Use of Full-scale Testing as a Means for Managing Pipeline Integrity

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Abstract

Pipeline operators and supporting service organizations use various means for establishing the mechanical integrity of pipeline systems. Typically, in-line inspection technologies provide the first source of data for making critical integrity management decisions. Inspection data are processed and utilized in a variety of ways, including finite element analysis, fracture mechanics, and risk-based software packages that all involve some form of numerical modeling. While there is no doubt that numerical modeling plays a critical and essential role in managing pipeline integrity, the increased use of full-scale testing could greatly enhance industry's ability to evaluate the threats associated with anomalies of various forms.

The fundamental goal of any full-scale test is to simulate real-world pipeline conditions and establish a true limit state condition by applying simulated loads that could lead to failure. These include various means of loading including bending, axial tension / compression, cyclic pressures, and burst pressures. Further, full-scale testing is an ideal means for validating repair technologies, including composite repair systems and steel sleeves. This paper provides several case studies on the full-scale assessment of dents, crack-like features in seam welds, and simulated bending associated with geohazard loads, as well as the assessment of repair technologies including composites and steel sleeves. Also included is a discussion on data acquisition systems, monitoring devices, and comments on safety and calculation of burst energies.

The goal of this paper is to provide readers with a better understanding on the benefits associated with full-scale testing, while at the same time presenting various options available for testing that include the fabrication of specialized fixtures and equipment to achieve desired loading conditions.

Introduction

The design and assessment of pipeline systems has undergone significant changes over the past 50 years. Advances in computer modeling and the ability to complete large calculations in short periods of time have provided design engineers alternatives to conventional design methods that once relied solely on hand calculations. Full-scale testing also generated empirical data, which was often to support analytical methods based on solid mechanics and shell theory.

The focus of this paper is to bring about a renewed interest in generating empirical data based on full-scale destructive testing for making critical integrity management decisions. It is the author's observation that operators are not evaluating the true severity of defects due to industry's reliance on numerical modeling absent validation via full-scale testing. Absent complete information, operators are sometimes being required to classify defects as more severe than necessary. The key is to properly integrate numerical modeling and full-scale testing to provide pipeline operators with the tools necessary to properly-assign threat levels.

One of the best examples of using full-scale empirical data in the history of the pipeline industry was the performance evaluation of pipe fittings subject to external loads. The work is reflected in a series of papers published by A.R.C Markl in the late 1940's and early 1950's (Markl, 1947, 1950, 1952, 1955). This work contributed greatly to the development of piping flexibility analysis methods that are still in use today. Flexibility factors act as "knock down factors" to the relative stiffness of a straight section of pipe. Stress intensification factors (SIFs) were also determined experimentally by Markl to relate fatigue life of a piping component (e.g., elbow, tee, or miter joint) to a girth weld on a straight section of pipe when subjected to displacement loads.

Figure 1 illustrates one of the S-N fatigue curves generated by Markl that plots failure data for 4-inch NPS elbows subjected to in-plane bending loads. Data sets such as these were used establish linear curve fits that were then used to establish SIFs. Numerous authors have published works both supporting and challenging the accuracy of the Markl work under various loading conditions using numerical methods, such as the in-plane elbow results plotted in Figure 2.

Another body of work that has impacted the pipeline industry are a series of burst tests conducted by Battelle Memorial Institute in the late 1960s and 1970s. Battelle was the recipient of the NG-18 program that produced numerous assessment methodologies, including B31G and the “log-secant” equation, that describes the relationship between the size of a longitudinally-oriented defect and the failure stress level in a pressurized cylinder. Provided in Figure 3 is a plot showing the empirical data used to develop the ASME B31G formulation for assessing corrosion severity in pipelines.

As with the work completed by Markl and Battelle, there are numerous other applications where laboratory testing served as the basis for the design of high-pressure transmission pipelines. This paper provides a high-level overview on full-scale test methods and several case studies where full-scale testing was used by the authors to support pipeline integrity management decisions. Commentary is also provided in selection of instrumentation devices and safety.

Test Methods

Conducting full-scale testing provides numerous opportunities for technical challenges. There are only a few full-scale test labs in North America. Three reasons come to the authors’ minds for their scarcity. First, today’s engineers are often more focused on theory and analysis than experimental methods. A casual review of the title associated with most graduate theses from the world’s major universities supports this observation. Graduate students are more likely to use data generated from numerical models than empirically-derived solutions based on experimentation.

Secondly, setting up a full-scale test lab is extremely expensive and requires levels of expertise not taught in most universities. The cost for starting up a full-scale test lab in the pipeline industry is on the order of $2 million. In contrast, the cost for starting a company utilizing numerical modeling is at least one order of magnitude less expensive.

Finally, conducting full-scale testing can be dangerous. As will be discussed in a subsequent section on safety, the energy levels associated with even moderately-pressurized samples can be expressed in pounds of TNT (i.e., 1 lbs. of TNT is equal to 1.489×10^6 ft-lbs.). Those testing high-pressure pipe samples should appreciate the potential energy levels and take the necessary precautions to ensure the safety of all personnel involved in the testing.

The sections that follow provide details on test plans, equipment and instrumentation required for testing, and a brief discussion on safety.

Test Plans

The key to conducting a good test is a good test plan. Well-written test plans ensure that all participants, including engineers and technicians, are aligned on the same test objectives. Even basic testing programs have multiple phases that require attention to detail to ensure the necessary information is obtained during the test. Examples include installing strain gages at the correct locations, applying the correct pressure and/or loads, and taking photos. Several figures are provided that were extracted from actual test plans.

- Figure 17: Corrosion burst test sample configuration
- Figure 18: Schematic diagram showing set-up for wrinkle bend testing
- Figure 19: Strain gage locations for wrinkle bend sample

Provided below are elements included in a typical test plan.

