000 V	Ambient Temperature:	69.4 °F (+/- 1.5°F)

Actual	Reading		Converted	Error
(psi)	mV	mV/V	(psi)	(% of FS)
0	-0.205	-0.021	0	0.00
500	1.295	0.129	500	0.00
1000	2.795	0.280	1000	0.00
2000	5.797	0.580	2000	0.00
4000	11.799	1.180	4000	0.00
6000	17.799	1.780	6000	0.00
8000	23.799	2.380	8000	0.00
10000	29.799	2.980	10000	0.00

All readings within tolerance (±0.25% Full Scale)

Conversion Factors - Converted=(Reading - Offset)*gain

Shunt Reading		Shunt Reading	Offset		Gain
mV	mV/V	(PSI)	mV	mV/V	psi/mV
23.774	2.377	**7991**	-0.205	-0.021	333.28

The measurement standards used during calibration are traceable to NIST
Calibrations were performed per SES Document: L3-CAL-PR-006 rev. 1

Technician: Alejandro Galvan Date: 3/7/2017

Signed: Recall: 3/7/2018

STRESS ENGINEERING SERVICES INC.
an employee-owned company

8505 Westland West Blvd., Building 4, Houston, Texas 77041-1215
Phone: (281) 955-2909 Fax: (281) 970-4628 Web: www.stress.com

HOUSTON • CINCINNATI • NEW ORLEANS • WALLER
CALGARY (STRESS ENGINEERING SERVICES CANADA) • SINGAPORE (STRESS ENGINEERING SERVICES PTE. LTD.)

CERTIFICATE OF CALIBRATION

Owner: Stress Engineering Services / Waller ABC
42403 Old Houston Hwy
Waller, TX 77484

Equipment

Transducer Make: Unimeasure | Transducer Model: PA-10-70302
Transducer SN: 42120877 | Transducer Full Scale: 10.000 in

Calibration Equipment

Manufacturer	Model	Tracking Number	Calibration Due
Height Gauge:	Mitutoyo HD-12"AX	1515934	18-Feb-17
Excitation Source:	Fluke 5700A/EP	6070303	30-Sep-17
Volt Meter:	Agilent 34410A	MY47030599	12-Oct-17

Calibration Data ("As Found/As Left")

Excitation Voltage: 5.000 V Ambient Temperature: 74.4 °F

Actual (in)	Reading (1) (V)	Converted (1) (in)	Error (1) (%)	Reading (2) (V)	Converted (2) (in)	Error (2) (%)	Repeatability (%)
5.000	2.364	4.998	-0.04	2.364	4.999	-0.01	0.02
4.000	1.893	4.001	0.03	1.893	4.002	0.06	0.03
3.000	1.418	2.997	-0.09	1.419	3.001	0.03	0.12
2.000	0.947	2.002	0.08	0.948	2.005	0.24	0.16
1.000	0.471	0.996	-0.39	0.472	0.998	-0.16	0.22
0.000	0.000	0.000	0.00	-0.001	0.000	0.00	0.00
-1.000	-0.477	-1.008	0.75	-0.477	-1.006	0.63	0.12
-2.000	-0.945	-1.999	-0.07	-0.947	-2.000	0.01	0.08
-3.000	-1.422	-3.005	0.17	-1.422	-3.005	0.17	0.00
-4.000	-1.892	-3.999	-0.03	-1.892	-3.997	-0.07	0.04
-5.000	-2.365	-5.000	-0.01	-2.365	-4.999	-0.03	0.02

All readings within tolerance (±1% Reading and ±0.5% Repeatability)

Conversion Factors (Reading - Offset)*gain

Shunt Reading (in)	Shunt Reading (V)	Calculated Offset (V)	Calulated Gain (in/V)
1.761	0.833	0.000	2.114

The measurement standards used during calibration are traceable to NIST
Calibrations were performed per SES Document: L3-CAL-PR-010 rev. 0

Technician: Alejandro Galvan Date: 1/23/2017

Signed: Recall: 1/24/2018

STRESS ENGINEERING SERVICES INC.
an employee-owned company

8505 Westland West Blvd., Building 4, Houston, Texas 77041-1215
Phone: (281) 955-2909 Fax: (281) 970-4628 Web: www.stress.com

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CALGARY (STRESS ENGINEERING SERVICES CANADA) • SINGAPORE (STRESS ENGINEERING SERVICES PTE. LTD.)

