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FULL-SCALE ELEVATED TEMPERATURE TESTING OF COMPOSITE REPAIRS IN BENDING AND COMPRESSION

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ABSTRACT

The increasing use of composite repair systems in critical and complex applications has brought greater scrutiny to their design and performance. This has been especially true in high-temperature, immersed environment applications where ambient temperature test results with industry standard de-rating factors are all that is available for design. Since this approach does not always adequately capture environmental effects or the performance of composite systems at elevated temperatures, it is beneficial to perform full-scale testing which accurately replicates the in-situ application. In order to accomplish this, a full-scale testing program was developed that subjected multiple composite repair systems to internal and external loads at temperatures up to 120 °C with and without water immersion.

This program involved the reinforcement of 12.75-inch x 0.375-inch pipe samples that had simulated corrosion defects. Full-scale load and pressure testing was conducted to simulate the long-term performance of the composite repair systems in the environmental conditions of the application. A strain based performance threshold of 0.4% strain at 120 °C and 100% SMYS was used to develop a competitive program that ranked the participating systems and reduced the number of acceptable repairs from six down to three. This approach increased the efficiency of the full-scale testing and allowed for more in-depth analysis of the top-performing systems.

The results of the full-scale testing of six composite repair systems at elevated temperature allowed for a quantitative measure of their effectiveness under in-situ conditions. Several of the systems were shown to provide inadequate reinforcement under these conditions; however, it was also observed that appropriately designed and installed systems are capable of meeting the intense demands of elevated temperature, harsh-service conditions.

INTRODUCTION

As the promising commercial benefits of composite repair systems continue to be realized in numerous industries, it is inevitable that the desired applications and conditions will increase in severity and technical complexity. This trend is being played out in the oil and gas pipeline industry where composite reinforcement systems have moved from relatively low strength corrosion mitigation systems to technically advanced tools reinforcing crack-like defects and planar seam flaws [1]. The severity of these advanced applications results in increased scrutiny from both pipeline operators and pipeline regulators due to the extremely high cost of failure. As a result, rigorous test programs are required that ensure performance of repair systems before installation in critical use. These assessments must replicate the external conditions acting on the system, including thermal and chemical elements, in addition to pressure considerations. Previous design philosophies have used de-rating factors to account for thermal effects in the reinforcement systems. It has been shown through testing that these de-rating factors do not always capture the actual performance degradation caused by thermal effects, specifically elevated temperatures [2].

For much of the life of the composite repair industry, small-scale material testing has been an acceptable method of system evaluation. Coupon level testing allows for the measuring of critical system properties such as tensile strength, glass transition temperature, inter-laminar shear capacity, and creep performance. All of these properties can provide valuable information relating to the capabilities of a repair system; however, they only represent individual components of an integrated repair system. A system's complete capabilities are only truly known when full-scale testing is utilized and all of the components of the repair system are forced to work in conjunction.

Design of the composite system described in this paper utilized a full-scale testing regime to represent the 120 °C in-situ conditions present during operation. Since the intended operating conditions subject the composite repair systems to bending and compressive loads in addition to internal pressure, full-scale tests were developed to simulate the combined loads that will be encountered during the life of the repair. Additionally, the expected in-situ operating environment introduced the possibility of external environment attack and corrosion at the composite-steel interface; therefore requiring testing to mimic these conditions. To reduce the monetary and time requirements of the project, a competitive test program was used to shrink the number of prospective systems from six down to three using a strain-based design threshold of 0.4% strain at 120 °C and an internal pressure of 100% of the pipe's specified minimum yield strength (SMYS). The design threshold of 0.4% strain was based upon previous studies where it was observed that reinforcement systems exhibiting strains of higher than 0.4% were not successful in the long-term reinforcement of similar corrosion anomalies [3]. The strain limit was validated experimentally by Alexander in his work evaluating the reinforcement of corrosion defects for offshore applications. It was found that composite reinforcement designs (namely thickness) that ensured hoop strains in the reinforced steel remained below this threshold were determined to be effective repairs for combined loading conditions including internal pressure, axial tension, and bending. Further, this hoop strain limit was based in part on long-term strain limits for hoop wrapped tanks according to ASME STP/PT-005, Design Factor Guidelines for High Pressure Composite Hydrogen Tanks [6]; which corresponds to a strain limit of 0.4% for carbon fiber systems.

The six initial composite repair systems considered in this study included both carbon fiber and E-glass systems. The distribution of carbon and E-glass systems are listed below according to manufacturer:

- System A – E-glass
- System B – E-glass
- System C – E-glass
- System D – Carbon
- System E – Carbon
- System F – E-glass

This paper presents the full-scale testing methodology used to select a qualified composite reinforcement system for the high temperature application.

TEST METHODS

Three primary methods of full-scale testing were implemented over the course of the test program. Internal pressure testing of the samples served as a screening tool to determine which of the initial six systems would be appropriate candidates for the more costly and complex full-scale bending and compression tests. A short-term pressure test at 120 °C and 100% SMYS served as the first filter through which the six systems were reduced to three. Additional pressure testing and evaluation resulted in two systems being selected for compression and bending testing.