- Project background and purpose
- Test sample fabrication details
- Pre-test sample preparation
- Safety requirements: calculated energy levels and shielding requirements
- Test set-up
- Test plan
- Reporting

Instrumentation and Equipment

Instrumentation is involved in every test. Even a simple pressure-to-failure test involves a pressure transducer and some type of recording device. More complex testing programs, such as the discussions on testing wrinkle bends included in this paper, can involve multiple strain gages, complex loading sequences, and even automated control systems for applying loads. Engineers design test programs and plans, but laboratory technicians are usually the ones who install instrumentation and execute testing programs.

Provided below is a list of equipment that can be used in a test lab focused on pipeline testing.

- Crack opening displacement gages (clip gages)
- Displacement transducers and LVDTs
- Load cells
- Pressure transducers
- Strain gages
- Temperature probes
- Data acquisition and control systems

In addition to instrumentation, testing requires equipment to apply loads (i.e. pressure, tension bending, etc.). Some equipment can be expensive and require experienced individuals to operate.

- Chamber for pressure testing containment (see Figure 6)
- Dent installation rig (see Figure 5)
- Hydraulic cylinders and pumps
- Loading frames
    - Three-point and Four-point bending (see Figure 13 and Figure 14)
    - Tension and compression
- Pressure equipment
    - Static pressure pumps
    - Cyclic pressure pumps

Safety

The pipeline industry is no stranger to safety. Pressure and load testing samples in a test lab requires constant vigilance. There are many facets in a lab safety program; however, one of the most practical is an appreciation for energy levels when testing with water and gas. Calculation of a test sample's stored energy allows engineers to scale and predict failure severity. Stored energy from a pressurized fluid is a function of pressure, volume, temperature, and fluid's bulk modulus (liquid) or compressibility (gas).

Provided below are some basic calculations that can be performed by any engineers armed with information related to volume and failure pressure. The example that is provided assumes a pressure-to-failure test is being conducted involving a 12.75-inch x 0.375-inch, Grade X52 pipe with a predicted failure pressure of 4,000 psig. Provided are calculations assuming water and nitrogen gas as the testing mediums. The equations used are taken from Antaki's *Piping and Pipeline Engineering* book (page 111) and ASME PCC-2-2015 (Page 218).

Burst testing using water (liquid)

$$E = \frac{1}{2}\frac{P^2V}{\beta}$$

Where: P = 4,000 psig (burst pressure)
V = 10,850 in^3
B = 330,000 psig

Using the above equation, the estimated energy level is 22,000 ft-lbs.

Burst test using nitrogen (gas)

$$E = 360\,P\,V\left(1 - \left(\frac{P_{atm}}{P}\right)^{0.286.}\right)$$

Where: P = 4,000 psig (burst pressure)
P_{atm} = 14.7 psig
V = 6.3 ft^3

Using the above equation, the estimated energy level is 7.3 x 10^6 ft-lbs., which is equal to 4.9 lbs. of TNT and is 330 times the energy level associated with liquid. The hazards associated with gas testing are significant as can be seen in the above calculations, although even the liquid sample's energy level of 20,000 ft-lbs. should not be neglected.

In addition to evaluating the stored energy in a sample, a full-scale test also requires the appropriate containment and/or shielding. Common forms of containment include below ground test bunkers with steel lids, steel containment boxes, pipe half shells that are bolted or pinned in place, and other mobile steel shields. Any form of containment requires a detailed engineering analysis to determine safe sample sizes and stored energy.

Provided in Figure 4 is a photograph of ADV's pressure containment chamber. This structure was designed to accommodate a 36-inch diameter sample that is 25 feet in length.

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 third case studies are more conceptual in nature, while the second and fourth case studies relate to technology and product validations.

Full-Scale Assessment of Dents

Full-scale testing of dents dates back 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 4 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 5 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 7 is a schematic diagram showing the configuration for Sample 2 that included four EDM notches, while Figure 8 shows the EDM notch geometry. All notches were all 3 inches in length. The depths for each EDM notch in Figure 6 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 9 is the meridional post-test sectional view of the EDM Notch C. Figure 10 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 particular 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 11 and Figure 12. The CT scan and post-test sectioning depth measurement had a difference of 1.9%.

Simulated Bending Associated with Geohazard Loads

Geohazard loads are a concern to many pipeline operators in North America. This category of loading has contributed to failures of wrinkle bends and girth welds due to bending and axial tension loading. A bending frame is required to simulate large-scale bending loads. It is also possible to use these large-scale test facilities to evaluate the reinforcing benefits of composite repair technologies. Provided in

[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).

Figure 13 and Figure 14 are photographs showing ADV's 3.0 million ft-lb bending frame, including pre-test photos showing the set-up for a wrinkle bend test.

Several recent studies have been conducted involving bend testing of girth welds and wrinkle bends, although no specific details are presented in this paper. Provided below are several key steps for consideration when conducting full-scale bend tests.

- Inspecting the features of interest should be conducted prior to testing, (e.g., wrinkle bends, girth welds, etc.). This allows test engineers to establish a baseline against which any test-induced features (e.g., cracking) can be compared.
- Instrumentation, including strain gages and displacement transducers, are valuable resources for monitoring samples during bend tests. They can also measure the loads applied to generate the required levels of stress and strain in the feature of interest.
- Often, combined loading contributes to pipeline failures. Testing programs that simulate geohazard loading should consider simultaneously applying internal pressure and bending loads.
- Prior to testing, engineers should determine whether or not low cycle, high strain conditions are present.

It is expected that geohazard loading will be an area of continued interest for the pipeline industry. For this reason, full-scale testing is essential to ensure that operators fully-understand the potential hazards associated with combined loading. It is also possible to evaluate and quantify the benefits of rehabilitation methods such as composite repair systems. For example, testing programs can be designed and executed that allow engineers to assess the benefits in applying composite materials for reinforcing wrinkle bends and girth welds. The ideal test program is one that compares the results of reinforced and unreinforced samples through multiple tests.

