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The Role of Full-Scale Testing in Managing Pipeline Integrity

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Abstract

One of the greatest challenges facing today's pipeline integrity engineers is determining the threat level a given feature or defect poses to a pipeline system. The process employed by most pipeline integrity engineers starts with inspection measurements made with in-line inspection tools or in-the-ditch inspection technologies. If the measured data are deemed a threat to pipeline integrity, an assessment is conducted using either closed-form engineering equations or numerical modeling techniques such as finite element analysis. To supplement assessment efforts, a well-designed and conducted full-scale testing program can provide valuable insights about the true performance characteristics of a defect and improve the accuracy of failure prediction methods.

This paper includes examples of how full-scale testing can be used to provide a more accurate and complete picture of defect performance under various loading conditions including burst, cyclic pressure, tension, and bending. Included is a brief description of the types of tests that can be conducted, accompanied with photos from actual tests. Information is also included on the types of equipment and measurement devices that are used in full-scale testing. The goal of this paper is to demonstrate the inherent benefits in employing full-scale testing as a means for better understanding and predicting the threat levels associated with certain defects.

Introduction and Background

Managing the integrity of a high-transmission pressure is multi-faceted and includes activities like inspection, assessing the impact of operating conditions, evaluating external loads like geohazards, and determining the impact that defects have on the integrity of the pipeline. There are several methods for quantifying the impact that defects have on the pipeline's pressure-carrying capacity, fatigue life, or strength as in the case of loading on girth welds. Although analytic solutions based on first principles (i.e., hand calculations) and finite element models provide useful insights, there are specific conditions when full-scale testing provides the most accurate estimate of defect severity. When material performance is central to the assessment, the results generated by full-scale testing are difficult to challenge.

The goal in conducting full-scale testing is to replicate conditions that exist in the field including pipe material, defects, environment, and loading conditions. The greater the ability to simulate real-world conditions, the more meaningful the full-scale test results will be. The *Introduction and Background* section of this paper outlines the conditions and elements essential to conducting a successful full-scale test. Also included are photographs from prior testing programs. The *Discussion and Closing Comments* provides commentary on how a pipeline operator or technology company might apply the concepts contained in this paper to their respective operational and business activities.

Types of Tests and Equipment

In the context of conducting full-scale pipeline testing there are five distinct types of tests used to replicate actual conditions to which pipelines are subjected. Provided below is a brief description on these types of tests, accompanied by photographs and schematic diagrams.

- **Burst test.** In burst testing, samples are normally pressurized to failure. The limit state of the pipe and associated defects are quantified. Strain gages are useful for measuring strain in the base pipe and regions having defects during pressurization. Burst testing is also an excellent method for validating the performance of repair technologies, including composite repair systems. Shown in Figure 1 is a photograph of a burst test that was used to determine the pressure capacity of a crack-like feature that was compared to burst pressure predictions from a fracture mechanics model. In some standards, such as ASME PCC-2 (1), pressure testing is required as a means to qualify a composite repair system.

- **Pressure cycle fatigue test.** A pipe sample is pressurized using a pressure cycle pump considering a specific pressure range and number of cycles. Fatigue testing is an excellent method for quantifying future performance of a defect or repair technology when a certain number of cycles are applied to simulate future years of service. Shown in Figure 2 is a photograph of a pressure cycle pumping unit that can achieve approximately 10,000 cycles per day on a 24-inch pipe sample. As with burst testing, pressure cycle testing is also an excellent method for validating the performance of repair technologies, including composite repair systems.

- **Axial tension testing test.** To conduct axial tension testing, a load frame is used to pull a pipe sample in tension (or push in compression). Specialized threaded end caps are typically welded to the pipe sample, which are then used to interface with the load frame. Shown in Figure 3 is a schematic of a load frame with a capacity to apply 1 million lbs (4,448 kN) tension, while a photograph of a tension sample loaded in the frame is provided in Figure 4.

- **Bend testing (4-point).** Bending testing is useful for quantifying the strain capacity of a pipe sample, often involving girth weld or corrosion features. The advantage of the 4-point configuration is the ability to achieve a constant bending moment between the vertically positioned hydraulic cylinders. This configuration only permits loading in one direction. A 4-pt bend frame with a capacity of 3 million ft-lbs (4.1 million N-m) is shown in Figure 5, where a pressurized 30-inch pipe with a defective girth weld was subjected to a bending load of sufficient magnitude to buckle the pipe outside the carbon-epoxy repair system installed over the girth weld.

- **High strain / low cycle bending test.** Certain features can fail when subjected to high strain / low cycle bending conditions, namely wrinkle bends and girth welds. For this reason, the use of a specialized frame is required to apply a fully reversible pure bending moment to the pipe sample, permitting bending and compression to be applied to the sample at a relatively fast rate (5-10 bending cycles per minute). To achieve this loading condition, a specially designed load frame is used, as shown in Figure 6, where a pair of hydraulic cylinders are used to apply a pure bending moment to the pipe sample. : This bending frame has a capacity of 800,000 ft-lb (1.1 million N-m). In this particular test a pressurized wrinkle bend sample was tested to generate an axial tension strain of +/- 1% in the wrinkle, resulting in a failure after approximately 100 cycles were applied. The same test was conducted involving a wrinkle reinforced with an E-glass composite repair system that increased the number of cycles to failure to almost 1,800 cycles.

Many of these tests are basic in nature to conduct with the right equipment and well-trained personnel; however, it is critically important that test engineers be cognizant of energy levels associated with certain loading conditions and take the necessary precautions to ensure personnel and equipment are safe at all times. Although not a major focus of this article, safety should be the number one goal of any company conducting full-scale testing. This means only experienced personnel with the appropriate testing equipment should oversee full-scale test labs and conducting tests.

Defect Creation

Because there are a limited number of real-world features that are available for experimental assessment, testing often requires the creation of simulated features and defects. An important advantage in creating features is the ability to construct a well-defined test matrix that includes variations of key variables, including corrosion depth and length, dent depth, and crack depth and length.

Corrosion features can be fabricated using conventional machining techniques, use of electric discharge machining (EDM), and chemical etching that can generate a pitted profile. Dents are fabricated by pressing an indenter into the pipe to a prescribed depth, often with pressure in the pipe during the denting process to ensure a representative level of plasticity is generated in the dent. There are several techniques for fabricating axial cracks, although one of the most repeatable involves the installation of an EDM notch into the pipe wall following by limited pressure cycling to generate a crack at the base of the notch. A photograph of an EDM machine is shown in Figure 7. Also, girth weld defects have been created by grinding out a portion of the root pass during weld fabrication or in the case of an existing girth weld, using an EDM notch to generate lack of penetration or incomplete penetration features. An example of a girth weld defect is shown in Figure 8.

