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REINFORCEMENT OF PLANAR DEFECTS IN LOW-FREQUENCY ERW LONG SEAMS USING COMPOSITE REINFORCING MATERIALS

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ABSTRACT

A comprehensive study was conducted to investigate the reinforcement of LF-ERW flaws located in a 16-inch x 0.312-inch (406-mm x 7.93-mm), w.t. Grade X52 ethylene pipeline. The study was prompted by an in-service leak that was discovered in an LF-ERW seam during routine maintenance activities. The investigation was subsequently expanded as a result of the discovery of several additional leaks. An initial failure analysis of the leak location was conducted followed by broader material testing, full-scale testing, and metallurgical analysis of the remaining pipe. The use of composite repair systems as a feasible method of LF-ERW seam reinforcement was also examined. As part of this study, testing was also conducted on 8.625-inch x 0.250-inch. (219-mm x 6.35-mm) pipe material having LF-ERW seams.

Test results documented the potential for composite repair systems to provide reinforcement to LF-ERW flaws and crack-like defects. Distinct contrasts were observed between the performance of samples with unreinforced and reinforced notches subjected to cyclic pressure and burst tests. Reinforced samples exhibited improvements in pressure cycle life and significantly increased burst pressure capacities as compared to unreinforced samples. The results of this program demonstrate that, when properly designed and installed, composite materials are an effective means for reinforcing LF-ERW long seam weld flaws and other planar defects. The composite repairs served to ensure that cracks neither form nor propagate during aggressive pressure cycling and burst testing. It should be noted that the testing program was specific to the operating and material conditions associated with a particular ethylene pipeline that is the subject of this paper.

INTRODUCTION

A study was conducted to investigate the use of composite repair systems to reinforce original manufacturing defects and cracks in LF-ERW seams (LF-ERW: low frequency electrical resistance weld). Full-scale testing was performed on 8.625-inch x 0.250-inch (219-mm x 6.35-mm), Grade X46 and 16-inch x 0.312-inch (406-mm x 7.93-mm), Grade X52 LF-ERW pipe materials with notches installed via electrical discharge machining (EDM) in the long seam welds of the pipe samples to simulate crack-like defects. This study was prompted by the discovery of a leak in a 16-inch (400-mm) ethylene pipeline. The 8-inch (200-mm) samples were taken from a previous project and were included in this study because they contained LF-ERW seams and were the most efficient approach for supplementing the limited amount of 16-inch (400-mm) pipe material available for this particular study.

To investigate the use of composite repairs as a feasible reinforcement technique, a series of pressure tests that included pressure cycling and burst tests were conducted on reinforced and unreinforced pipe samples. The tested composite repairs included systems manufactured by Milliken-Pipe Wrap and Western Specialties. Milliken-Pipe Wrap used its Atlas carbon-epoxy repair system, while Western Specialties installed its ComposiSleeve hybrid steel-composite (water-activated urethane) repair system. The unreinforced samples were tested as reference cases and underwent both cyclic pressure and burst testing. Installation of the repair systems was performed by the manufacturers on 16-inch (400-mm) and 8-inch (200-mm) pipe samples. The 16-inch (400-mm) and 8-inch (200-mm) samples were cut to lengths of 8 ft. (2.44 m) and 4 ft. (1.22 m), respectively.

This paper includes a *Test Methods* section, which provides details on the test samples and testing configuration, while the *Test Results* includes data from the pressure cycle and burst tests. The *Conclusions* section provides several closing comments relating the study's findings to the actual operation of the pipeline.

TEST METHODS

The sections that follow provide information on the test samples used in this test program, along with details on specific aspects of the test program and design details on the composite reinforcing technologies.

Test Sample Details

To simulate the reinforcement of crack-like defects, EDM notches were installed in the 8-inch (200-mm) and 16-inch (400-mm) pipe samples. These notches were located such that they interacted with the pipe's ERW weld seam (bond line). Schematics showing details of the EDM notches, including location and geometry, are provided in Figure 1. Photographs of the EDM notches are shown in Figure 2. Prior to installation of the notches, in-depth inspection efforts were conducted to ensure that the notches were placed in the bond line of the long seam welds. To generate microcracking at the base of the EDM notches, pressure cycles are typically applied to test samples prior to actual testing (including composite installation); however, after multiple failures occurred in less than 100 cycles it was concluded that even without pre-cycling the flaws associated with the LF-ERW seams were adequate for testing.

It can be seen in these schematics and photographs shown in Figure 1 and Figure 2 that three (3) EDM notches were installed per sample. This was done to increase the statistical significance of each sample. The failed samples were examined after testing to ensure that the EDM notches intersected the LF-ERW seam. The samples that did not fail were sectioned through the notch and a metallographic examination was performed to ensure that the notches corresponded with the LF-ERW seam.

Confirmation of the interaction between the EDM notches and the LF-ERW seam line for the 16-inch (400-mm) Milliken-Pipe Wrap reinforced sample is shown in Figure 3; demonstrating that the EDM notch intersected the bond line. The photographs shown are post-test sections taken through the EDM notches (after all phases of pressure cycle and burst testing were completed). This particular ethylene pipeline system does not experience cyclic pressure loading, so there was no reason to perform aggressive pressure cycling or address issues related to fatigue loading.

Test Overview

Both cyclic pressure and burst testing were performed on pipes that had been repaired using the two (2) repair systems. Pressure testing was also conducted on samples with EDM notches that had not been reinforced as a baseline case. Details on the installation and test methods used for each case are provided below.