Finally, the authors have observed that making integrity decisions with only numerical modeling can lead to unconservative assumptions regarding the capacity of certain features subjected to geohazard and operational loads. Failure to integrate factors such as pipe ovality and residual stresses can grossly-overpredict the capacity of pipeline systems unless appropriately integrated into finite element models. The ideal assessment scenario is one that integrates both numerical modeling to define appropriate loading and boundary conditions, and then utilizes full-scale testing to validate the numerical models and establish the true limit state of the pipe. Once this scenario is complete, engineers are armed with a validated numerical model that can be used to evaluate a variety of geohazard loading conditions.

Assessment of Repair Technologies Including Composites and Steel Sleeves

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.

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 15: View of simulated dent
- Figure 16: 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 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.

[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.

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.

Closing Comments

As has been presented, the use of full-scale testing provides pipeline operators will powerful information for making informed decisions related to managing threat levels of various anomalies and features. The use of full-scale testing is not merely a suggestion for the pipeline community, but is strongly recommended for scenarios involving challenging loading conditions, complex features and anomalies, and assessing various repair options.

The ideal study is one that involves numerical modeling and full-scale testing. One of the best examples of this is addressed in the 2016 paper, IPC2016-64311, presented at the International Pipeline Conference (Alexander et al, 2016) that discussed a study involving large diameter elbows reinforced with composite materials. Finite element models were validated which permitted the operator to evaluate the benefits of reinforcing elbows considering a wide range of loading and boundary conditions in the pipe system. Full-scale testing often requires creativity on the part of testing engineers, especially when considering experiments involving combined loading conditions. Challenging and difficult decisions facing today's pipeline operators are made less difficult when integrating insights and results from full-scale testing.

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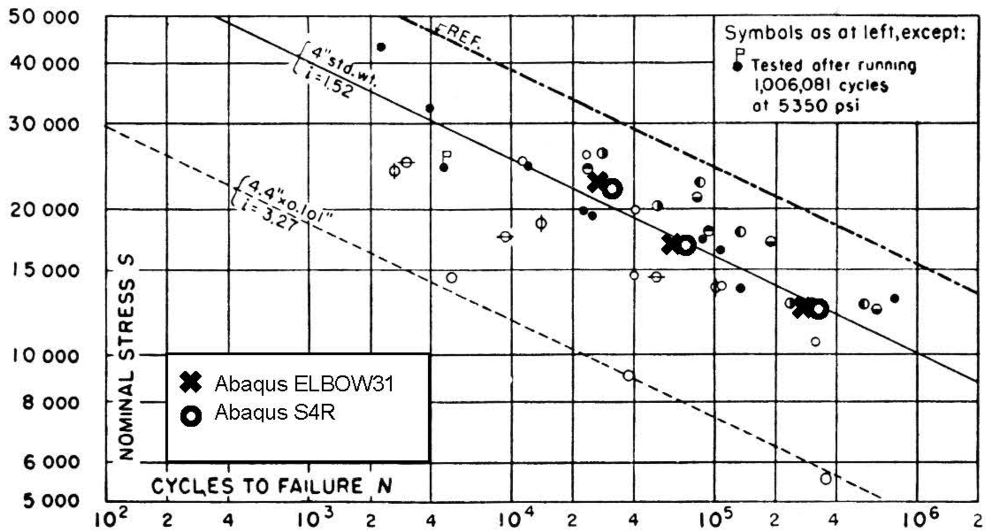

Figure 8. Fatigue results for long radius elbows, out-of-plane
Fig. 9 from (Markl, 1952)

Figure 1: Fatigue results for long radius elbows subjected to out-of-plane bending loads
(Fig. 9 from the 1952 Markl paper)

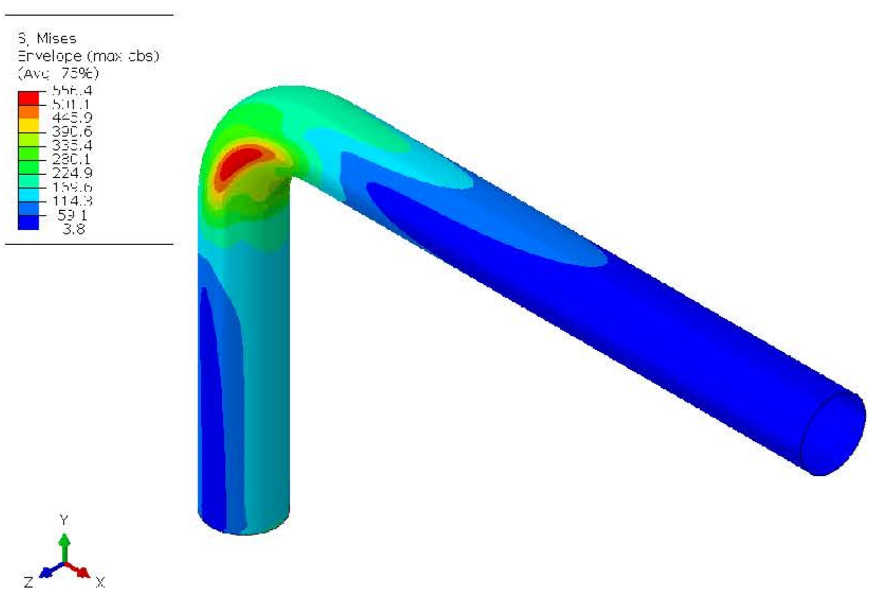

Figure 2: FEA contour plot for long radius elbows subjected to in-plane bending loads
(Figure 6 from the 2015 Sousa paper)

