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STATE-OF-THE ART ASSESSMENT OF TODAY'S COMPOSITE REPAIR TECHNOLOGIES

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ABSTRACT

For almost 30 years composite repair technologies have been used to reinforce high pressure gas and liquid pipeline transmission systems around the world. The backbone of this research has been full-scale testing, aimed at evaluating the reinforcement of anomalies including, corrosion, dents, vintage girth welds, and wrinkle bends. Also included have been the assessment of reinforced pipe geometries including welded branch connections, elbows, and tees. Organizations sponsoring these research efforts have included the Pipeline Research Council International, regulatory agencies, pipeline operators, and composite repair manufacturers. Many of these efforts have involved Joint Industry Programs; to date more than 15 different industry-sponsored programs and independent research efforts have been conducted involving more than 1,000 full-scale destructive tests.

The aim of this paper is to provide for the pipeline industry an updated perspective on research associated with composite repair technologies. Because of the continuous advance in both composite technology and research programs to evaluate their effectiveness, it is essential that updated information be provided to industry to minimize the likelihood for conducting research efforts that have already been addressed. To provide readers with useful information, the authors will include multiple case studies that include the reinforcement of dents, wrinkle bends, welded branch connections, and planar defects.

INTRODUCTION

Composite repair technologies play a critical role in the integrity management programs of many of today's gas and liquid pipelines. Much of the research associated with the development of composite repair systems has been funded by the gas transmission pipeline industry, with an emphasis on repairing high pressure pipelines. The primary use of composite materials has been to repair corrosion, although research dating back to the mid-1990s has also been conducted for repairing dents and other mechanical damage (the latter being accompanied by grinding to remove gouges or indications of cracked material) [4]. More recently, efforts have been undertaken to evaluate the ability of composite materials to reinforce plain dents [10], wrinkle bends [3], branch connections, elbows/bends [7, 13], girth welds, and even crack-like features [11].

This paper provides background documentation on repairing defects in pipelines, including external corrosion [9] and dents, using composite materials. The goal for making any repair is to restore strength to damaged sections of pipe to ensure performance levels are at least as sound as the original pipe. The effects of static and cyclic pressure should be considered in the design of any repair [8]. Additionally, if appropriate, accounting for the presence of external loads (e.g. axial and bending) should be considered, as well as elevated temperatures if they exist in service.

It is imperative that the recommended installation techniques provided by each manufacturer be followed. The only composite repair systems that should be used are those manufactured by companies with certified training programs, where hands-on installation classes are required for certified installers.

From a design standpoint, any composite repair system that is used to repair a pipeline must demonstrate that it can meet the requirements of the ASME PCC-2 [2] and ISO 24817 industry standards. Composite manufacturers must be able to produce documentation from a third-party organization demonstrating their compliance with these standards, including meeting the required material and performance properties. Additionally, when composite materials are used to repair and/or reinforce anomalies in addition to corrosion (i.e. dents, branch connections, wrinkles, etc.), testing should be conducted to demonstrate that adequate performance levels can be achieved. Examples are available in the open literature on how these types of qualification programs are accomplished and several case studies are included in this paper.

The sections of this paper that follow include a brief background on the ASME PCC-2 composite repair industry standard, four case studies providing documentation on the reinforcement of dents, wrinkle bends, welded branch connections, and planar defects.

INDUSTRY STANDARDS

During the early periods during which composite materials were used to repair pipelines, industry was without a unified standard for evaluating the design of composite repair systems. Under the leadership of technical experts from around the world, several industry standards were developed that include ASME PCC-2 and ISO 24817 (hereafter referred to as the *Composite Standards*). Interested readers are encouraged to consult these standards for specific details; however, listed below are some of the more noteworthy contributions these standards are providing to the pipeline industry.

- The Composite Standards provide a unifying set of design equations based on strength of materials principles. Using these equations, a manufacturer can design a repair system so that a minimum laminate thickness is applied for a given defect. The standards dictate that for more severe defects greater reinforcement from the composite material is required.

- The most fundamental characteristic of the composite material is the strength of the composite itself. The Composite Standards specify minimum tensile strength for the material of choice based on maximum acceptable stress or strain levels.
- Long-term performance of the composite material is central to the design of the repair systems based on the requirements set forth in the Composite Standards. To account for long-term material strength degradation, safety factors are imposed on the composite material that essentially require a thicker repair laminate than if no degradation was assumed.
- One of the most important features of the Composite Standards is the organization and listing of ASTM tests required for material qualification of the composite (i.e. matrix and fibers), filler materials [12], and adhesive. Listed below are several of the ASTM tests listed in ASME PCC-2 (note that there are also equivalent ISO material qualification tests not listed here).
    - Tensile Strength: ASTM D 3039
    - Hardness (Barcol or Shore hardness): ASTM D 2583
    - Coefficient of thermal expansion: ASTM E 831
    - Glass transition temperature: ASTM D 831, ASTM E 1640, ASTM E 6604
    - Adhesion strength: ASTM D 3165
    - Long term strength (optional): ASTM D 2922 [2]
    - Cathodic disbondment: ASTM-G 8

With the development of standards for composite repairs, industry can evaluate the performance of competing repair systems based on a set of known conditions. It is anticipated that the Composite Standards will either be accepted in-part or in-whole by the transmission pipeline design codes such as ASME B31.4 (liquid), ASME B31.8 (gas); the CSA Z662 specifically mentions ASME PCC-2 a design requirement standard for composite repair systems used to repair pipelines.

