The use of ILI technology for the detection and measurement of elevated stress associated with CSCC

by Ron Thompson[1], Ray Gardner[2], Katrina Dwyer[2], Richard Gonzales[2],
Andrew Corbett[1], Guillermo Solano[1]
1. Novitech Inc, Vaughan, ON, Canada.
2. Xcel Energy, Denver, CO, USA.

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Abstract

This study focuses on the development of a new sensor measurement system called IDD-SM (Internal Depth Detection with Stress Measurement) that can be used to model elevated stresses around cracking and other significant anomalies. The primary research of the study is the relationship between stress and changes in the magnetic properties around CSCC (circumferential stress corrosion cracking) locations in steel pipe. This study also builds on the previous body of work between Novitech and Xcel Energy in three previously published papers on CSCC at PPIM in 2019, 2020 and 2021.

Axial and circumferential magnetic flux leakage (AMFL & CMFL) are also used to detect, characterize, and quantify suspect CSCC locations. The combined results from AMFL, CMFL and IDD-SM sensor systems is being further optimized to increase the probability of detection (POD) and the probability of identification (POI) and sizing at suspect CSCC locations.

The 6.625" nominal diameter pipes used in this testing were provided by Xcel Energy and contained a series of CSCC locations that were originally detected by Novitech using MFL and IDD sensor systems during a scheduled in-line inspection (ILI). These pipes containing samples of CSCC have been removed from service and sent to the Novitech R&D Technology Centre in Toronto, Canada. These pipes were re-inspected with multiple pull tests, providing signal-to-signal comparisons of identical CSCC features with increasing levels of bending moments to measure the magnitude of elevated stress.

This study also includes the IDD-SM algorithm development that is being used to quantify and rank CSCC colonies for severity in combination with the AMFL and CMFL results. These findings are then used to determine prioritization of investigations and possible repairs at suspect locations.

Introduction

The successful deployment of AMFL with IDD-SM sensor technology for the detection of CSCC has allowed Xcel Energy to transition from a CSCC susceptibility-based model [1],[2],[3] to a direct inspection model for the management and mitigation of this threat [4],[5],[6].

To detect and size metal loss, geometric deformations, and cracks (including CSCC, axial cracks, and off-angle cracking) Xcel Energy and Novitech Inc performed an AMFL and IMU (inertial measurement unit) inspection followed with a CMFL run, both of which included Geometry and IDD-SM sensor systems.

This inspection approach along with CSCC detection has simplified Xcel Energy's pipe maintenance operations by reducing the number of ILI runs required to evaluate these threats as well as reducing the number and scope of pipeline excavation and exposure areas required to investigate CSCC occurrences compared to those originally predicted by susceptibility factors.

The probability of detection (POD) and the probability of identification (POI) capabilities of greater than 90% for the AMFL with IDD-SM systems has been derived from a confirmed 120 occurrences of CSCC. To date, a total of 5 different operators have contributed their field findings in NPS 6, 8 and 10 pipelines. Further analysis into the capabilities of the ILI systems have been determined via destructive testing of greater than 25 occurrences of CSCC.

Based on the reliability of the ILI data, Xcel Energy has been able to re-evaluate the risk profile associated with CSCC and, in an extreme case, return to full operation of a pipeline previously isolated at a reduced pressure.

To further increase operational reliability and to reduce the risk associated with CSCC, Novitech and Xcel Energy are exploring the application of magnetomechanical effects related to in-line inspection technology. This initiative leverages the effects that stress has on ferro-magnetic materials to inspect for elevated and high levels of stress associated with CSCC.

From the operator's perspective, the ability to detect these elevated and high levels of stress associated with stress concentrators can provide additional information helpful in prioritizing excavation work. From an in-line inspection perspective, this initiative can further improve POD and POI noting that stress intensification signals should largely be absent from blunt type anomalies, assisting in discriminating cracking and cracking in corrosion from just corrosion.

Magnetism and Stress

The magnetomechanical effect is the term used to describe the changes of magnetization levels of a ferromagnetic material resulting from the application of stress. It is a group of physical phenomena whose practical applications range from actuators (magnetostriction) to sensor technology (magnetoelastic effect), the latter of which creates the possibility of measuring mechanical force or stress by measuring magnetic parameters of the material [7], [8].

