GREEN PAPER

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Using Full-scale Testing as a Means for Managing Pipeline Integrity

A comprehensive overview of full-scale testing practices for pipeline integrity assurance.

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ADV INTEGRITY

ADV Integrity (ADV) is an engineering consulting firm focused on providing custom engineered solutions for asset integrity assessment and management of onshore and offshore oil and gas equipment. ADV serves clients in the upstream, midstream, and downstream sectors with offices in Magnolia, Texas (Houston) and Grand Rapids, Michigan.

ADV is unique because we seamlessly integrate full-scale and sub-scale testing, numerical modeling, metallurgy, design, and failure analysis to assess, validate, and predict mechanical performance of critical components and pipeline integrity. For oil and gas operators full-scale testing allows better understanding and interpretation of system capacities, including the influence of material properties, loads, and threats on pipeline system performance. As pipeline integrity subject matter experts, we have worked with operators from around the world to help them quantify the effects of threats on the integrity of their critical systems. Practical and usable data from full-scale testing supplemented with analytical results greatly facilitate informed integrity and risk management programs.

In addition to our operator clients, we work with small and large technology companies to validate their technologies. Our clients include advanced inspection companies, repair and rehabilitation technologies, manufacturers, tool companies, and consulting companies seeking to validate their numerical analysis results.

ADV is uniquely positioned to serve both technology providers and pipeline operators and have been doing so since the inception of the company.

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OPENING REMARKS

Managing the integrity of North America's aging pipeline systems is one of the most challenging undertakings facing today's engineers employed by pipeline operators. The challenge is further intensified when considering the critical role that pipelines play in the everyday lives of those in North America, including natural gas pipelines that supply energy for our power grid and liquid pipelines that provide fuel for our transportation systems and feedstock for our refineries and chemical plants. Without pipelines our standard of living would be greatly reduced.

The process employed by most pipeline integrity engineers starts with inspection measurements made using in-line inspection (ILI) tools or in-the-ditch inspection technologies. If the measured data indicates a feature is a threat to pipeline integrity, an assessment is conducted using either closed-form engineering equations or numerical modeling techniques like finite element analysis. A central goal of pipeline integrity management is to deal with the challenges associated with operating an aging infrastructure as not all injurious features and defects need to be repaired. Along with advanced inspection and engineering assessment methods, full-scale testing can play an important role in helping pipeline executives and integrity engineers make the best decisions concerning injurious defects. Essentially, full-scale testing helps "sharpen the pencil" to ensure that integrity dollars are spent where they achieve the highest return on investment.

Listed below are thoughts on how pipeline operators can benefit in implementing full-scale testing as part of their integrity management programs.

- The ability to accurately simulate real world conditions using pipe material removed from service. This includes generation of simulated defects, simulating operating environments, and applying representative loads.

- Confirming the accuracy of engineering calculations used to estimate the severity of pipeline defects and features. Absent full-scale validation testing, engineering calculations can be overly conservative resulting in significant costs associated with unnecessary digging and repair efforts.

- Quantifying the limits of pipeline materials subjected to actual operating and extreme loading conditions.

- Validating the performance of technologies like composite repair systems, various inspection technologies, and composite pipe materials.

This **Green Paper** includes examples of how full-scale testing can be used to provide a more accurate and complete picture of defect behavior 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 used in full-scale testing.

The goal of this **Green Paper** is to demonstrate the inherent benefits in employing full-scale testing as a means for better understanding and quantifying the threat levels associated with certain pipeline defects. Everything presented is based on actual work completed for pipeline companies who benefitted from full-scale testing. 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.

Provided in this booklet are examples of where full-scale testing has been used to evaluate the effects of dents, girth welds, wrinkle bends, cracks, and the benefits associated with using composite reinforcing materials. A discussion is also provided on the creation of simulated defects and techniques employed for their creation.

SIMULATED DEFECT CREATION

Because there are a limited number of real-world features 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.

Different methods are used to generate simulated defects. Corrosion features can be fabricated using conventional machining techniques, electric discharge machining (EDM), and chemical etching to 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 followed by limited pressure cycling to generate a crack at the base of the notch. 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.

The sections that follow provide examples of how simulated defects were generated and then tested destructively to quantify their severity.

DENTS

Most pipelines have dents. Since the inception of the pipeline industry, dents have been a threat. Over the past 40 years a significant body of research has been conducted to quantify the threats posed by dents and mechanical damage, including full-scale burst and pressure cycling. With advances in ILI technologies, the accuracy of assessment methods has improved significantly to the point where operators are able to pinpoint and risk-rank dents that pose the greatest threat to their pipeline system.

Provided in **Figure 1** are photographs 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 the 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. Cyclic pressure testing is one of the

Figure 1: Photographs of a dent installation test rig

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 including the ability to predict future performance. **Figure 2** 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 were applied.

In addition to testing, results from numerical finite element models are often compared to results generated in testing. The Creaform laser scanning technology is useful for capturing the geometry of pipeline defects (**Figure 3**), which is then used as input into finite element models (**Figure 4**).