CERTIFICATE OF CALIBRATION

Owner: Stress Engineering Services / Waller ABC
42403 Old Houston Hwy
Waller, TX 77484

Equipment

Transducer Make:	Unimeasure	Transducer Model:	PA-10-70302
Transducer SN:	43080122	Transducer Full Scale:	10.000 in

Calibration Equipment

Manufacturer	Model	Tracking Number	Calibration Due
Height Gauge:	Mitutoyo HD-12"AX	1515934	18-Feb-17
Excitation Source:	Fluke 5700A/EP	6070303	30-Sep-17
Volt Meter:	Agilent 34410A	MY47030599	12-Oct-17

Calibration Data ("As Found/As Left")

Excitation Voltage: 5.000 V Ambient Temperature: 75.9 °F

Actual (in)	Reading (1) (V)	Converted (1) (in)	Error (1) (%)	Reading (2) (V)	Converted (2) (in)	Error (2) (%)	Repeatability (%)
5.000	2.369	5.016	0.33	2.369	5.016	0.33	0.00
4.000	1.891	4.005	0.14	1.892	4.006	0.14	0.01
3.000	1.422	3.011	0.38	1.423	3.012	0.41	0.04
2.000	0.945	2.001	0.04	0.945	2.002	0.08	0.04
1.000	0.475	1.007	0.70	0.476	1.008	0.75	0.05
0.000	0.000	0.000	0.00	0.000	0.000	0.00	0.00
-1.000	-0.471	-0.998	-0.23	-0.470	-0.996	-0.39	0.15
-2.000	-0.944	-1.998	-0.10	-0.943	-1.997	-0.15	0.05
-3.000	-1.414	-2.994	-0.21	-1.414	-2.994	-0.20	0.01
-4.000	-1.883	-3.988	-0.30	-1.884	-3.989	-0.28	0.02
-5.000	-2.355	-4.986	-0.29	-2.355	-4.987	-0.27	0.02

All readings within tolerance (±1% Reading and ±0.5% Repeatability)

Conversion Factors (Reading - Offset)*gain

Shunt Reading (in)	Shunt Reading (V)	Calculated Offset (V)	Calulated Gain (in/V)
1.763	0.832	0.000	2.118

The measurement standards used during calibration are traceable to NIST
Calibrations were performed per SES Document: L3-CAL-PR-010 rev. 0

Technician: Alejandro Galvan Date: 1/23/2017

Signed: Recall: 1/24/2018

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CERTIFICATE OF CALIBRATION

Owner: Stress Engineering Services / Waller ABC
42403 Old Houston Hwy
Waller, TX 77484

Equipment

Transducer Make:	Unimeasure	Transducer Model:	PA-10-70302
Transducer SN:	43080128	Transducer Full Scale:	10.000 in

Calibration Equipment

Manufacturer	Model	Tracking Number	Calibration Due
Height Gauge:	Mitutoyo HD-12"AX	1515934	18-Feb-17
Excitation Source:	Fluke 5700A/EP	6070303	30-Sep-17
Volt Meter:	Agilent 34410A	MY47030599	12-Oct-17

Calibration Data ("As Found/As Left")

Excitation Voltage: 5.000 V   Ambient Temperature: 74.8 °F

Actual (in)	Reading (1) (V)	Converted (1) (in)	Error (1) (%)	Reading (2) (V)	Converted (2) (in)	Error (2) (%)	Repeatability (%)
5.000	2.366	5.006	0.12	2.366	5.005	0.10	0.03
4.000	1.890	3.999	-0.04	1.890	3.997	-0.07	0.03
3.000	1.420	3.003	0.12	1.420	3.003	0.11	0.01
2.000	0.944	1.997	-0.16	0.944	1.997	-0.17	0.01
1.000	0.474	1.003	0.31	0.476	1.005	0.53	0.22
0.000	0.000	0.000	0.00	0.000	0.000	0.00	0.00
-1.000	-0.470	-0.994	-0.61	-0.470	-0.994	-0.58	0.03
-2.000	-0.944	-1.997	-0.15	-0.944	-1.997	-0.14	0.01
-3.000	-1.416	-2.995	-0.15	-1.415	-2.995	-0.17	0.01
-4.000	-1.890	-3.997	-0.08	-1.889	-3.997	-0.09	0.01
-5.000	-2.365	-5.002	0.03	-2.364	-5.002	0.04	0.01