Magnetomechanical effect modelling has been the subject of constant study and review with each contribution accounting for a specific variable in the modelling i.e. alloying elements, temperature range, load range, microstructure, residual stresses, etc., or by refining the existing models and exploring its application in a particular experimental set up [9], [10].

Since the basic physical principal points to changes in flux density for a given magnetizing field under the influence of mechanical stress, it would seem that a practical application can be explored, for the pipeline industry, by way of incorporating specifically designed sensor systems and analysis process to an in-line inspection tool technology that already functions on magnetic principles.

The complexity of this phenomena has made it particularly difficult to model under all conditions. Publicly available research relies heavily on experimentation, using it to determine areas of correspondence and disagreements between proposed theoretical solutions and real-world observations as well as to add corrections, empirical factors, or approximations to bring the proposed models closer to the reality of the phenomena.

Because of current modelling limitations, this study has also made extensive use of experimentation culminating in the design and manufacturing of a complete ILI systems tested on actual CSCC colonies under varying bending loads, as described in the following sections. This research effort has been used to determine sensitivity levels and responses to areas of bending stress.

IDD-SM sensor module development

The IDD sensor module that was developed for the detection of CSCC was further enhanced by improving sensor positioning, sensor tracking and magnetic sensor flux density. Electronic circuit designs were also developed to improve signal to noise ratios of the sensor arrays. The IDD-SM sensors are incorporated into each arm of the Geometry module to reduce the tool length and overall complexity of the system.

Tool assembly and set up for AMFL + IDD-SM sensor array

As shown below in **Figure 1** the ILI tool was assembled allowing the testing of a complete system. This system included AMFL modules, main electronics module, Geometry/IDD-SM module, battery/IMU module and triple odometer systems. The systems were evaluated using the same protocols that were employed for AMFL and CMFL tools, via a pull test. Sampling distances for all pull testing were set at 0.020” (0.5 mm) resulting in sampling densities of 640 per square inch for the AMFL sensors, and 128 per square inch for the IDD-SM sensors.

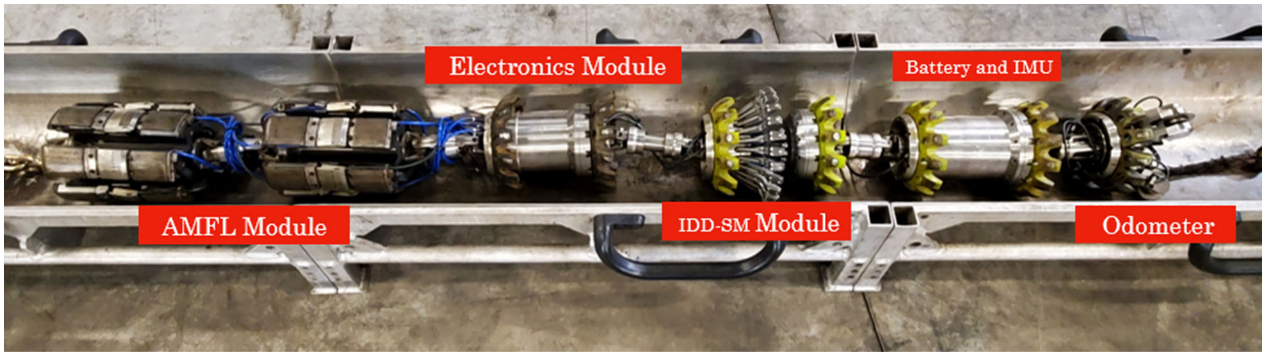

Figure 1 - *Complete ILI tool assembly for AMFL + IDD-SM testing*

Test Pipe

A cut-out section of API 5L-X42, NPS 6, 0.188” nominal wall, 25 ft in length pipe, that contained 9 occurrences of CSCC was selected for testing. Although this test piece was surely subjected to bending stress while it was in service (leading to the development of the 9 CSCC colonies), once it was cut out and allowed to relax the pipe was observed to be straight.

The test pipe was extended to a total of 60 ft by adding two additional sections of the same diameter, grade, and wall thickness. The extra length would assist in providing leverage as the pipe is point bend loaded and as a transition and stabilization section for the tool as its pulled through the pipe (pipe of interest at the centre).