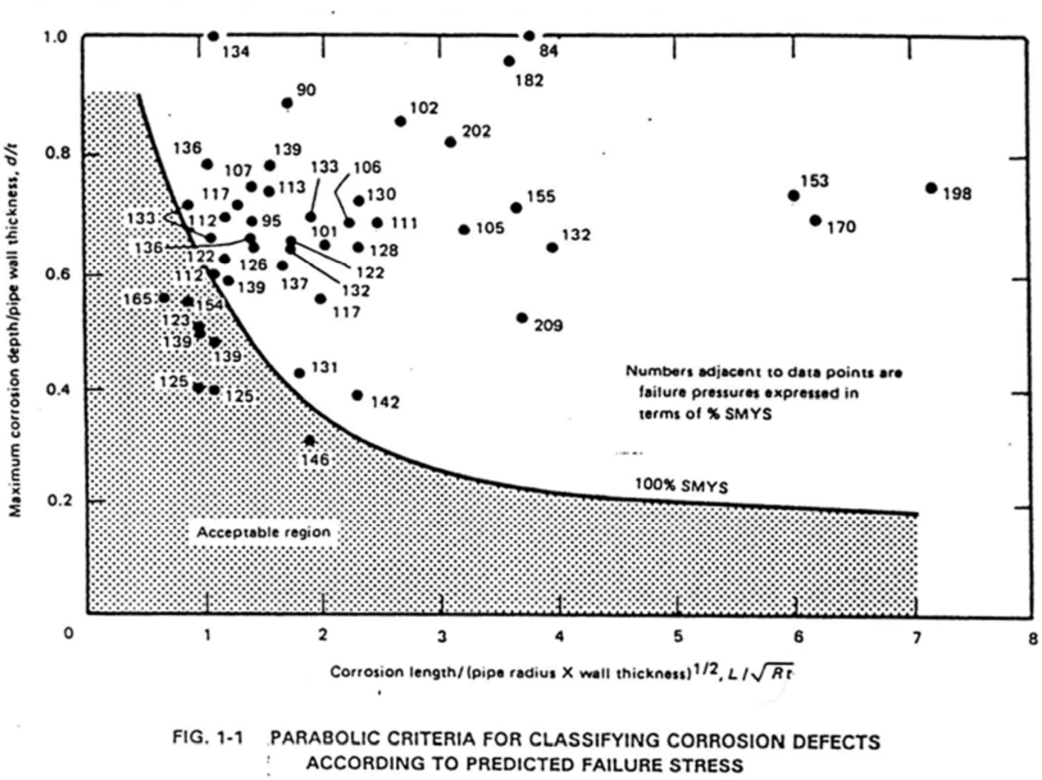

Figure 3: Empirically-based plot used as basis for ASME B31G

Figure 4: Photograph of ADV's pressure containment chamber

Figure 5: Photographs showing the dent installation test rig

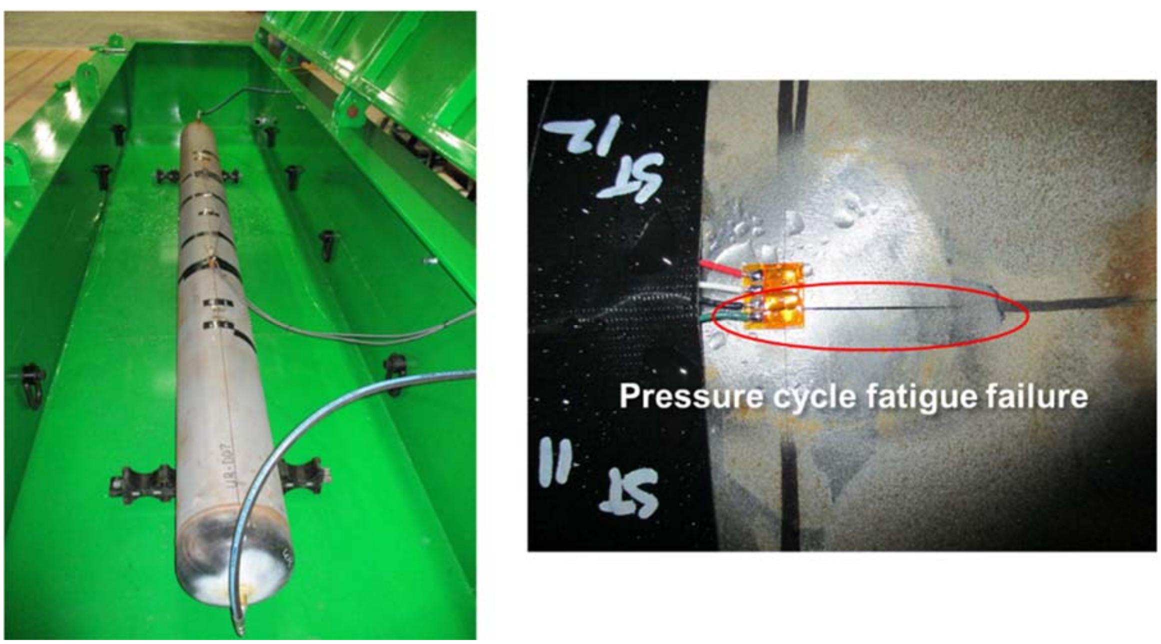

Figure 6: Photographs the dent test sample and associated fatigue crack