Internal Pressure Testing

Initial qualification of the proposed composite repair systems focused on meeting an agreed upon strain threshold of 0.4% strain at 120 °C and an internal pressure of 100% SMYS. This approach eliminated inadequate repair systems prior to entering the more complex and costly phases of full-scale testing. The repair systems were installed at ambient temperature conditions and followed the repair manufacturer's recommendations. All installations were performed by personnel provided by the repair manufacturers. A 14-hour window after installation was permitted for each manufacturer to post-cure their repair using heating blankets. The test samples used during pressure testing were 12.75-inch x 0.375-inch, Grade X42 pipes that contained a 6-inch x 8-inch region machined to simulate 75% corrosion. A schematic of the test samples is shown in Figure 1. A photograph of the test setup used for internal pressure testing is shown in Figure 2. Induction heating was used to increase the sample temperature to 120 °C. Strain gages were installed in the simulated corrosion region in order to compare the strain reduction provided by each respective reinforcing system. The locations of these strain gages are shown in Figure 3. Not shown in Figure 3 is the location of a fourth gage that was installed on the outside surface of the repairs in the center of the sample. A thermocouple installed on the base pipe near Gage #3 was used to monitor the temperature of the sample. Within 18 hours of the cure period, the samples were heated to 120 °C and then pressurized.

Samples that achieved the required strain criteria in internal pressure testing at 100% SMYS were subjected to a long-term 1,000 hour exposure study which included full immersion at 120 °C to simulate external environment attack followed by short-term pressure-to-failure testing. Figure 4 is a photograph showing one set of samples being submerged. The immersion water solution had 7% chloride and 2.5% sulfate weight percent concentrations. The same sample geometry and strain gage layout was maintained for 1,000 hour testing from earlier pressure testing.

Full-Scale Compression Testing

Two repair systems were selected for use in full-scale compression testing. Operator-defined criteria, in conjunction with the strain-based screening process led to the selection of System D and System F for full-scale compression testing. As with internal pressure testing, compression tests were intended to simulate in-situ operating conditions. Two load cases were considered for each sample. The first load case was a Design Capacity test that involved pressurizing the sample to 72% SMYS and applying a compressive load of approximately 450 kips (1 kip = 1,000 lbs). This load and pressure was held for 30 minutes. The second load case simulated a Hot Shutdown scenario in which the internal pressure was reduced to zero and the compressive load was maintained. Again, the compressive load was held for 30 minutes. Following successful completion of both load cases, the samples were then subjected to increasing compressive loads until gross plastic deformation, as measured by displacement transducers, occurred. All full-scale compressive testing was completed at a temperature of 120 °C.

The samples used in full-scale compression testing were 12.75-inch x 0.375-inch, Grade X60 pipes that contained an 8-inch x 12-inch region machined to simulate 50% corrosion. A schematic of the samples is shown in Figure 5. Strain gages were installed in the corroded region to compare the strain reduction provided by each respective reinforcing system. The layout of these strain gages is shown in Figure 6. A photograph of a compression sample installed in the load frame is given in Figure 7.

Slightly different repair thicknesses were used between the two respective repair manufacturers. System D had a thickness of approximately 0.93-inches while System F had a thickness of approximately 0.69-inches. A greater thickness typically corresponds to a larger number of composite repair layers and affects the amount of reinforcement provided by a given system. The amount of reinforcement required for the application was determined by the repair manufacturers independently.

Full-Scale Bending Testing

The full-scale bend testing samples were the same configuration as those used for full-scale compression testing. Additionally, the strain gage layout was maintained from full-scale compression testing. Bend testing of the two composite reinforcement systems was performed using hydraulic cylinders and a four-point bending test frame. A photograph of the full-scale bend testing setup is shown in Figure 8.

As with full-scale compression testing, two load cases were used to simulate possible in-situ conditions at the repair site. Both load cases were conducted at 120 °C. A Design Capacity test consisted of pressurizing the sample to 72% SMYS and applying a bending moment of 129,073 ft-lbs. This load was applied twice with the sample rotated 180° between each step in order to subject the sample to both tension and compression. In each scenario, the load and internal pressure was maintained for 30 minutes. The second load condition simulated a hot shutdown scenario in which internal pressure was removed while the bending moment was held constant, again for 30 minutes. This was performed such that the simulated corrosion region was placed in compression. Following completion of both load scenarios, the bending moment was increased until failure occurred. The thicknesses used in full-scale bend testing were similar to those used for full-scale compression with System D having a thickness of approximately 0.93-inches and System F having a thickness of approximately 0.69-inches.

RESULTS

Results of the full-scale testing efforts were compared to strain-based thresholds and binary pass-fail criteria associated with expected in-situ load conditions.

Design Strain Threshold Internal Pressure Testing

The results of the pressure test at 120 °C are shown in Figure 9. It can be seen that Systems D, E, and F were the only repairs to remain within the 0.4% strain threshold, and thus, were the three systems selected for additional testing.

1,000 Hour Environmental Exposure Testing

Pressure-to-failure testing following the 1,000 hour soak showed similar failure pressures for each of the repair systems. A photograph of the samples being removed from the 1,000 hour soak is shown in Figure 10. System E exhibited the highest failure pressure with each system achieving a pressure in excess of 160% SMYS. The corresponding failure pressures are listed below in Table 1.

Table 1: Failure pressures following 1,000-hr soak

System	Failure Pressure (psi)	% SMYS
System D	4,141*	168
System E	4,245	171
System F	4,160	168

*The failure pressure recorded in System D was determined following testing to be a fitting leak rather than a failure of the pipe or repair system itself.