Once the entire test pipe was assembled, it was allowed to relax on a level concrete surface and then anchored at either end (simply supported), bolting the anchors in place where the pipe rested eliminating the possibility of pre-stressing the pipe. In its anchored position the test piece was re-evaluated, and again found to be straight as shown in **Figure 2**.

Figure 2 - *Test piece is straight in its resting position*

The existing 9 CSCC colonies were depth sized by Phased Array Ultrasonics (PAUT) by two independent companies and two different experienced technicians, each with their own equipment, calibration piece and set-up. Depth predictions were within 10% of each other. Circumferential extent was visually measured with the assistance of black and white magnetic particle inspection methods.

The CSCC colonies ranged in depth from 30% to 95% of the nominal wall thickness and had a circumferential extent of 0.6” to 1.6”. **Figure 3** shows the two most significant indications (Feature 4513 and 4515), both sized at 95%. These two indications are exemplified throughout this paper to present the findings of the study.

The 9 CSCC colonies were naturally found aligned axially, in three separate clusters, at the same o'clock position circumferentially on the pipe and, as such, the pipe orientation in the test was selected so that the applied point load would subject the CSCC colonies to the maximum induced bending stress.

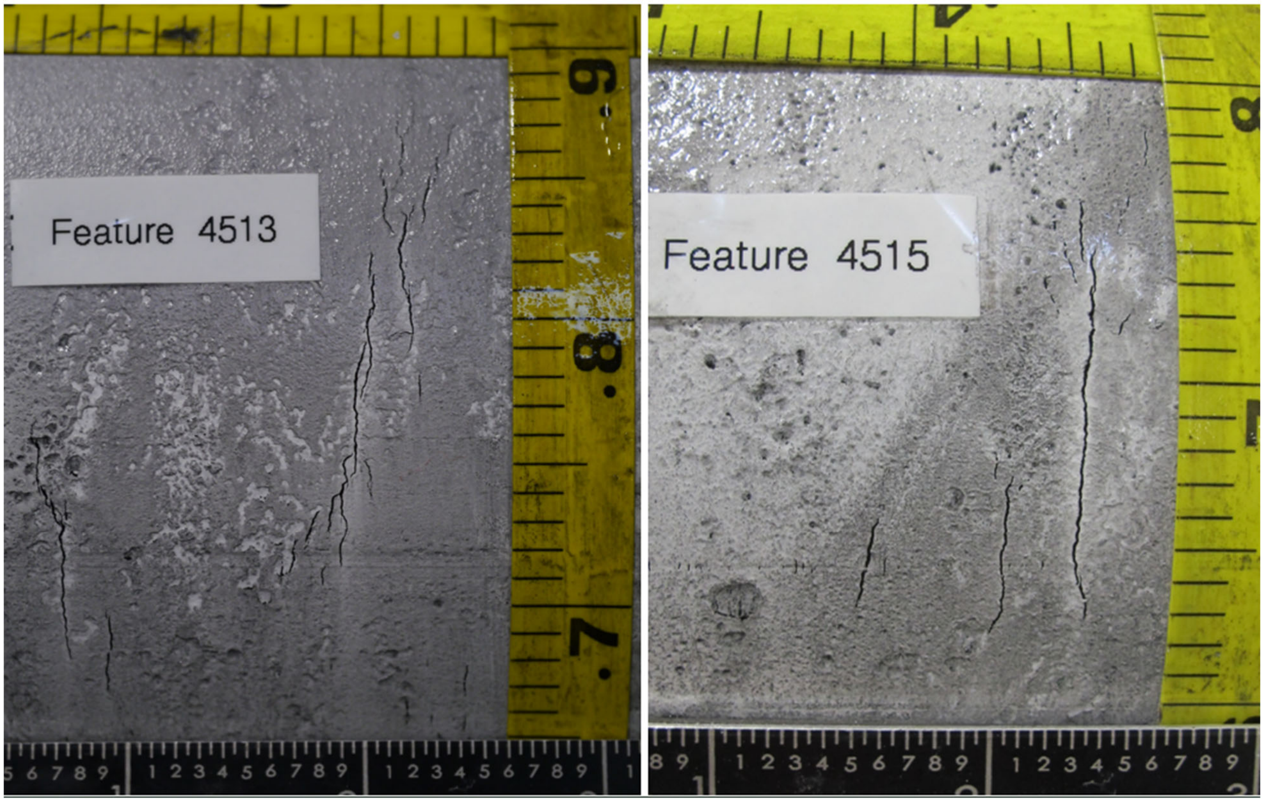