CASE STUDIES

Over the past 30 years an extensive body of research has been accumulated focused on evaluating the performance of composite reinforcing technologies, encompassing more than 1,000 burst and cyclic pressure tests. Funding has been provided by pipeline operators, composite manufacturers, research organizations, and regulatory agencies; many of these involving Joint Industry Programs (JIPs). Interested readers are encouraged to review resources listed in the *Reference* section of this paper. From among the JIPs, four case studies are included that provide technical details on studies addressing reinforcement of dents, wrinkle bends, welded branch connections, and planar defects.

Reinforcement of Dents

It is recognized that the vast majority of composite repairs are used to reinforce corrosion; however, the repair of dents is also common place. A study was conducted to evaluate the repair of dents subjected to cyclic pressure service [8]. This study assessed the performance of plain dents, dents in girth welds, and dents in longitudinal ERW seams. **Figure 1** provides a schematic diagram of the test sample that involved 12.75-inch x 0.188-inch, Grade X42 pipe material. The dents were relatively severe in nature and were initially installed at 15% of the pipelines nominal diameter. After pressure cycling 10 cycles the residual dent depth was on the order of 3%. The samples were pressurized from 10% to 72% SMYS and cycled until either failure or 250,000 cycles; results are presented graphically in **Figure 2** that also includes results for unreinforced test samples. Product H, which is an E-glass / epoxy system, was tested beyond the standard testing protocol and achieved 358,470 cycles before a leak developed in the ERW seam of the pipe. The conclusion is that this particular repair system was able to increase the integrity of the damaged pipe to be at least as good as the undamaged ERW seam.

For specific details on this work, interested readers are encouraged to read IPC Paper No. IPC2010-31524 [8] that provides details on this research program. One of the important observations made in this particular research program is that not all composite repair systems perform equally. Several systems were able to achieve the targeted 250,000-cycle run-out condition; however, two systems did not achieve average cycles to failure much greater than 40,000 cycles. This observation regarding composite performance supports the notion that composite manufacturers must be able to demonstrate the worthiness of their system in repairing pipelines by performance testing.

For purposes of this discussion, dents represent local damage in the form of curvature changes, while mechanical damage involves dents combined with material loss in the form of a gouge or scratch. It is recognized that mechanical damage is a leading cause of pipeline failures. What makes mechanical damage so severe is the formation of cracks, specifically micro-cracking, which develops at the base of the gouge in the highly stressed region of the dent. During pressurization the elevated stresses at the crack tip propagate the crack to the point where failure occurs during a single cycle or over a period of time due to cyclic pressure loading. When composite materials are used to repair mechanical damage, it is essential that any form of cracking be removed by grinding. Experimental work has demonstrated that, in general, composite materials lack adequate reinforcement to ensure that cracks do not propagate when the repaired pipes are pressurized. On the other hand, experimental investigations have shown that when gouges are removed by grinding, composite materials reduce stresses in the dented region and significantly increase the fatigue life over unrepaired mechanical damage.

Reinforcement of Wrinkle Bends

Numerous independent investigations have been undertaken by pipeline companies evaluating the effects of wrinkle bends [5]. It has been concluded based on these investigations that axial tension loading does not generate failures consistent with those observed in the field. Rather, the primary source of loading that has contributed to wrinkle bend failures that generate high strain, low cycle bending associated with movement of the pipeline. As such, full-scale testing integrating cyclic bending loads have been used to simulate real world pipe-soil interaction conditions. The displacements identified as generating high strain, low cycle failures from sub-scale testing efforts were imposed on the full-scale samples.

The goals for the full-scale testing efforts were three-fold:

1. Produce a high-strain low cycle failure in a low number of cycles (i.e., 150 cycles)
2. Produce a fracture surface similar to actual failures
3. Demonstrate the effectiveness of composite reinforcement.

Included in this paper are results for two test samples using wrinkles removed from the same wrinkle bend. The pipe material was 24-inch OD with a 0.25-inch wall thickness and contained a DSAW weld intersecting the wrinkle bends. The pipe material used to fabricate samples was taken from service. Full-scale testing included the effects of internal pressure and cold temperatures. The first sample is an unreinforced sample having a wrinkle bend that interacted with a seam weld. The second sample was reinforced with an E-glass epoxy composite repair system.