Performance Metrics

One of the most important and challenging elements in using full-scale testing as a means for establishing the structural integrity for a pipeline is determining what constitutes success. Numerous measurement values can be extracted from a full-scale test such as burst pressure, number of cycles to failure, magnitude of bending required to generate a leak in a defective girth weld, strain in a dent during pressure cycling, and reduction in tensile strength in a composite as a function of temperature. The test engineer uses these results to evaluate the relative severity of a defect that permits managing integrity of the respective pipeline defect. Listed below are several important performance metrics that used in full-scale testing:

- Burst pressure – what is the maximum pressure that can be achieved before a particular defect fails such as a corrosion or crack-like feature?
- Fatigue life – what is the maximum number of pressure cycles that can be applied before a particular defect fails, such as a dent or crack-like feature?
- Tension and bending load capacity – what is the maximum applied load that can be achieved before a particular defect fails, such as a circumferentially oriented crack-like feature?
- Strain capacity – what is the maximum strain that can be achieved before a particular defect fails, such as a circumferentially oriented crack-like feature?

Instrumentation

An important use of full-scale testing results is validating numerical models. A criticism sometimes levied against numerical models is embodied in the saying, “All models are wrong, but some are useful.” The use of full-scale testing helps to calibrate numerical models and ensure their results align with real-world conditions. In order for useful measurements to be extracted from a full-scale test, testing engineers must identify what measurements need to be made and determine the instrumentation required for making those measurements. Listed below are some of the devices commonly used in full-scale testing, along with a brief commentary.

- Strain gages are one of the most useful devices in testing, especially when correlating results with numerical models is required. The key is knowing where to locate strain gages to ensure maximum strains (or stresses) are measured.

- A clip gauge is a device used to the measure crack tip opening displacement (CTOD) of sub-scale samples in fracture mechanics, but this device can also be used to measure the opening of EDM notches during pressure cycling as shown in Figure 9. Clip gauges can also be useful for controlling the pressure cycle pump by terminating cycling when measurements are made indicating a crack has formed at the base of the EDM notch.
- Displacement transducers make displacement measurements and are useful for applications where elevated strain conditions exist (greater than 0.5%, displacement transducers are extremely useful. In one study where tensile loads were applied to generate strains greater than 3%, displacement transducers were used to calculate strain values after strain gages disbonded.
- Load cells can be used for a variety of applications, but they are often used to measure contact forces between two bodies under load.
- Pressure transducers are an essential element in pipeline testing. They are used to measure burst pressures, but also play a critical role as instruments in controlling the applied pressure ranges to a fatigue sample. They are also used with hydraulic cylinders to measure pressures that are then used to calculate applied loads (i.e., force equals piston area times hydraulic pressure).
- Thermocouples are used to measure temperature. Most testing for pipeline applications is done at ambient conditions; however, the author has tested pipe fittings down to -51°F and composite reinforcing materials up to 250°F.
- Data acquisition (DAQ) systems are used to capture data made by the above instruments and measurement devices. DAQ systems play a critically important role in generating data that is eventually post-processed for test reports but can also be used for controlling equipment such as pumps and load frames.
- General test lab equipment including cranes, pressure test containment boxes and other assorted pieces of equipment are essential to safely conduct full-scale destructive tests. Provided in Figure 10 is a photograph showing an inside view of the test lab where all of the tests presented in this paper have been conducted.

Case Studies

The use of case studies is the central theme in this paper. Provided are a few examples illustrating how full-scale testing provided critical information for pipeline operators related to defect assessments and technology validations. The first and second case studies are more general in nature, while the third case study relates to technology and product validation.

<u>Full-Scale Assessment of Dents</u>

Full-scale testing of dents dates to at least the 1980s. Research and trade organizations such as the Pipeline Research Council International (PRCI), the American Petroleum Institute (API), and the Gas Technology Institute (GTI) have funded large bodies of research focused on the assessment of dents. Regulatory agencies such as the Pipeline and Hazardous Materials Safety Administration (PHMSA) and the Bureau of Safety and Environmental Enforcement (BSEE) have also provided significant funding to study dents.

The assessment of dents has changed significantly over the past 25 years. In the early 1990s, dent assessments typically involved only dent depth as a means for quantifying defect severity. Pipeline codes and regulations at that time limited operators to having dent depths based on a certain percentage of the pipe diameter (e.g., 2% or 6%). By the late 1990s, in-line inspection (ILI) technologies had advanced to the point where tools were able to provide depth and length measurements, thus allowing engineers to explore the use of finite element analysis as a means for quantifying dent severity. API funded a large study focused on the assessment of constrained rock dents (Alexander and Kiefner, 1999) that integrated full-scale testing and finite element analysis (FEA). A set of generic stress concentration factors (SCFs) using FEA were generated for operators that could be used to quantify the relative severity of a particular dent. Advances in computational speed also greatly enhanced the industry's ability to construct and analyze detailed finite element models. Today's advanced ILI technologies and powerful FEA packages have made the use of generic SCF-based tools and related techniques obsolete. As an example, ILI companies like ROSEN are able to import data from high resolution geometry tools directly into FEA software and calculate dent-specific stresses and SCFs (Dotson et al, 2014). A Joint Industry Program, known as the Dent Validation Collaborative Industry Program (DV-CIP) was used to validate ROSEN's approach to using SCFs as a means for risk-ranking dent features (DV-CIP study, 2015).

Throughout all of the advances in numerical modeling, full-scale testing has always played an important role, including the API work, studies funded by PRCI (Bolton et al, 2008), and even the ROSEN DV-CIP study. At the current time, plain dents (i.e., dents that do not have any interacting features such as welds, gouges, or corrosion) can be modeled using FEA with a reasonably high level of certainly; however, the presence of interacting features greatly diminishes the ability to simulate real-world features. For this reason, full-scale testing is essential to quantify the deleterious impact that seam welds, girth welds, corrosion, and other features have on the fatigue life and pressure-carrying capacity of dents in pipelines.

Provided in Figure 11 is a photo showing a dent installation rig and a process by which dents are created in the test lab. A hydraulic ram is used to radially force a rigid indenter into a pipe sample. While the indenter is held in place, the pipe sample is pressurized to a specified pressure level (e.g., 72% SMYS) to achieve gross plasticity in the dent. It is a relatively simple process, but extremely effective in creating damage and simulating real-world features. It is well-known that plain dents do not typically fail due to pressure overload but are susceptible to the effects of cyclic pressure loading. Figure 12 shows a photo of a dented test sample along with a fatigue crack that developed in the shoulder of the dent after approximately 10,000 pressure cycles had been applied.

Cyclic pressure testing is one of the simplest and most practical forms of full-scale testing. The test produces useful information that can assist pipeline operators in quantifying the severity of a particular dent feature.

Crack-like Features in Seam Welds

One of the major concerns currently in the pipeline industry are crack-like features in longitudinal (long) seam welds. The presence of these features reduces the pressure-carrying capacities of pipelines for both static and cyclic pressure loading. Two categories are of particular interest with respect to long seam welds that have led to pipeline failures: low frequency electric resistance welds (LF ERW) and selective seam corrosion. The ability to measure the geometry of cracks through advances in ILI technologies have greatly enhanced industry's ability to assess and quantify long seam features.

