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FEASIBILITY ASSESSMENT OF LSM TECHNOLOGY FOR GEOHAZARD APPLICATIONS
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ABSTRACT

Large Standoff Magnetometry (LSM) technology has shown potential for quantifying pipe stresses and deformation. With growing interest in the application of LSM for geohazard-related large pipe deformation, the need for better understanding the data, interpretation, sensitivities, and gaps associated with technology is becoming critical. This presentation will describe the efforts undertaken to systematically validate the LSM technology by way of studying it under controlled conditions in a full-scale testing setup that aims to simulate deformations in a geohazard scenario. This presentation will discuss the results of the LSM inspection performed using a 323.9 mm OD x 4.8 mm wall, 36.576 m long pipe (12.75 in OD x 0.188 in wall, 120 ft long pipe) that was maintained under pressure and subjected to gradually increasing bending loads to achieve large strains.

Results from two sets of blind tests (each with a different vendor), for various bending load levels on the pipe will be presented and discussed in the context of comparison with measured/truth data. The discussion provided in this paper will be valuable for operators in understanding applicability, gaps, and potential improvements in the LSM technology in the context of qualitative strain estimation originating from geohazard loading conditions. The study will establish a valuable framework for improved real-world implementation of the LSM technology in characterizing pipe deformation due to geological hazards (geohazards).

DISCLAIMER

INTRODUCTION

Geohazard loading continues to be a major concern for some pipeline operators. In the past, geohazard loading has been one of the primary contributing factors to the failure of girth welds, pipe bends, and wrinkle bends, making it critical to quantify the stresses and strains associated with the loading. LSM technology has the potential for quickly and accurately estimating pipeline stresses and strains that can be readily used in the decision-making processes with regards to threat levels and appropriate mitigations.

LSM inspection technologies are based on a physical phenomenon called inverse magnetostriction (also commonly referred to as the "Villary effect"), wherein the application of mechanical stress influences the magnetic field associated with the stressed component [1, 2]. Successful application of LSM relies on the accurate calibration of changes in the magnetic field and their quantification in terms of stress and/or strain. The work discussed in this paper originated from the need to demonstrate such quantification on a simulated, full-scale test sample with an eye on applicability for geohazard loading scenarios.

This paper documents the full-scale testing efforts undertaken to evaluate the capabilities and limitations of the LSM technology from the perspective of quantifying stresses or strains in a pipeline subjected to geohazard loading conditions. The goal of the full-scale testing was to bend a representative, real-world pipe sample to predetermined loading/deflection levels, scan the bent pipe using LSM technologies from multiple vendors, and then compare the stress/strain results provided by the LSM results to those that are directly measured during the test – effectively validating the technology and increasing confidence in the use of LSM for pipeline curvature/strain measurement.

The basis of the design for the full-scale testing setup, measured data during the tests, and the LSM results provided by the two vendors (Speir Hunter and Transkor) are discussed. The information provided in this paper is valuable for operators in understanding applicability, gaps, and potential improvements in the LSM technology in the context of stress/strain estimation originating from geohazard loading conditions.

TESTING METHODOLOGY

The full-scale test program was designed and setup by ADV Integrity, Inc. (ADV) at their test facility in Waller, Texas. Two LSM vendors participated in the program. Each vendor was assigned an inspection session that was planned over a period spanning two to three days. In the spirit of consistency in comparing results, the test parameters were tightly controlled between the two sessions including, pipe size and grade, test sample length, hydrotest pressure, pressure during inspection, and lateral displacement levels.

Testing was performed using a new 36.6 m (120 ft) long, NPS 12 (nominal pipe size 12), Grade X52 pipe that was maintained under internal pressure and sequentially loaded to higher stress/strain levels by bending the pipe (by the application of lateral loads), while being inspected by LSM-based instruments under load. The focus of the project was on determination of global stress/strain distribution, as opposed to localized feature-related stress concentrations. Consequently, no synthetic flaws were introduced into the pipe, and the pipe was not scanned for local defects (cracks, weld defects, etc.) prior to the start of the test sessions. The vendors were apprised of this requirement and were introduced to the test setup before their respective scan sessions. Vendor representatives were also allowed access to the test site before the actual inspections to allow for setting up global positioning satellite (GPS) reference points and for the general inspection of the test setup.

Care was taken to minimize the use of ferrous materials in the construction of the test set-up to avoid interference with the LSM readings. LSM works on the principle of changes in the magnetic domains in ferromagnetic materials; therefore, presence of magnetic materials in the vicinity of the LSM instruments is not desirable.

The testing setup and procedures were planned in accordance with the test objectives listed below:

1. At least 30.5 m (100 ft) long carbon steel pipe as the test sample
2. Test sample to be fabricated to allow application of internal pressure (to approximately 25% SMYS)
3. Bending loads to be applied to the test sample to generate both elastic and plastic loading conditions, subject to the following constraints:
    - Minimum central deflection for scanning in elastic regime approximately 4 inches
    - Achieve approximately 1% strain in the plastic loading regime
    - Target maximum mid-span deflection to approximately 63.5 cm to 76.2 cm (25 in to 30 in) at approximately 1% strain
    - Minimize the load requirement on the winch system being used to bend the pipe by pulling at mid-span
4. Access to be planned to allow inspection of the bent pipe with LSM scanners without personnel being directly on the pipe (for safety reasons) or too close to the pipe
5. Adequate safety precautions to ensure that accidental discharge of pressure from the test sample will not pose a danger to test personnel
6. Minimize (or eliminate where possible) the use of ferrous material to reduce the potential for interference with LSM data

Pre-test activies were divided into four main workstreams:

1. Test fixture design and construction
2. Inspection cart design and fabrication
3. Test pipe sample fabrication
4. Pipe sample loading schedule development (test plan)

Details of these activites are described below.

Test Fixture Design and Construction

This workstream involved designing a concrete runway for the LSM instrument carrier cart access and the installation of cement-filled (without rebar) aluminum bollards to be used as supports when bending the test pipe sample. Where possible, use of ferrous materials was minimized in the construction. A 3-point bending configuration was chosen for the test. This configuration allowed a reasonable balance between mid-span deflections needed for target stresses/strains and the winch force required to hit the stress/strain targets.

A schematic of the original test setup concept is shown in Figure 1. The original setup concept included two outer supports (the cement-filled aluminum bollards), 30.5 m (100 ft) apart, as reaction points to the applied load. In the interest of reducing the mid-span deflection needed to achieve high target strains two additional supports (inner supports) with a 18.3 m (60 ft) span, were added to the design. With a 3-point bending configuration, the mid-span deflection is a cubic function of the span length, so a small reduction in the span-length results in a relatively large reduction in the mid-span deflection under the same load. All supports were made using 3.0 m (10 ft) long, 304.8 mm (12 in) diameter aluminum pipes grouted in a 1.8 m (6 ft) deep hole. Furthermore, the second set of inner supports were installed at an offset of 11.4 cm (4.5 in) to the original supports such that inner supports were only engaged at higher mid-span deflections (see Figure 2). This arrangement of the inner supports allows the transition of the bent test sample into the plastic deformation regime with reduced mid-span deflection – this is illustrated in Figure 3.

The bending load was applied using a winch mounted on a concrete winch block located at mid-span, approximately 6.1 m (20 ft) away from the pipe. A system of winch rope and slings/straps was designed to allow the winch to pull on the test pipe in a 3-point bending configuration at mid-span.

To mitigate safety concerns due to an accidental energy release (e.g., a girth weld flaw), blast shields were placed at each end of the pipe. Additionally, the pipe was loosely strapped to the supports (without interfering with the rotational response) so as to avoid any whiplash in case of accidental parting failure during bending.