Full-Scale Compression Testing

Results of the compression testing at 120 °C showed that both of the tested systems (System D and System F) could survive the operator designated load conditions without gross short-term deformation. Analysis of the long-term life of samples under compressive loading was performed by FEA methods and is reported elsewhere [4]. Failure of the repair systems both occurred in the base pipe outside of the repair location. Plots of axial compressive load versus axial displacement for both samples are shown in Figure 11 and Figure 12.

The maximum loads achieved and a comparison of the maximum failure loads versus the design compressive load is provided in Table 2.

Table 2: Failure loads in full-scale compression testing

System	Maximum Compression Load (kips)	% Design Load
System D	1,088	241
System F	1,045	232

Full-Scale Bending Testing

The operator designed hold periods were successfully completed by both systems in full-scale bend testing. This result was achieved both with the simulated corrosion region in tension and in compression. As with the other tests in the program, both samples then exhibited failure loads in excess of the design load conditions. Plots of the bending moment versus deflection during bending to failure for both systems are shown in Figures 13 and 14. The maximum bending moment achieved by both systems is given in Table 3. Analysis of the long-term life of samples under bending loading was performed by FEA methods and is reported elsewhere [4].

Table 3: Failure moments in full-scale bending testing

System	Maximum Bending Moment (ft-lbs)	% Design Load
System D	297,737	230
System F	297,352	230

DISCUSSION

The primary objective of this test program was to validate the elevated temperature design basis of a select number of qualified repair systems by subjecting them to full scale internal pressure, compression, and bending testing.

This first round of full-scale testing served two important purposes from an operator's business perspective. It allowed for a quantitative measure of the effectiveness of these repairs at temperature, and provided a cost-effective screening tool to minimize the amount of environmental exposure and long-term testing performed. By installing strain gages under the repairs prior to the initial elevated temperature pressure testing, a maximum strain threshold could be specified in order for systems to advance to the next stage of testing. This maximum strain threshold at 120 °C and 100% SMYS was set at 0.4% strain in the reinforced steel membrane. This allowed the experiment to competitively rank several systems while simultaneously imposing an absolute performance threshold on them.

The primary purpose for the environmental exposure testing was to qualify the systems for external environment attack. Corrosion at the composite-steel interface was a primary concern for this test. No significant performance loss was seen after the environmental exposures, and no evidence of environmental attack was found. In fact one of the systems saw a decrease in measured strain in the steel membrane after the exposure, suggesting that additional curing led to improved performance.

The 1,000 hour full-scale testing provided a needed reference point to allow comparison of full scale tests with the long-term creep testing performed. Since the short term samples [2] were all conducted on lab-assembled and oven-cured sheets of composite material, the 1,000-hour test provided a survival proof test at a known stress level, using hand-laid composite on a pipe shape, which is representative of actual in-field install conditions. This gave increased confidence in the creep curve calculated from small scale testing.

Using these tests as a screening tool limited the expense and effort spent analyzing systems that were inadequate for the desired application. Ultimately, two systems were selected to demonstrate their technical capabilities in full-scale axial compression and bending tests at temperature. Limiting the full-scale compression and bending testing to two pre-qualified systems allowed for an acute examination of their performance at elevated temperature while remaining cost-effective for the operator.

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6. ASME STP/PT-005, *Design Guidelines for High Pressure Composite Hydrogen Tanks*, American Society of Mechanical Engineers, 2006