Installation of Reinforcement Systems

The repair systems were installed at Stress Engineering Services Inc.'s (SES) test facility located in Houston, Texas. The composite repair installations were performed by each respective manufacturer. Prior to installation of the repair systems, the pipe samples were sandblasted to a near-white metal (NACE 2). A photograph of the Atlas system prior to testing is shown in Figure 4. The Atlas system uses a carbon-fiber fabric with a field-impregnated epoxy resin matrix. Photographs showing installation of the ComposiSleeve system are given in Figure 5 and Figure 6. This particular system employs two half-shells that are adhered to the pipe using a high-strength acrylic and overwrapped with a water-activated pre-impregnated E-glass/urethane composite system.

Cyclic Pressure Testing

Cyclic pressure testing was performed prior to burst testing for all samples. The intent in cycling was to provide an opportunity for crack growth at the base of the EDM notch. The desired pressure range for all samples was 10% to 72% of the Specified Minimum Yield Strength (SMYS). For the 8-inch (200-mm) samples, this corresponded to pressures ranging from 267 psi to 1,920 psi (1.84 MPa to 13.24 MPa), while the pressures for the 16-inch (400-mm) samples were 202 psi to 1,460 psi (1.39 MPa to 10.07 MPa). The internal pressure range was monitored using pressure transducers that were continuously recorded. Each sample type (i.e., 8-inch (200-mm) vs. 16-inch (400-mm), repaired vs. unrepaired) had a target number of pressure cycles that was specified prior to the start of testing. Table 1 provides the target number of cycles for each sample type. This particular line does not see a significant number of pressure cycles to pressure conditions were selected in testing to reflect this condition (150 and 350 cycles for the 8-inch (200-mm) and 16-inch (400-mm) pipe, respectively); however, for conservatism the target number of cycles for each size was increased by a factor of 10 for the reinforced test samples. It should be noticed that the quality of the seams in the 8-inch (200-mm) pipe were so poor that several of the test samples failed in the pressure cycle, so that 150 cycles was never reached.

During pressure testing, strain gages and clip gages were used to monitor stresses in the pipes and crack growth in the EDM notches, respectively. Clip gages specifically measured notch growth during cycling and were only installed on the unreinforced samples. Strain gages were able to be installed both on unreinforced and reinforced samples (i.e., the strain gages could be installed beneath some of the repairs). Photographs showing clip gages installed on an unrepaired sample are given in Figure 7. A strain gage installed over an EDM notch is shown in Figure 8; the gage is shown as installed with the ComposiSleeve repair where washers were installed to prevent the gages from being crushed during installation of the steel half-shells. It should be noted that the wire mesh shown in Figure 8 is specific to ComposiSleeve repairs.

Pressure data were provided for the pipeline for approximately 390 days. A rainflow count of the data was completed to assess the number of cycles experienced by this particular pipeline. Plotted in Figure 10 is a histogram showing the results for the pressure data. As observed, this particular pipeline experiences minimal pressure cycling. Using Miner's Rule to develop a single equivalent cycle number for a pressure range of 202–1,460 psi (1.39 MPa to 10.07 MPa) (10% to 72% SMYS) for the given data, the result is 0.52 cycles per year. Using this relation, the 3,500 cycles applied to the 16-inch (400-mm) test samples corresponds to 6,736 years of service (i.e. 3,500 cycles / 0.52 cycles per year). From these data one can conclude that this particular pipeline system experiences minimal pressure cycling.

Burst Testing

Following pressure cycling, the surviving samples were burst tested in a covered pit with bolted shielding. A pressure transducer was used to monitor the internal pressure. Strain gages used during pressure cycling were continuously recorded during burst testing.

Burst testing consisted of an initial pressurization to 90% SMYS to simulate hydrotest conditions as required by the regulators for this pipeline system, which was held for 30 minutes. This corresponded to 2,400 psi (16.55 MPa) for the 8-inch (200-mm) samples and 1,825 psi (12.58 MPa) for the 16-inch (400-mm) samples. Following the hold period, the internal pressure was reduced to zero prior to pressurizing the sample to failure. Values for pressures equal to 72% SMYS, 90% SMYS, and 100% SMYS for both 8-inch (200-mm) and 16-inch (400-mm) samples are provided in Table 2.

Composite Repair Design

A central objective of this program was quantifying performance of the tested composite repair systems. Because this program was the first of its kind in terms of reinforcing cracks in LF-ERW seams, the repair manufacturers recognized the importance of installing adequate amounts of material to minimize crack initiation and propagation. Each manufacturer was responsible for the design of their system, although SES provided some assistance in terms of the amount of material that would be required to minimize strains in the reinforced steel.

The installation procedures employed by both manufacturers were similar to those used for repairing other pipeline anomalies such as corrosion and dents. The thickness of the ComposiSleeve system was similar to what would be expected for a typical corrosion repair; however, the thickness of the Atlas carbon system was thicker than what might be expected for a typical corrosion repair. It is possible that both systems might have been overdesigned (i.e. greater thickness than actually required); however, the solid performance of both systems as demonstrated in testing illustrated the benefits in having thick repairs. At the present time there is no guidance available from the composite repair standards (ASME PCC-2-2015 and ISO 24817), so both manufacturers designed repairs outside conventional designs typically used for the reinforcement of corrosion defects.

Once testing was completed with satisfactory results, all parties participating in this study recognized that follow-on work would likely be conducted to optimize the composite designs by making adjustments to the thickness of the repairs. Provided below are the measured composite repair thicknesses.