The overall test setup, including the placement of the strain gages and linear displacement sensor used, is shown in Figure 4.

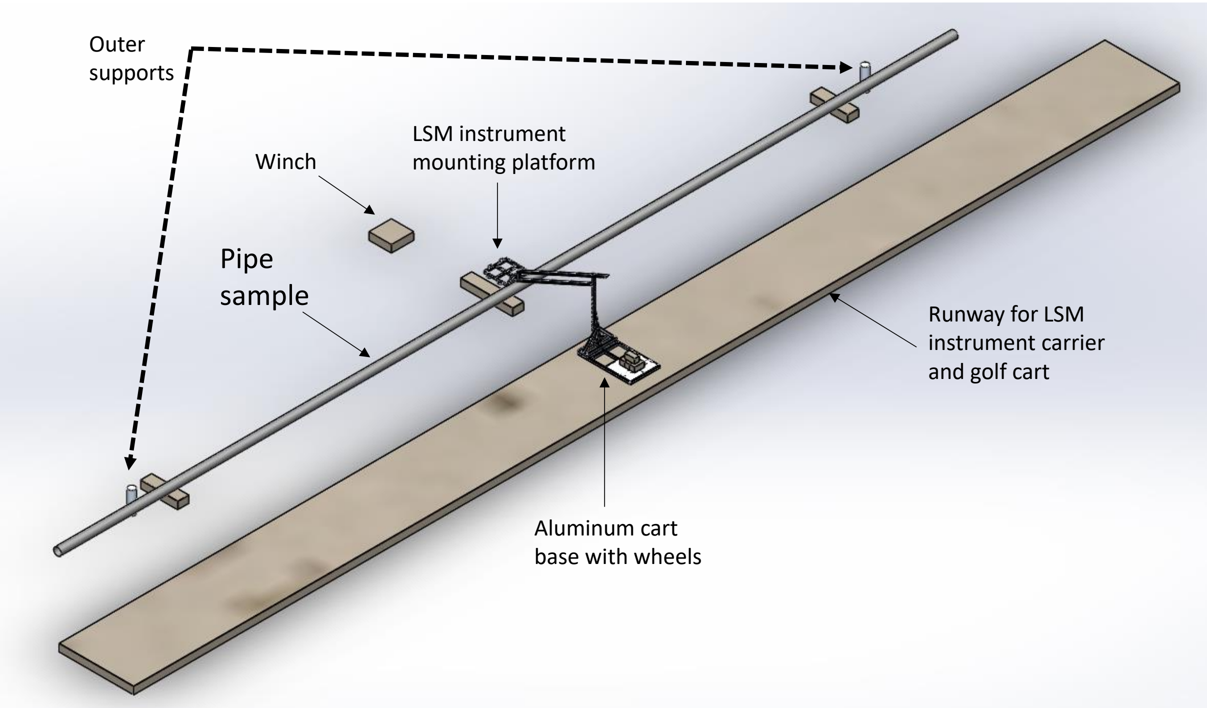

Figure 1: Initial test system layout with outer supports only

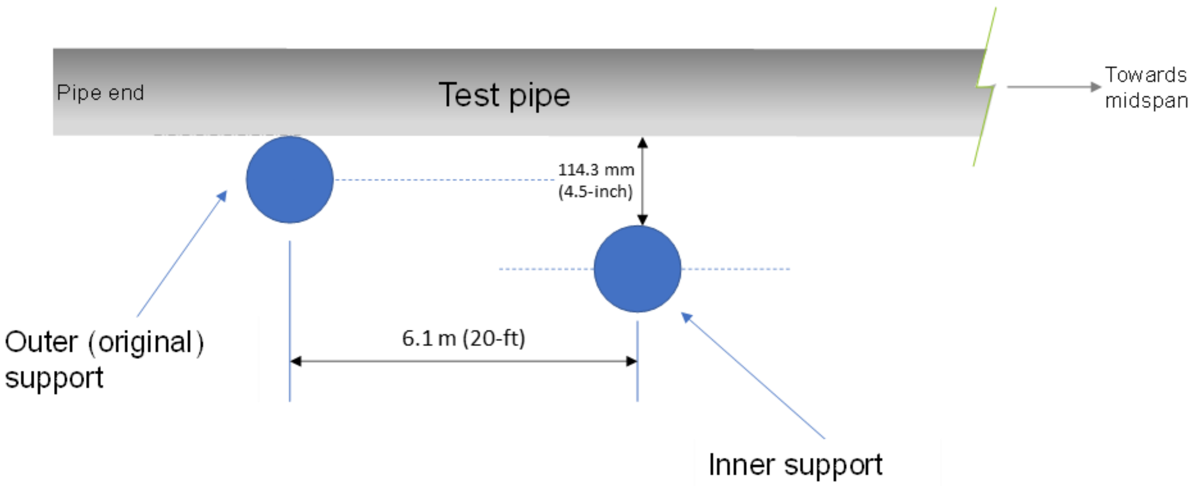

Figure 2: Schematic showing the details of the offset between the outer and inner supports

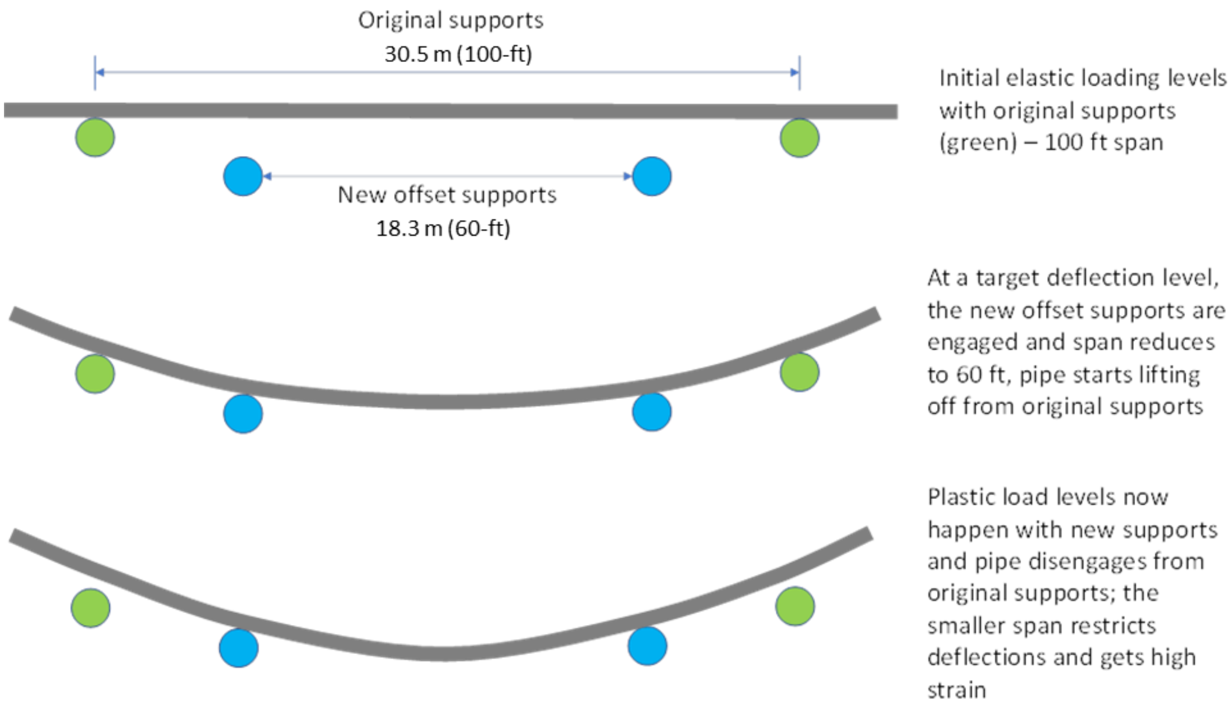

Figure 3: Schematic explaining the transition from elastic to plastic regime and the role of inner supports