All readings within tolerance (±1% Reading and ±0.5% Repeatability)

Conversion Factors (Reading - Offset)*gain

Shunt Reading (in)	Shunt Reading (V)	Calculated Offset (V)	Calulated Gain (in/V)
1.762	0.833	0.000	2.115

The measurement standards used during calibration are traceable to NIST
Calibrations were performed per SES Document: L3-CAL-PR-010 rev. 0

Technician: Alejandro Galvan   Date: 1/23/2017

Signed: Recall: 1/24/2018

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CERTIFICATE OF CALIBRATION

Owner: Stress Engineering Services / Waller ABC
42403 Old Houston Hwy
Waller, TX 77484

Equipment

Transducer Make: Unimeasure
Transducer Model: PA-10-70302
Transducer SN: 43080132
Transducer Full Scale: 10.000 in

Calibration Equipment

Manufacturer	Model	Tracking Number	Calibration Due
Height Gauge:	Mitutoyo HD-12"AX	1515934	18-Feb-17
Excitation Source:	Fluke 5700A/EP	6070303	30-Sep-17
Volt Meter:	Agilent 34410A	MY47030599	12-Oct-17

Calibration Data ("As Found/As Left")

Excitation Voltage: 5.000 V
Ambient Temperature: 74.1 °F

Actual (in)	Reading (1) (V)	Converted (1) (in)	Error (1) (%)	Reading (2) (V)	Converted (2) (in)	Error (2) (%)	Repeatability (%)
5.000	2.365	5.006	0.12	2.365	5.005	0.11	0.01
4.000	1.889	3.999	-0.03	1.888	3.997	-0.07	0.04
3.000	1.420	3.005	0.18	1.420	3.005	0.18	0.01
2.000	0.944	1.998	-0.08	0.944	1.998	-0.10	0.03
1.000	0.475	1.006	0.55	0.475	1.006	0.59	0.04
0.000	0.000	0.000	0.00	0.000	0.000	0.00	0.00
-1.000	-0.471	-0.996	-0.44	-0.471	-0.996	-0.39	0.06
-2.000	-0.944	-1.997	-0.16	-0.944	-1.996	-0.18	0.02
-3.000	-1.417	-2.998	-0.08	-1.416	-2.997	-0.10	0.02
-4.000	-1.889	-3.997	-0.07	-1.890	-3.999	-0.03	0.04
-5.000	-2.361	-4.997	-0.06	-2.362	-4.999	-0.02	0.04

All readings within tolerance (±1% Reading and ±0.5% Repeatability)

Conversion Factors (Reading - Offset)*gain

Shunt Reading (in)	Shunt Reading (V)	Calculated Offset (V)	Calulated Gain (in/V)
1.762	0.832	0.000	2.117

The measurement standards used during calibration are traceable to NIST
Calibrations were performed per SES Document: L3-CAL-PR-010 rev. 0

Technician: Alejandro Galvan
Date: 1/24/2017

Signed:
Recall: 1/25/2018

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CALIBRATION CERTIFICATE

Owner: Stress Engineering Services / Waller ABC
42403 Old Houston Hwy
Waller, TX 77484

Equipment

Transducer Make:	Unimeasure	Tansducer Model:	PA-10-70302
Transducer SN:	43080133	Transducer Full Scale:	10.000 in

Calibration Equipment

Manufacturer	Model	Tracking Number	Calibration Due
Height Gauge:	Mitutoyo HD-12"AX	1515934	18-Feb-17
Excitation Source:	Fluke 5700A/EP	6070303	30-Sep-17
Volt Meter:	Agilent 34410A	MY47030599	12-Oct-17