- Western Specialties ComposiSleeve
  - 8-inch repairs: 0.25-inch steel | 0.201-inch composite (200-mm repairs:6.35-mm steel | 5.1-mm composite)
  - 16-inch repairs: 0.25-inch steel | 0.220-inch composite (400-mm repairs: 6.35-mm steel | 5.6-mm composite)
- Milliken-Pipe Wrap Atlas
  - 8-inch repairs 0.631-inch composite (200-mm repairs 16-mm composite)
  - 16-inch repairs 0.701-inch composite (400-mm repairs 17.8-mm composite)

TEST RESULTS

This section of the paper provides the results from the test program described previously. Results are presented for both the cyclic pressure and burst testing phases of the program. It should be noted that strain gage results are only presented for the Atlas test samples as strain gage results associated with the ComposiSleeve system were unreliable as they were likely damaged during installation.

Cyclic Pressure Testing

Cyclic pressure testing resulted in all repaired samples achieving the designated 1,500 cycles and 3,500 cycles for 8-inch (200-mm) and 16-inch (400-mm) samples, respectively. Two (2) of the five (5) unreinforced test samples did not reach the target number of cycles during pressure cycling. Failure of these samples occurred during the initial pressure increase of the first cycle. Strain results for several of the samples that did reach the target number of cycles are provided in Figure 11. The strain ranges in these plots were taken from strain gages that were installed across EDM notches. Linear trend lines were added to this plot showing a general strain range increase with the unreinforced samples, while there appear to be minimal strain range changes on the composite material is installed.

In a similar round of tests, base pipe and notch strain data were recorded during pressure cycling of the 16-inch (400-mm) samples. A comparison between the 16-inch (400-mm) unreinforced and reinforced notch data through the first 500 cycles is shown in Figure 12. As observed, the Atlas carbon-epoxy composite system managed to maintain the strain range during pressure cycling to 700 $\mu\varepsilon$ though 500 cycles, while the unreinforced notch gages eventually failed after 350 cycles due to excessive crack growth. Trend lines are included for select data confirming this strain range pattern with increasing cycle number.

A summary of the cyclic pressure testing results can be found in Table 3. In this table, the pressure range and number of cycles completed are given for each of the samples tested. Additionally, details regarding the failure pressures of the two (2) samples that failed during the first pressure cycle are also provided.

Burst Pressure Testing

Burst testing was performed on all samples that reached the target number of cycles during cyclic testing. Comparisons of the results from pressure to failure tests are presented in Table 4; the burst pressures have been averaged for each of the sample groups and compared to the average failure pressure for the respective unreinforced sample set. Each of the reinforced sample sets exhibited an average burst pressure increase of at least 130% relative to the unreinforced samples of the same diameter. All samples, except for Unreinforced Sample #2, which failed at 2,105 psi (14.51 MPa) (79% SMYS), had burst pressures that exceeded 100% SMYS (2,667 psi (18.39 MPa) for the 8-inch (200-mm) pipe and 2,028 psi (13.98 MPa) for the 16-inch (400-mm) pipe).

Strain data were recorded for all of the burst tests. However, for brevity, only results for the Milliken-Pipe Wrap system used to reinforce an 8-inch (200-mm) pipe sample are presented (cf. Figure 13). As observed in this plot, the reinforced sample exhibited lower strain values at a given pressure than those measured in the unreinforced sample. This is shown as a shift to the left (i.e., increase in slope) in the curve plotting pressure versus hoop strain, which represents an increase in stiffness that is required for a repair system to reinforce pipeline anomalies.

A comment is made regarding the ability of the composite reinforcing systems to minimize—or in some cases mitigate—crack growth and propagation. The images provided in Figure 3 were taken after all pressure cycling and burst testing was complete on one of the Milliken-Pipe Wrap samples. These images show that not only was the EDM positioned in the ERW bond line, but that the Milliken-Pipe Wrap Atlas system prevented any growth of the EDM notch.

In addition to testing the anomalies associated with the EDM notches, planar defects removed from the actual pipeline were tested. The defects were identified via an in-line combination magnetic flux leakage tool; the two most significant anomalies found were selected for further composite reinforcement validation testing. Figure 14 includes two photographs showing these two anomalies after burst testing. As noted, both failed at pressures in excess of two times the Maximum Operating Pressure (MOP) of the line and the failure occurred outside the repairs. Shown in Figure 15 is a post flaw inspection of one of the reinforced samples where there appears to be no growth in the flaw during the pressure test.

CONCLUSIONS

The potential for composite repair systems to provide reinforcement to LF-ERW flaws and crack-like defects was demonstrated in this study. Distinct contrasts were observed between the performance of samples with unreinforced and reinforced EDM notches when subjected to cyclic pressure and burst tests. Reinforced samples exhibited improvements in pressure cycle life and significantly increased burst pressure capacities when compared to unreinforced samples. A direct comparison of these results showed that both of the tested reinforcement systems are likely to improve the performance of pipes with crack-like defects to some degree. The results indicate a consistency in performance of the Atlas system, which is crucial to demonstrate a quality repair. The ability of the wet wrap to conform to the outside surface of the pipe, while also providing reinforcement, was a key contributor to the success of this technology.

The results of this study demonstrated that, when properly designed and installed, composite materials are an effective means for reinforcing LF-ERW long seam welds and other planar defects to ensure that cracks neither form nor propagate during aggressive pressure cycling and burst testing. The results associated with this program are applicable to the 16-inch (400-mm) ethylene pipeline. The testing program was specific to the operating and material conditions associated with this particular ethylene pipeline.