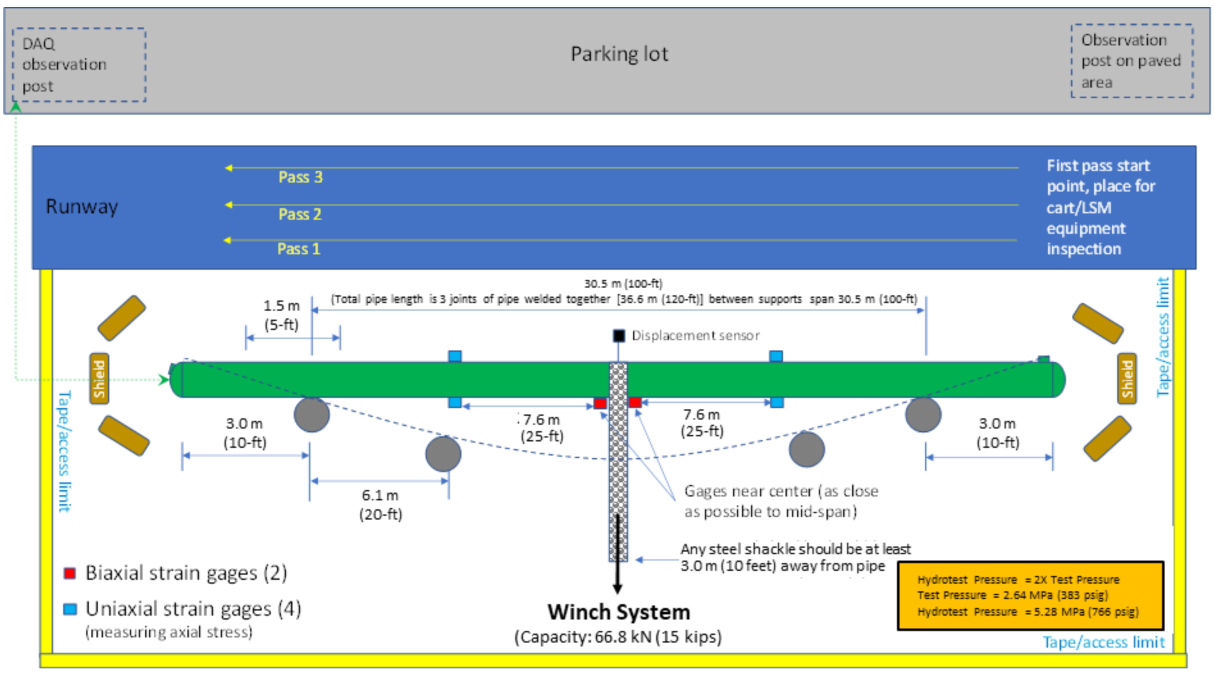

Figure 4: Schematic showing a summary of the test setup, including placement of instrumentation used

Inspection Cart Design and Fabrication

The mobile inspection cart was built entirely of aluminum parts (except wheel bearings) and was designed to be pulled along the length of the test pipe using a separate pulling vehicle – in the present case, a golf cart was used.

Adjustable aluminum extension arms on the aluminum cart were designed and fabricated to allow changes in the inspection height and to maintain a sufficient distance between the LSM instruments and the golf cart. At the end of the extension arms a mounting platform was fabricated with a design that would allow LSM scanners to be securely attached in a variety of different ways. Space was provided in the design on the main cart body for placement of counterweight to prevent the cart from tipping over during the inspection runs. Thick rubber wheels were used to minimize the vibrations caused due to surface contours or debris on the concrete runway. A drawing of the cart is shown in Figure 5.

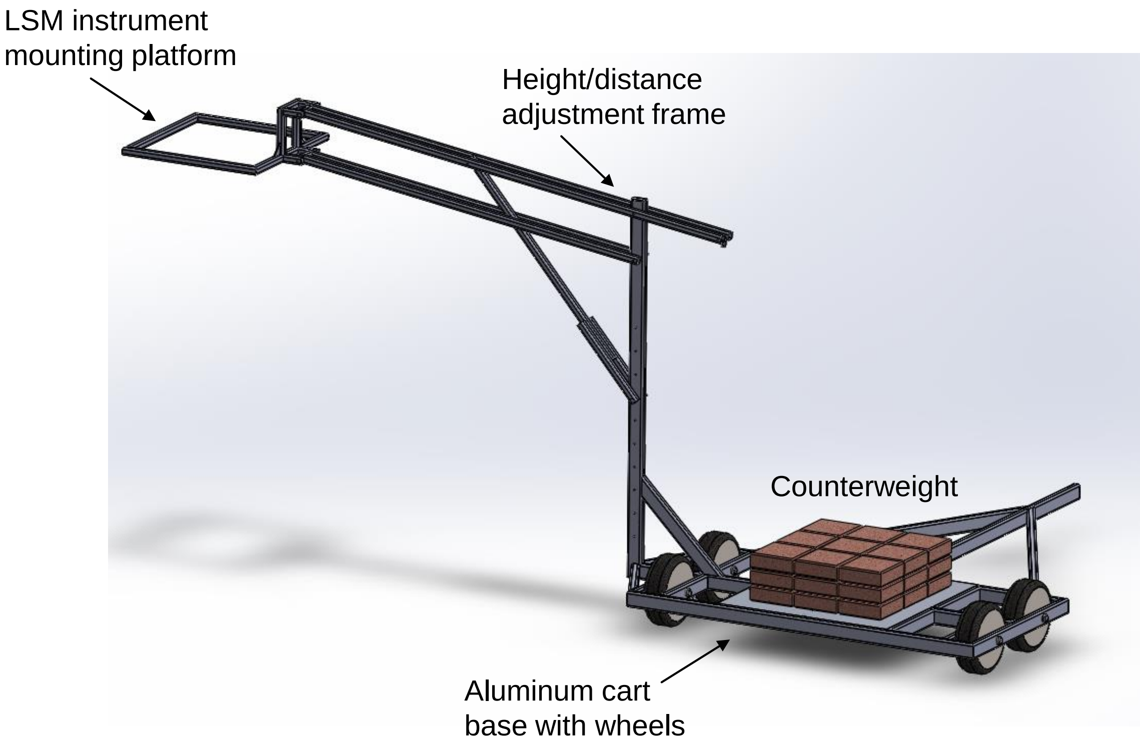

Figure 5: Initial design rendering of the aluminum cart for carrying LSM instruments

Test Pipe Sample Fabrication

The pipe sample used for testing was a 36.6 m (120 ft) long, NPS 12 pipe sample (323.9 mm OD x 4.8 mm wall) welded together from three (3) 12.2 m (40 ft) long joints. The pipe grade was X52, with material data indicating the actual yield strength was 455.1 MPa (66 ksi).

Two biaxial strain gages were positioned near the mid-span of the pipe on the tensile side to measure axial and hoop strains. Four uniaxial strain gages were mounted 4.6 m (15 ft) from the midspan, two on each side with one on the compression side and one on the tension side, to measure axial strains. A string potentiometer sensor was attached opposite to the winch (compressive side of the test sample) at the midspan to measure the mid-span deflection of the pipe. A pressure transducer recorded the sample pressure throughout the test. All sensors were connected to a data acquisition system and located remotely to maintain a safe distance from the sample to record measurements.