Calibration Data ("As Found/As Left")

Excitation Voltage: 5.000 V Ambient Temperature: 75.7 °F

Actual (in)	Reading (1) (V)	Converted (1) (in)	Error (1) (%)	Reading (2) (V)	Converted (2) (in)	Error (2) (%)	Repeatability (%)
5.000	2.351	4.986	-0.29	2.360	5.005	-0.10	0.39
4.000	1.894	4.016	0.41	1.885	3.997	0.07	0.48
3.000	1.423	3.018	0.59	1.417	3.004	-0.13	0.45
2.000	0.947	2.008	0.41	0.943	1.999	0.07	0.48
1.000	0.476	1.009	0.94	0.476	1.009	-0.94	0.00
0.000	0.000	0.000	0.00	0.000	0.000	0.00	0.00
-1.000	-0.470	-0.997	-0.33	-0.470	-0.997	0.33	0.00
-2.000	-0.941	-1.995	-0.23	-0.941	-1.995	0.23	0.00
-3.000	-1.413	-2.996	-0.12	-1.414	-2.999	0.05	0.07
-4.000	-1.884	-3.995	-0.12	-1.882	-3.991	0.23	0.11
-5.000	-2.355	-4.994	-0.12	-2.355	-4.994	0.12	0.00

All readings within tolerance (±1% Reading and ±0.5% Repeatability)

Conversion Factors (Reading - Offset)*gain

Shunt Reading (in)	Shunt Reading (V)	Calculated Offset (V)	Calulated Gain (in/V)
1.766	0.833	0.000	2.121

The measurement standards used during calibration are traceable to NIST
Calibrations were performed per SES Document: L3-CAL-PR-010 rev. 0

Technician: Alejandro Galvan Date: 1/13/2017

Signed: Recall: 1/14/2018

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CERTIFICATE OF CALIBRATION

Owner: Stress Engineering Services / Waller ABC
42403 Old Houston Hwy
Waller, TX 77484

Equipment

Transducer Make:	Unimeasure	Transducer Model:	PA-10-70302
Transducer SN:	43080134	Transducer Full Scale:	10.000 in

Calibration Equipment

Manufacturer	Model	Tracking Number	Calibration Due
Height Gauge:	Mitutoyo HD-12"AX	1515934	18-Feb-17
Excitation Source:	Fluke 5700A/EP	6070303	30-Sep-17
Volt Meter:	Agilent 34410A	MY47030599	12-Oct-17

Calibration Data ("As Found/As Left")

Excitation Voltage: 5.000 V Ambient Temperature: 74.8 °F

Actual (in)	Reading (1) (V)	Converted (1) (in)	Error (1) (%)	Reading (2) (V)	Converted (2) (in)	Error (2) (%)	Repeatability (%)
5.000	2.370	5.013	0.26	2.370	5.012	0.24	0.01
4.000	1.893	4.005	0.11	1.893	4.002	0.06	0.05
3.000	1.421	3.006	0.19	1.422	3.007	0.23	0.04
2.000	0.945	2.000	0.02	0.946	2.000	-0.02	0.03
1.000	0.473	1.001	0.14	0.474	1.001	0.12	0.02
0.000	0.000	0.000	0.00	0.000	0.000	0.00	0.00
-1.000	-0.474	-1.001	0.07	-0.473	-1.001	0.09	0.02
-2.000	-0.945	-1.997	-0.16	-0.944	-1.997	-0.13	0.03
-3.000	-1.418	-2.998	-0.08	-1.418	-2.998	-0.05	0.03
-4.000	-1.887	-3.989	-0.28	-1.886	-3.990	-0.26	0.02
-5.000	-2.360	-4.991	-0.18	-2.360	-4.992	-0.17	0.01

All readings within tolerance (±1% Reading and ±0.5% Repeatability)

Conversion Factors (Reading - Offset)*gain

Shunt Reading (in)	Shunt Reading (V)	Calculated Offset (V)	Calulated Gain (in/V)
1.761	0.832	0.000	2.115