Figure 3 – *Most severe CSCC studied with AMFL + IDD-SM technology*

Test Set-up

The test pipe was point bend loaded with a tow strap and come along at the position of each CSCC area introducing bending stress in and around the crack areas. A load cell was used to measure the applied bending force and positional references were made in the floor to measure pipe deflection as result of the loading as shown in **Figure 4**.

Best efforts were made to ensure the set-up reflected a 'simply supported structure under point load' at each stage of the test, which meant moving the anchor point of the tow strap to each position of the sample piece where a CSCC colony was to be subjected to bending force, ensuring that the applied was always applied perpendicular to the pipe.

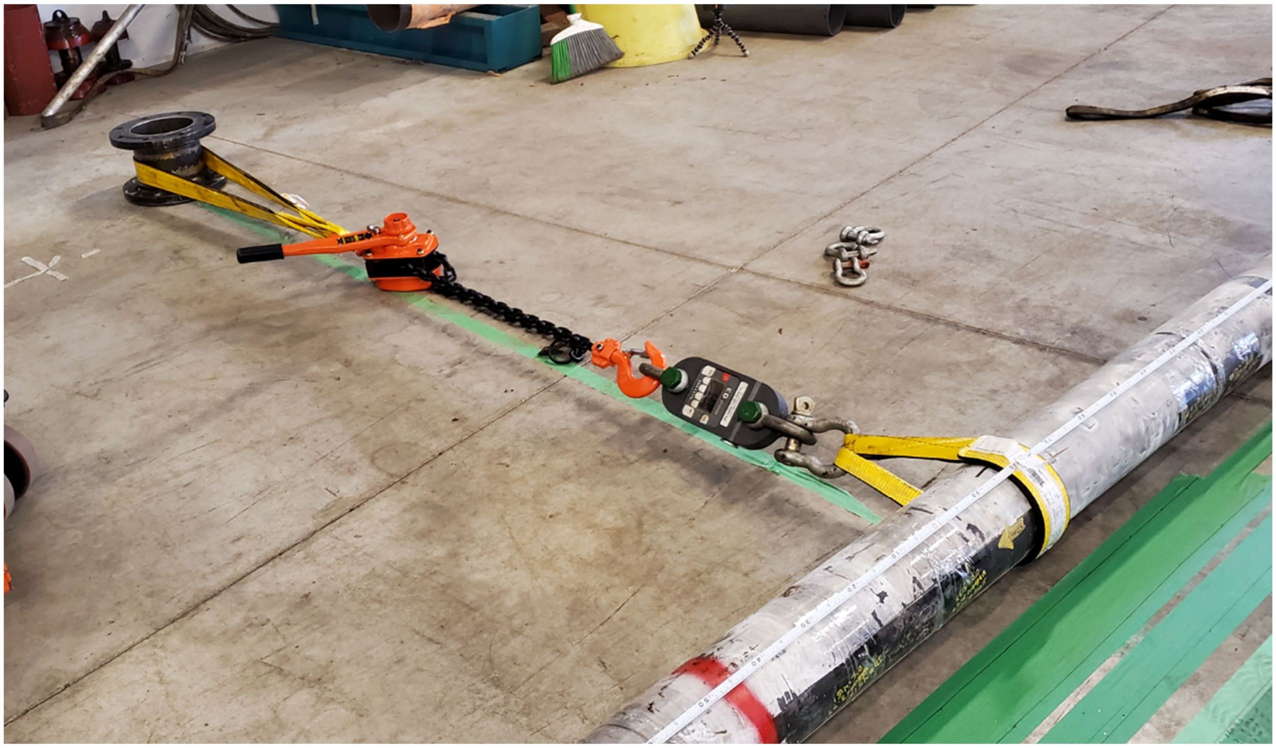

Figure 3 - *Pipe simply supported and point loaded at each CSCC cluster location introducing bending stress*

A preliminary finite element modeling (FEA) model was used to determine the proposed pipe loading was well within the elastic zone of the pipe, and to gain a better understanding of the expected level of stress in and around the crack areas. **Figure 5** shows an example of the finite element modeling (FEA) with predicted strain fields in the area around CSCC Features 4513 and 4515. **Figure 6** shows the specific areas surrounding each Feature through the load range of the test, beginning with a zero load, straight pipe then deflecting the pipe in 4-inch increments to 12" of off axis displacement.