Before pressurizing for inspection, the fabricated test sample was hydrotested at two times the test pressure (5.3 MPa or 766 psig, or approximately 50% of SMYS) to ensure integrity of the fabrication welds during the test.

Test Pipe Sample Loading Schedule

One of the main objectives in testing was to assess the capability of the LSM technologies in distinguishing between various stress states in a mechanically-loaded pipe. Accordingly, the load schedule framework centered around various load levels (characterized by mid-span deflection) to be imparted to the test pipe sample. The load levels were developed on the basis of preliminary finite element analysis (FEA)-based calculations with actual elastic-plastic material properties. The load levels targeted elastic regime (typically characterized with stress) as well as plastic regime (typically characterized with strain) loading on the pipe. An example load schedule is shown in
Table 1.

With

Test Day	Load Level	Test Pipe Internal Pressure	Target Mid-span Deflection
Test Day #1	No Bending Load	2.86 MPa (383 psig)	0
	Load Level 1 (elastic)	2.86 MPa (383 psig)	0.15 meters (6 inches)
	Load Level 2 (elastic)	2.86 MPa (383 psig)	0.30 meters (12 inches)
Test Day #2	Load Level 3 (borderline yield based on actual properties)	2.86 MPa (383 psig)	0.45 meters (18 inches)
	Load Level 4 (plastic)	2.86 MPa (383 psig)	~0.61 meters (~24 inches)
	Load Level 5 (Max Strain, plastic)	No pressure	~0.76 meters (~30 inches)

reference to
Table 1, five load levels (characterized by mid-span deflections) were targeted for the test.

Test Day	Load Level	Test Pipe Internal Pressure	Target Mid-span Deflection
Test Day #1	No Bending Load	2.86 MPa (383 psig)	0
	Load Level 1 (elastic)	2.86 MPa (383 psig)	0.15 meters (6 inches)
	Load Level 2 (elastic)	2.86 MPa (383 psig)	0.30 meters (12 inches)
Test Day #2	Load Level 3 (borderline yield based on actual properties)	2.86 MPa (383 psig)	0.45 meters (18 inches)
	Load Level 4 (plastic)	2.86 MPa (383 psig)	~0.61 meters (~24 inches)
	Load Level 5 (Max Strain, plastic)	No pressure	~0.76 meters (~30 inches)

Additionally, a "No Bending Load" step was also included to serve as a baseline/reference scan with the pipe pressurized at 2.6 MPa (383 psig) – or in LSM terminology, to serve as the reference magnetic profile data set.

Table

Test Day	Load Level	Test Pipe Internal Pressure	Target Mid-span Deflection
Test Day #1	No Bending Load	2.86 MPa (383 psig)	0
	Load Level 1 (elastic)	2.86 MPa (383 psig)	0.15 meters (6 inches)
	Load Level 2 (elastic)	2.86 MPa (383 psig)	0.30 meters (12 inches)
Test Day #2	Load Level 3 (borderline yield based on actual properties)	2.86 MPa (383 psig)	0.45 meters (18 inches)
	Load Level 4 (plastic)	2.86 MPa (383 psig)	~0.61 meters (~24 inches)
	Load Level 5 (Max Strain, plastic)	No pressure	~0.76 meters (~30 inches)

1:Example load schedule

Load Levels 1 and 2 targeted elastic bending stress levels of approximately 21% SMYS and 71% SMYS. In the elastic regime, the stress-strain relationship is linear, so these stress levels could be readily interpreted in terms of equivalent strain levels as well. Load Level 3 is labeled as "120% SMYS" and is intended to capture the near-yield (based on actual yield strength) response of the pipe. This stress is more than 100% SMYS on account of the fact that the actual yield is 455.1 MPa (66 ksi) – approximately 27% higher than the SMYS of 358.5 MPa (52 ksi). Load Levels 4 and 5 were designed for plastic regime response and targeted strain levels of 0.6% and 1.5%, respectively. For all load levels, except Load Level 5, the test pressure in the pipe was maintained at 2.6 MPa (383 psig), or 20% of SMYS. For Load Level 5, it was planned to reduce the pressure in the pipe for safety considerations. The load levels are represented graphically in Figure 6 and Figure 7 in terms of stress and strain, respectively.

Provisions were also made to accommodate multiple inspection heights (distance of the LSM scanning device from the pipe) and multiple passes in the test schedule for repeatability purposes.