There is current interest in crack-like features from a full-scale testing standpoint. One area of interest is the ability to generate synthetic cracks using various installation techniques in a test lab environment. Another is destructively testing cracks via burst and pressure cycling to determine their limitations in terms of pressure-carrying capacity and long-term service life.

The following case study presents a process for generating synthetic cracks for development of inspection technology. The study was conducted for Inspection Associates, Inc. to generate cracks from EDM starter notches. The test program included three 12.75-inch x 0.375-inch, Grade X42 pipe samples. This paper includes the results for one of these samples (Sample 2).[1]

Figure 13 is a schematic diagram showing the configuration for Sample 2 that included four EDM notches, while Figure 14 shows the EDM notch geometry. All notches were all 3 inches in length. The depths for each EDM notch type are listed in Table 1. Samples were placed in an enclosed test chamber and pressure cycled between 4 to 72% SMYS, or 100 to 1,779 psig, until strain gage readings indicated that cracking had developed at the base of some EDM notches. The goal was to generate a wide range of crack-like features, but not necessarily a crack at the base of each EDM notch.

Table 1. Notch depths for all samples

Notch	Depth %WT
A	5%
B	10%
C	15%
D	20%

Figure 15 is the meridional post-test sectional view of the EDM Notch C. Figure 16 is a cross-sectional view of the same notch with an observed crack. A total of 16,751 cycles were applied to Sample 2 prior to sectioning. The initial depth of EDM Notch C was measured to be 0.066 inches (17.6% of the pipe's nominal wall thickness). The crack depth was 0.062 inches, resulting in a total crack depth of 0.128 inches (34.1% of the pipe's nominal wall thickness).

The primary purpose of this study was to evaluate the technical performance capabilities of Inspection Associates' Computed Tomography (CT) technology. After testing, but prior to sectioning, all of the EDM notches were scanned using the CT technology. The CT scans measured a depth of 0.130 inches for EDM Notch C. The meridional and transverse CT scans of this notch are shown in Figure 17 and Figure 18. The CT scan and post-test sectioning depth measurement had a difference of 1.9%.

<u>Assessment of Repair Technologies Including Composites and Steel Sleeves</u>

The pipeline industry has utilized steel sleeves since the earliest days of pipeline welding. In spite of the long-term use of steel sleeves, the magnitude of full-scale testing programs validating their use is limited. For example, it is challenging to find papers in the open literature that quantify factors such as the presence of filler materials (Alexander and Beckett, 2016), welds having poor workmanship, and the effects of aggressive cyclic pressure loading on the performance of steel sleeves. Additionally, recent testing using strain gages installed beneath steel sleeves has quantified the strain reduction provided by the steel sleeve.

In contrast to limited data recently published on steel sleeve performance, composite repair systems have been subjected to extensive testing using full-scale testing to validate their performance capabilities. It is estimated that since 2005, pipeline industry, including operators, regulators, and composite repair companies, have contributed more than $20 million (USD) in research in evaluating composite repair technologies. Interested readers are encouraged to review some of the papers cited in the References section of this paper.

[1] Interested readers are encouraged to review the 2020 PPIM co-authored with Inspection Associates, Inc. on the CT validation study (Alexander et al, 2020).

This paper includes results from a Joint Industry Program (JIP) that evaluated the performance of steel sleeves. The study was funded by four pipeline operators and a steel sleeve manufacturer (Alexander et al, 2019). The motivation for conducting this study was that some U.S. operators have interpreted regulations (i.e., CFR 192 for gas pipelines and 195 for liquid pipelines) as requiring steel sleeves to be made from pre-tested pipe. The current regulatory environment is performance-based rather than prescriptive, so there is latitude in interpretation of this requirement. For this reason, a full-scale testing program was initiated to validate the performance of manufactured steel sleeves. Ironically, this program is very similar to validation studies conducted to advance the use of composite materials.

There were several technical objectives associated with these studies. The first objective was to quantify strain reduction provided by the steel sleeves in reinforcing corrosion and dent anomalies. The second objective was to demonstrate the increase in burst pressure capacity and pressure cycle fatigue life, although it is doubtful anyone in the pipeline industry questions the reinforcing benefits of Type A and Type B steel sleeves. The final objective, and one unique in nature to the authors' knowledge, was to demonstrate the importance in having a load transfer material installed in the annulus between the pipe and steel sleeve.[2]

Provided below are several technical details associated with the steel sleeve study.

- 24-inch x 0.375-inch, Grade X65 pipe with 50% corrosion
    - Type B sleeve, pressure cycled ΔP = 5% to 72% SMYS (100 to 1,463 psi)
    - Steel sleeves 0.375-inch thick

- 24-inch x 0.250-inch, Grade X52 pipe with 15% deep initial dent
    - Type B sleeve, pressure cycled ΔP = 9% to 72% SMYS (100 to 780 psi)
    - Steel sleeves 0.250-inch thick

Several photos are included from the steel sleeve qualification study showing various stages of the testing process:

- Figure 19. View of simulated dent
- Figure 20. Strain gage locations for the dented samples

There were two primary means for comparing results for unreinforced and manufactured steel sleeve reinforced features. The first was quantifying the number of cycles to failure. While the number of cycles to failure is useful for quantifying service life, it is rather limited in providing an in-depth quantitative comparison of the performance between different repair systems. The second means for comparing performance involves the use of strain gages installed in corrosion and dent regions. The strain measurements obtained during pressure cycling can be analyzed allowing a quantitative means of evaluating reinforcing systems, which in this study happened to be Allan Edwards' steel sleeves.

Results for all six test samples are presented in Table 2. Using the Miner's Rule formulation, equivalent cycle numbers were calculated for both the corrosion and dent samples assuming a

[2] Interested readers are encouraged to read paper IPC2016-64104 that addressed the performance of different load transfer materials, Alexander, C., Beckett, A., *An Experimental Study to Evaluate the Performance of Competing Filler Materials Used with Type B and Stand-Off Steel Sleeves*, Proceedings of IPC 2016 (Paper No. IPC2016-64104), 11th International Pipeline Conference, September 26-30, 2016 Calgary, Alberta, Canada.

pressure range of 72% SMYS. Interested readers are encouraged to read the 2019 PPIM by Alexander, Edwards, and Precht that provides greater detail on this program and explanation on the Miner's Rule calculations. Also included in this table are the estimated service lives in "years" based on the Kiefner annual pressure cycle count formulation, as well as the last column in this table that reflects the fatigue life of reinforced samples relative to results for the unreinforced samples. As observed, the minimum calculated fatigue life of all the reinforced samples was 424 years considering the "light cycling" condition, which most represents the operating conditions of a natural gas transmission pipeline system.