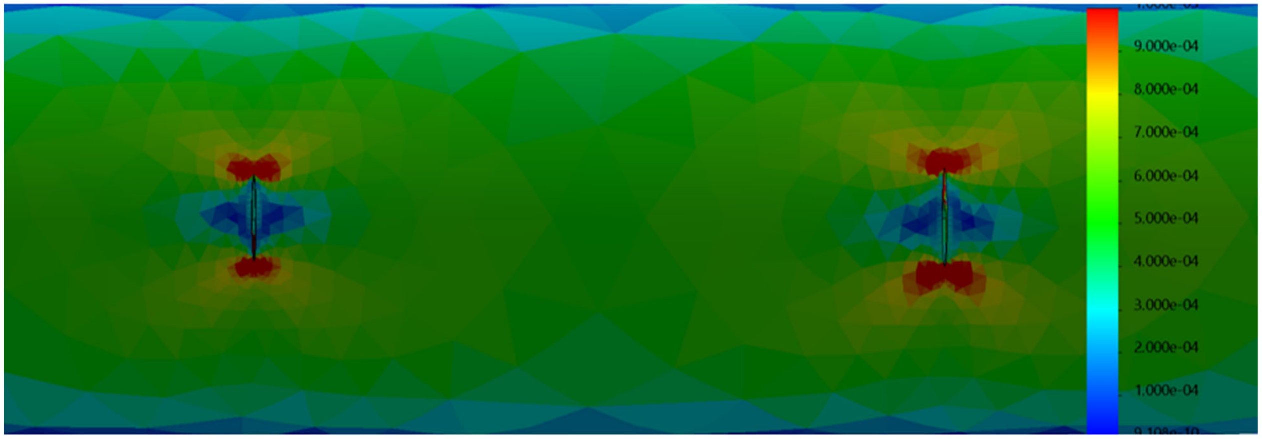

Figure 5 - *Finite Element Modelling with predicted strain fields under highest load test levels (70% SMYS) for Features 4513 and 4515.*