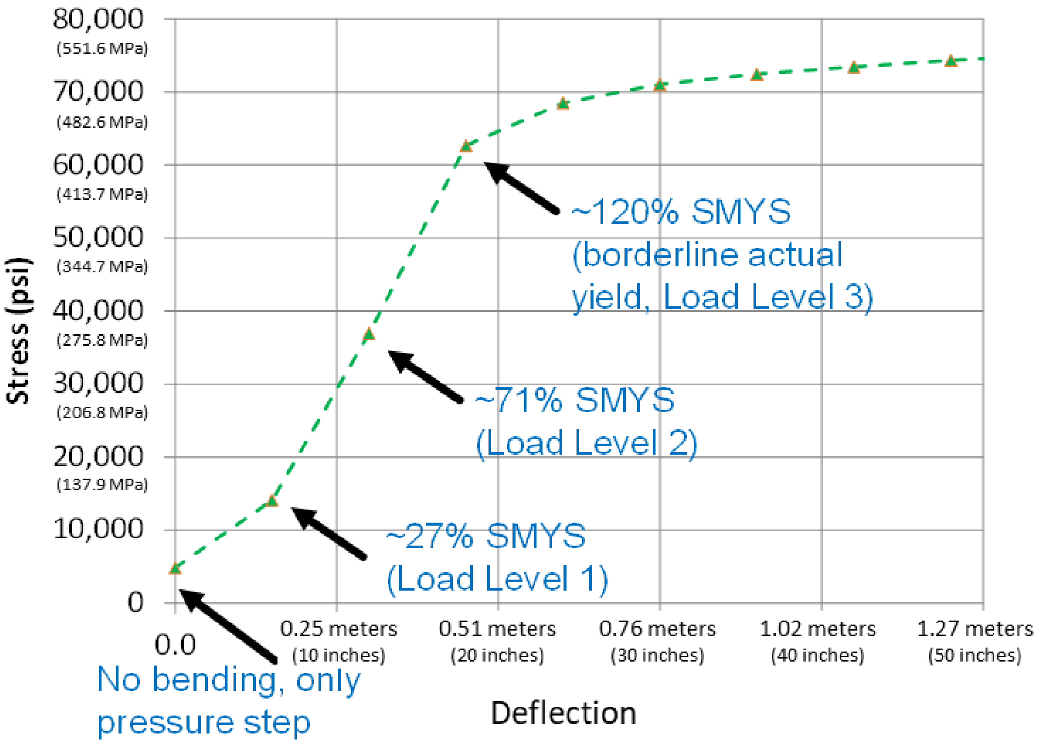

Figure 6: Stress-based interpretation of the load levels for the test

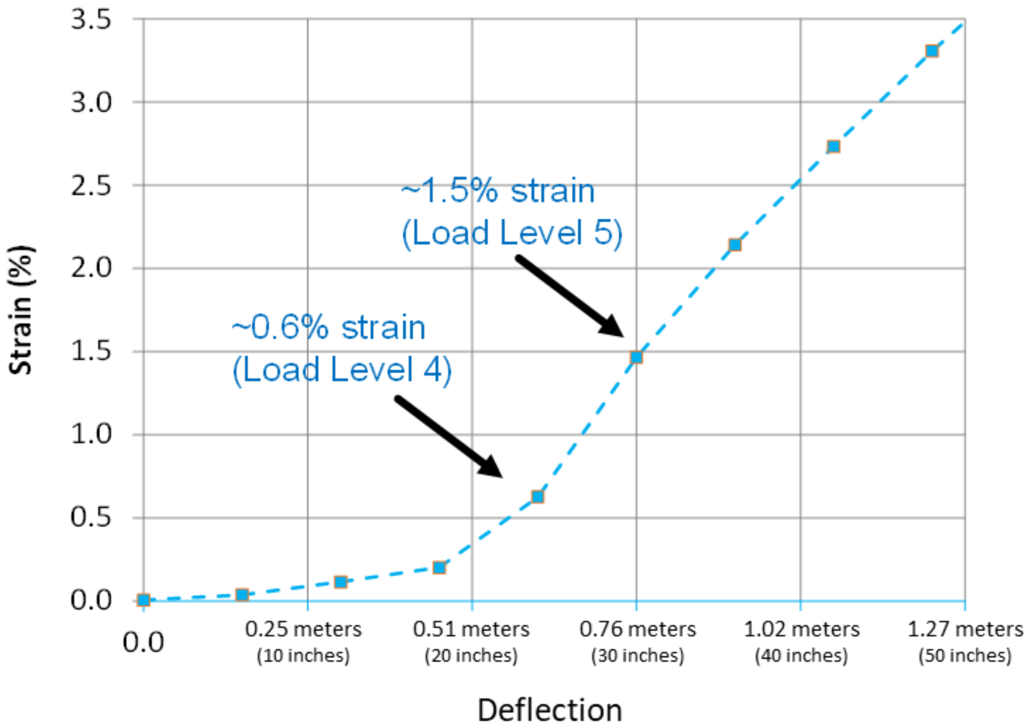

Figure 7: Strain-based interpretation of the load levels for the test

The inspection sessions were planned in communication with the two vendors, with each session lasting for approximately one (1) week including mobilization, hydrotest, inspections, and demobilization of the test setup. Vendor representatives were allowed on site for pre-test inspection, safety checks, and setting GPS reference points.

Each session typically started with mobilization of the pipe, instrumentation, and test equipment several days before starting the test. Hydrotesting was performed one day before the first test day, and pipe was depressurized after the test. The sessions were planned such that the elastic load levels were executed on the first day of the test, and the plastic load levels were executed over the subsequent days. This arrangement allowed the field teams to confer with their respective engineering teams to ensure that the data collection in the elastic regime was successful before the pipe was deformed permanently in the plastic regime.

Each test day started with pressurizing the pipe sample to the designated test pressure (2.6 MPa or 383 psig) before commencing inspections. Before initiating inspection runs for each load level, a hold period of approximately 15 minutes was maintained before the personnel could approach the test sample and the inspection cart (for safety purposes to guard against any potentially transient response following loading). The inspections were performed with the aluminum inspection cart being pulled in a straight line along the purpose-built runway adjacent to the test pipe.

The pipe was depressurized at the end of test day to ensure safe, overnight storage at the facility.

Test Outcomes

Measured Test Data

As mentioned previously, two biaxial strain gages were positioned near the mid-span of the pipe on the tensile side to measure axial and hoop strains. The intent of these strain gages was to capture the maximum global strain in the pipe (expected to be at mid-span). Additionally, stress/strain data were recorded using four uniaxial strain gages mounted 4.6 m (15 ft) from the midspan, two on each side with one on the compression side and one on the tension side. The intent of these gages was to provide supplementary measurements in the event that the mid-span gages failed on account of high strain or plastic collapse conditions during Load Levels 4 and 5.

The mid-span deflection was measured using a string potentiometer sensor attached opposite to the winch (compressive side of the test sample) to measure the mid-span deflection of the pipe. With respect to the load levels discussed in the loading schedule, the target stress/strains were correlated to a corresponding target mid-span deflection using FEA results. These target deflections were then used to control the winch pull during the test.

To ensure consistency of the test setup and measurements between the two inspection sessions, the mid-span deflection versus maximum measured strain data for the two sessions were plotted together – shown in Figure 8. A reasonably good correlation is observed confirming consistency between the two inspection sessions.

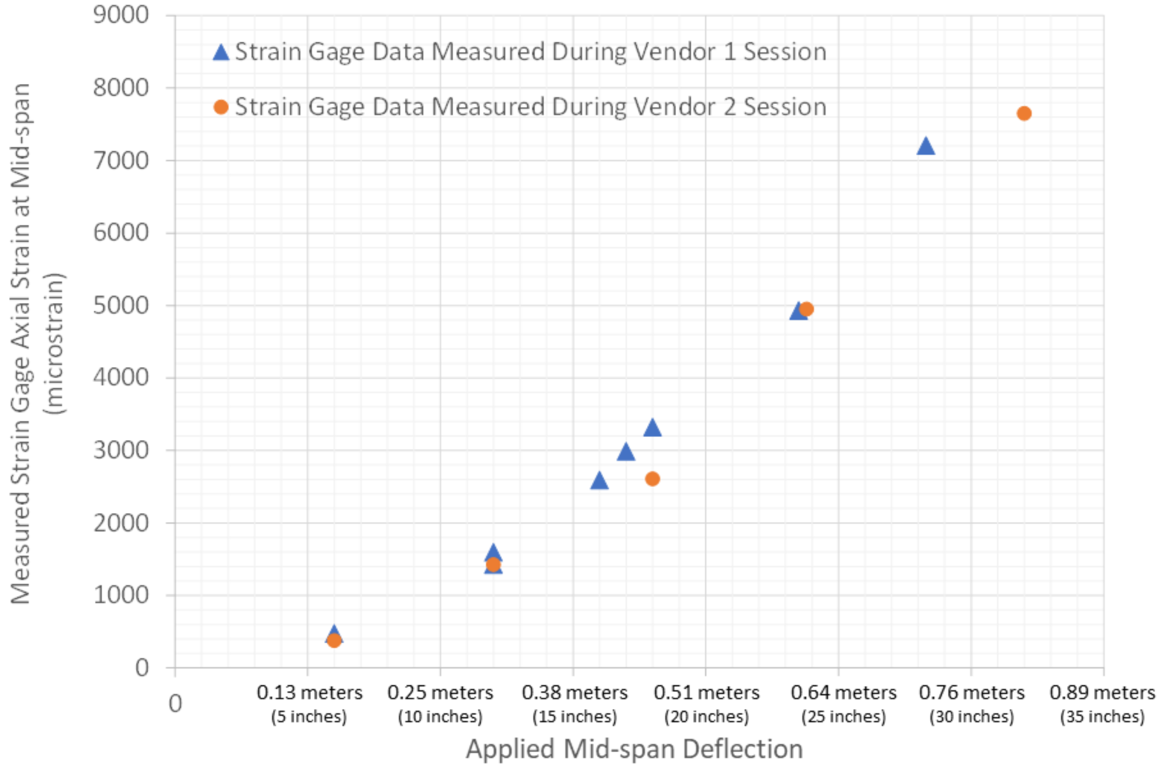

Figure 8: Mid-span deflection vs measured axial strain data between test sessions for Vendor 1 and Vendor 2

LSM Inspection Results

The LSM inspection results provided by the vendors were compared to the actual stress/strain data measured during the test ("truth" data). Vendor 1 aimed for reporting strains and provided the results after post-processing the LSM inspection data using two difference approaches: 1) based on estimation of centerline/curvature of the pipe and then using the curvature-strain relationship to estimate the strain in the pipe, and 2) based on direct interpretation of von Mises stress from the perturbation of the magnetic field upon the application of load, and then estimation of strains using linear-elastic relationship. For both methods, a direct interpretation in terms of strains was provided. A summary of the results is shown Table 2; with the data graphically represented on a unity plot in Figure 9.