Table 2. Summary of Pressure Cycle Results

Sample Numbers	Defect Type	Reinforcement Type	Cycles to failure at ΔP = 72% SMYS (1)	Design Cycles (Cycles to failure / 5) (2)	Life in Years ("Light" Cycling) (3)	Life in Years ("Very Aggressive" Cycling)	Failure Ratio (Reinforced / UR)
24C-UR-1	Corrosion	Unreinforced	5,336	1,067	106 Years	3 Years	1.00
24C-AESS-3	Corrosion	Allan Edwards Steel Sleeve	21,247	4,249	424 Years	15 Years	3.98
24C-AESS-7	Corrosion	Allan Edwards Steel Sleeve	32,020	6,404	640 Years	23 Years	6.00
24D-UR-4	Dent	Unreinforced	13,004	2,601	260 Years	9 Years	1.00
24D-AESS-6	Dent	Allan Edwards Steel Sleeve	29,743	5,949	594 Years	21 Years	2.29
24D-AESS-8	Dent	Allan Edwards Steel Sleeve	30,391	6,078	607 Years	22 Years	2.34

NOTES:

(1) The "cycles to failure" values presented are based on a sum of applied pressure cycles using Miner's Rule assuming a pressure range equal to 72% SMYS.

(2) A fatigue safety factor of 5 was selected for this study.

(3) The "Light" and "Very Aggressive" pressure cycle conditions are based on work by Kiefner et al as reported in "Estimating Fatigue Life for Pipeline Integrity Management" (IPC2004-0167).

(4) COLOR CODING: **Unreinforced (BLACK) | Allan Edwards Steel Sleeves (BLUE)**

(5) Allan Edwards samples 24C-AESS-7 and 24D-AESS-8 were re-tested to evaluate the effect of sleeve fit-up as concerns existed regarding the make-up of the initial two repaired samples. As noted, the fatigue life for the corrosion sample increased by 50%, but minimal improvement was observed with the dent sample (i.e., 2%).

The experimentally determined fatigue lives represent many years of services for the gas transmission operators who provided co-funding for this study. The provided test results are also of benefit to liquid operators, although liquid operators should evaluate the estimated fatigue lives in relation to their particular pressure histories. Once pressure was permitted in the annulus between the pipe and steel sleeve, the sleeves' longitudinal and girth welds were subjected to stresses that eventually contributed to their failures.

Several key aspects were identified that affect the quality of a steel sleeve repair. It has been shown that poor fit up of steel sleeves can reduce their effectiveness in reinforcing pipelines. Using a filler material improves the load transfer between the pipe and the repair allowing for longer service life. Along with the importance of a good fit-up, it is also important to ensure the filler material has been properly installed to facilitate good load transfer from the pipe to the sleeve. Full-scale test was essential to determine these insights as numerical modeling alone would have failed to capture these critical findings.

Conclusions

The pipeline industry has used full-scale testing since its inception. Even before numerical models and analytic solutions were developed, design and metallurgical engineers learned that pipe materials have limits and the best way to determine those limits involved pressurization to failure. An excellent example of the use of full-scale testing involved the seminal work conducted by A.R.C. Markl (2) in the 1940s and 1950s as an employee at Tube Turns that resulted in the development of Stress Intensification Factors for pipe fittings (elbows and tees) that are still in use today. Another example is the extensive burst testing on corroded pipe samples conducted by John Kiefner (3) that led to the development of ASME B31G, RSTRENG, and other calculation methods for assessing corrosion. More recently, over 1,000 full-scale burst, pressure cycle, axial tension, and bending tests have been conducted by the authors and others over the past 20 years that have contributed to the world-wide use of composite reinforcing technologies.

Full-scale testing has and will continue to contribute significantly to our understanding on the capabilities and limitations of pipe materials, repair system, and other pipeline-focused technologies. A well-designed, instrumented, and executed full-scale test can provide valuable insights for design and integrity engineers charged with the responsibility of constructing and maintaining safe pipelines. With the aging pipeline infrastructure around the world, the use of full-scale testing will continue to play a critical role in maintaining the integrity of pipelines and ensure that appropriate levels of conservatism exist in their operation.

References

(1) ASME PCC-2, Repair of Pressure Equipment and Piping, published by the American Society of Mechanical Engineers, 2002.

(2) Markl, A. R. C., *Fatigue Tests of Welding Elbows and Comparable Double Miter Bends*, Trans. ASME, Vol. 69, 1947, pp. 869-879.

(3) Kiefner, J. F., *Final Report on Continued Validation of RSTRENG*, Prepared for the Line Pipe Research Supervisory Committee, Pipeline Research Committee of PRC International, January 1, 1996.

(4) Alexander, C., and Denowh, C., Use of Full-scale Testing for Managing Pipeline Integrity, Pipeline Pigging & Integrity Management Conference, Houston, Texas, February 17-21, 2020.

(5) Alexander, C., Edwards, C., and Precht, T., Steel Sleeves: A New Look at a Widely-Used Repair Method, Pipeline Pigging & Integrity Management Conference, Houston, Texas, February 18-22, 2019.

(6) Alexander, C., Medford, J., Rickert, J., A Validation Study of Computed Tomography Inspection Technology Using Full-scale Test Articles with Crack-like Features, Pipeline Pigging & Integrity Management Conference, Houston, Texas, February 19-20, 2020.

Figure 1. Photograph of a burst test to evaluate a crack-like feature

Figure 2. Pressure cycle pumping unit

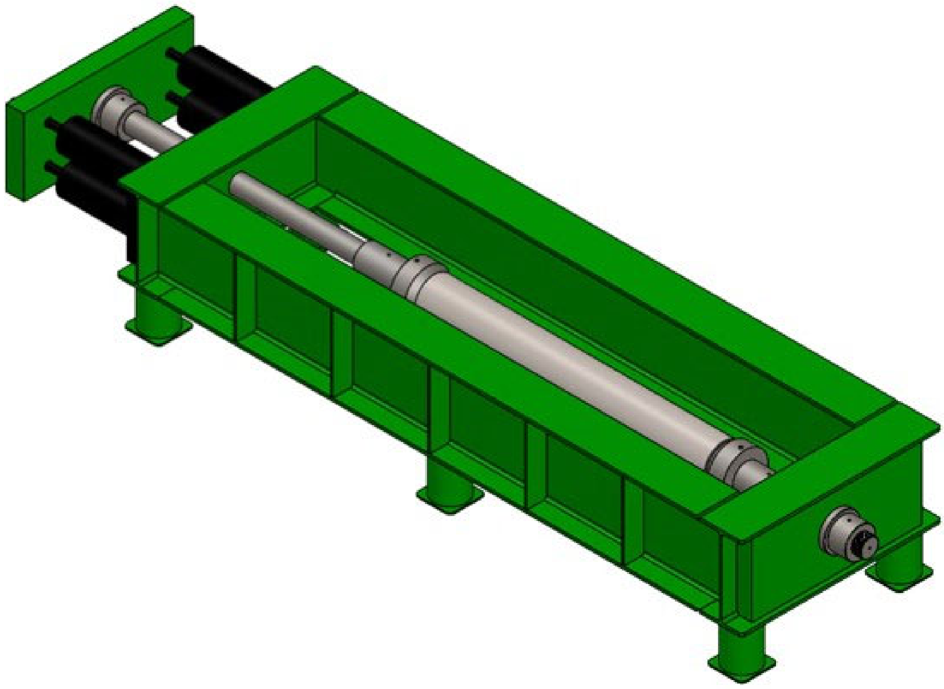


Figure 3. Axial tension load frame (1 million lbs capacity (4,448 kN))