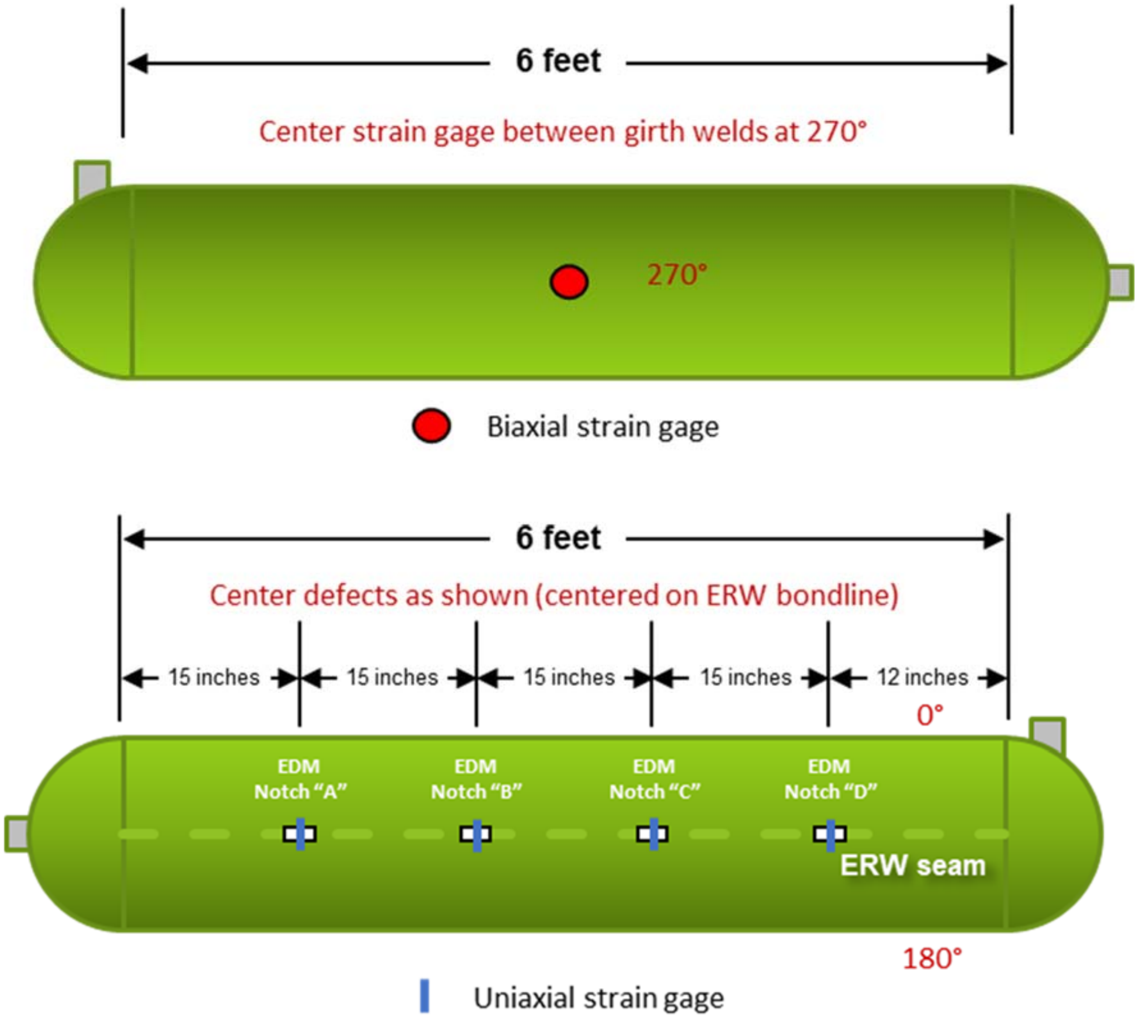

Figure 7: Schematic for EDM notch Sample 2

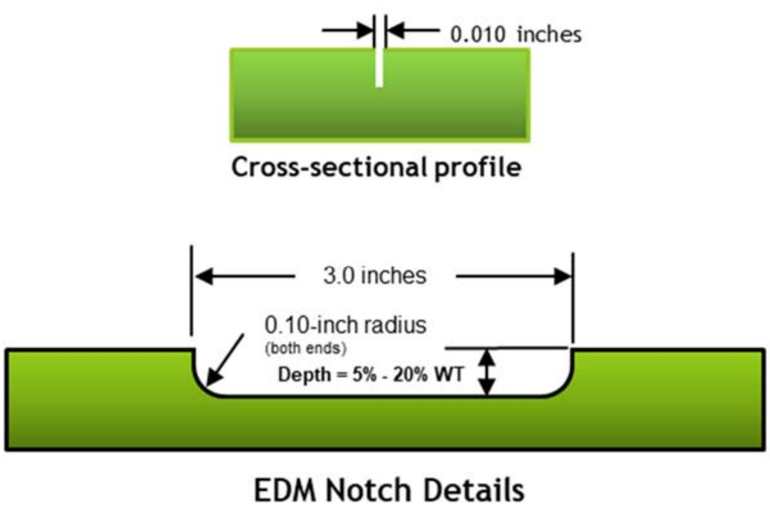

Figure 8: EDM notch geometry for EDM notch Sample 2

Figure 9: Meridional post-test sectional view of the EDM Notch C

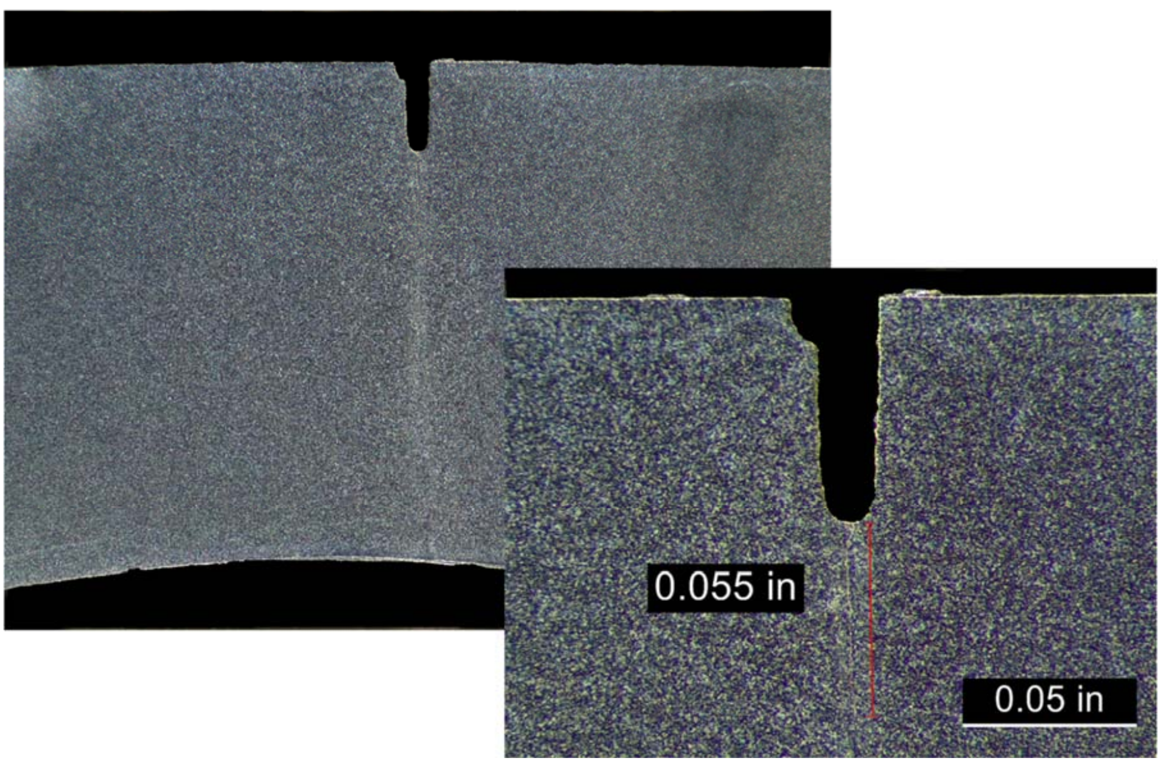

Figure 10: Transverse post-test sectional view of the EDM Notch C (with observed crack)