Figure 2: Photograph showing failure of pressure cycled dent

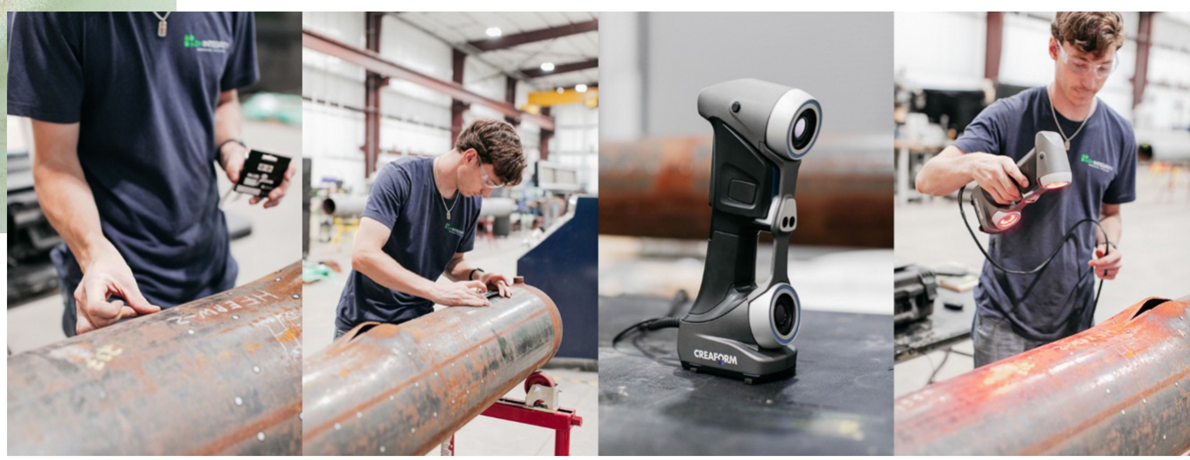


Figure 3: Scanning a pipe using the Creaform laser scanner

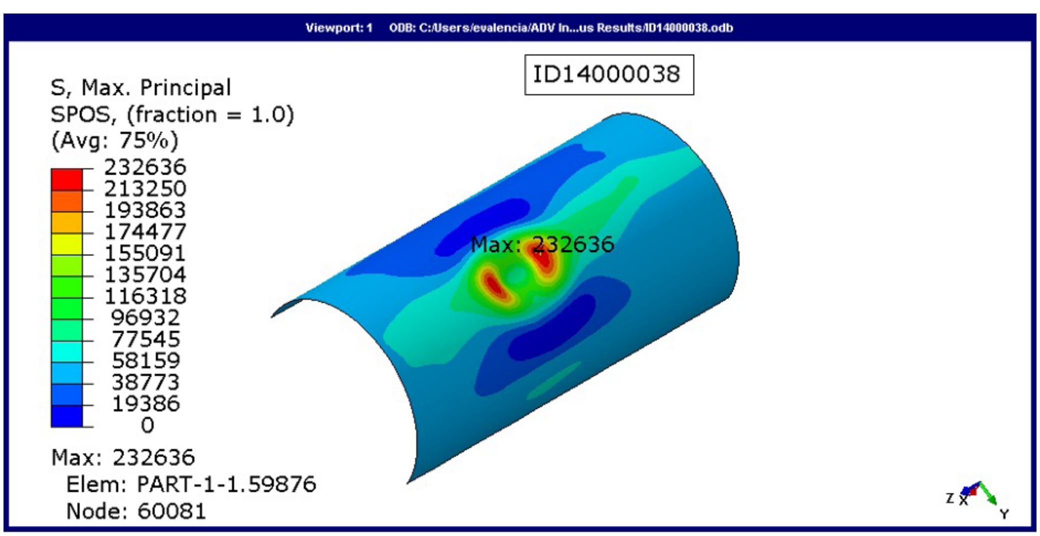


Figure 4: Finite element model contour plot showing a dent

GIRTH WELDS

Geohazard loading has been a consistent threat to pipeline integrity, specifically where vintage, undermatched and/or defective girth welds are present. The Pipeline and Hazardous Materials Safety Administration (PHMSA) reported that between 2001 and 2021 the number of onshore gas transmission pipeline incidents that occurred in the US due to loads induced by natural forces categorized under Earth Movement was 35, totaling an approximate cost of $70,000,000 (USD)[1]. In 2018 alone, at least six (6) landslide-induced ruptures occurred, three (3) of which were on pipelines built after 2014 (retrieved from www.phmsa.dot.gov). When pipelines fail due to geohazard loading, the feature most susceptible are the girth welds.

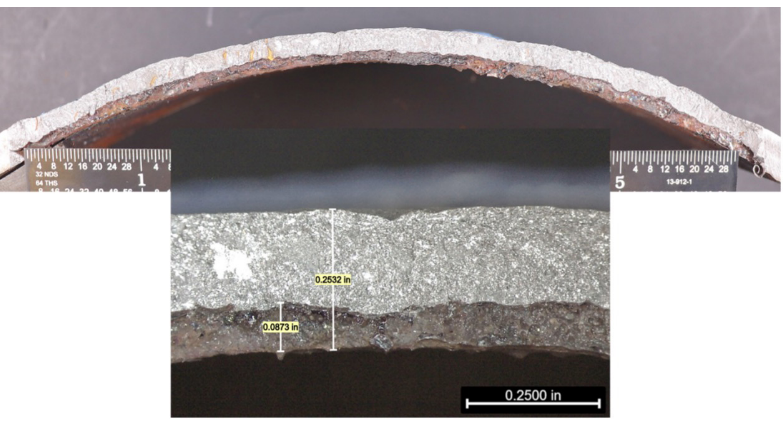


Figure 5: Test sample showing girth weld lack of penetration feature

Pipeline loss of containment from geohazard loading occurs from high axial strain on a pipeline imposed by the displaced pipeline. When the loading is in tension, failure generally occurs as a rupture at a girth weld and thus the vulnerability to failure in tension is largely governed by the tensile strain capacity of girth welds. When the loading is in compression, a buckle first forms, followed in some instances by a crack at the buckle. Full-scale testing is an ideal means for evaluating the strain capacity of vintage welds and can include lack of penetration features.