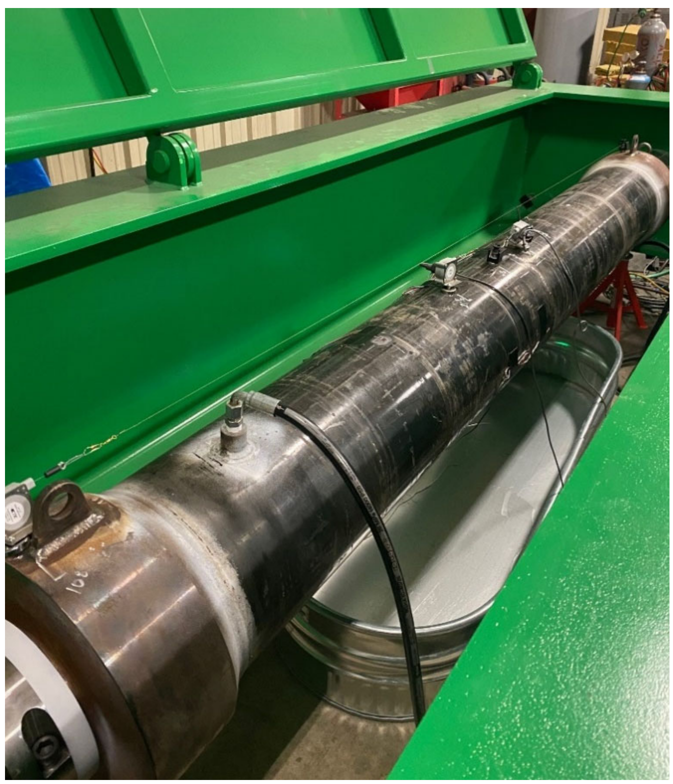


Figure 4. Photograph showing axial tension sample

Figure 5. Four-point bend frame (3 million ft-lb (4.1 million N-m) capacity)
(30-inch pipe shown in [top]; 12-inch pipe after bend test [bottom])

Figure 6. High strain bending frame (800,000 ft-lb (1.1 million N-m) capacity)