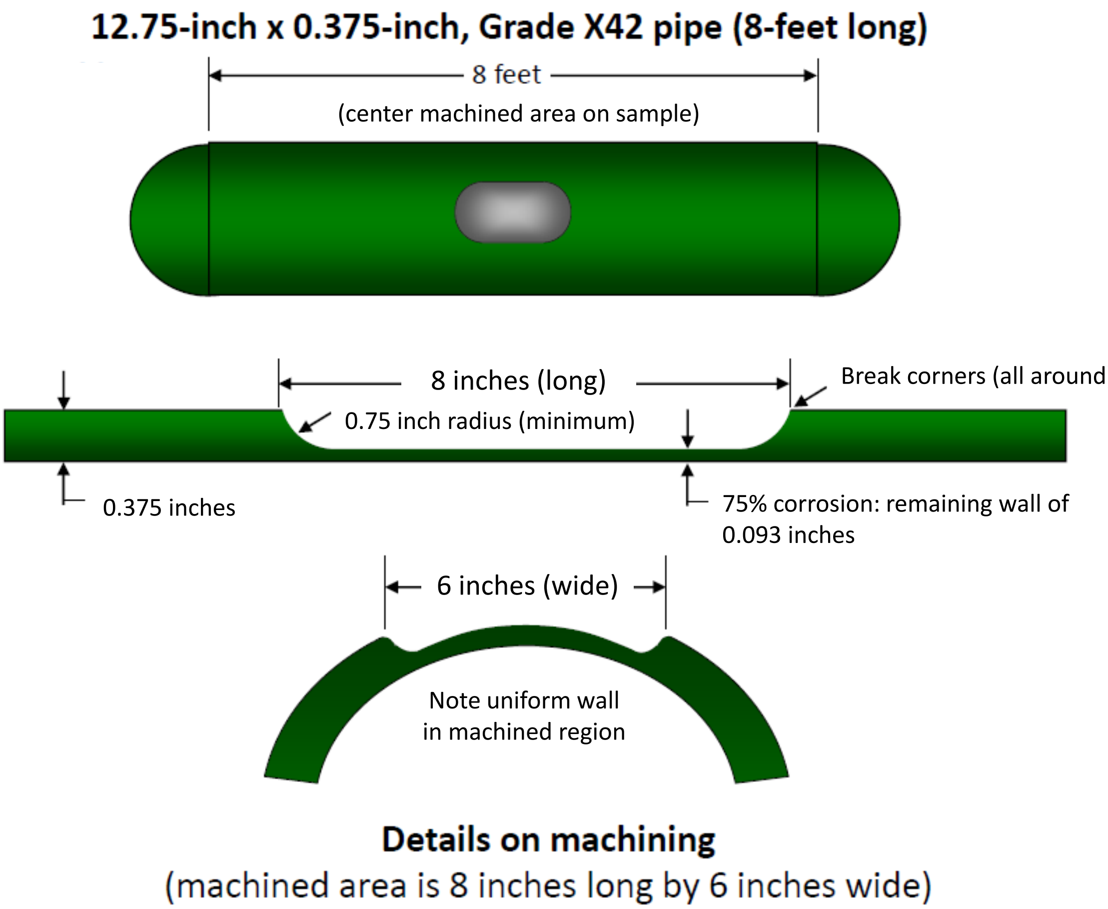


Figure 1: Schematic of simulated corrosion region in internal pressure testing samples
(The 6-inch width is a circumferential arc length and not a straight-line measurement)

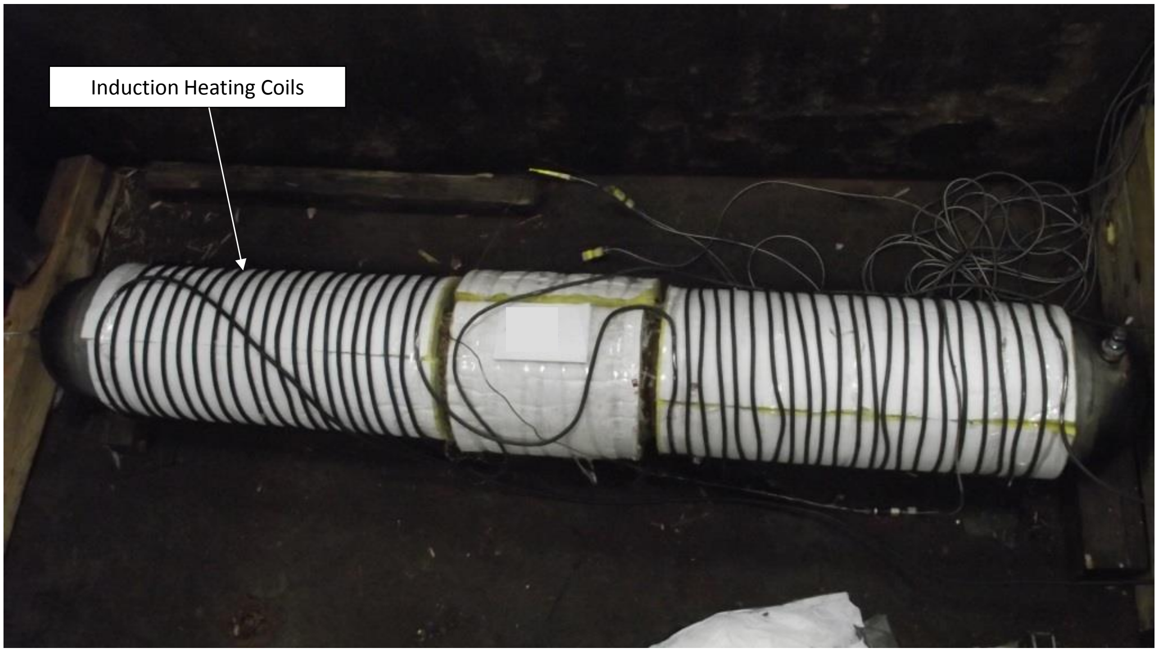
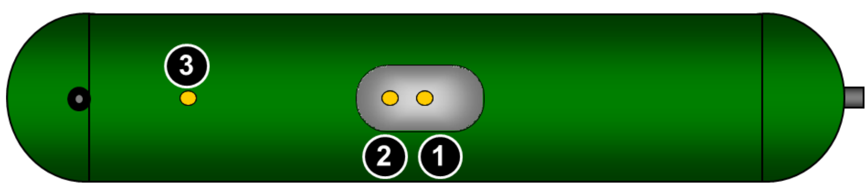


Figure 2: Test Sample wrapped with insulation and induction heating coils



Locations for strain gage installations

(Install thermocouple near Gage #3, insulate sample during pressure test)

Gage #1: centered axially, centered circumferentially
Gage #2: offset 2” axially from Gage #1, centered circumferentially
Gage #3: offset 12” axially from girth weld, centered circumferentially
Gage #4 (not shown): located on outside of repair, centered over simulated corrosion