Pre-test preparation involved the following activities:

- End fixtures fabricated, samples cut, and sand blasted (**Figure 3**)
- Instrumentation attached (strain gages and displacement transducers)
- Reinforce one sample with Armor Plate® Pipe Wrap composite wrap.

The reinforced sample was sand blasted to NACE 2 specifications (i.e., near white metal) and reinforced with the composite repair, which was a 12-layer wrap having an approximate thickness of 0.75 inches. The orientation of the layers alternated between the hoop and axial direction, with a sequence involving 2 axial layers followed by 1 hoop layer (i.e. 8 total axial layers and 4 total hoop layers). **Figure 4** is a photograph of the test set-up that includes insulation placed around the sample to maintain the 40°F cold temperature conditions.

The unreinforced test was controlled based on the wrinkle displacements in order to mimic what was done in the sub-scale testing phase. A decision was made to proceed with using displacements of +/- 0.1-inches on the unreinforced sample in order to produce bending strains of sufficient magnitude to produce fatigue cracks in approximately 150 cycles. The reinforced sample would be subjected to similar bending loads based on the results from the unreinforced sample.

The nominal internal pressure for the test was chosen as 475 psi (43.8% SMYS). The expected pressure range during testing is 450-500 psi accounting for variations due to temperature and loads. The testing temperature was set from 35-55°F on the sample. This temperature was chosen as it should be approximately equal to the minimum temperatures experienced by buried pipe. Furthermore, it was identified as being less than the ductile to brittle transition temperature of the weld material based on information provided by the pipeline operator. Finally, using temperatures greater than 32°F allowed for the use of water rather than a glycol mixture.

The basic steps involved in testing the unreinforced wrinkle were as follows:

- Load the sample in the frame
- Circulate water in sample until 40°F temperature reached
- Increase internal pressure to 425 psi
- Apply bending loads to cycle wrinkle +/- 0.1-inches until failure occurs.

As opposed to a displacement-controlled condition for the unreinforced sample, the reinforced wrinkle bend sample was deformed by applying a prescribed bending moment. While displacing the unreinforced sample of +/- 0.1-inches, the bending moment required to achieve this condition was measured. This bending moment was then applied to the reinforced test sample to ensure that a comparable test condition existed.

Testing was accomplished without any unexpected incidences. The target displacements were achieved with 30 second cycle times. Failure in the unreinforced sample occurred after 87 cycles were applied. The failure occurred in the form of a thru-wall crack that developed in the seam weld that ran through the wrinkle. During testing internal pressure, axial displacement of the wrinkle, bending loads, and strain was measured.

The reinforced sample was tested after all testing was complete on the unreinforced sample. In contrast to the 87 cycles achieved with the unreinforced sample, the reinforced sample achieved 1,031 cycles before a leak was detected beneath the composite. The bending full-scale testing confirmed two points with respect to low cycle, high strain loading on wrinkle bends. First, wrinkle bends with a seam weld are more susceptible to failure than wrinkle bends without a seam weld. Secondly, a composite reinforcement can significantly increase the life of a wrinkle bend.

With regards to the composite, **Table 1** provides a summary comparison of the test data from the unreinforced sample and the reinforced sample. The results show a significant improvement in the performance of the composite reinforced sample in terms of increased stiffness (i.e. lower deflections), reduction in strains, and an increase in the fatigue life. The cycles to failure increased by 11.9 times, greater than a full order of magnitude. The strains at the wrinkle apex were reduced by over 80% at the center of the sample where failures are expected to occur.

The primary conclusion from the extensive body of completed testing work is that composite materials are an effective means for reinforcing wrinkle bends subjected to low cycle, high strain bending conditions. This is accomplished by stiffening the wrinkle both axially and circumferentially, which in turn reduces strain in the wrinkle and increases the overall fatigue life.

Reinforcement of Welded Branch Connections

Welded branch connections are common in transmission pipelines. A study was conducted for a gas transmission pipeline operator to evaluate the ability of composite materials to reinforce branch connections. Of particular interest was the reinforcement of branch connections subjected to in-plane and out-of-plane bending loads. The study involved simulating the bending loads on branch connections in service. Bending loads were applied to the branch pipe in the plane of the run and branch pipe (i.e. in-plane), as well as out of the plane (i.e. out-of-plane). Samples were also tested to determine the effectiveness of the composite in strengthening the branch connections.

The unreinforced sample referenced in this study used an under-reinforced saddle branch connection, while the reinforced sample corresponded to a composite reinforced saddle branch connection (i.e. composite material installed over the under-reinforced saddle branch connection). The run pipe materials included in this study were 24-inch x 0.250-inch, Grade X70 pipes and the branch pipes were 8.625-inch x 0.322-inch, Grade X52 pipes. A total of four samples were tested. **Figure 5** provides drawings and photographs providing further details on this particular study. As noted in this figure, the unreinforced sample experienced significant deformation, whereas the reinforced sample was undeformed in the area of reinforcement event though the applied load was 140% of the load applied to the unreinforced sample.