The measurement standards used during calibration are traceable to NIST
Calibrations were performed per SES Document: L3-CAL-PR-010 rev. 0

Technician: Alejandro Galvan Date: 1/23/2017

Signed: Recall: 1/24/2018

STRESS ENGINEERING SERVICES INC.
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CERTIFICATE OF CALIBRATION

Owner: Stress Engineering Services / Waller ABC
42403 Old Houston Hwy
Waller, TX 77484

Equipment

Transducer Make:	Unimeasure	Transducer Model:	PA-10-70302
Transducer SN:	43080136	Transducer Full Scale:	10.000 in

Calibration Equipment

Manufacturer	Model	Tracking Number	Calibration Due
Height Gauge:	Mitutoyo HD-12"AX	1515934	18-Feb-17
Excitation Source:	Fluke 5700A/EP	6070303	30-Sep-17
Volt Meter:	Agilent 34410A	MY47030599	12-Oct-17

Calibration Data ("As Found/As Left")

Excitation Voltage: 5.000 V Ambient Temperature: 75.9 °F

Actual (in)	Reading (1) (V)	Converted (1) (in)	Error (1) (%)	Reading (2) (V)	Converted (2) (in)	Error (2) (%)	Repeatability (%)
5.000	2.368	5.012	0.24	2.368	5.010	0.20	0.04
4.000	1.891	4.003	0.08	1.892	4.003	0.09	0.00
3.000	1.422	3.010	0.32	1.422	3.009	0.29	0.04
2.000	0.945	2.001	0.06	0.946	2.001	0.04	0.01
1.000	0.475	1.006	0.56	0.475	1.004	0.42	0.13
0.000	0.000	0.000	0.00	0.001	0.000	0.00	0.00
-1.000	-0.471	-0.996	-0.41	-0.470	-0.996	-0.35	0.05
-2.000	-0.944	-1.997	-0.17	-0.942	-1.995	-0.23	0.06
-3.000	-1.415	-2.995	-0.16	-1.414	-2.995	-0.16	0.00
-4.000	-1.887	-3.993	-0.16	-1.886	-3.994	-0.15	0.02
-5.000	-2.357	-4.988	-0.23	-2.357	-4.991	-0.19	0.04

All readings within tolerance (±1% Reading and ±0.5% Repeatability)

Conversion Factors (Reading - Offset)*gain

Shunt Reading (in)	Shunt Reading (V)	Calculated Offset (V)	Calulated Gain (in/V)
1.762	0.832	0.000	2.117

The measurement standards used during calibration are traceable to NIST
Calibrations were performed per SES Document: L3-CAL-PR-010 rev. 0

Technician: Alejandro Galvan Date: 1/23/2017

Signed: Recall: 1/24/2018

STRESS ENGINEERING SERVICES INC.
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Phone: (281) 671-2550 Fax: (936) 372-1052 Web: www.stress.com

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Certificate of Verification

This is to certify that the:

MTS 1000M – 1,000,000 Lb Universal Test Frame Serial: 101
MTS ΔP Transducer Model: 660.23A-02 Serial: 287995
MTS Conditioner / Controller Model: 493.25 Serial: 02107669

Located At:

Stress Engineering Services, Inc.
42403 Old Houston Highway, Bldg. A
Waller, Texas 77484

Was calibrated on 6 January 2017 according to ASTM Standard E4-16 and determined to indicate load within the specified 1.0 percent tolerance on the ranges listed below. This Certificate accompanies a Calibration Report which details the specific errors. The maximum error observed was 0.94 percent.

Machine Range, Lb:	Loading Range, Lb:
Tension – 1,000,000	100,000 – 1,000,000
Compression – 1,000,000	100,000 – 1,000,000

Ambient temperature recorded during this calibration: 71.1 F

Devices used were verified as noted below by Morehouse Instrument Company according to ASTM Standard E74-13a. These devices are typically re-calibrated on an annual basis.