Figure 3: Location of installed strain gages for internal pressure testing

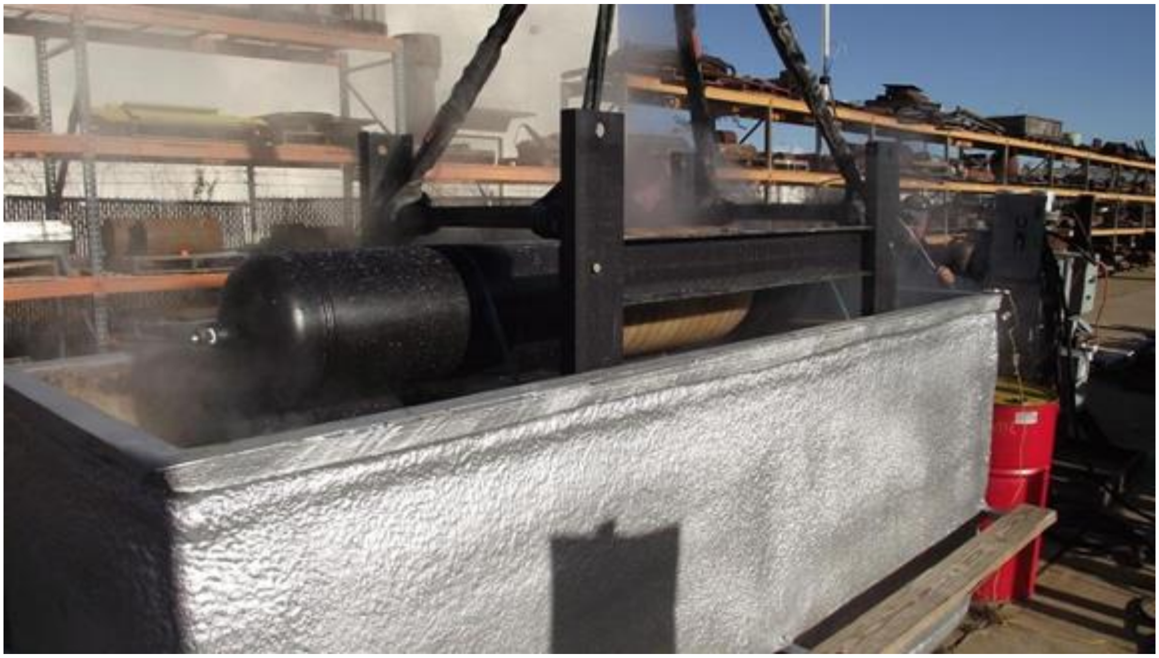


Figure 4: Samples being submerged for 1,000-hour soak

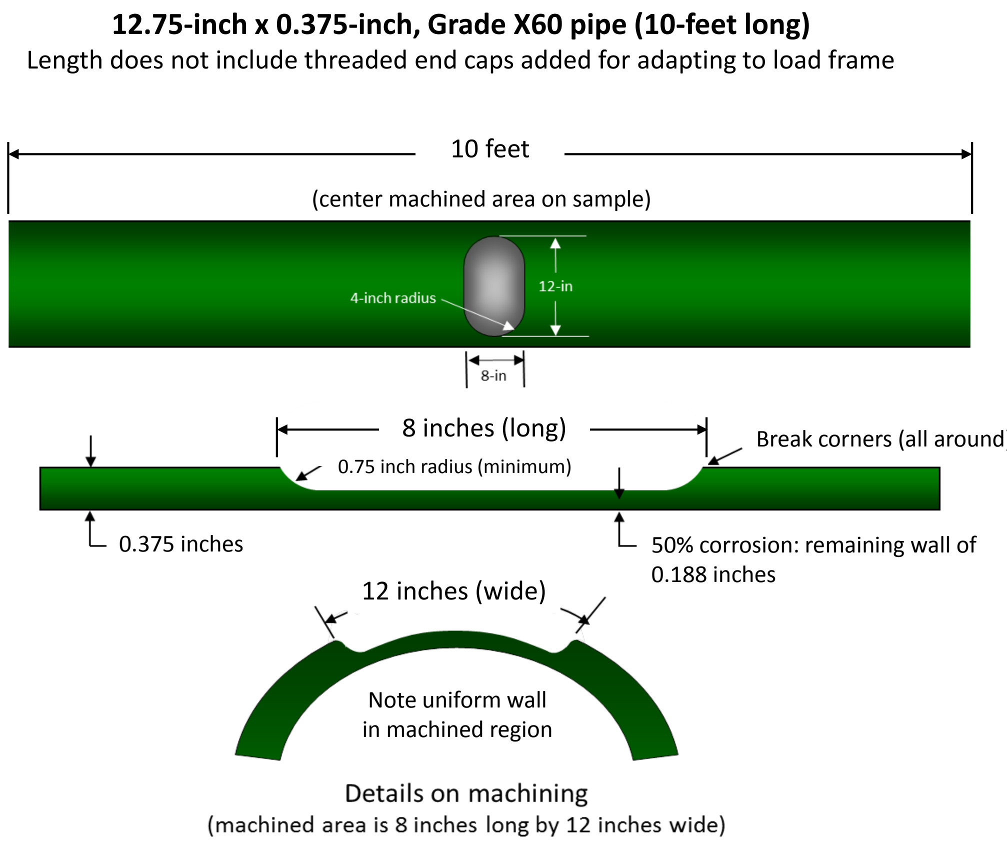
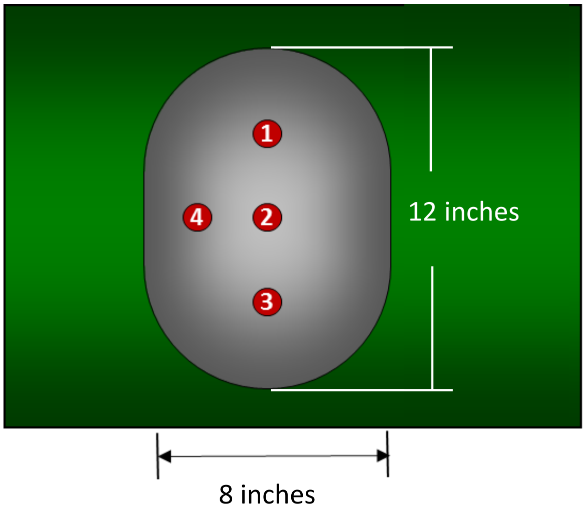