These results show that strain estimates based on three dimensional mapping and curvature estimation method showed a significantly better comparison with the measured data. The strains reported using direct stress estimation based on magnetostrictive principles did not match well with the measured data, especially for higher load levels. The details of the transfer function between the magnetic field fluctuations and the stress estimates were not shared with ADV; however, the vendor reported that the strain estimates were based on application of a linear-elastic relationship between stress and strain. It is hypothesized that for the near-yield/post-yield response associated with Load Levels 3, 4, and 5, the strain estimates derived using linear-elastic relationship are not correctly representing the strains in the test sample.

Table 2: As-reported LSM strain values vs measured strains: Vendor 1

Load Level #	Measured Deflection	Strain Gage Average Measured Axial Strain (%)	LSM Reported Bending Strain Using Curvature Estimation (%)	LSM Reported Bending Strain w/o Curvature Estimation (%)
Load Level 1	0.15 meters (6 inches)	0.048	0.053	0.097
Load Level 2	0.31 meters (12 inches)	0.160	0.190	0.137
Load Level 3	0.46 meters (18 inches)	0.332	0.343	0.180
Load Level 4	0.60 meters (23.5 inches)	0.493	0.480	0.150
Load Level 5	0.72 meters (28.3 inches)	0.721	0.833	0.287

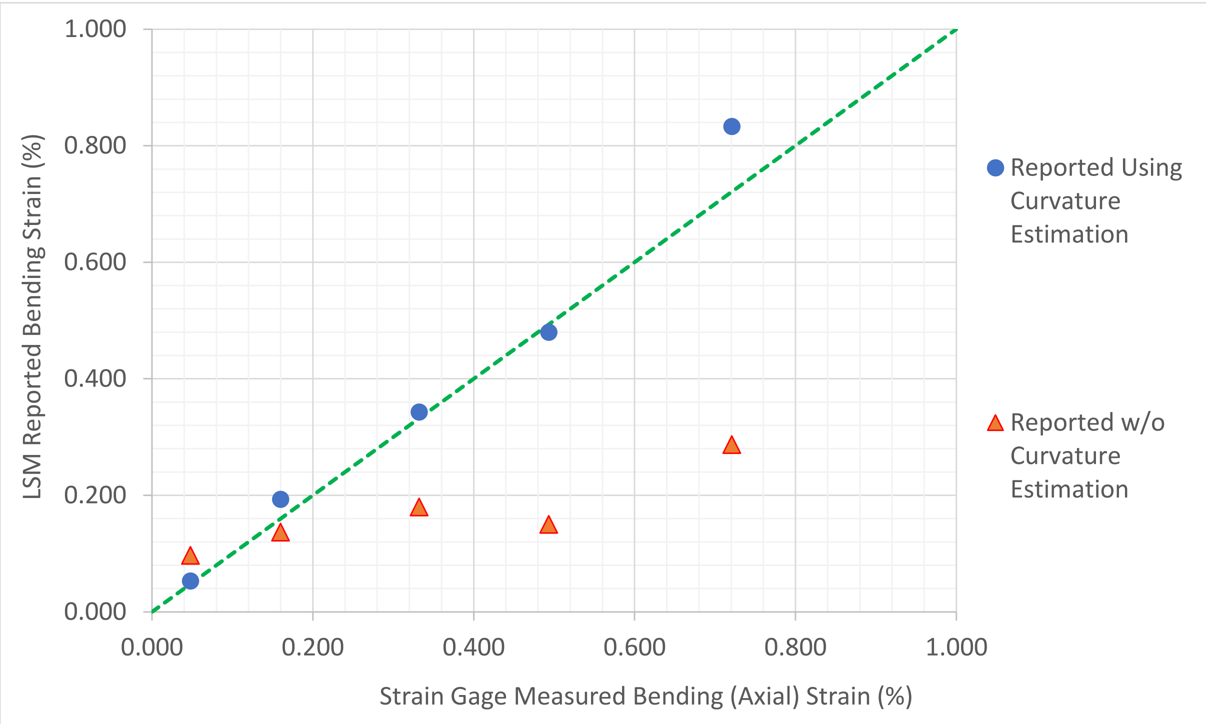

Figure 9: Unity plot: as-reported LSM vs measured strains: Vendor 1

Vendor 2 provided LSM inspection results only in terms of estimated stresses. A summary of the results is shown in Table 3. Since the test data was being measured in terms of strains, and because comparison of strains is valid over elastic as well as plastic regimes, the stresses reported by Vendor 2 were converted to strains using linear-elastic relationship – dividing the reported stresses by Young's modulus for steel (206.8 GPa or 30 x 10^6 psi). As discussed in reference to Vendor 1 data, this linear relationship is not valid for loading in the plastic regime; however, in light of the probability of detection data provided by Vendor 2 (ranging over stress values less than 100% SMYS), it is inferred that the fundamental calculations underlying Vendor 2's methodology is valid in the linear-elastic regime.

The interpreted strain data are graphically represented on a unity plot in Figure 10. With reference to data presented in Table 3 and Figure 10, the correlation between the measured strains and the interpreted strains deteriorates significantly after Load Level 2. As was in the case of Vendor 1, this is primarily due to stress/strain interpretation using a linear-elastic understanding in the plastic loading regime.

Table 3: Interpreted LSM strain values (at mid-span) vs measured strains: Vendor 2

Load Level #	Measured Deflection	Strain Gage Average Measured Axial Strain (%)	LSM Reported Stress	Interpreted LSM Strain (%)
Load Level 1	0.15 meters (6 inches)	0.038	155.1 MPa (22.5 ksi)	0.075
Load Level 2	0.31 meters (12 inches)	0.142	233.7 MPa (33.9 ksi)	0.113
Load Level 3	0.46 meters (18 inches)	0.261	177.9 MPa (25.8 ksi)	0.086
Load Level 4	0.60 meters (23.8 inches)	0.495	131.0 MPa (19.0 ksi)	0.063
Load Level 5	0.81 meters (32 inches)	0.765	Not Reported	Not Reported