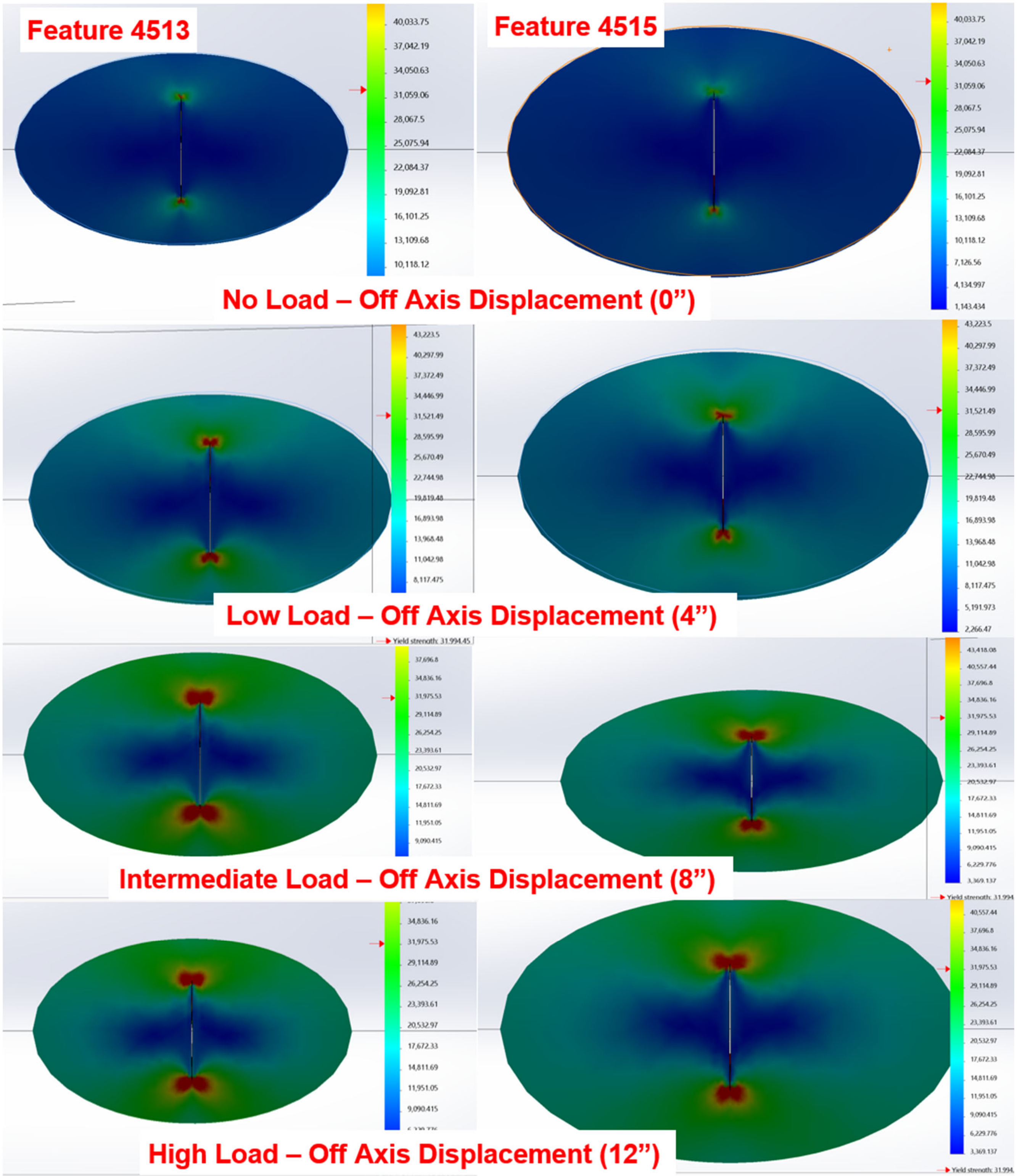

Figure 6 - *Finite Element Modelling with predicted strain fields*

Multiple ILI pull tests were performed at each stage of loading, displacing the pipeline 4", 8" and 12" from its original straight-line position (off axis displacement), as seen in **Figure 7**.

The pipe was then allowed to relax back again to its resting position and pull tested again. The process was repeated at each CSCC cluster resulting in a total of 27 Pull tests, adding to a combined 249 AMFL + IDD-SM complete C-Scan maps of the CSCC colonies.

Once the load was removed, the pipe returned to within 1.5" of its original position, there was no evidence of plastic deformation, which was again confirmed upon releasing the pipe from its anchor points. The remnant deflection during the test (1.5" off axis) was the result of friction with the floor preventing the pipe from returning to its exact starting point.

With the test completed the circumferential extent of the cracks was measured once more to ensure no crack growth as result of the experiment.

Figure 7 - *Bending stress introduced by displacing the test pipe up to 16" from its straight rest position*

Test results, Findings and Discussion

The amplitude signal response from the IDD-SM and AMFL sensors were used to generate a C-Scan map of the CSCC areas.

While there are many characteristics from the sensor signals that are used to draw conclusions with respect to the observed anomalies, this portion of the study focused on sensor amplitude response to the only variable of the test (bending stress) as the crack depth and circumferential extent remained unchanged throughout the experiment.

The following observations can be made with respect to IDD-SM and AMFL signals:

1. Repeatability: At each level of loading the pull tests was repeated 3 times and the amplitude responses for both IDD-SM and AMFL in and around the crack areas was found to be consistent, with less than 5% signal amplitude variability between pull tests.

2. IDD-SM response to increased levels of bending stress in the crack and surrounding areas: There is a marked increase in signal amplitude with each level of increased loading, with the base signal more than doubling through the load range of the experiment. The C-Scan display in **Figure 8** has been color coded to signal amplitude illustrating this fact.

3. IDD-SM response in the base metal: There is no change in the signal responses during increased loading and bending stresses in the base metal. There were no features detected in the unblemished base material. The IDD-SM sensors only detected a change in bending stress when associated with a stress concentrator.