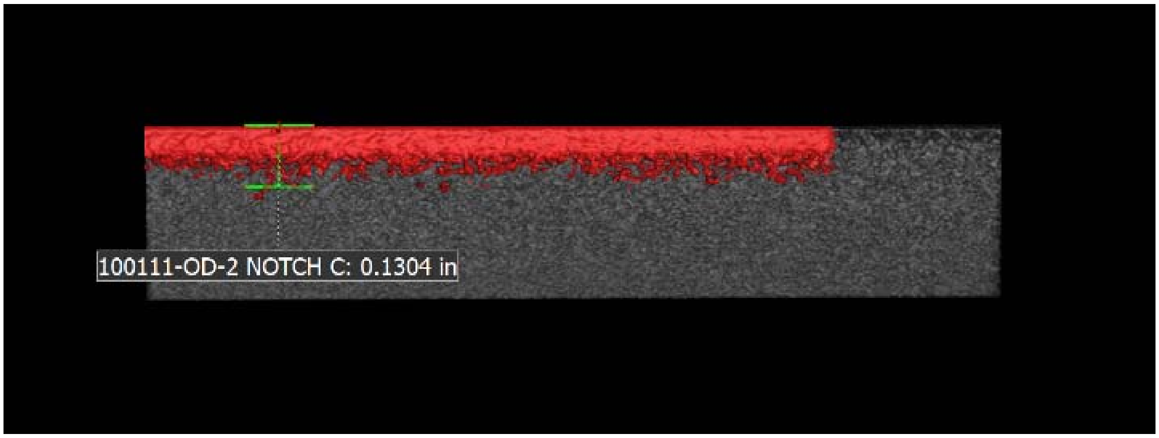

Figure 11: Meridional post-test CT scan EDM Notch C

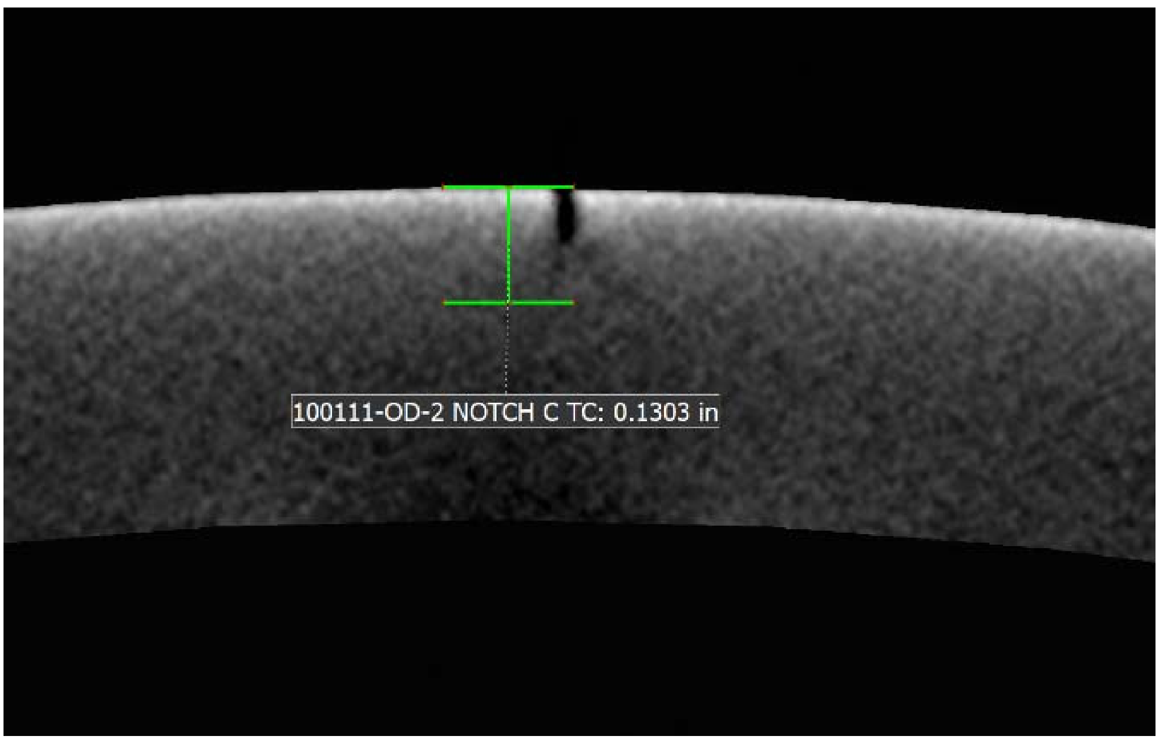

Figure 12: Transverse post-test CT scan EDM Notch C

Figure 13: Photographs showing set-up of the 3.5 million ft-lb bending frame

Figure 14: Photographs showing set-up of a wrinkle bend test in the bending load frame