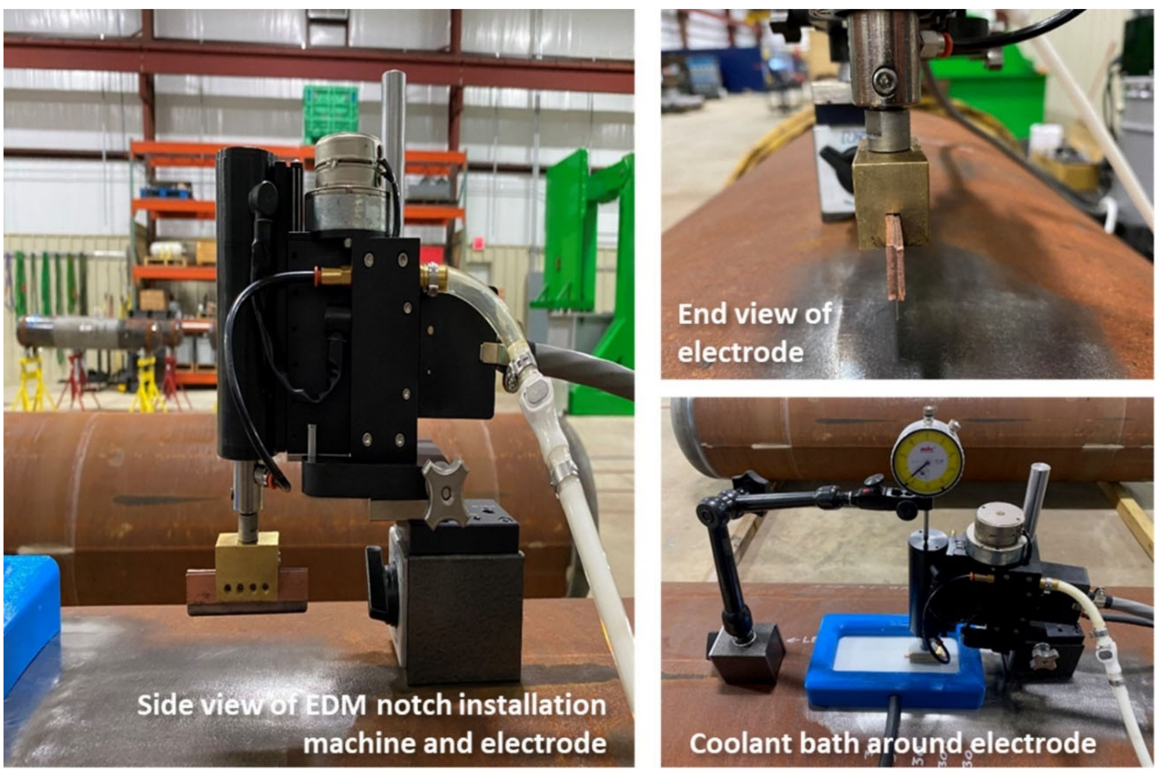


Figure 7. Photographs showing the installation of an EDM notch

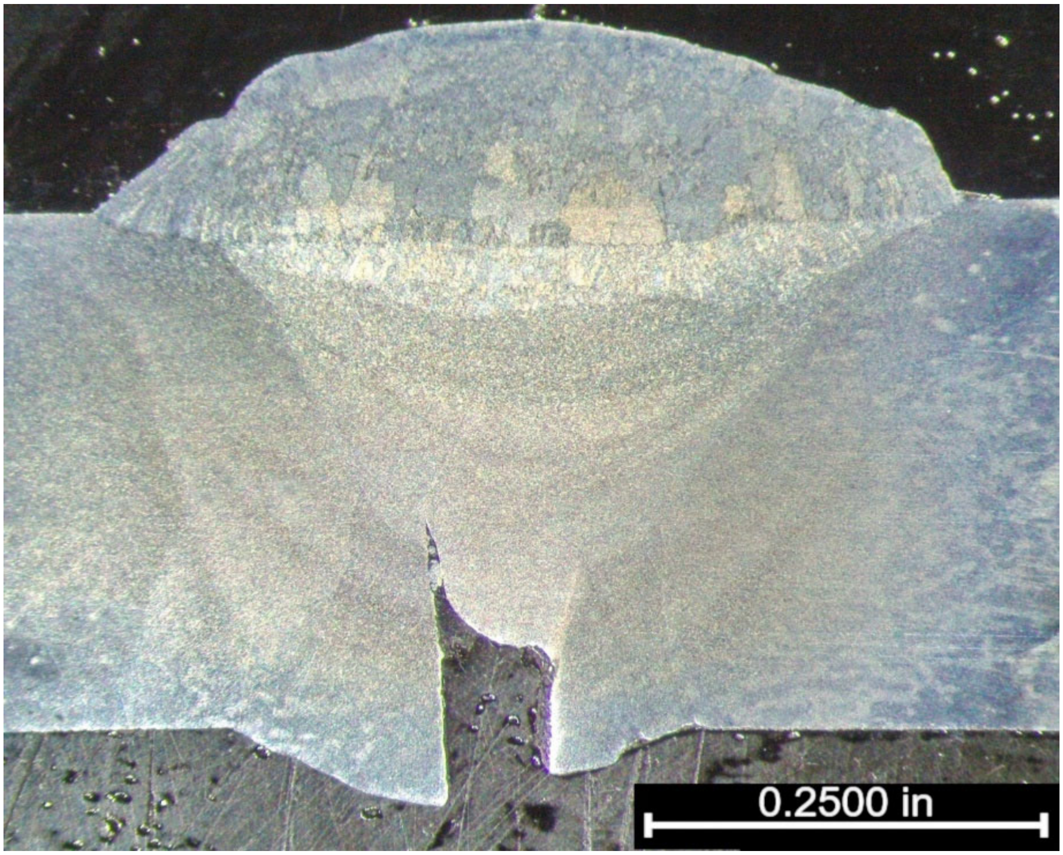


Figure 8. Girth weld defect installed in test sample

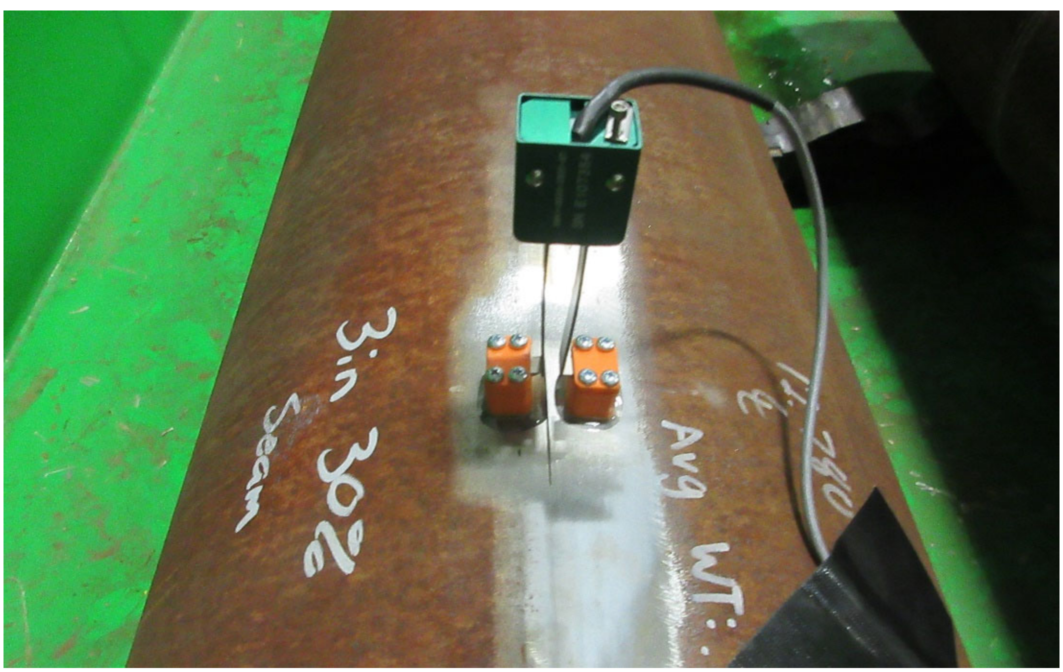
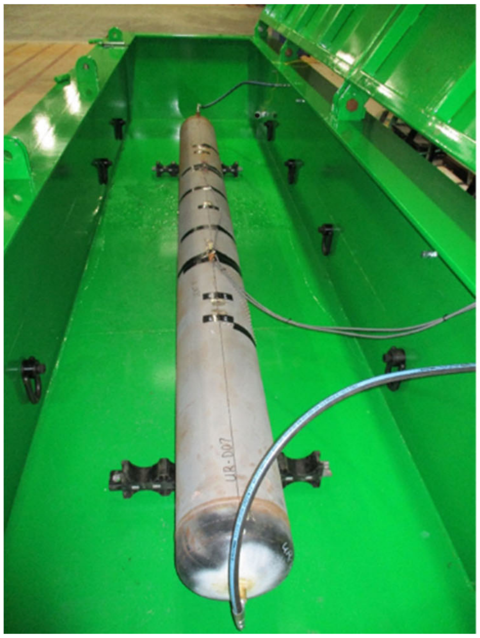