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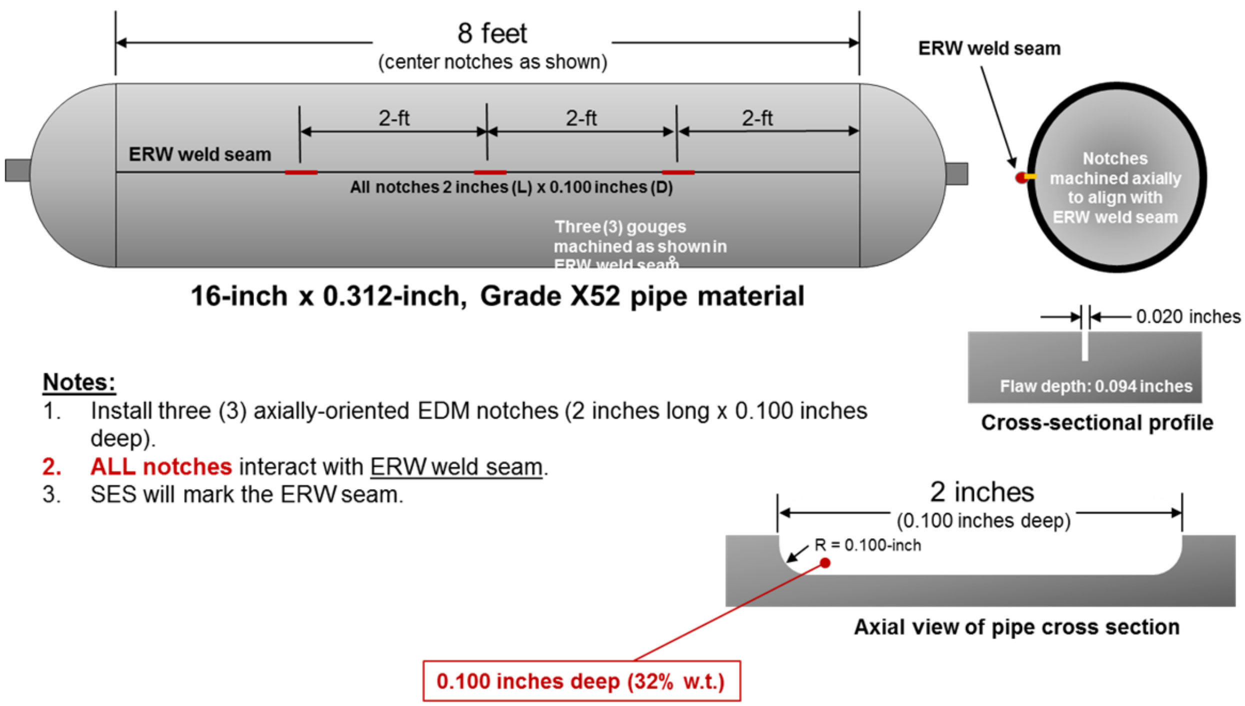