4. IDD-SM response in areas of metal loss: No relevant signals were found in areas of superficial metal loss which were otherwise apparent in the AMFL data.

5. AMFL response to increased levels of bending stress in the crack and surrounding areas: While there is a change in the amplitude response with increasing levels of stress, these increases are modest and did not show a clear relationship between AMFL signals and changes bending stress.

6. AMFL response in the base metal: Just as with the IDD-SM sensors, the base metal showed no change in the AMFL signals despite being subjected to increasing levels of bending stress.

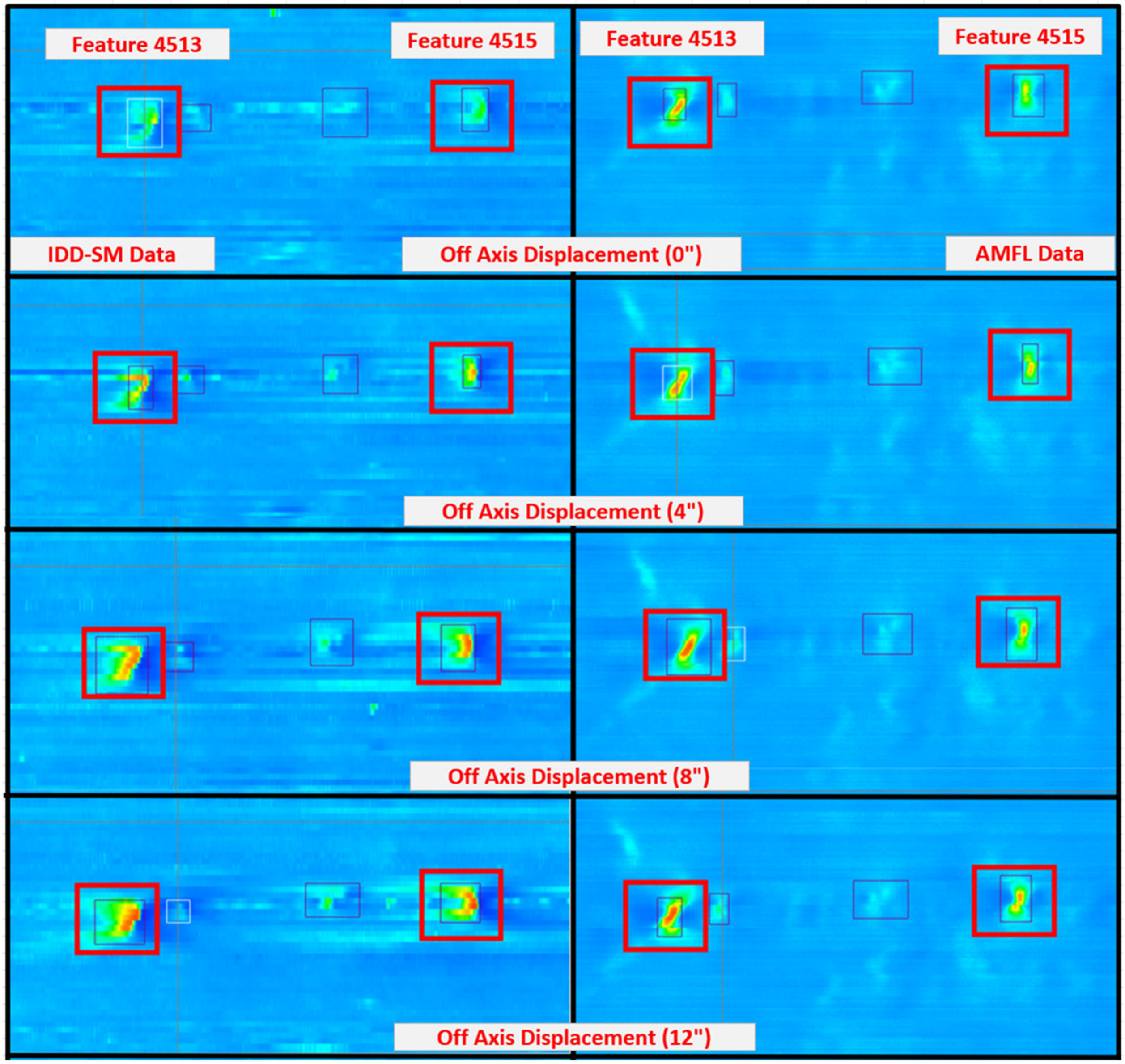

Figure 8 – *IDD-SM and AMFL C-Scan Display of each level of loading at the CSCC locations*

Conclusions

The IDD-SM sensor system shows a significant response to stress intensification associated with crack-like features. It does not appear to have detected any changes in the magnetization of steel associated with stress in unblemished areas or with blunt type features.