In full-scale testing, loading includes either axial tension loading as shown in **Figure 6**, or the use of a 4-point bending frame as shown in **Figure 7**. This photo also includes a cross-section of the weld showing a lack of penetration feature.

Sub-scale testing can be useful for determining the strain capacity of a girth weld. Provided in **Figure 8** are a series of photographs showing a longitudinal tensile test specimens with a girth weld loaded in tension, with strains measured using a Digital Image Correlation (DIC) camera. Using the DIC camera, strain was captured locally at the weld center and globally across a 2-inch gage length.

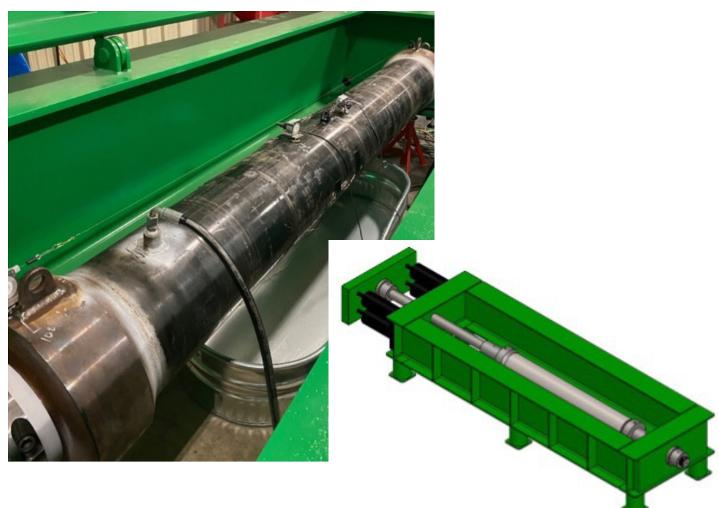


Figure 6: Tension frame used to load girth welds (1 million lbs. capacity)

[1] According to PHMSA's website: "Property Damage values are presented in dollars for the most recently completed calendar year. Value of gas lost is adjusted using the Energy Information Administration, Natural Gas City Gate Prices. All other values are adjusted using the Bureau of Economic Analysis, Government Printing Office inflation values."

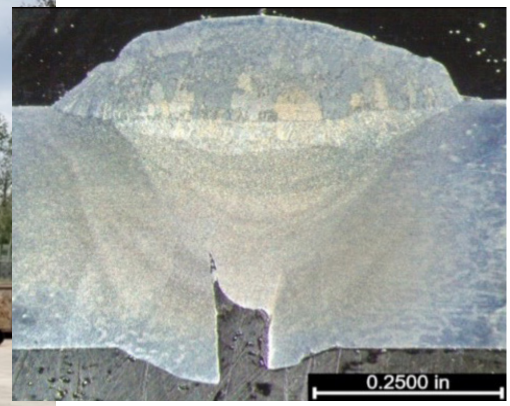
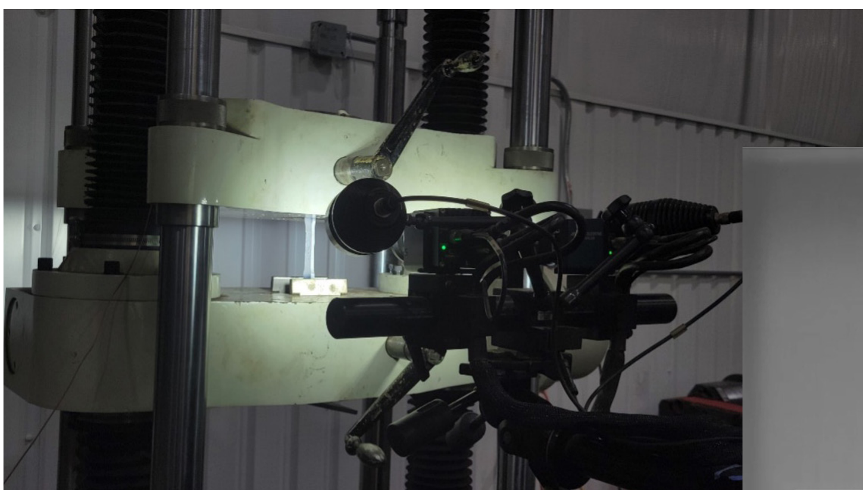