Figure 15: View of simulated dent after indenter removal

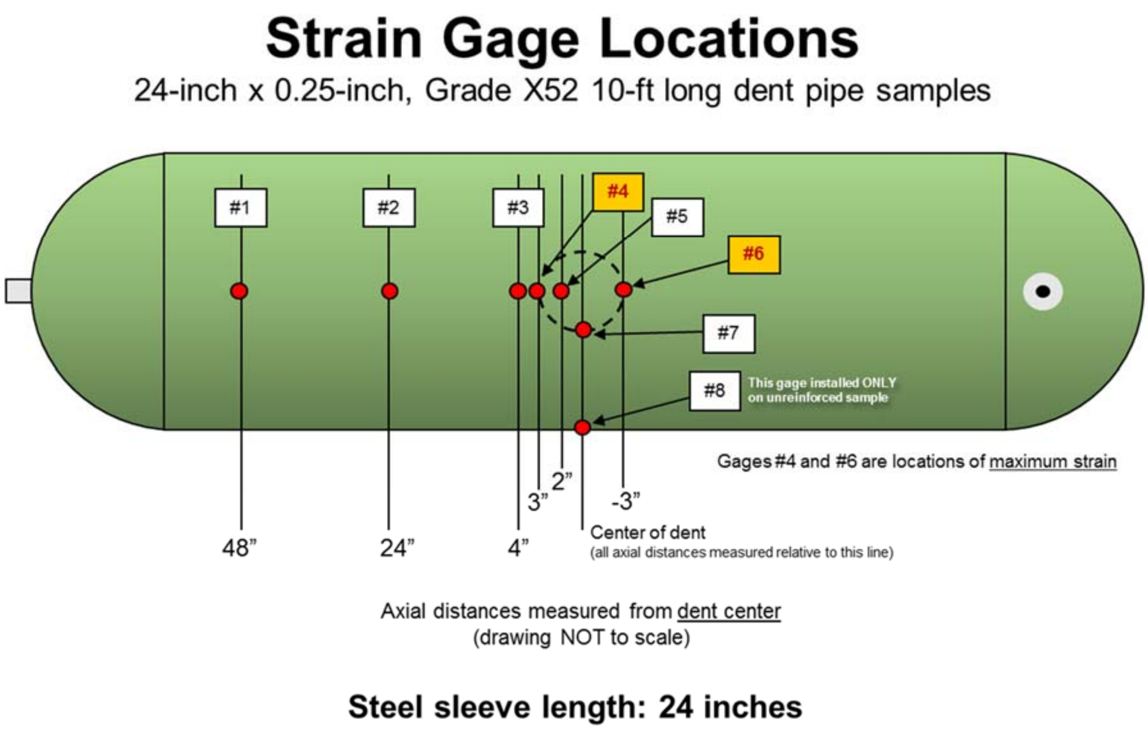

Figure 16: Strain gage locations for the dented samples

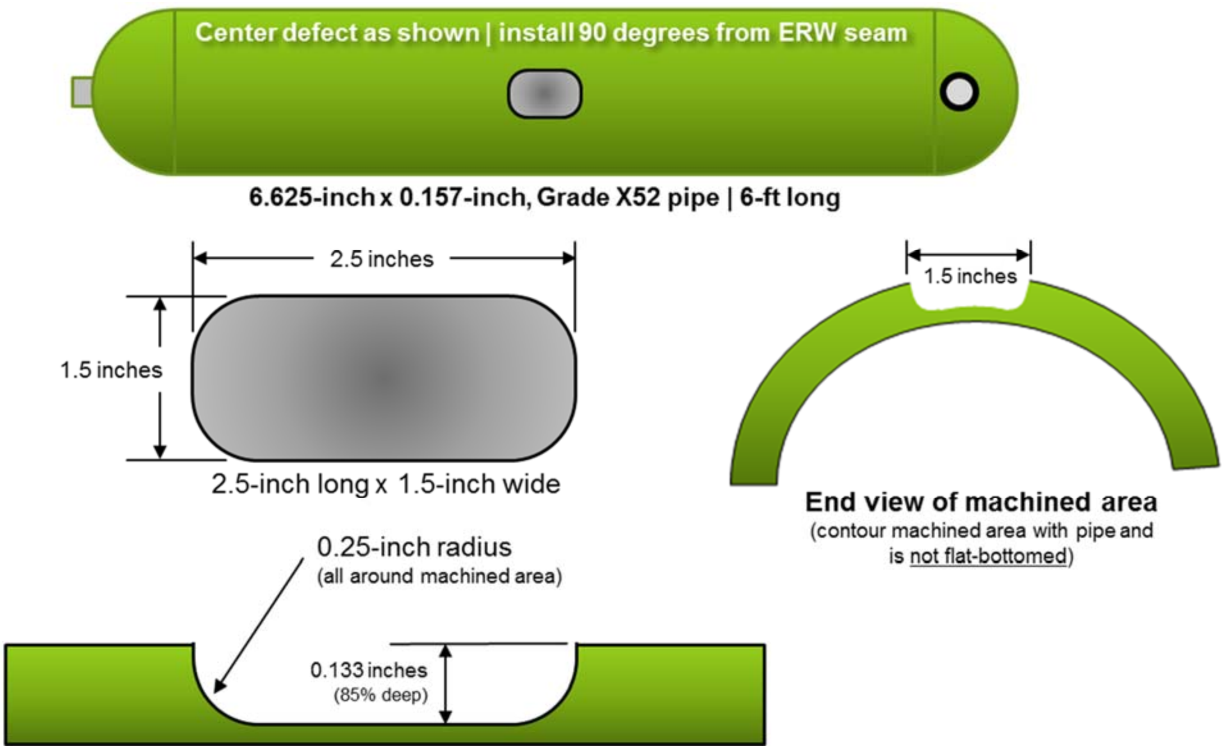

Figure 17: Corrosion burst test sample configuration