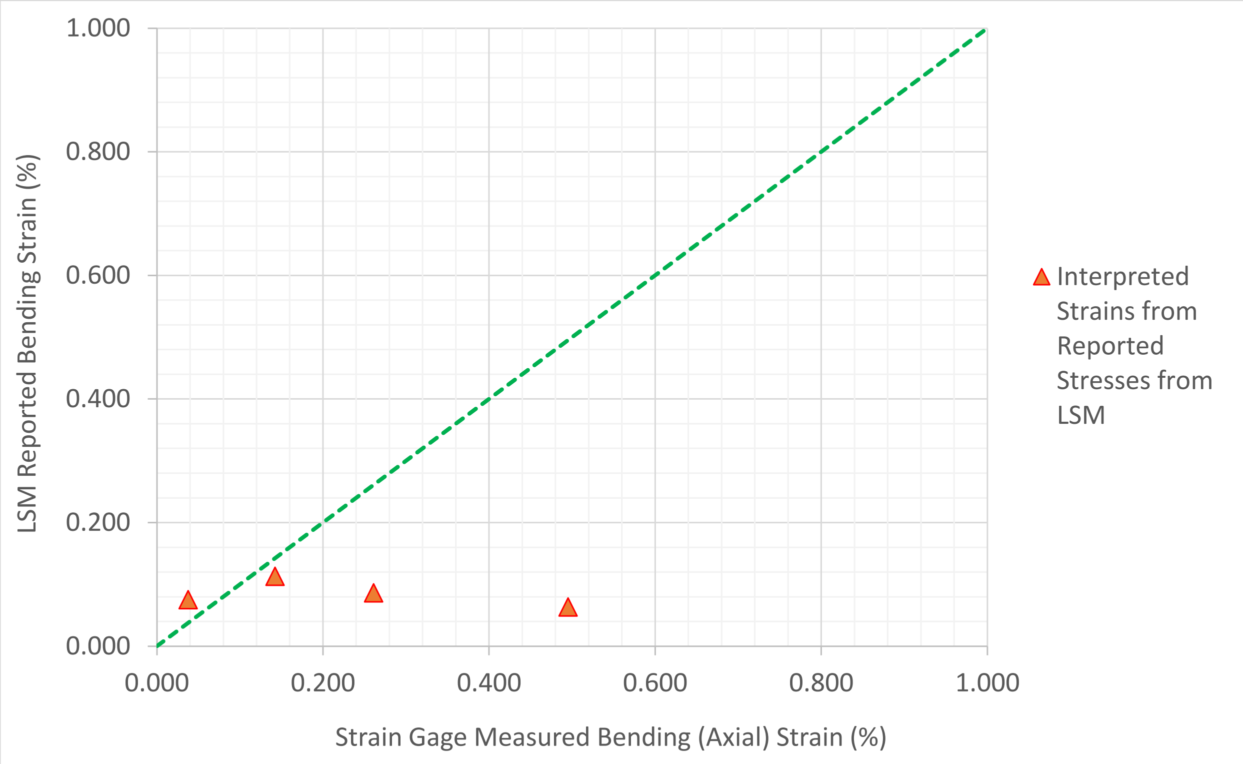

Figure 10: Unity plot: as-reported LSM vs measured strains: Vendor 2

For Vendor 1, using the curvature determination approach, the strain results compared reasonably well with the measured data; however, for both vendors, the direct interpretation of stress did not show a good correlation with measured data – especially for load levels at which pipe stress approached and/or exceeded yield.

Gaps and Recommendations

Over the course of the project, several gaps were identified from the perspective of application of the LSM technology for real-world stress/strain measurements in pipelines; these are discussed in the sections that follow. Gaps are labeled as either "technological" or "informational", where technological gaps should be interpreted as opportunities for future development of the technologies. In discussing emerging technologies like LSM, some gaps may be merely manifestations of limited information exchange between the developers of the technologies and independent observers – these gaps are identified as informational gaps and should be interpreted as requiring additional clarity and transparency. Both types of gaps need to be closed for a deeper understanding of the LSM inspection results to maximize the likelihood for its application in actual service conditions. Addressing these gaps over future evaluation opportunities will provide additional granularity into the real-world application of the LSM technology.

Linear-Elastic vs Plastic Loading (Technological)

Current LSM technologies are based on direct correlation between magnetic field fluctuations (magnetic profiles) to elastic stress [1, 2, 3]. In the linear-elastic regime, such correlation can be readily interpreted in terms of elastic strain. However, as the stress in the pipe approaches the yield strength of the pipe material, it is expected that the correlation will break down due to the nonlinear relation between stress and strain. This is illustrated in Figure 11. Consider the example of a commonly-used theoretical concept of elastic-perfectly plastic material (left side schematic in Figure 11). In this context, beyond yield, with increasing applied loads, the strain would increase infinitely without any increase in stress. So, attempting to correlate magnetic field fluctuations to stress will necessarily underpredict the post-yield load levels where strain is a more appropriate parameter of interest.

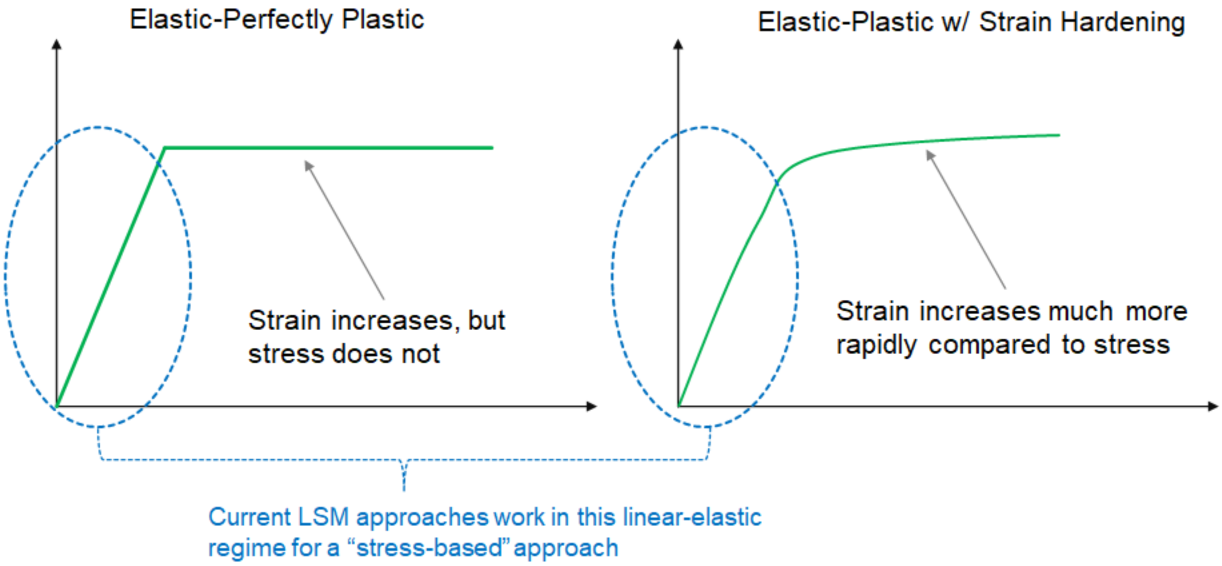

Figure 11: Linear-elastic vs elastic-plastic material response: w/o strain hardening (left), w/ strain hardening (right)

Details of alternative approaches are not within the scope of this work, but a non-linear Ramberg-Osgood-type relationship that incorporates strain hardening may be suitable for use in high strain cases, instead of a linear-elastic relationship. The success of such alternative approach would be predicated on the understanding of how the magnetic field fluctuates under high strain conditions. To the authors' knowledge, such formulation has not yet been developed for use in LSM inspection technologies. Advancing future studies along this direction would be greatly beneficial in increasing the practical applicability of LSM-based inspection in real-world scenarios.

Residual Stresses/Strains (Informational)

The issue of residual stresses was not addressed in the final reports provided by the vendors. In the present setup, residual stresses would have been present on account of two practical issues: 1) fabrication weld residual stresses localized at the girth welds between the joints, and 2) stresses due to the test setup wherein the pipe is loaded under the action of self-weight and the weight of the water volume in the test pipe (as pressurizing medium). It is possible that these stresses were treated as reference or baseline stresses and not explicitly quantified; however, in that case, the stresses/strains reported for the subsequent load levels would be expressed in relative terms over the baseline state of stress and may not represent the absolute state of stress at a given load level. Additional information on how residual stresses are addressed are essential to correctly interpret the inspection results.