Figure 7: 4-point bending frame with 3 million lb.-ft capacity



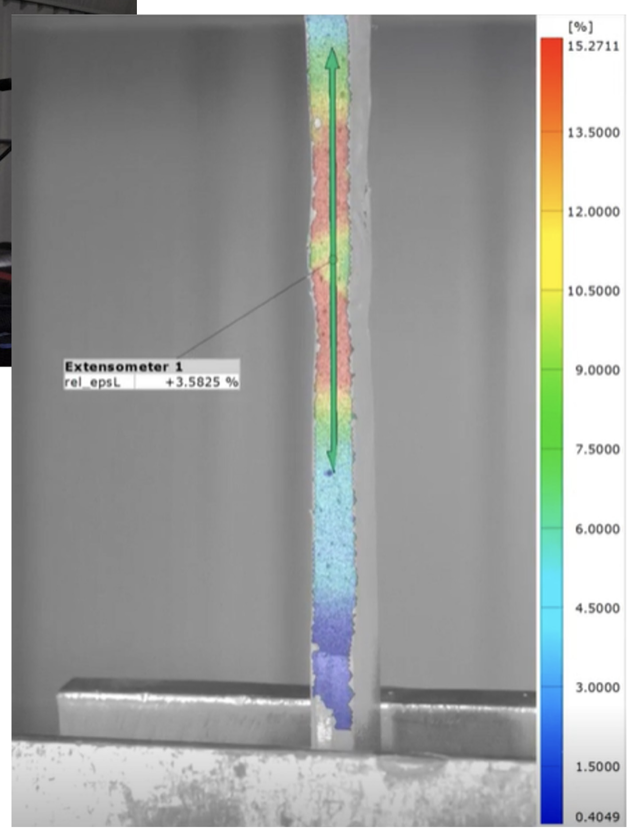


Figure 8: DIC camera during specimen tensile test (top); exemplar strain contour plot from DIC camera (right)

PLANAR DEFECTS AND CRACK-LIKE FEATURES

Some of the most significant work involving full-scale testing has been completed in relation to evaluating the impact of planar defects and crack-like features on the pressure capacity of vintage pipe materials. Current crack assessment methods tend to underestimate the failure pressure of vintage pipeline materials having cracks. There are several reasons for this, but the primary being the underestimation of fracture toughness using conventional sub-scale testing methods.

Current assessment methods use fracture toughness values based on specimens that present higher strain constraint (as compared to what's more applicable for thin wall pipes) and result in predicting lower failure pressures than actually exist . Shown in **Figure 9** is a graph plotting measured toughness as a function of crack-tip constraint as a function of sample geometry. As shown, the highest level of restraint and lowest measured toughness is the compact tension (CT) sample. The CT sample is the primary means used by the pipeline industry for quantifying fracture toughness. In contrast, the full-scale burst test presents the least amount of restraint and allows the most accurate representation of toughness for an actual pipeline. Full-scale testing is the best available and most direct option for accurately characterizing fracture toughness properties in an internally pressurized pipeline. A photo of a burst test on a pipe sample having a crack-like feature is shown in **Figure 10**.

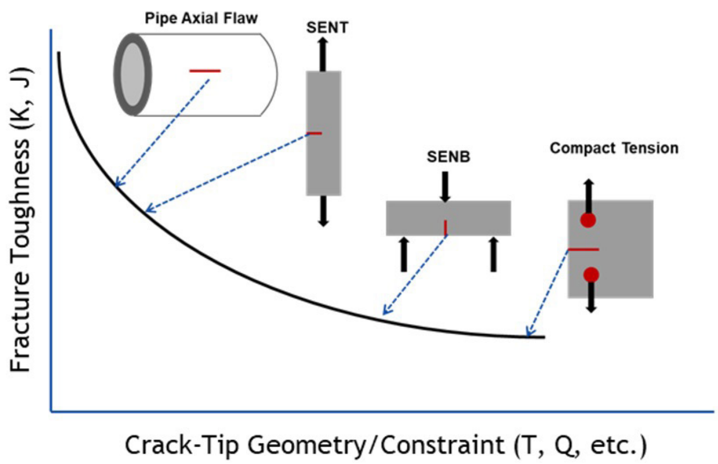


Figure 9: Measured toughness as a function of crack-tip constraint

As has been stated previously, the pipeline industry's current approach to managing cracks often requires large levels of conservatism because of uncertainties associated with crack geometry and

Figure 10: Photograph of a burst test to evaluate a crack-like feature

material properties. An improved methodology is possible using full-scale test results that remove uncertainties with pipe materials that are required when relying purely on sub-scale fracture mechanics test results. This is illustrated graphically in **Figure 11** in the Failure Assessment Diagram (FAD).

An improved FAD can be generated using full-scale test results, as opposed to the conventional methodology that employs sub-scale test samples. The uncertainties associated with predicting failure pressures can be addressed by replacing sub-scale testing that uses uniaxial testing as the means for quantifying material properties with full-scale testing that directly measures behavior of the pipe subject to internal pressure loading.