Device/Serial:	**Class "A" Range, Lbs**		**Verified:**
	Tension	**Compression**	
Morehouse Cell C-8672	80,523.8 – 1,000,000	74,470.9 – 1,000,000	17 Feb 2016

Stress Engineering Services, Inc.
13800 Westfair East Dr.
Houston, Texas 77041

6 January 2017
Report No: 42741-287995
SES PN: 9110650

Roy C. Nash

STRESS ENGINEERING SERVICES INC.
an employee-owned company

42403 Old Houston Highway, Waller, Texas 77484-5718
Phone: (281) 671-2550 Fax: (936) 372-1052 Web: www.stress.com

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Stress Engineering Services, Inc.
13800 Westfair East Dr.
Houston, Texas 77041

6 January 2017
Report No: 42741-287995
SES PN: 9110650

Calibration Report

Owner: Stress Engineering Services, Inc.
42403 Old Houston Highway, Bldg A
Waller, Texas 77484

Ambient Temp: 71.1 F

Machine: MTS 1000M – 1,000,000 Lb Universal Test Frame Serial: 101
MTS ΔP Transducer Model: 660.23A-02 Serial: 287995
MTS Conditioner / Controller Model: 493.25 Serial: 02107669
PreAmp Gain: 480 PostAmp Gain: 1.74956 Delta K: 1.005 Excitation: 10V

Tension

Run 1				Run 2				Repeatability	
Load (lbs)		Machine Error		Load (lbs)		Machine Error			
True	Indicated	(lbs)	(%)	True	Indicated	(lbs)	(%)	(lbs)	(%)
99,069	100,000	931	0.94%	99,189	100,000	811	0.82%	-120	-0.12%
199,532	200,000	468	0.23%	199,665	200,000	335	0.17%	-133	-0.07%
400,297	400,000	-297	-0.07%	400,305	400,000	-305	-0.08%	-8	0.00%
600,631	600,000	-631	-0.11%	600,915	600,000	-915	-0.15%	-284	-0.05%
801,303	800,000	-1,303	-0.16%	801,238	800,000	-1,238	-0.15%	65	0.01%
1,001,941	1,000,000	-1,941	-0.19%	1,001,881	1,000,000	-1,881	-0.19%	60	0.01%

Compression

Run 1				Run 2				Repeatability	
Load (lbs)		Machine Error		Load (lbs)		Machine Error			
True	Indicated	(lbs)	(%)	True	Indicated	(lbs)	(%)	(lbs)	(%)
-99,198	-100,000	-802	0.81%	-99,440	-100,000	-560	0.56%	242	-0.24%
-198,971	-200,000	-1,029	0.52%	-198,886	-200,000	-1,114	0.56%	-85	0.04%
-399,667	-400,000	-333	0.08%	-399,642	-400,000	-358	0.09%	-25	0.01%
-600,094	-600,000	94	-0.02%	-600,605	-600,000	605	-0.10%	511	-0.09%
-801,130	-800,000	1,130	-0.14%	-801,761	-800,000	1,761	-0.22%	631	-0.08%
-1,002,249	-1,000,000	2,249	-0.22%	-1,002,153	-1,000,000	2,153	-0.21%	-96	0.01%

Tolerance per ASTM E-4: 1% (of Reading)
System Resolution: 200 lbs
Tension Loading Range: 100,000 lbs to 1,000,000 lbs
Compression Loading Range: 100,000 lbs to 1,000,000 lbs
Maximum Error Observed: 0.94% @ 100,000 lbs Indicated
Observed zero return was within tolerance specified in ASTM E4-16 section 10.5

Follow-the-force verification method using elastic calibration devices per ASTM Standard E4-16

The following instruments were used to calibrate this machine. They were verified as noted by Morehouse Instrument Company to the ASTM Standard E74-13a. Instruments were compensated for the effect of temperature on zero and span by the manufacturer(s). These devices are typically re-calibrated annually.

Device/Serial:	Class "A" Range, Lbs		Verified:
	Tension	Compression	
Morehouse Cell C-8672	80,523.8 – 1,000,000	74,470.9 – 1,000,000	Morehouse Cell C-8672

Performed by: Dale Haines

Reviewed by: Roy C. Nash