Figure 1: Schematic of 16-inch Pipe Samples with EDM Notches

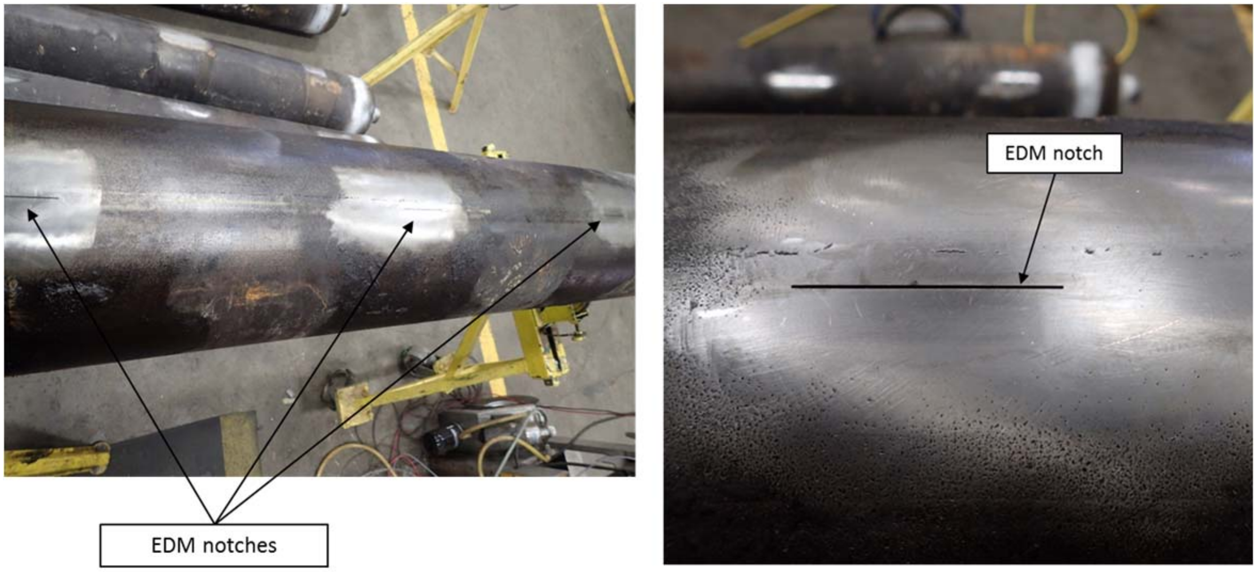

Figure 2: Photographs of EDM Notches

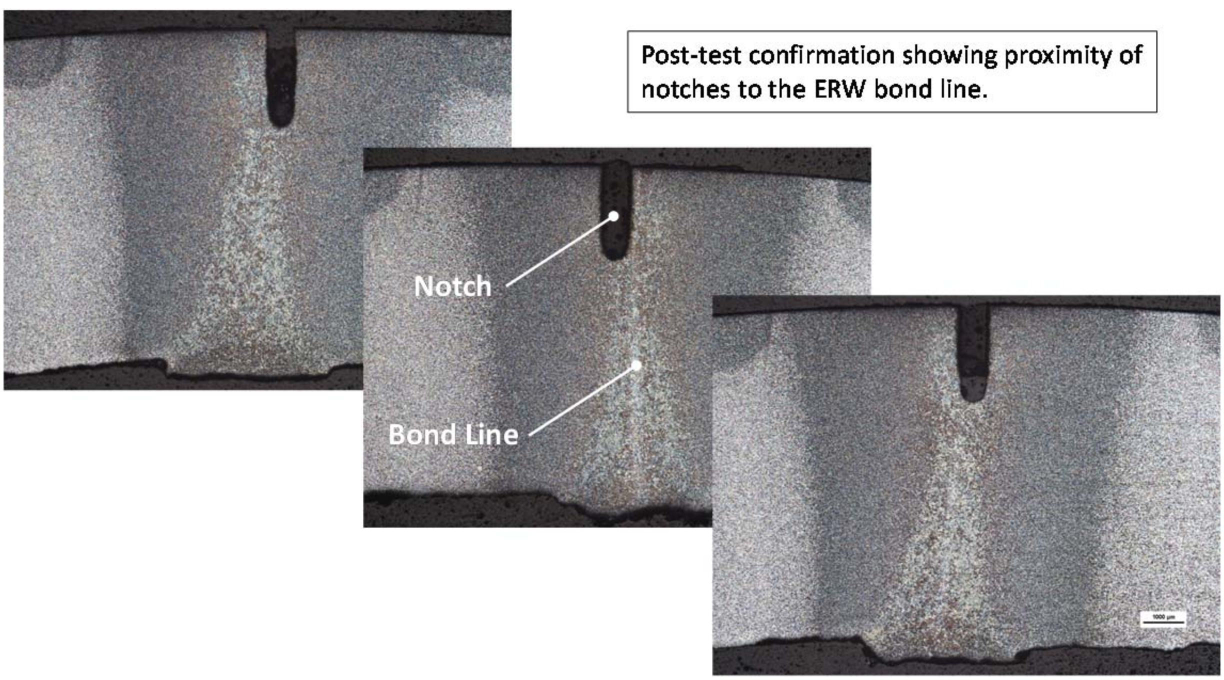

Figure 3: Sections of EDM Notches through LF-ERW Bond Lines of 16-inch pipe
(Taken after burst testing from one of the Milliken-Pipe Wrap samples)