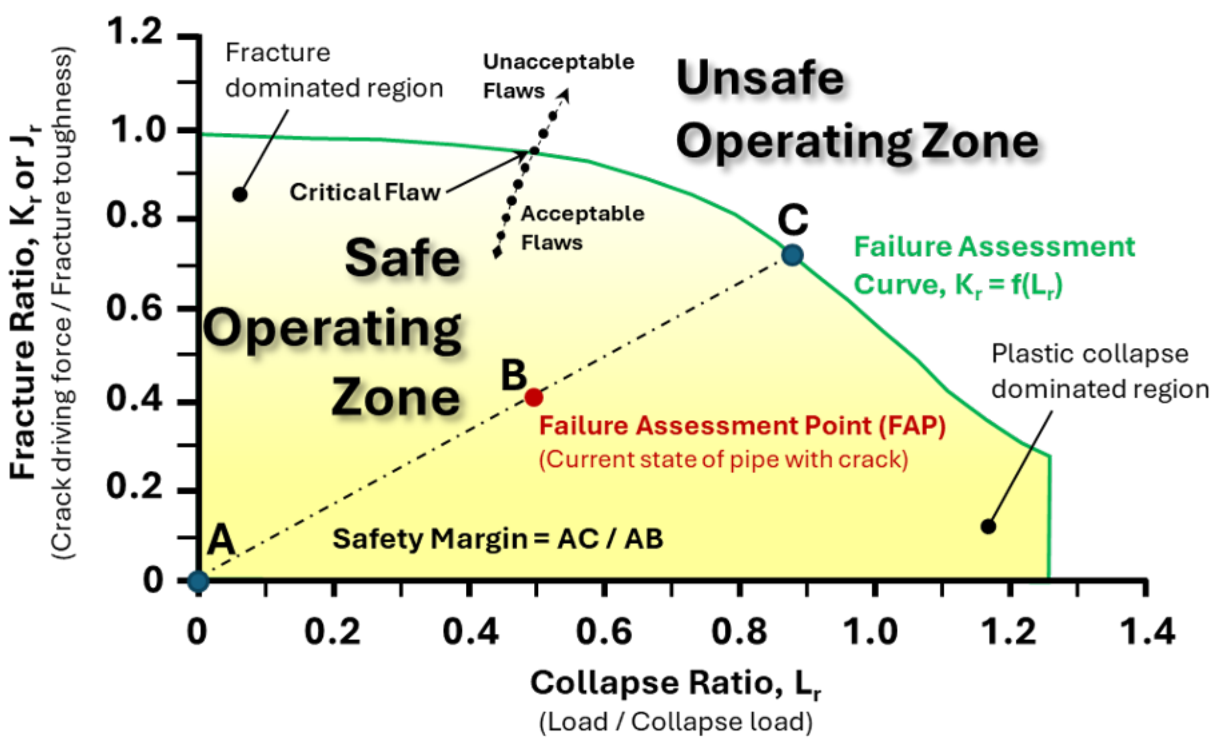


Figure 11: Exemplar Failure Assessment Diagram

There are several approaches for testing cracks. One involves testing actual cracks in pipe materials removed from service. The other option, and the one more often used in full-scale testing, involves the creation of cracks generated by pressure cycling notches installed via EDM. **Figure 12** includes a photograph of an EDM machine and schematic diagrams of two notch geometries. **Figure 13** includes several macrographs showing a crack that initiated from an EDM notch.