The conclusion from this study was that when properly-designed and installed, composite materials can reinforce branch connections subjected to internal pressure in conjunction with in-plane and out-of-plane loading. To ensure optimum performance, the reinforcement must have adequate stiffness, related primarily to elastic modulus and thickness of the composite material, as well as employment of proper installation techniques.

Reinforcement of Planar Defects

A study was conducted to investigate the reinforcement of LF-ERW (low frequency electric resistance weld) flaws located in a 16-inch x 0.312-inch, Grade X52 ethylene pipeline [11]. 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, in addition to the 16-inch NPS samples (cf. **Figure 6**) testing was also conducted on 8.625-inch x 0.250-inch. (219-mm x 6.35-mm) pipe material having LF-ERW seams.

EDM (electric discharge machining) notches were installed in the ERW bond line, as shown in **Figure 7**. 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. As shown in **Figure 8**, the composite reinforcement system was able to provide reinforcement in reviewing so that no crack growth was observed in the EDM notch even after burst testing. What is also important in reviewing the images in this photo is the precision achieved when the EDM notches were installed in the ERW bond line.

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.

UNCONVENTIONAL APPLICATIONS

One of the subjects addressed in this paper is the reinforcement of what could be called "unconventional applications" of composite reinforcement. Historically, the largest application of composite wraps has been to reinforce corrosion anomalies, with a second being the reinforcement of plain dents. As has been presented, using advanced engineering methods that involve analysis and testing it is possible to apply composite materials to reinforce a wide range of pipeline features and anomalies that include elbows / bends, tees, wrinkle bends, girth welds, planar defects, and even crack-like features.

It cannot be emphasized too strongly that when composite materials are used to reinforce unconventional applications pipeline operators should carefully consider the demands placed on the repair. This includes not only the loading itself, but limitations of the composite reinforcement such as strain capacity, maximum operating temperature range, and adhesion to the pipe. When these types of issues are questioned on the front end of the design process and coupled with a rigorous assessment process, technically-sound composite reinforcements are produced. This is also consistent with U.S. federal pipeline regulations [1] relating to pipeline repair, stating that when composites are used to reinforce pipelines they must be *repaired by a method that reliable engineering tests and analyses show can permanently restore the serviceability of the pipe.* There is a rich history of successful composite reinforcements having satisfied the intent of this requirement and contributed significantly to the integrity of pipeline systems around the world.

CLOSING COMMENTS

This paper has provided for industry stakeholders information regarding the use of composite repair systems to repair and reinforce high pressure transmission pipelines. Contents have included results from previous research programs, as well as insights obtained in evaluating the use of composite materials for the pipeline industry. There are several noteworthy observations associated with the current body of work.

- Prior research has shown that when properly-designed and installed, composite materials are effective in restoring the integrity of damaged pipe sections. Loading of interest has included internal pressure (static burst and cyclic fatigue), axial tension, and bending.
- Although by definition repair systems qualified to meet the requirements of standards, such as ASME PCC-2 and ISO 24817, can be used to reinforce corrosion subjected to static pressures, any additional loading conditions or anomalies will require supplementary full-scale destructive testing. Examples of additional loads include cyclic pressures, axial tension, and bending loads. This is one of the major points of contention in industry; just because a system is qualified to repair one type of defect does not qualify that system to repair all defects.
- When failures have occurred with composite repair systems, the primary causes of failure are poor installation techniques; this includes not allowing the repair to cure properly before the pipeline system is placed back in service.

Composite repair suppliers are encouraged to provide thorough documentation including material traceability. This process helps ensure that what is being installed on the pipeline is consistent with what has been committed by the manufacturer. All composite systems should be installed by a certified applicator in accordance with a written procedure that is available on site and undergo adequate inspection before being placed into service. Finally, all materials used in a composite repair should be properly-marked with shelf and pot life information and batch number information for traceability.

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Table 1: Test results for the wrinkle bend bending test samples

Testing Variable Results	Unreinforced Sample Results	Reinforced Sample Results
Cycles to failure	87	1,031
Wrinkle displacements	+0.10 inches -0.10 inches	+0.03 inches -0.04 inches
Strain range (wrinkle apex)	14,000 με (1.4%)	2,400 με (0.24%)
Strain range (+/- 30 degrees relative to wrinkle apex)	9,000 με (0.9%)	2,700 με (0.27%)
Strain range (0 degrees adjacent to wrinkle)	2,870 με	1,900 με
Strain range (+/- 180 degrees relative to wrinkle apex)	1,200 με	1,550 με