Figure 4: Milliken-Pipe Wrap Atlas System – as Repaired and Set up for Testing

Figure 5: Installation of the Western Specialties ComposiSleeve

Figure 6: Installation of the Western Specialties ComposiSleeve System

Figure 7: Photograph of Clip Gages on Unreinforced Samples

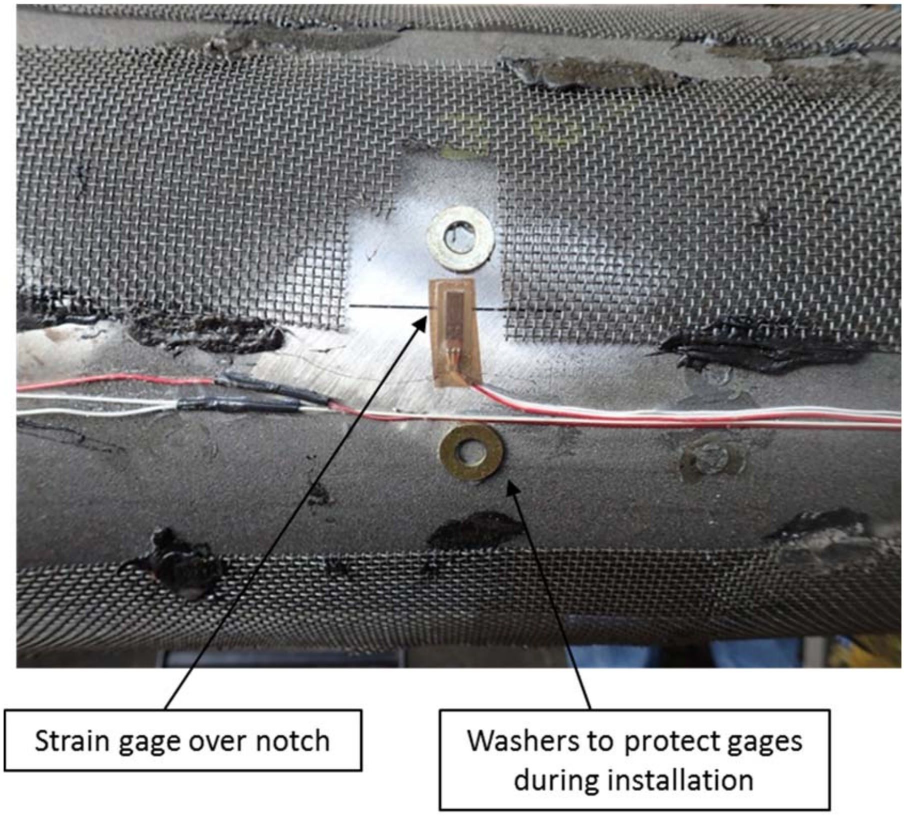

Figure 8: Photograph of Notch Strain Gage on ComposiSleeve Sample

Figure 9: Photograph of Pipe Samples Installed for Pressure Cycling

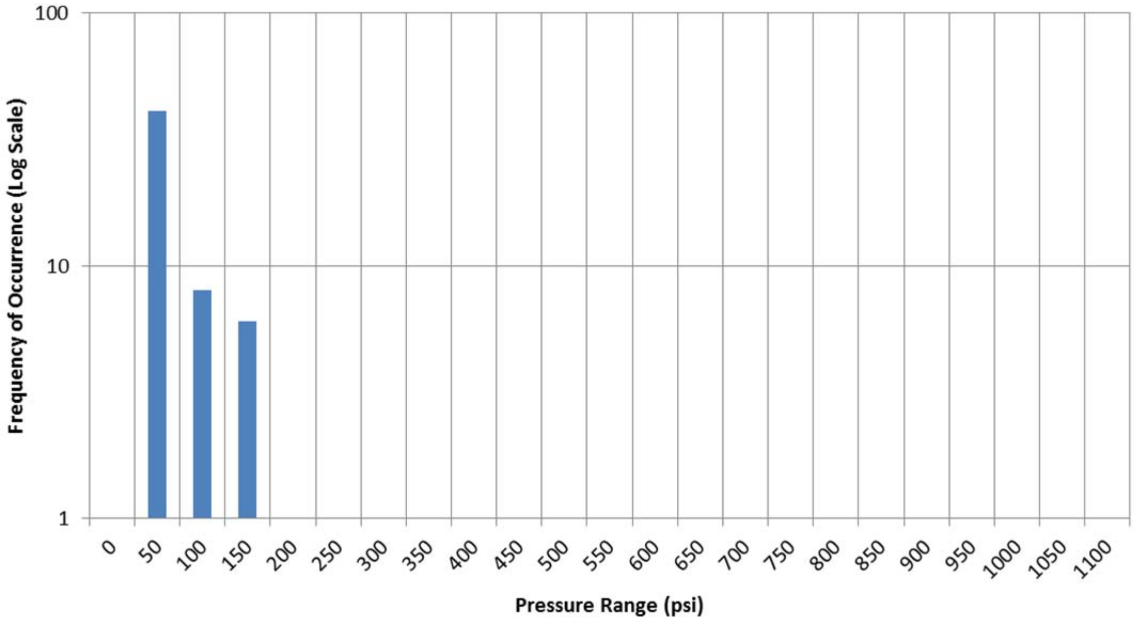

Figure 10: Histogram of Pressure Cycle Data (390 days of data collected)

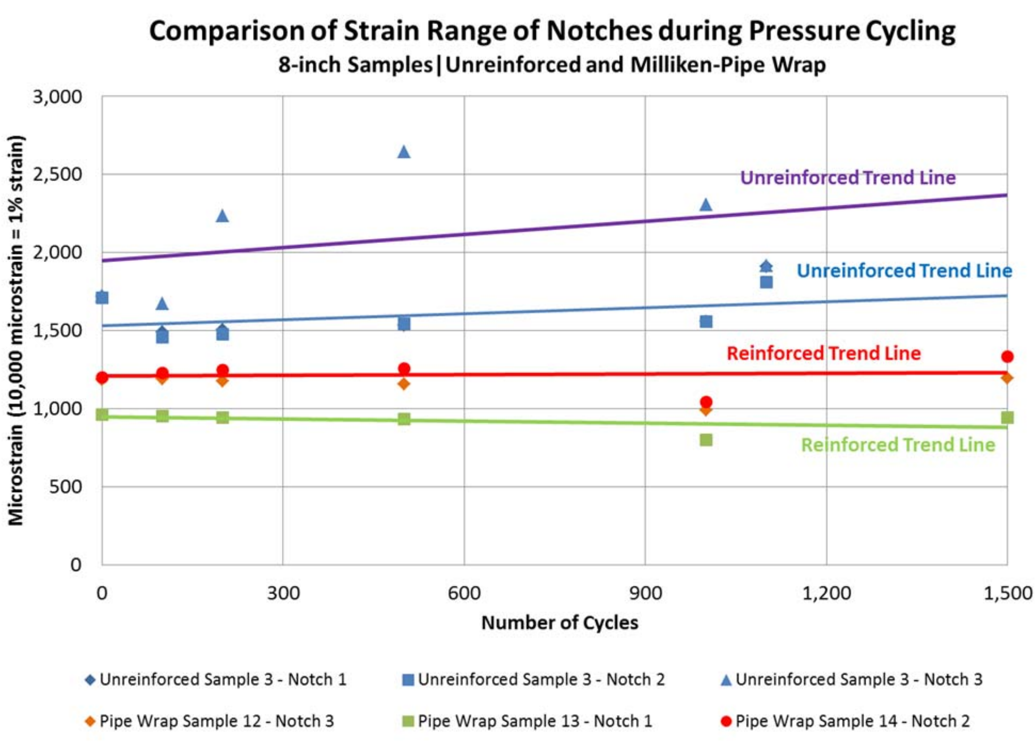

Figure 11: Notch Strain Range vs. Number of Cycles (selected 8-inch diameter samples)