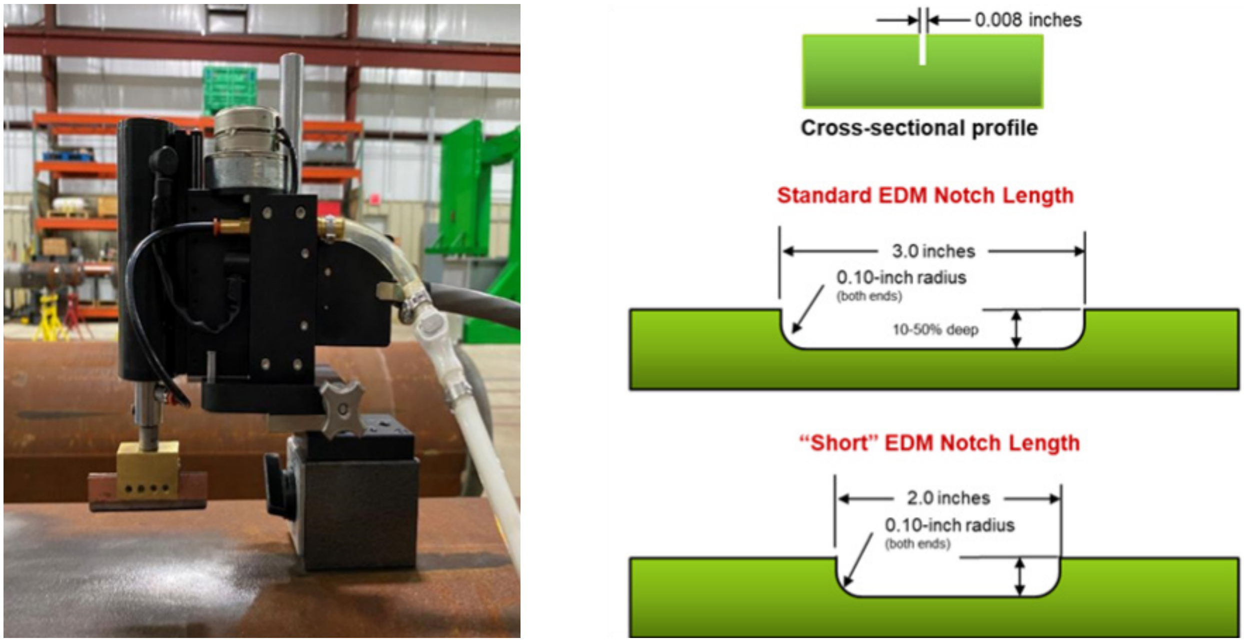


Figure 12: Machine used to install EDM notch and a typical geometry schematic

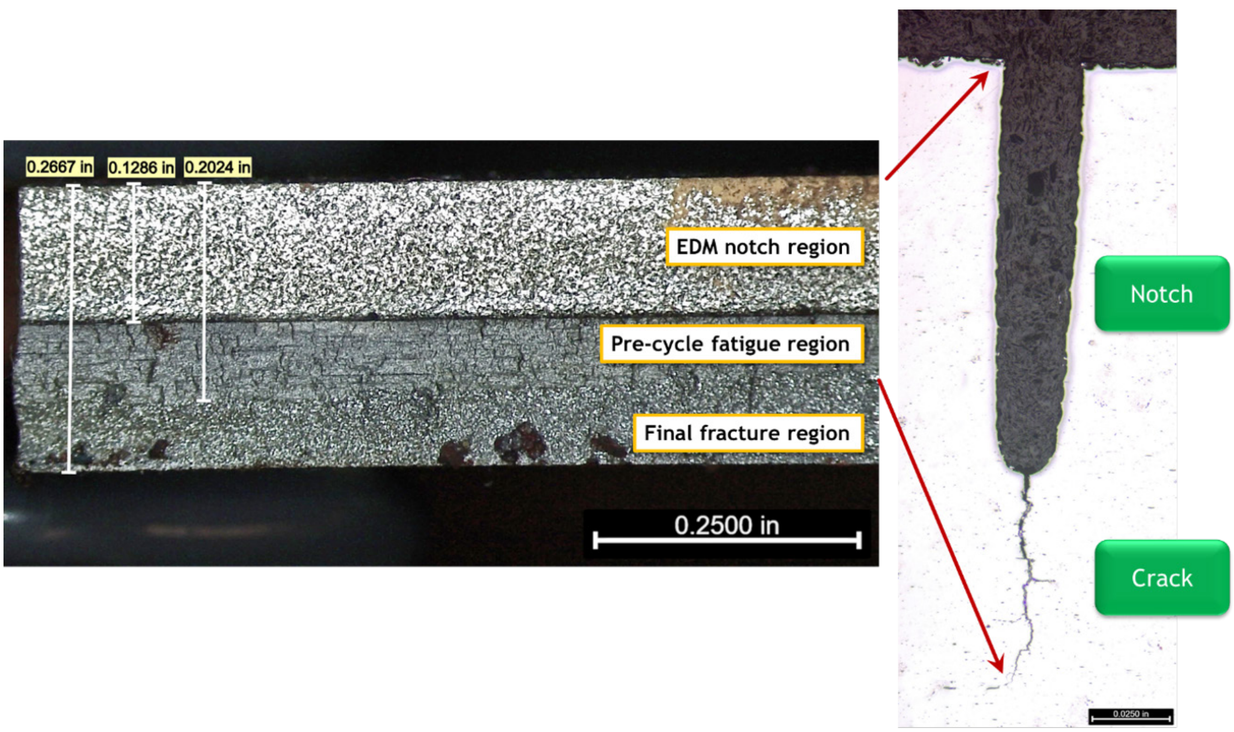


Figure 13: Microcracking observed at the base of an EDM notch (meridional and cross-section views)

Although the intent in this **Green Paper** is intended to be high-level, the body of work completed in relation to a comprehensive full-scale testing program involving vintage 26-inch A.O. Smith pipe material provides extremely valuable data. Although the test methods employed in this study can be applied to all pipe materials, these presented results are only applicable to the 26-inch x 0.281-inch, Grade X52 A.O. Smith pipe evaluated in a prior test program. **Figure 14** was prepared to illustrate how the results in this program can be used to provide guidance for which crack-like flaws require excavation and repair. Once a "burst pressure failure curve" (i.e., API 579, MAT-8, actual, etc.) has been established correlating burst pressure as a function of crack depth, the pipeline operator has a choice in defining the threat level they are willing to accept. The threat level[2] is based on the safety factor associated with failure pressure relative to operating pressure.

In addition to actual burst pressure results, the provided plot includes a comparison of predicted burst pressures using the following calculation methods.

- API 579 using specified minimum yield strength (SMYS)
- API 579 using actual yield strength
- API 579 using lower shelf Charpy V-notch (CVN) values

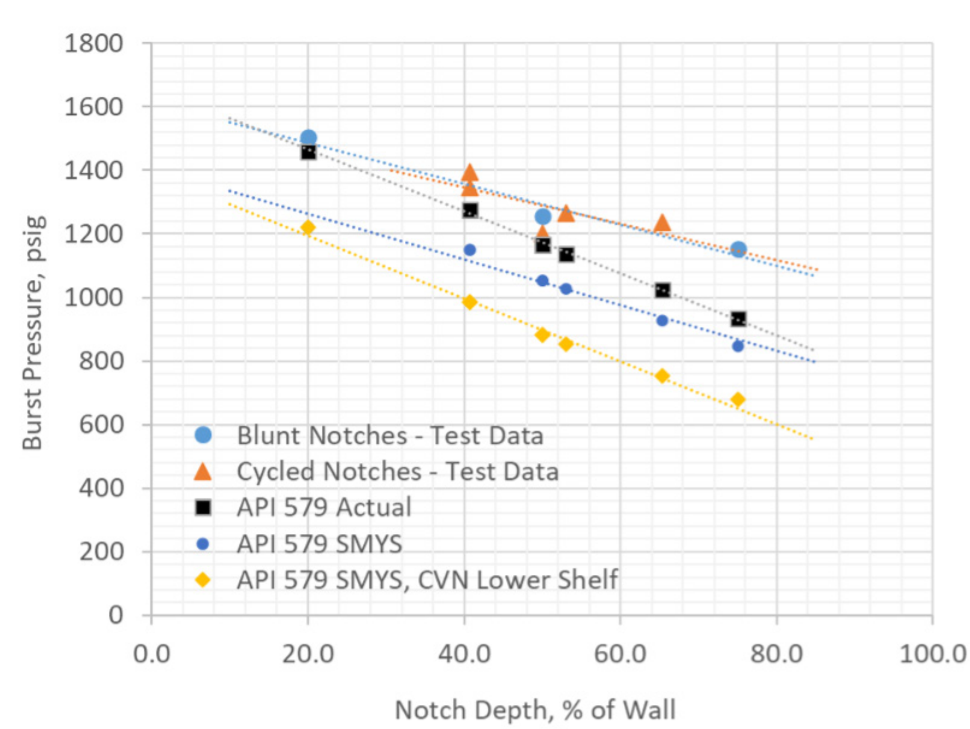


Figure 14: Predicted and actual burst pressures as functions crack depth

[2] The term "threat" is used here rather than "risk." Risk is defined as the product of likelihood of occurrence (i.e., threat) and consequence of failure. Consequence is outside the context of this body of work (and is very operator-specific), but threat management is directly related to defect assessment that was at the center of this study.