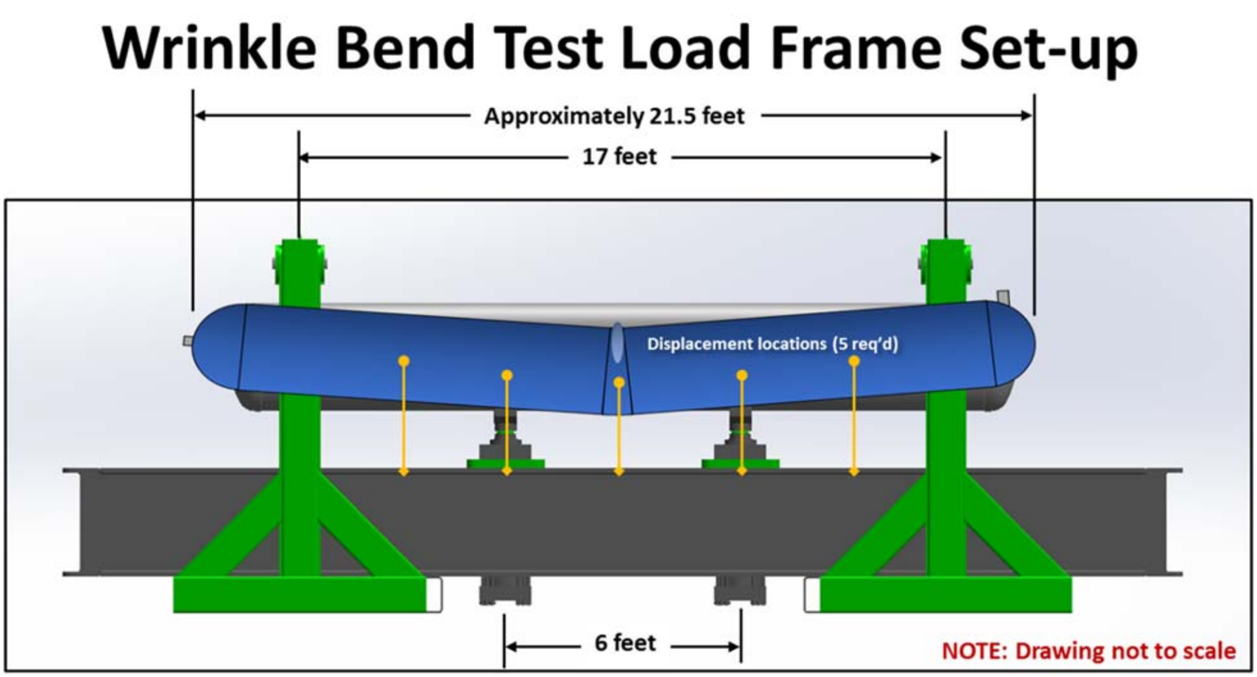

Figure 18: Schematic diagram showing set-up for wrinkle bend testing

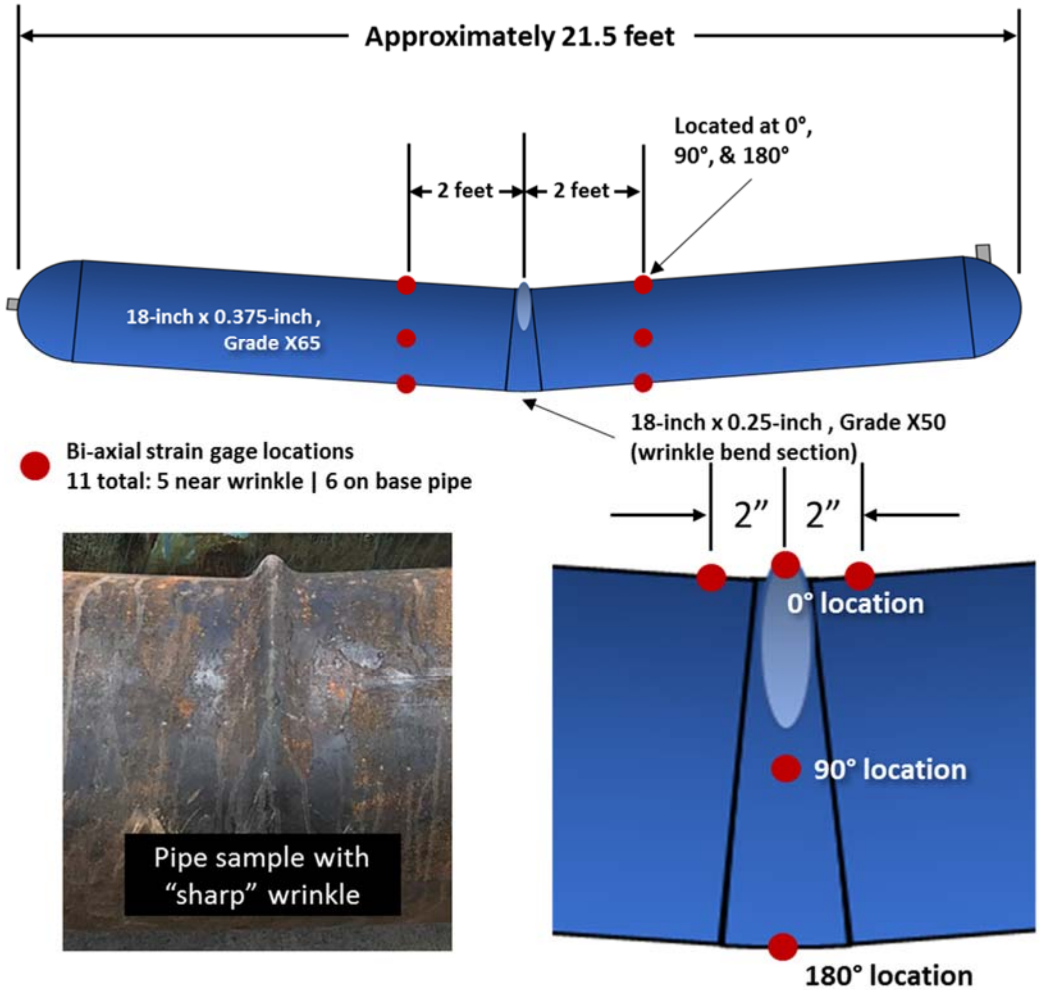

Figure 19: Strain gage locations for wrinkle bend sample