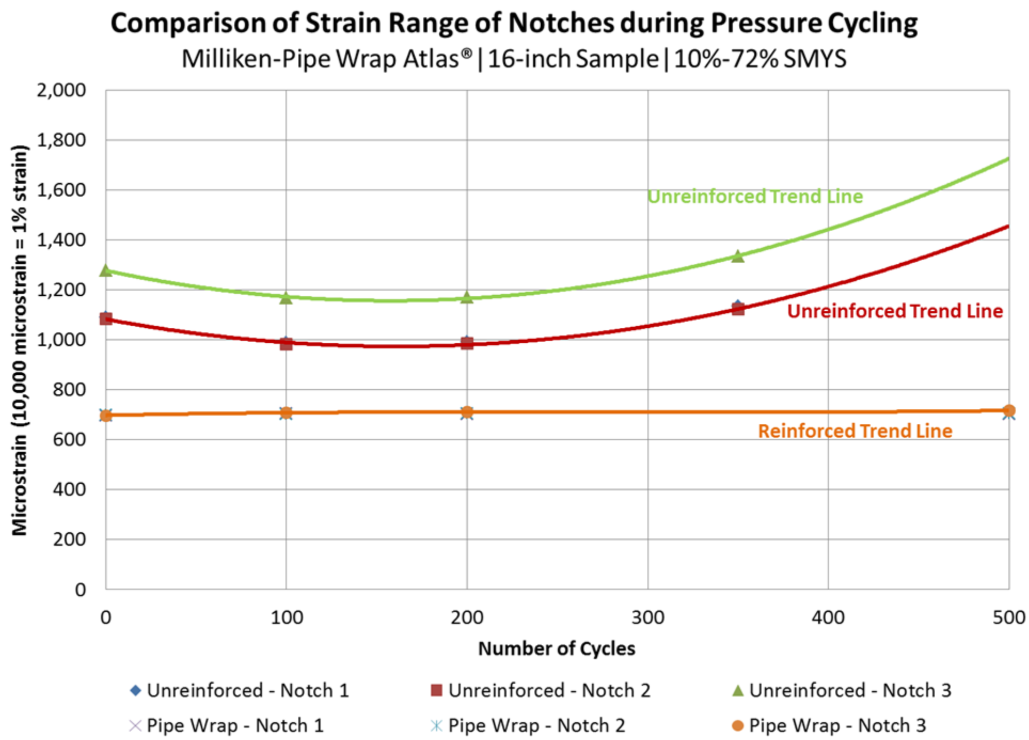

Figure 12: Notch Strain Range vs. Number of Cycles (selected 16-inch diameter samples)

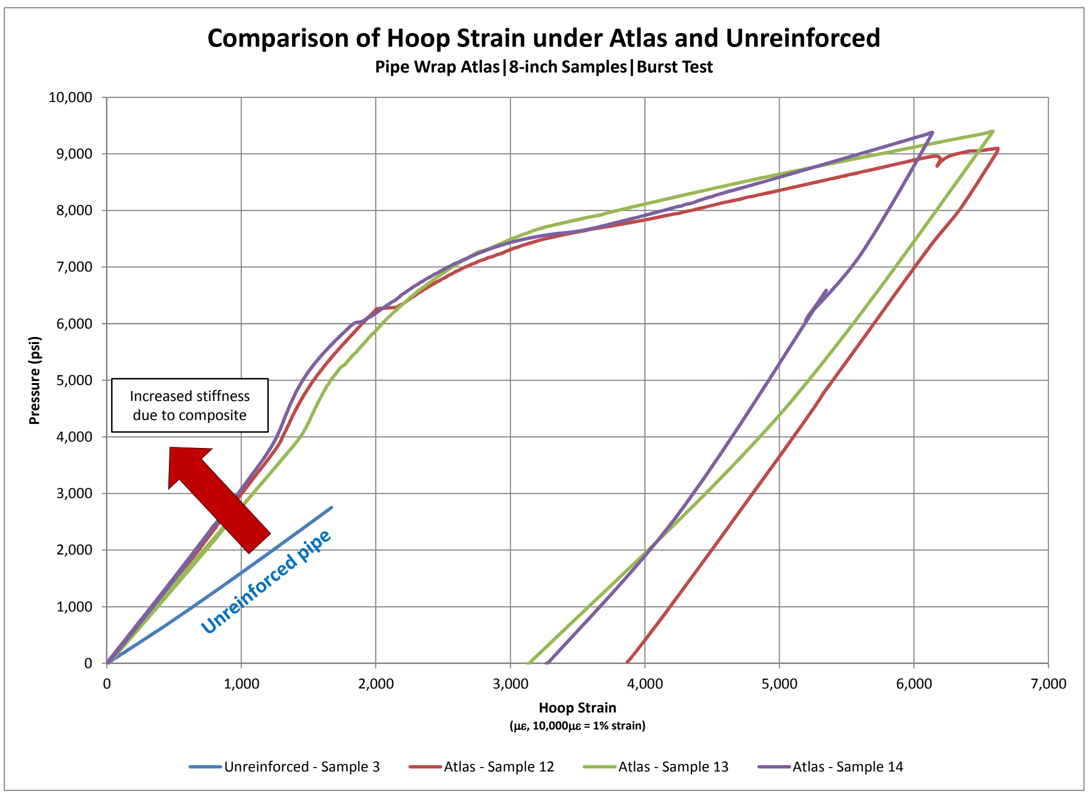

Figure 13: Pressure vs. Hoop Strain (8-inch Milliken-Pipe Wrap Atlas)