A final method for presenting the comparison of results is illustrated in **Figure 15**, showing differences between predicted and actual failure pressures from full-scale testing. Average differences for each calculation method were calculated and are included in the list below.

- API 579 using SMYS | **Difference of 18.8%** (maximum difference of 41.2%)
- API 579 using actual yield strength | Difference of 9.2%
- API 579 using actual Lrmax | Difference of 8.3%
- API 579 using lower bound CVN values | **Difference of 30.6%**
- MAT-8 based on fracture toughness from CVN data | Difference of 25.5%
- API 579 based on fracture toughness from full-scale test | **Difference of -0.6%**

As discussed previously, the largest differences exist when the minimum specified material properties are used (i.e., SMYS and lower bound CVNs), but the most accurate assessment method is achieved when using fracture toughness based on full-scale test results. These findings support the importance in having accurate material properties when estimating the failure pressures of pipes with crack-like features. Even the use of actual yield strength and Charpy values have a profound impact on better managing the conservatism of the fracture models.

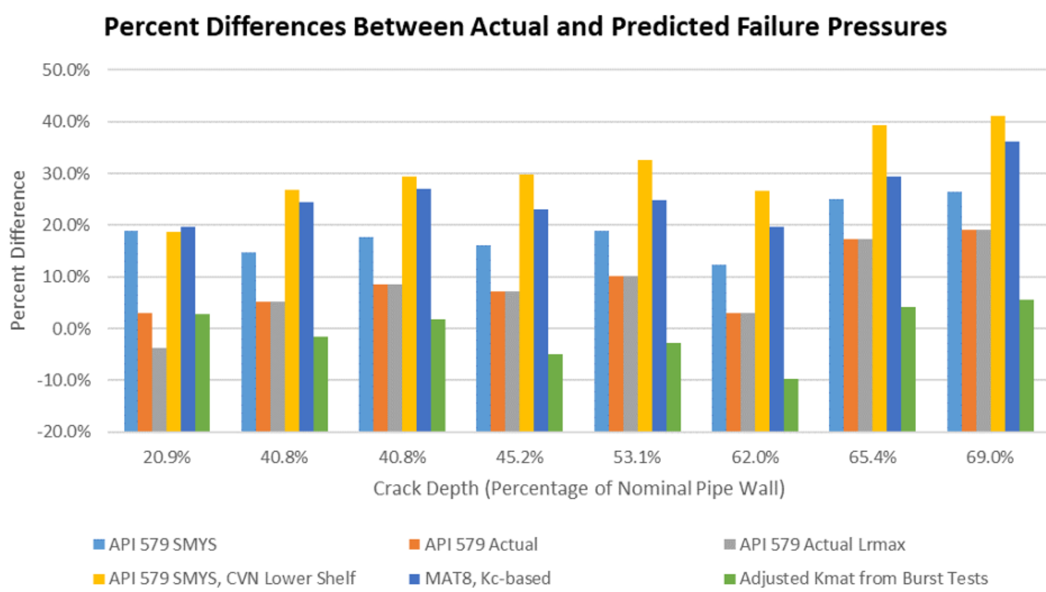


Figure 15: Graph showing difference between predicted and actual failure pressures

The findings presented in this Green Paper demonstrate the benefits associated with completing research programs involving full-scale testing . Additional work will only improve our confidence in accurately predicting burst pressures of crack-like features and selecting safety factors based on our capacity to accurately characterize material behavior. Increased understanding of material performance and crack behavior improves our confidence in selecting fracture models and safety factors that support a robust crack management program that balances the demands associated with safe operation and repair-driven excavation activities.

WRINKLE BENDS

Wrinkle bends were a common method for constructing bends in transmission pipelines until the mid-1950s. There are literally tens of thousands of wrinkle bends in North America, with more than 100 in-service failures since their construction more than 70 years ago. Wrinkle bends typically fail as circumferentially oriented cracks due to high strain / low cycle bending fatigue. There are several challenges associated with testing wrinkle bends: the first is obtaining actual wrinkles removed from service and the second is simulating the extreme bending loads to which they are subjected.