Figure 5: Schematic of simulated corrosion region in compression samples
(The 12-inch width is a circumferential arc length and not a straight-line measurement)



Gages to be spaced equally as shown
Gage #1: centered axially, offset +3 inches circumferentially
Gage #2: centered axially, centered circumferentially
Gage #3: centered axially, offset -3 inches circumferentially
Gage #4: offset -2 inches axially, centered circumferentially

Gage #5: 18 inches axially from end cap girth weld, centered circumferentially
Gage #6: on **TOP** of repair, centered above Gage #2

Figure 6: Location of installed strain gages for compression testing

Figure 7: Compression sample in load frame

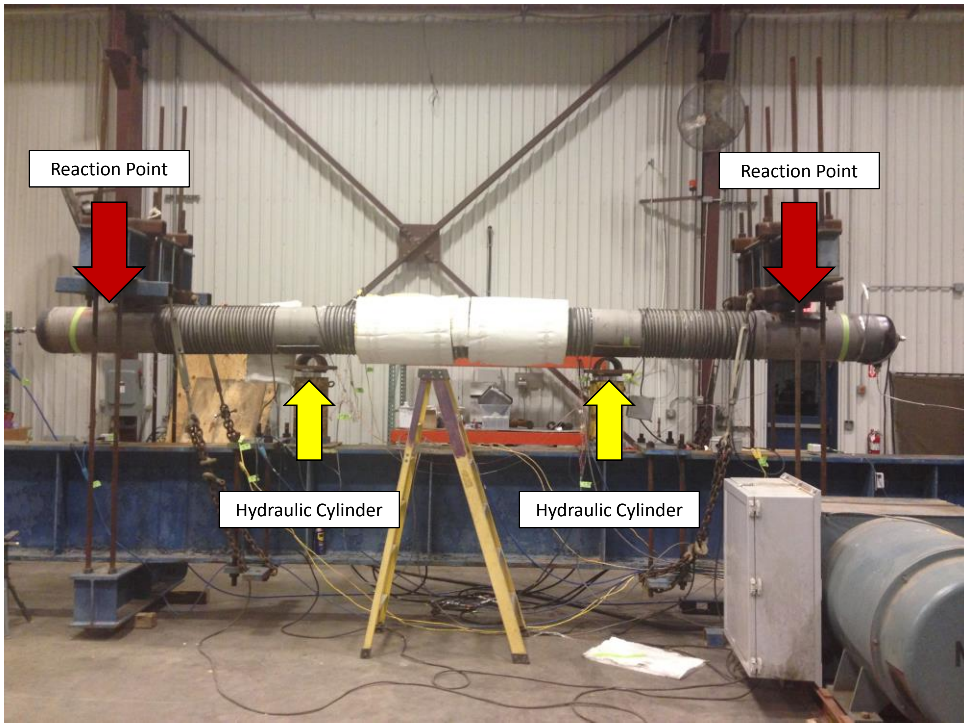


Figure 8: Full-scale bend test setup

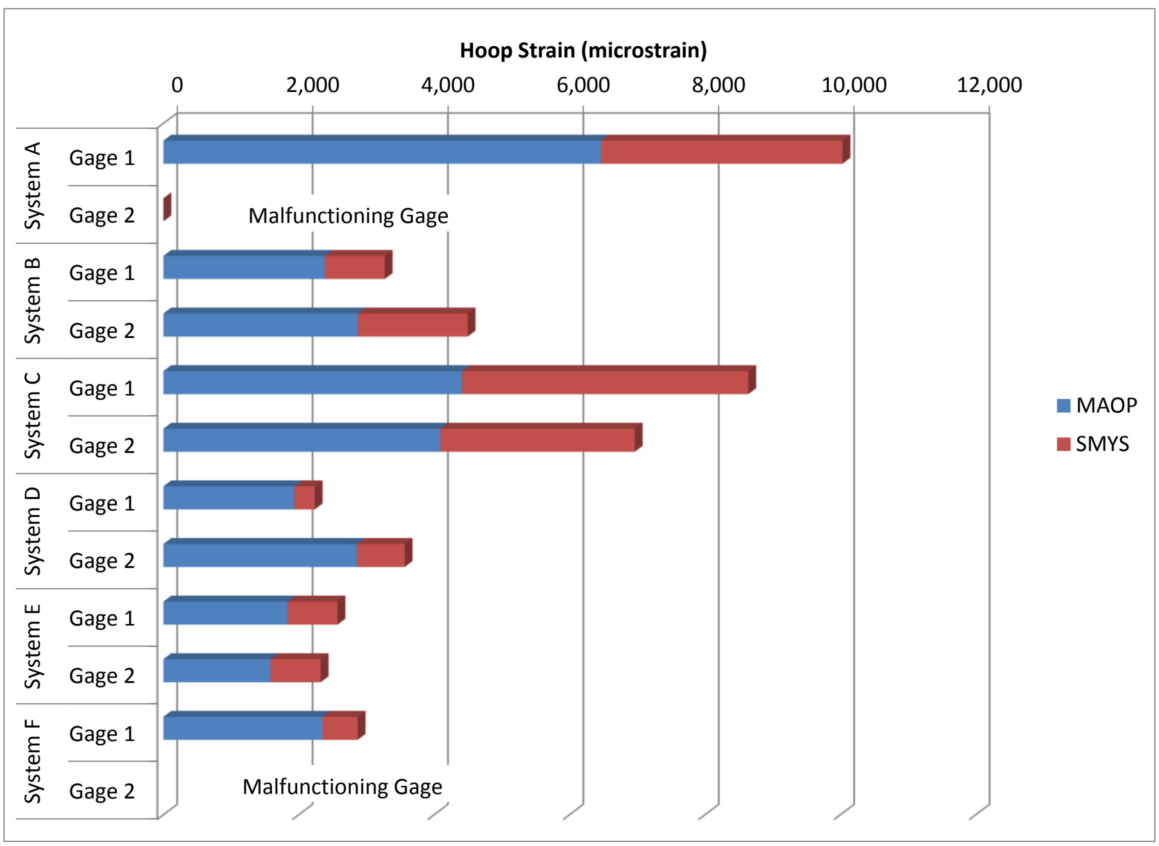


Figure 9: Hoop strain measurements for all systems during internal pressure testing