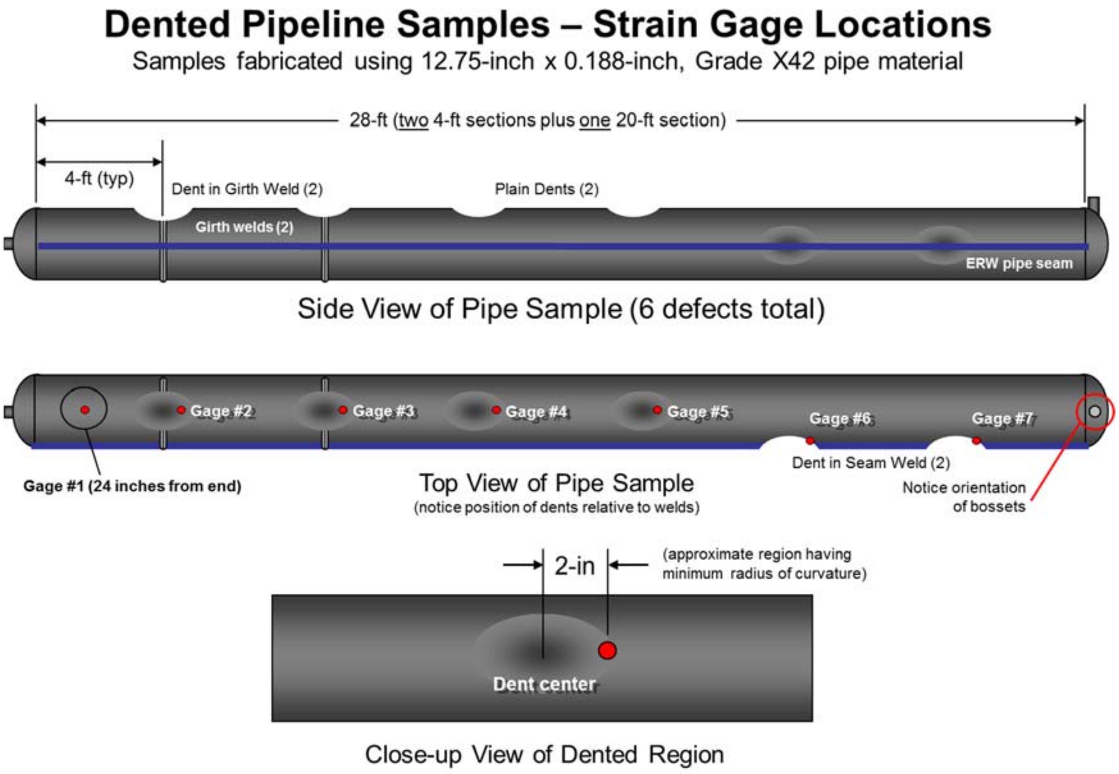


Figure 1: Schematic showing diagram of dent test samples

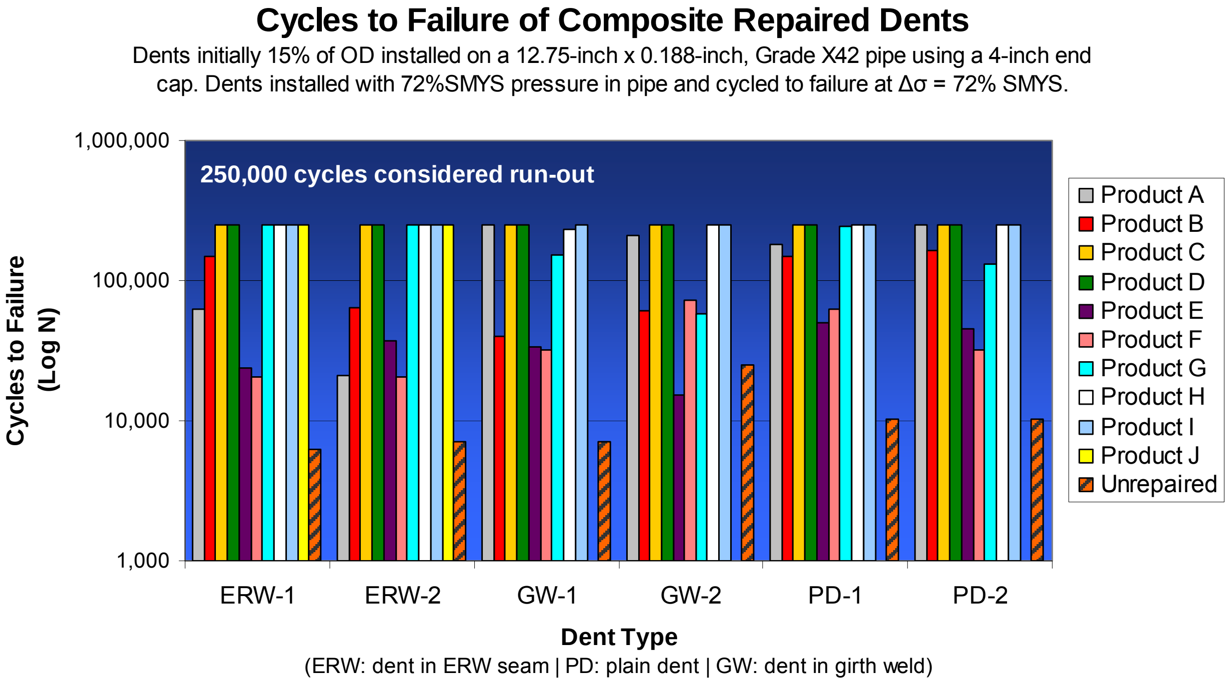


Figure 2: Pressure cycle test results for composite reinforced dents