Figure 9. Clip gage used to measure EDM notch opening

Figure 10. Full-scale test facility

Figure 11. Photographs showing the dent installation test rig



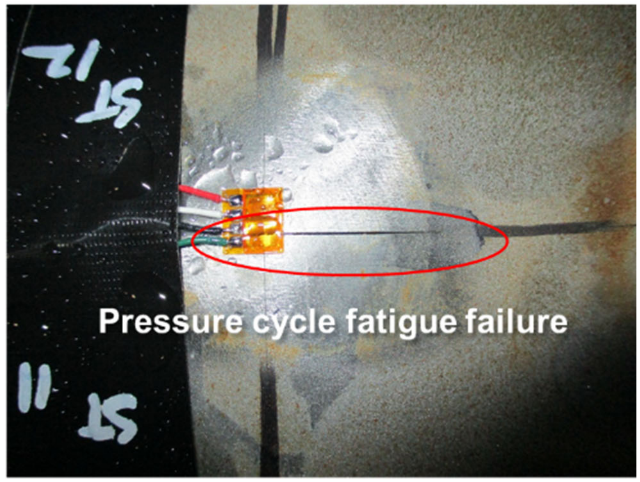


Figure 12. Photographs the dent test sample and associated fatigue crack

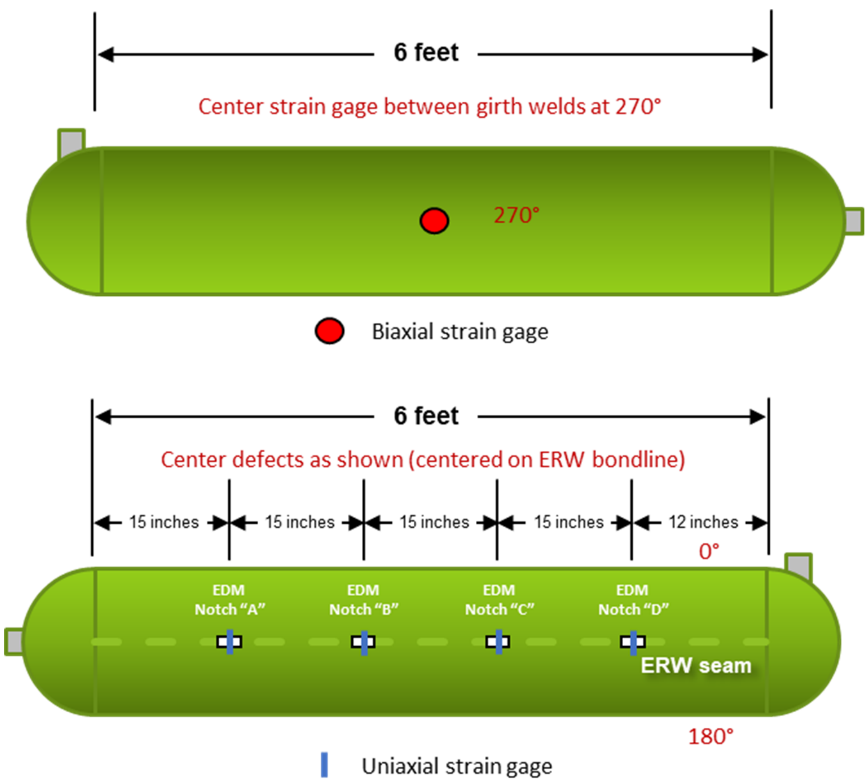


Figure 13. Schematic for EDM notch Sample 2

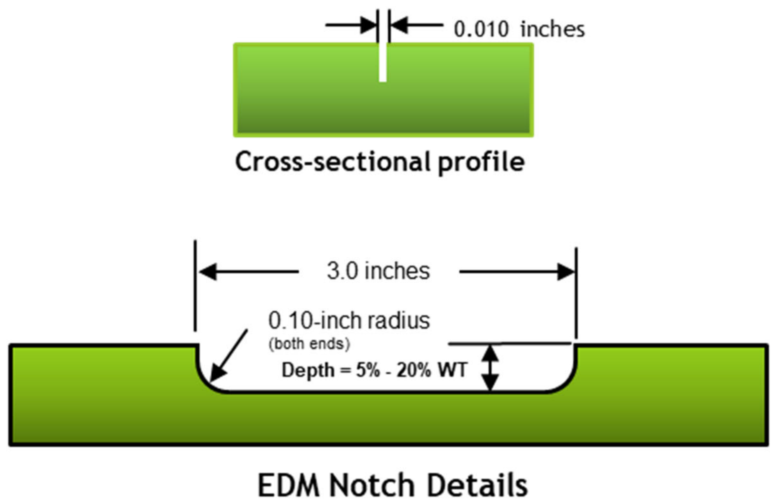


Figure 14. EDM notch geometry for EDM notch Sample 2

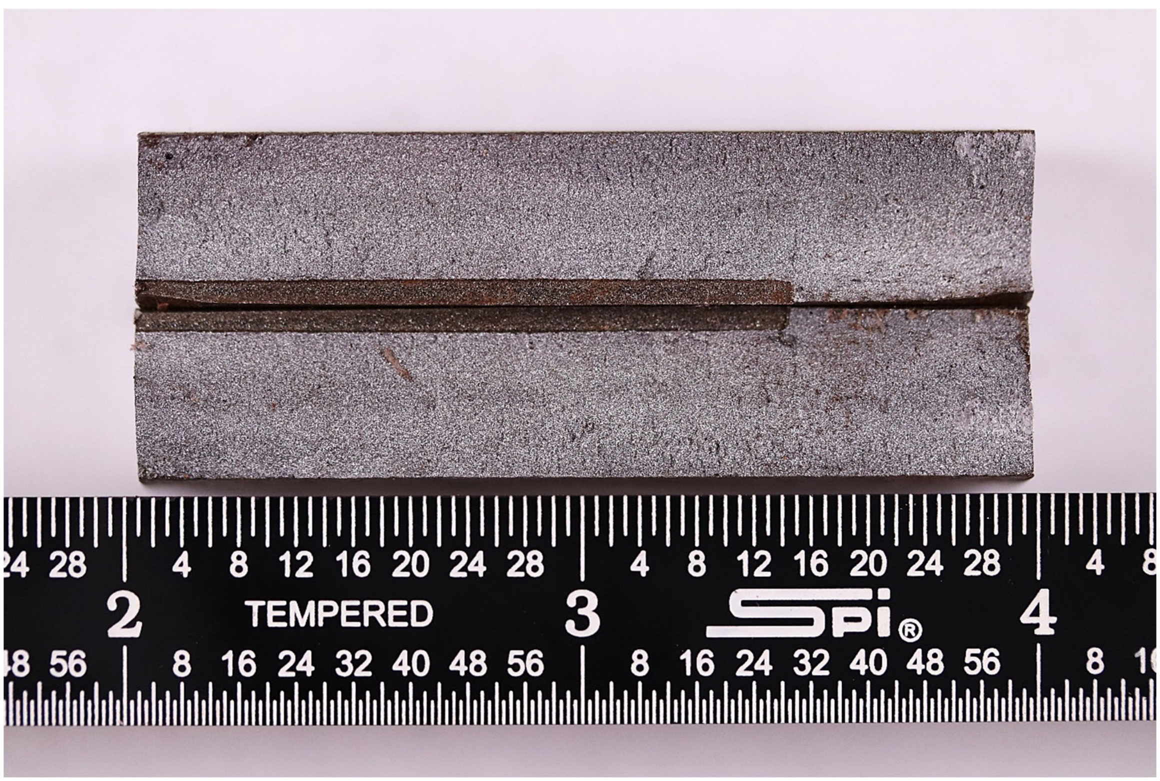