Figure 10: Samples following 1,000-hour soak at 120 °C in chlorinated water

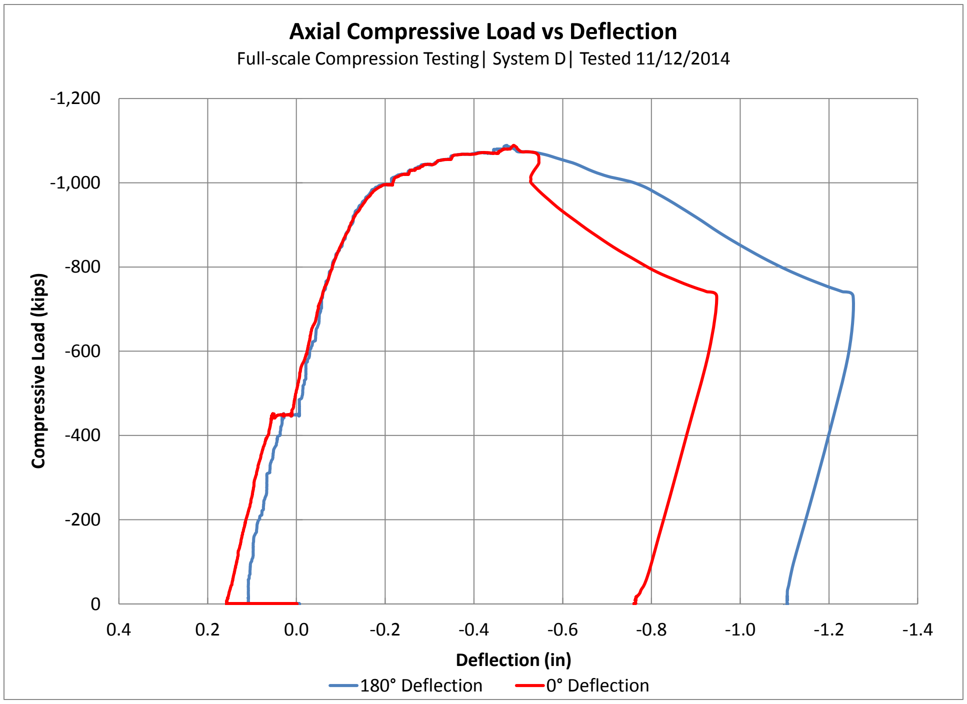


Figure 11: Full-scale compression to failure test – System D

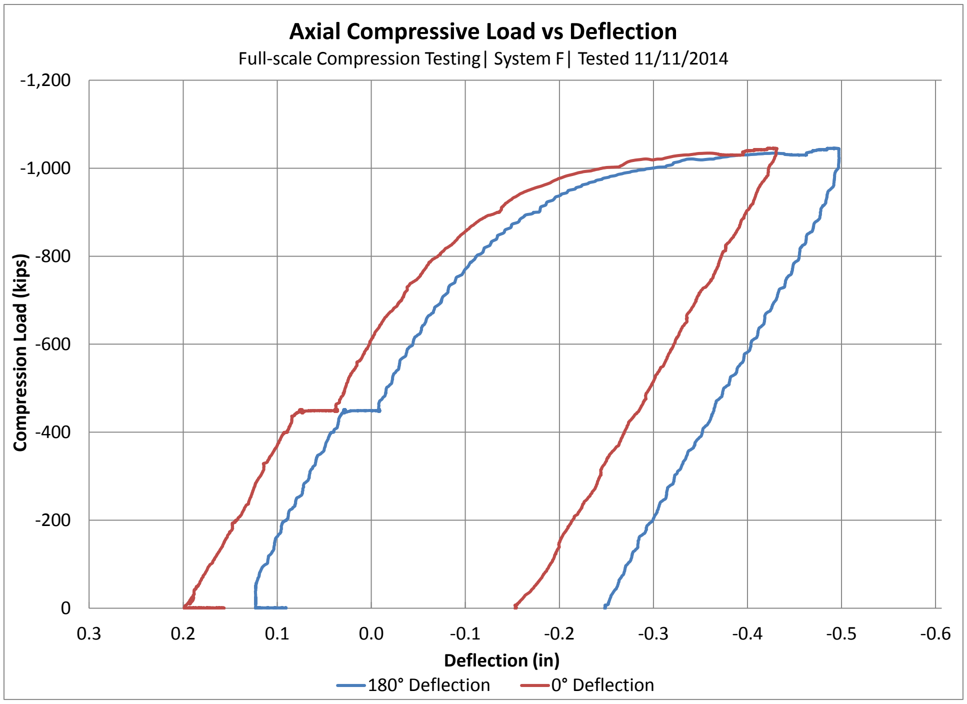