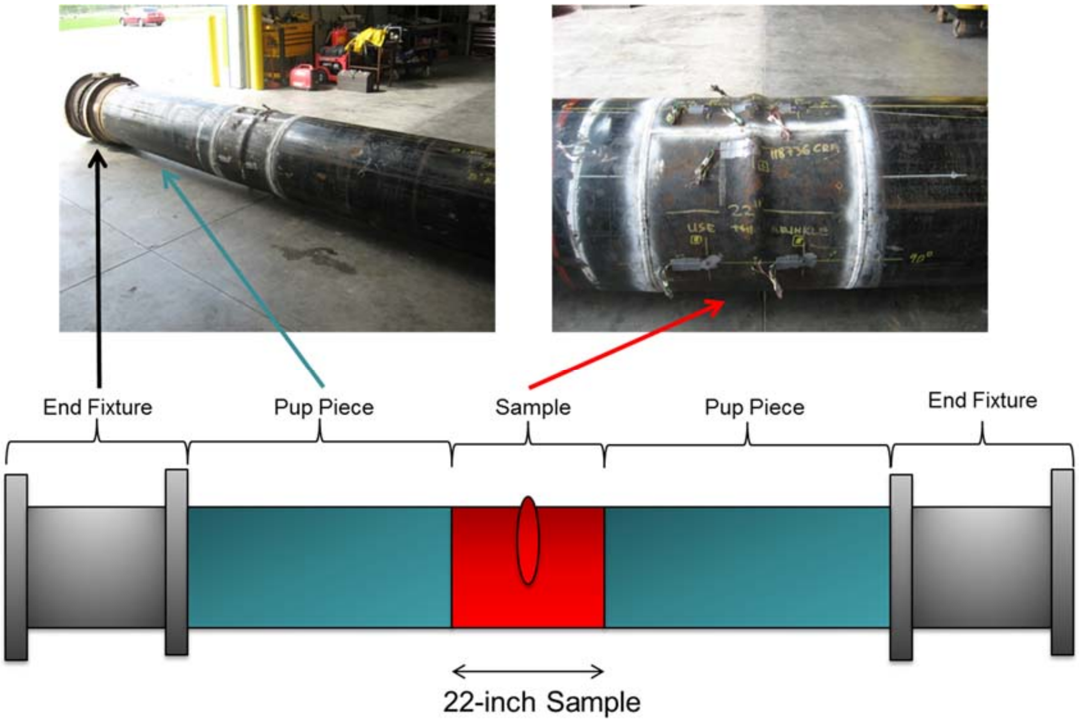


Figure 3: Full-scale sample preparation including end fixtures

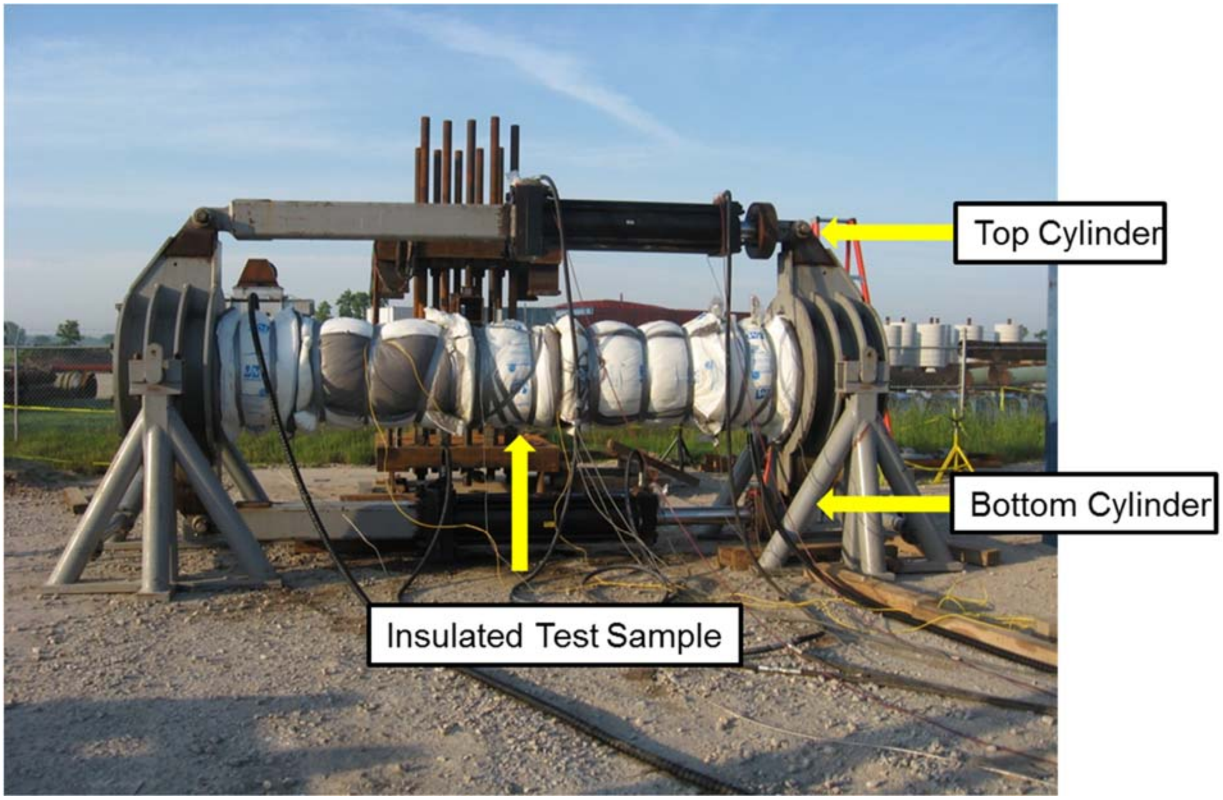
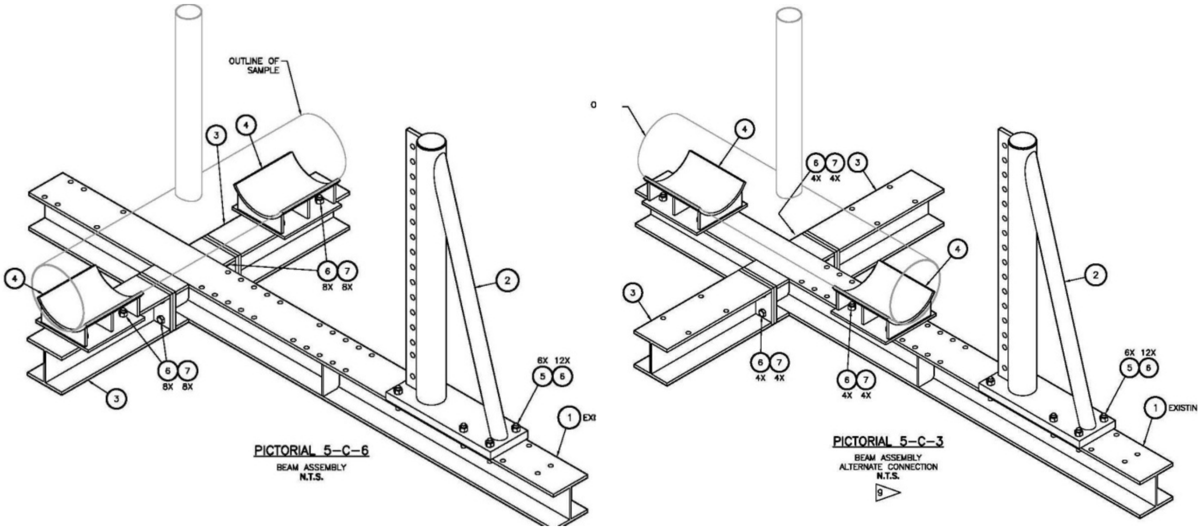
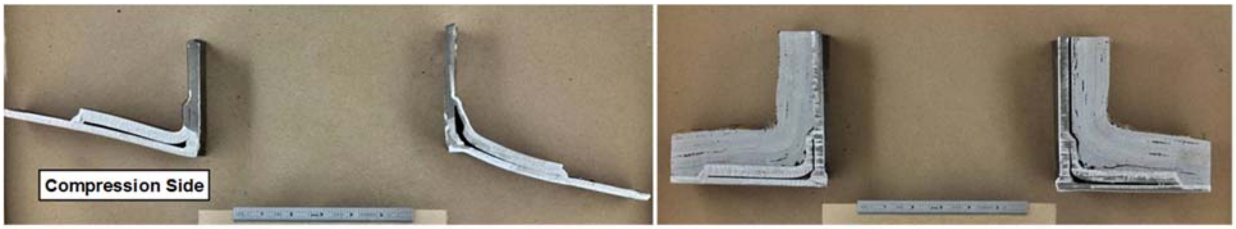


Figure 4: Photograph showing full-scale sample in load frame



Diagrams showing set-up for in-plane (left) and out-of-of-plane (right) bending tests

Final displacements for in-plane unreinforced (left) and reinforced (right) bending tests