Circumferential Resolution (Informational)

Within the extent of the details provided in the LSM inspection reports, there was no indication of whether the precise location of the high strain region can be identified over a circumferential section. For example, with reference to the sketches in

Figure 12, when a pipe is bent in the direction of the force, Point A on the circumference is under maximum tensile stress conditions, whereas Point C is under maximum compressive stress conditions. All other points along the circumference experience a lower level of stress. It was not evident from the inspection reports whether the LSM technologies would be able to distinguish between the stress states of Point A and Point C (or even Point B). In the absence of such distinguishing capability (or adequate circumferential resolution), the LSM results would manifest in a volume-averaged interpretation over part (or whole) of the circumference leading to uncertainty in the stress prediction. Additionally, any local stress riser along the circumference may carry the potential of being misinterpreted as a bend-induced effect. It is recommended that future efforts address (and quantify) this issue.

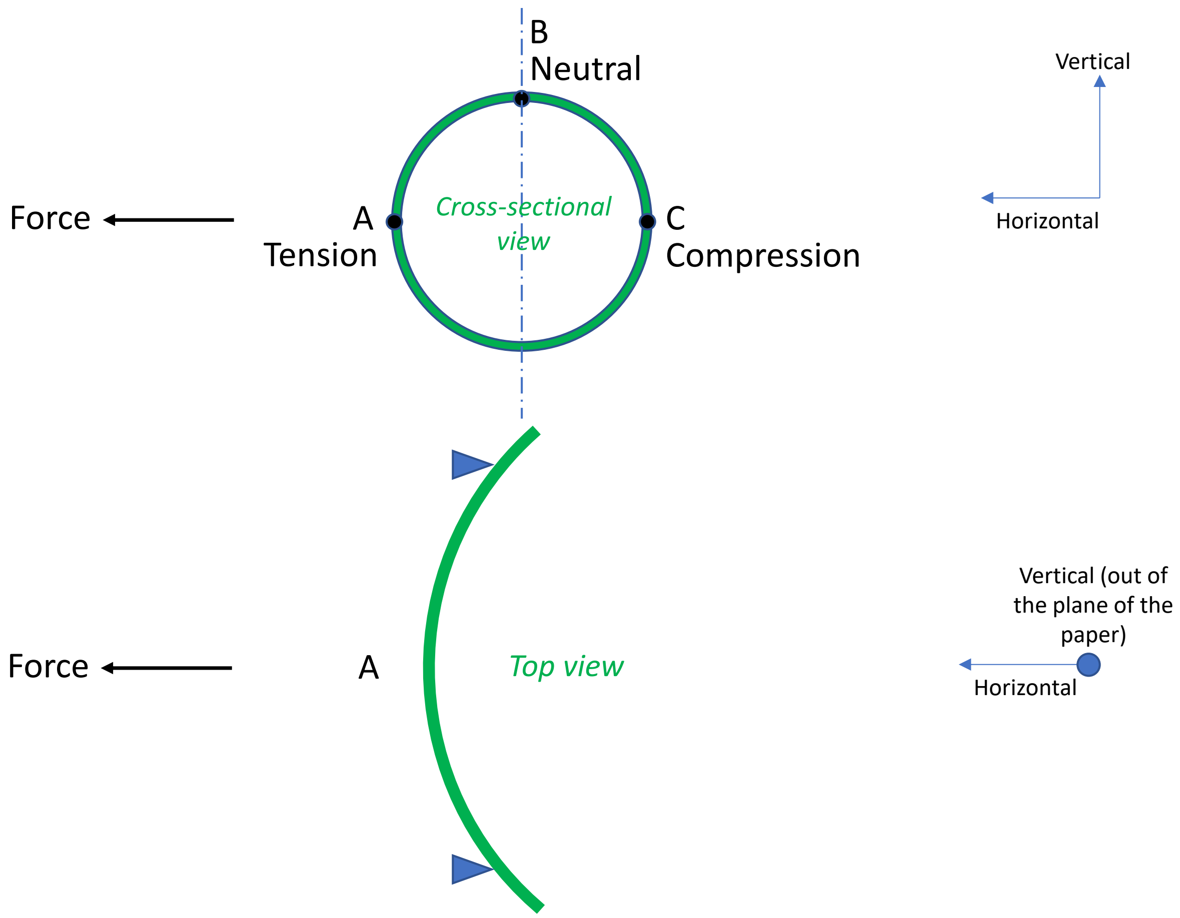

Figure 12: For a given force direction, varying state of stress around the pipe circumference

Axial Resolution (Informational)

For the approximate 3-point bending configuration of the pipe that was tested with a point load applied at mid-span and simply supported ends, the bending moment distribution varies linearly from zero the supports to maximum at mid-span. Since bending stress is directly and linearly-proportional to bending moment, a linear distribution of stress is expected along the length of the pipe from the supports to mid-span. Theoretically, the LSM inspection signal resulting from such stress distribution would also vary linearly with a peak indication exactly at mid-span. If the axial resolution of the scanning and data processing system is not sufficiently fine, the results would manifest in a volume-averaged interpretation over a given length. The uncertainty in stress prediction would be significant, especially if this effect compounds with circumferential resolution limitations. It would be valuable to the users of the LSM technology to understand and quantify this effect in future.

Local vs Global Stress Sources (Informational)

In the present case, the pipe joints used for fabricating the test sample were in new condition and did not contain any flaws or local features that could result in localized stress concentrations. However, in the real-world, the pipes being inspected may contain dents, gouges, cracks, or pits that could be potential sources of localized stress concentrations. In the presence of features/flaws, it is unclear how global bending stresses/strains would be isolated and presented – especially without the aid of supplementary line mapping information. For example, with reference to
Figure 12, the maximum global tensile stress/strain would be at Point A – however, it is not clear how the magnetic field data would manifest if there is a localized flaw/feature at Point B or Point C and whether the bending stress/strain magnetic signature at Point A can be isolated from the magnetic signatures for a flaw/feature at any other point along the circumference.

Magnetic Profiles Associated with Stress/Strain Levels (Informational)

The PRCI team requested magnetic profile data for the inspection sessions as part of the deliverables in the respective final reports. However, these data were not shared by the vendors on account of proprietary considerations. These data were being requested so that the PRCI team can examine whether changing load levels fundamentally manifest as noticeable changes in the associated magnetic profiles. It is recommended that future efforts be undertaken to encourage the vendors to provide this data in a manner that protects their proprietary information, but also provides the needed information; perhaps using normalized profile plots, or using a “contour heat map” type representation as is common in presented finite element model results.

Use of GPS Data (Informational)

Both vendors used some form of GPS assistance in planning their inspection runs; however, the details of the GPS technology and the use of the resulting data in interpreting the LSM results were not discussed in their individual final reports. Without additional information, it cannot be determined whether or not the GPS information has any bearing on the inspection results presented in the final reports. However, with the goal of this project focusing on the determination of stress/strain in the pipe, GPS data may not have been directly used (or needed) for the results. For inspections in the real-world, exact positional data for the pipeline and any associated geohazard induced stress/strain is paramount and will require incorporation of GPS data.

CONCLUSIONS

The full-scale testing program undertaken in this project to verify results from LSM technologies was successfully executed and all project objectives were met. For the LSM technologies used by the two vendors who participated in the program, a reasonable correlation was observed between the data reported by strain gages (during the test) as compared to that reported by the LSM technologies when bending is in the linear-elastic regime. When relying solely on the magnetostrictive effects, and within the bounds of the current understanding of the phenomenon (which builds on linear-elastic theory), the correlation between the LSM data and the measured strains breaks down when bending induces plastic strain in the pipe. Based on the results shown by one of the vendors in the study, when bending strains are in the plastic regime, the LSM data needs to be supplemented by pipe curvature information for correct interpretation of the readings. From the perspective of detection and quantification of high strain deformation in pipes, LSM technologies will greatly benefit from additional fundamental research efforts in extending the understanding of magnetostrictive effects in the plastic strain regime (correlating plastic strains to magnetic profiles/signatures).

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