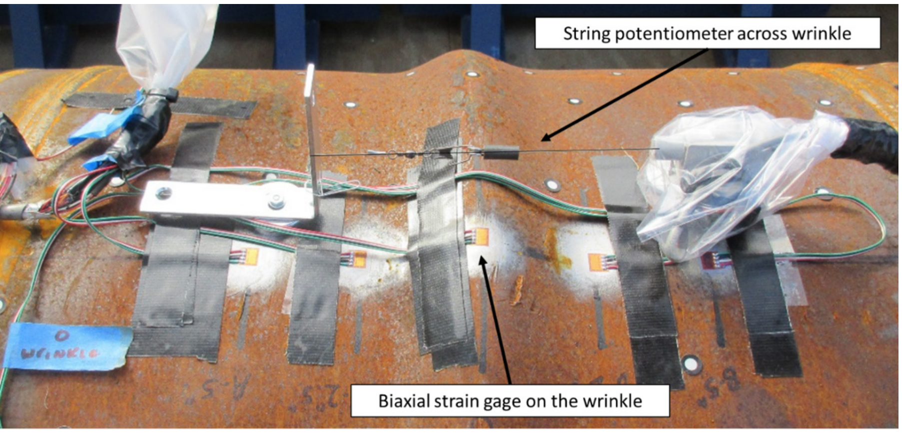


Figure 16: Photograph showing close-up of wrinkle

Figure 16 shows a photo of an instrumented wrinkle prior to testing, while **Figure 17** shows a 1 million ft-lbs. high strain / low cycle bending frame. Also included in this photo is an image of the wrinkle removed from service that was installed between two thick-wall pipe pieces. In testing, the pipe is typically pressurized to 72% SMYS and the pipe sample is subjected to fully reversed bending of sufficient magnitude to generate +/- 1% strain in the wrinkle that results in failures on the order of 150 to 200 bending cycles. **Figure 18** includes a failure in a wrinkle associated with a circumferential crack that developed in the wrinkle during testing.

Testing wrinkle bends is an effective method for quantifying the number of cycles a wrinkle feature can survive. Once this value is determined pipeline operators can determine if geohazard loading in a particular region might generate similar conditions. If they do exist, remediation efforts might be required.

Figure 17: High strain / low cycling 1 million ft-lb bending load frame

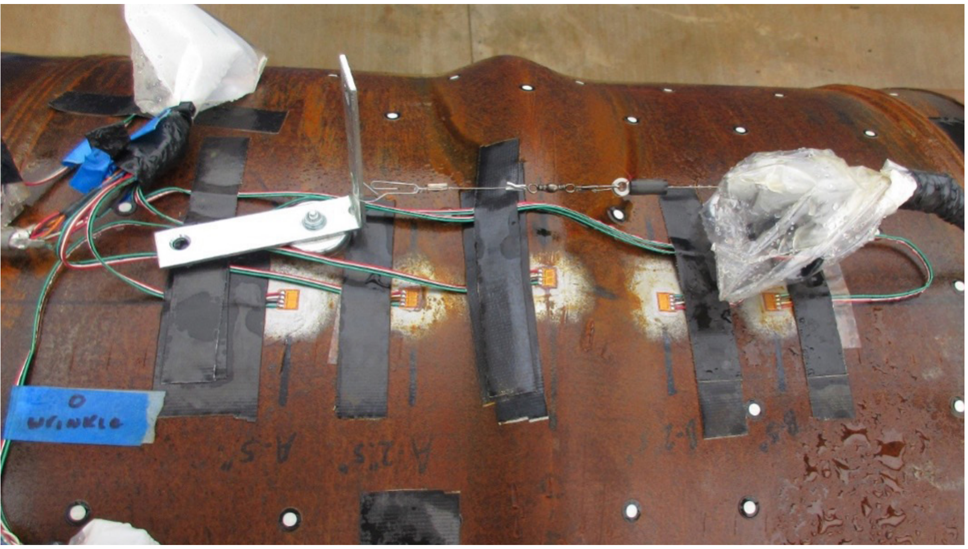


Figure 18: Circumferential crack developed in the wrinkle during testing

COMPOSITE TECHNOLOGIES

For more than 30 years composite repair technologies have contributed significantly to the integrity management efforts of many pipeline companies. Full-scale testing has been essential to validate composite repair technologies. More importantly, the successful performance of composite repair systems used to reinforce pipe samples with defects including severe corrosion, dents, girth welds, wrinkle bends, and cracks have contributed to the acceptance of composites with both pipeline operators and regulatory bodies. Unquestionably, without full-scale testing the composite repair industry would not be where it is today. All defects evaluated via full-scale testing presented in this **Green Paper** have been successfully reinforced with composite materials.

As stated previously, full-scale testing is useful for not only evaluating the threats associated with certain defects and features, but is also useful for validating and increasing the adoption of technologies like composite repair systems.

CLOSING REMARKS

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 [3] 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 [4] that led to the development of ASME B31G, RSTRENG, and other calculation methods for assessing corrosion. Additionally, 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 systems, 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.

[3] Markl, A. R. C., Fatigue Tests of Welding Elbows and Comparable Double Miter Bends, Trans. ASME, Vol. 69, 1947, pp. 869-879.
[4] 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.

ABOUT THE AUTHOR

Dr. Chris Alexander, PE is General Manager, Engineering of ADV Integrity, previously serving as President and Founder prior to Acuren's acquisition of ADV in April 2024. For the past 30 years he's focused his energies on designing, evaluating, and testing a wide range of technologies, including the use of composite materials to repair pipelines and offshore risers. His work has involved finite element analysis, in situ monitoring, and full-scale destructive testing. He received B.S., M.S., and Ph.D. degrees in Mechanical Engineering from Texas A&M University and is a licensed Professional Engineer in Texas. He has authored more than 150 technical papers and has made presentations internationally on a wide range of subjects. In addition to his strong technical background, as a strategic business consultant he has a passion to serve and connect innovators with organizations that require advanced technologies. As a "connector" he has built an international network that helped facilitate ADV Integrity's early-stage rapid growth that started in 2017.

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