Figure 12: Full-scale compression to failure test – System F

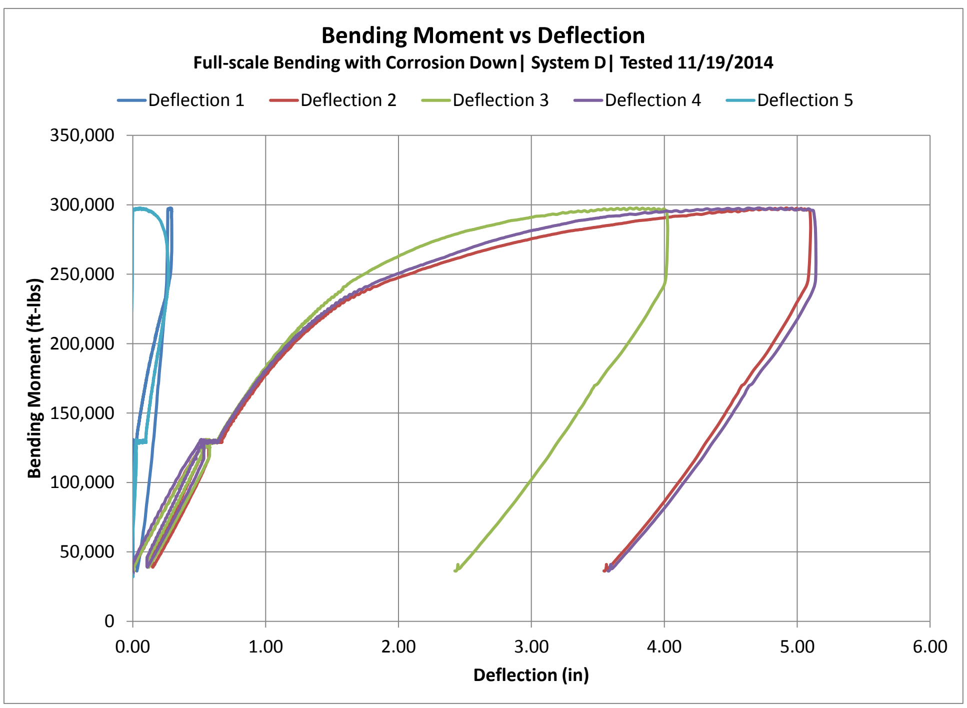


Figure 13: Full-scale bending to failure test – System D

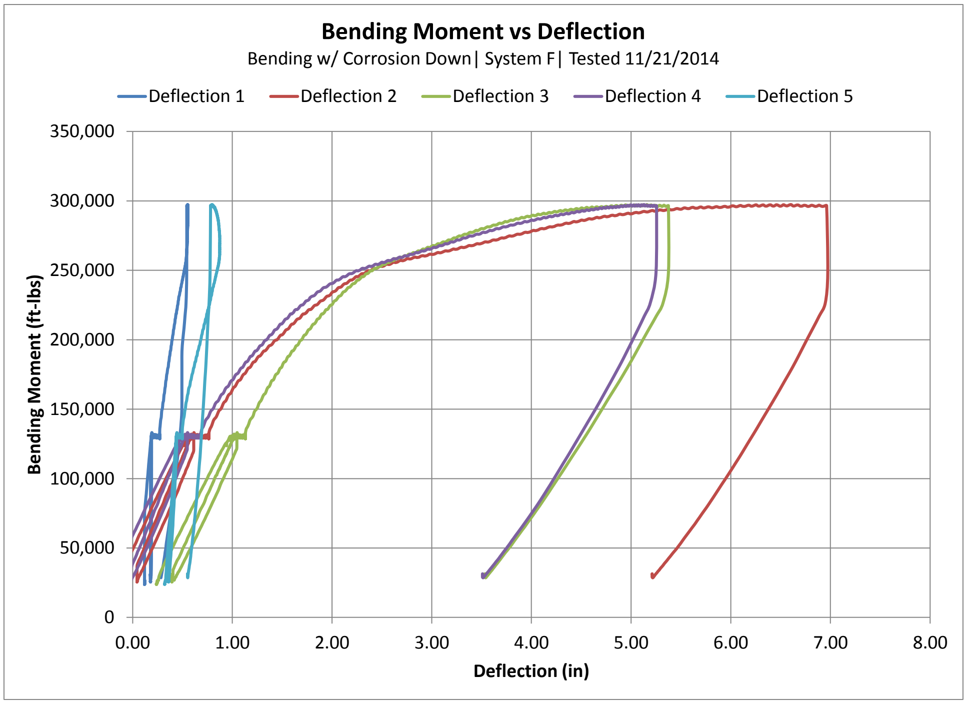


Figure 14: Full-scale bending to failure test – System F