The IDD-SM data, in concert with AMFL, provides a higher level of reliability when determining occurrences of CSCC or a circumferentially oriented features that acts like a stress concentrator. This facilitated the identification of crack-like indications from signals that stem from blunt type features. This advancement can also be particularly effective providing insight into critical areas where the pipe is subjected to high stress as result of bending forces, has developed CSCC, but it has not yet grown to significant depths.

The same principles used to detect circumferentially oriented cracking (AMFL+IDD-SM) should apply to axially oriented cracking, where the CMFL module in combination with IDD-SM sensors should be able to identify axial features that act as stress concentrators. This could include many forms of cracking, seam flaws, and potentially selective seam weld corrosion. As with CSCC, the primary function of the IDD-SM module would be to help quantify and improve discrimination between crack-like and blunt features.

As with the current experiment, extending the application of the IDD-SM sensor module to axially oriented stress concentrators will require verification via testing and live runs coupled with excavation work. This work opens the door to future areas of study whereby Magnetostriction phenomena could be applied to quantify levels of stress associated with most types of crack-like features irrespective of the crack orientation.

The current development of the IDD-SM sensor technology provides a clear path in utilizing signal response as part of the discrimination process differentiating blunt type features from stress concentrators. The work required to utilize this information and to generate a stress scale measurement system is ongoing and will need further refinement of current theoretical models. Experimentation accounting for bending, tensional and hoop stresses in combination with broad range of axial stress concentrators such as crack colonies of varying sizes, seam flaws, selective seam weld corrosion will also require further study.

REFERENCES

[1] R. R. Fessler and A. D. Batte, “Criteria for susceptability to circumferential SCC,” in *Pipeline Research Council International Report, Catalog No. PR-313-113603-R01*, Houston TX, 2013.

[2] “CEPA Recommended Practices for Managing Near-neutral pH Stress Corrosion Cracking 3rd Edition,” CEPA Pipeline Integrity Working Group, Calgary, 2015.

[3] J. Dawson and I. Murray, “An approach for evaluating the suceptibility of a pipeline to circumferential SCC,” in *Proceedings, Pipeline Pigging and Integrity Management Conference*, Houston TX, 2019.

[4] R. Thompson, R. Gardner, K. Dwyer and J. Hare, “The detection and sizing of circumferentially oriented stress corrosion cracking using axially oriented magnetic flux leakage inspection,” in *Proceedings, Pipeline Pigging Integrity Management Conference*, Houston, TX, 2019

[5] R. Thompson, R. Gardner, K. Dwyer, and A. Corbett, “A Cased Study in the detection and sizing of Circumferential stress corrosion cracking" Vaughan, Ontario, Canada and Denver Colorado, USA 2020.

[6] R. Thompson, R. Gardner, K. Dwyer R. Gonzales, A. Corbett and G. Solano, “Pipeline Integrity Management of CSCC using multiple ILI technologies”, in *Proceedings, Pipeline Pigging Integrity Management Conference*, Houston, TX, 2021.

[7] D. C. Jiles, "Theory of magnetomechanical effect", *J. Phys. D: Applied Physics,* 28, 1537, 1995

[8] Craik D. J. and Wood M. J. "Magnetization changes induced by stress in a constant applied field" *J.Phys. 0. Appl.Phys. 4 1009, 1971.*

[9] M.J. Sablik, Y.Chen and D.C.Jiles, "Modified Law of Approach for the Magnetomechanical Model", *Review of Progress in QuantitativeNondestructive Evaluation,* 1565, 2000

[10] DC. Jiles, S.J. Lee, J. Kenkel and K. Metlov, "Superparamagnetic magnetization equation in two dimensions," Appl. Phys. Letts., 77, pp: 1029-1031,2000