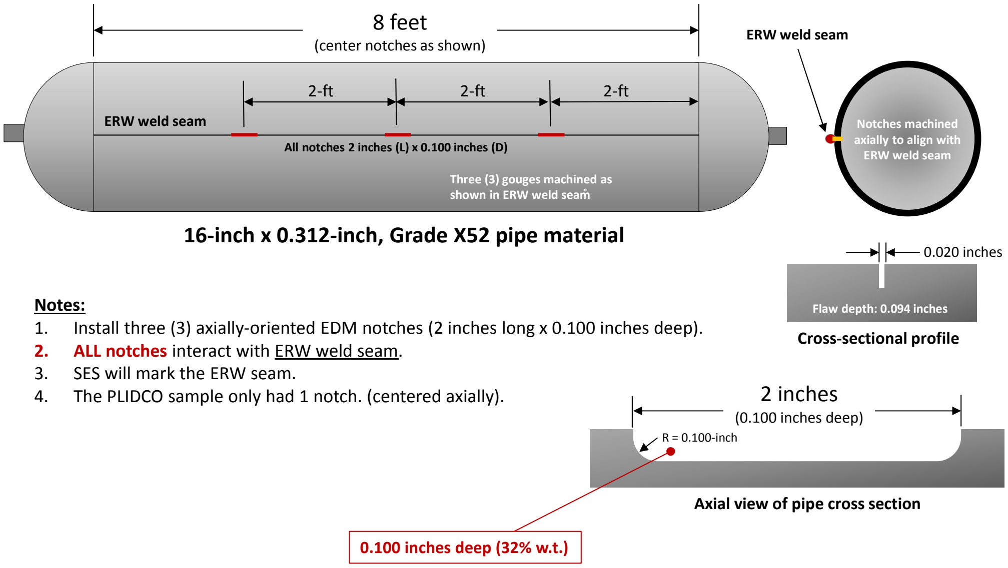


Unreinforced In-plane Sample
(after 13.3 inches displacement at 88.6 kip-feet bending)

Reinforced In-plane Sample
(after 4.7 inches displacement at 124.0 kip-feet bending)

Post-test sections showing results for the unreinforced and reinforced conditions

Figure 5: Diagrams and photographs for the branch connection tests



Notes:

1. Install three (3) axially-oriented EDM notches (2 inches long x 0.100 inches deep).
2. **ALL notches** interact with ERW weld seam.
3. SES will mark the ERW seam.
4. The PLIDCO sample only had 1 notch. (centered axially).

Figure 6: Schematic of 16-inch Pipe Samples with EDM Notches

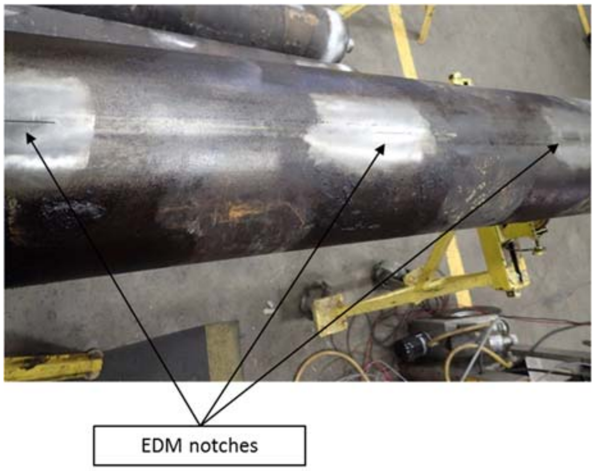


Figure 7: Photograph of EDM notches

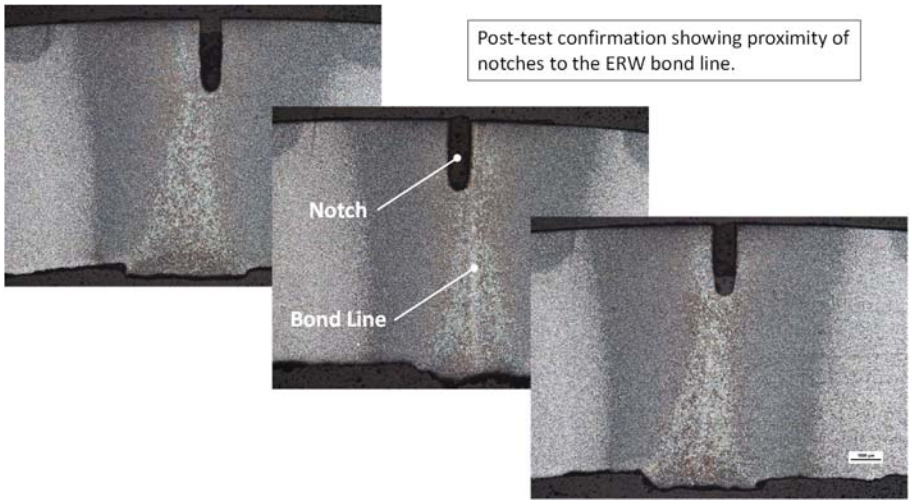

Post-test confirmation showing proximity of notches to the ERW bond line.

Figure 8: Sections of EDM notches through ERW bond lines after testing reinforced sample