Figure 15. Meridional post-test sectional view of the EDM Notch C

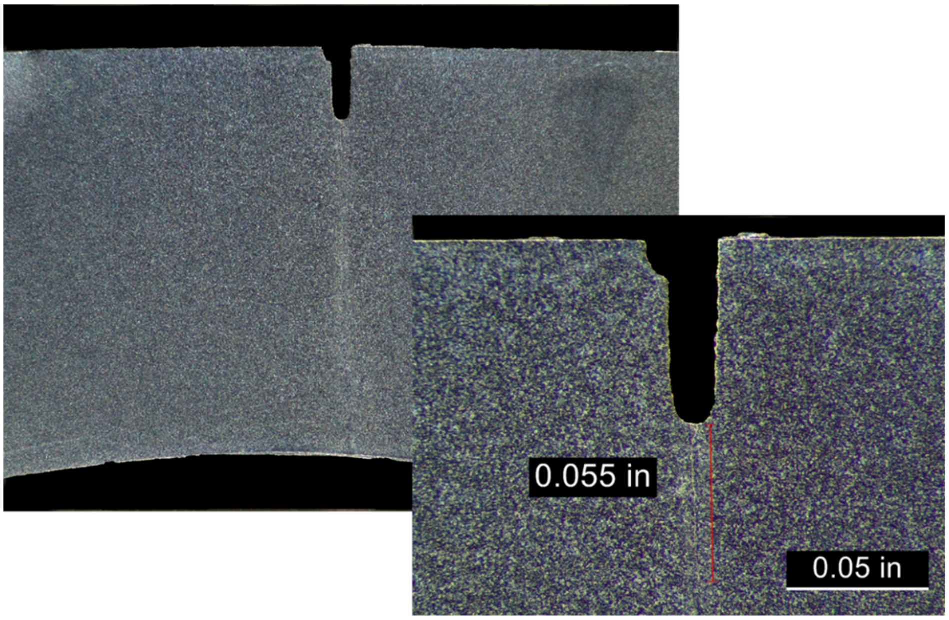


Figure 16. Transverse post-test sectional view of the EDM Notch C with crack

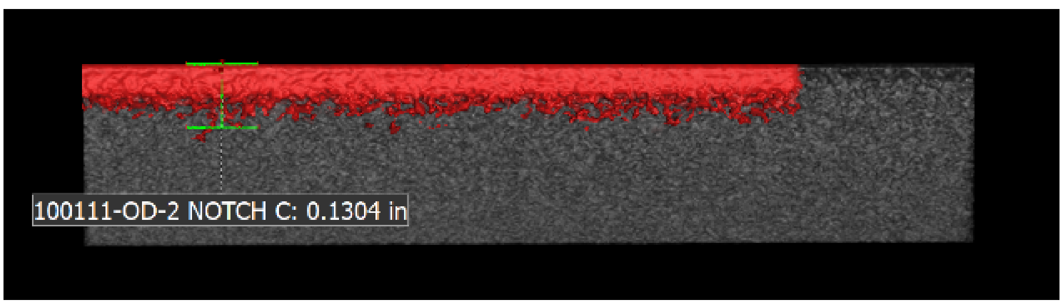


Figure 17. Meridional post-test CT scan EDM Notch C

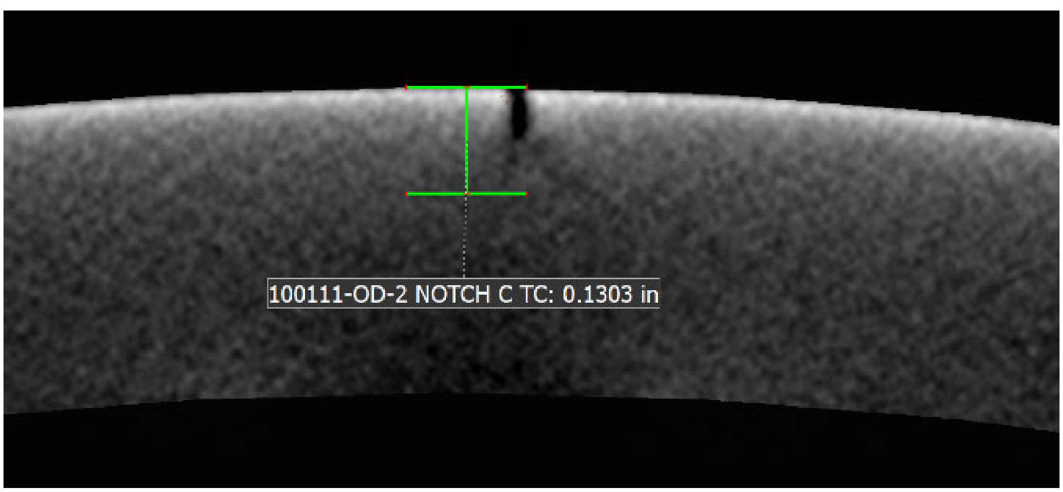


Figure 18. Transverse post-test CT scan EDM Notch C

Figure 19. View of simulated dent after indenter removal

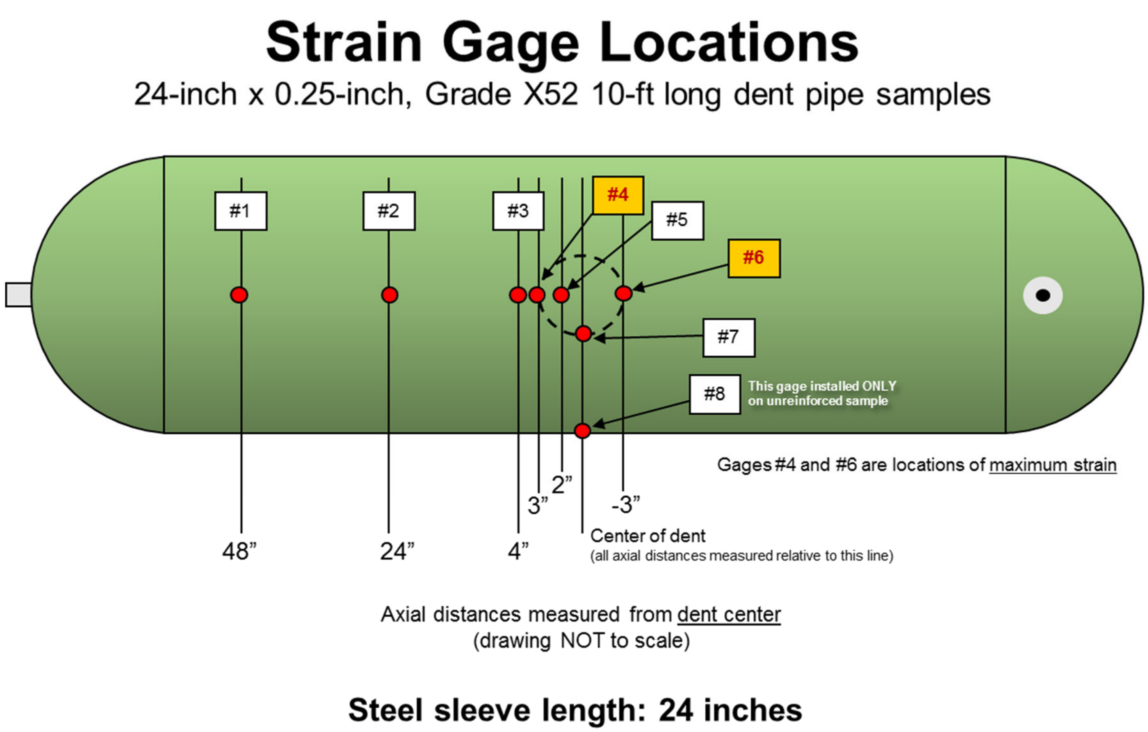


Figure 20. Strain gage locations for the dented samples