Figure 14: Photos Showing Burst Tests of Actual Reinforced Seam Planar Defects

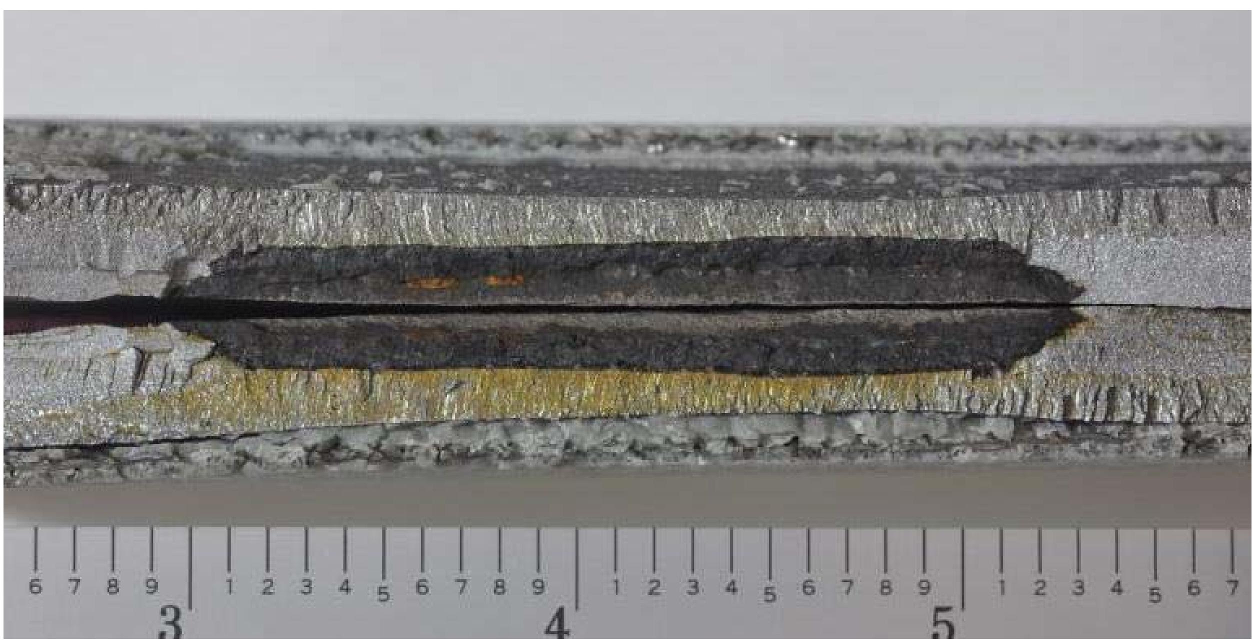

Figure 15: Post Flaw Inspection of EDM notch in Reinforced Sample (Failure Occurred outside Reinforcement)

Table 1: Target Number of Cycles for Reinforced and Unreinforced Samples

Repair Type	Nominal Pipe Diameter	Target Number of Cycles
Unreinforced	8 inches (203 mm)	150
	16 inches (406 mm)	350
Milliken-Pipe Wrap - Atlas	8 inches (203 mm)	1,500
	16 inches (406 mm)	3,500
Western Specialties - ComposiSleeve	8 inches (203 mm)	1,500
	16 inches (406 mm)	3,500

Table 2: Burst Test Samples – Pressures for various percentages of SMYS

Nominal Pipe Diameter	72% SMYS	90% SMYS	100% SMYS
8 inches (203 mm)	1,920 psi (13.24 MPa)	2,400 psi (16.55 MPa)	2,667 psi (18.39 MPa)
16 inches (406 mm)	1,460 psi (10.07 MPa)	1,825 psi (12.58 MPa)	2,028 psi (13.98 MPa)

Table 3: Summary of Pressure Cycling Results

Reinforcement Type	Nominal Pipe Diameter	Sample(s) #	Cyclic Pressure Ranges	Cycles Completed
Unreinforced	8-in (203 mm)	1	267–1,920 psi (1.84–13.24 MPa)	167 (failed during cycling) (NOTE)
Unreinforced	8-in (203 mm)	2, 3	267–1,920 psi (1.84–13.24 MPa)	150
Unreinforced	8-in (203 mm)	4	267–1,920 psi (1.84–13.24 MPa)	1 (Failed at 1,720 psi (11.86 MPa))
Unreinforced	8-in (203 mm)	10	267–1,920 psi (1.84–13.24 MPa)	1 (Failed at 1,554 psi (10.71 MPa))
Unreinforced	16-in (406 mm)	16	202–1,460 psi (1.39–10.07 MPa)	350
Milliken-Pipe Wrap - Atlas	8-in (203 mm)	12 - 14	267–1,920 psi (1.84–13.24 MPa)	1,500
Milliken-Pipe Wrap - Atlas	16-in (406 mm)	15	202–1,460 psi (1.39–10.07 MPa)	3,500
Western Specialties ComposiSleeve	8-in (203 mm)	5, 8, 9	267–1,920 psi (1.84–13.24 MPa)	1,500
Western Specialties ComposiSleeve	16-in (406 mm)	11	202–1,460 psi (1.39–10.07 MPa)	3,500

NOTE: This sample was in some regards “sacrificial” in that the original intent was to apply 1,000 pressure cycles to generate pre-crack in the EDM notch. However, after this sample failure and others failed after one cycle (i.e., Samples #4 and #10); all attempts to apply 1,000 cycles were abandoned.

Table 4: Average Burst Pressures of Unreinforced and Reinforced Samples

Reinforcement Type	Nominal Pipe Diameter	Number of Samples	Average Burst Pressure (if applicable)	% Increase from Unreinforced
Unreinforced	8 inches (203 mm)	6	2,428 psi (16.74 MPa)	N/A
	16 inches (406 mm)	1	2,304 psi (15.89 MPa)	N/A
Milliken-Pipe Wrap - Atlas	8 inches (203 mm)	3	9,283 psi (64 MPa)	382
	16 inches (406 mm)	1	$6,440^+$ psi (44.4 MPa)	280
Western Specialties ComposiSleeve	8 inches (203 mm)	3	4,019 psi (27.71 MPa)	166
	16 inches (406 mm)	1	$3,478^+$ psi (23.98 MPa)	151

Note: Only one (1) 16-inch pipe sample was tested for each configuration due to limited material.