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Case Studies in the Application of Advanced Technology to Pipeline Flaw Assessment

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ABSTRACT. Pipeline operators have been quick to adopt technological advances in a number of areas, including inline inspection (ILI). However, when it comes to evaluating flaws and other damage detected by ILI and other means, much of the pipeline industry still relies on simplified assessment methodologies that don't take advantage of all data sources and improved understanding of failure mechanisms. This paper makes the case that adopting new technologies for flaw assessment is overdue, as these technological advances will be beneficial to the industry.

This paper presents four case studies to demonstrate typical applications of advanced flaw assessment technology:

1. An automated pressure cycle fatigue analysis (PCFA) system that processes SCADA data and generates reports in nearly real time.
2. Advanced analysis of dents and wrinkle bends using ILI data.
3. Finite element modeling of overpressure events.
4. Virtual burst test simulation.

BACKGROUND

Over the past 26 years, the PPIM conference has showcased advances in inline inspection (ILI) and other data collection technology. Competitive pressures have driven ILI vendors to innovate continuously. Pipeline operators have been quick to adopt new technologies for both inline and in-the-ditch inspection. As a result, operators now have access to significantly higher quality data that was available at the time of the first PPIM conference. However, pipeline operators seldom take full advantage of higher quality data. One of the present authors (TLA) has made this point repeatedly at previous PPIM conferences. For example:

- **PPIM 2010** [1]. The practice of flaw boxing, which was developed for MFL wall loss data, is largely a waste of time with high-resolution ultrasonic (UT) thickness data. Moreover, flaw boxing combined with a B31G assessment considers only the length and maximum depth of a corrosion flaw, and thus ignores >99% of the UT data. By contrast, an automated effective area calculation is much faster than manual flaw boxing, and it considers all of the thickness data, resulting in a more accurate prediction of the remaining strength of a corroded pipe.

- **PPIM 2012** [2]. A “conservative” flaw assessment can actually be unsafe. False positives, where anomalies that do not pose a threat are remediated, result in unnecessary expenditures. This would not be a problem if an operator had an infinite integrity budget, but in the real world, unnecessary expenditures consume a finite budget. This can lead to false negatives, where real threats are not remediated. On the other hand, an advanced assessment that leads to realistic predictions of threat levels optimizes the finite integrity budget, and thus improves reliability. The contrast between simplified and advanced assessments, given a finite budget, is illustrated in Fig. 1, which was taken from Ref [2].

- **PPIM 2113** [3]. Traditional methods for assessing cracks and other planar defects in longitudinal seams in pipelines date back to approximately 1970. These methods have a number of serious shortcomings and can result in gross underestimates or overestimates of burst pressure. The field of fracture mechanics has advanced considerably since 1970, and crack assessment methods that are vastly superior to the traditional models are now available.

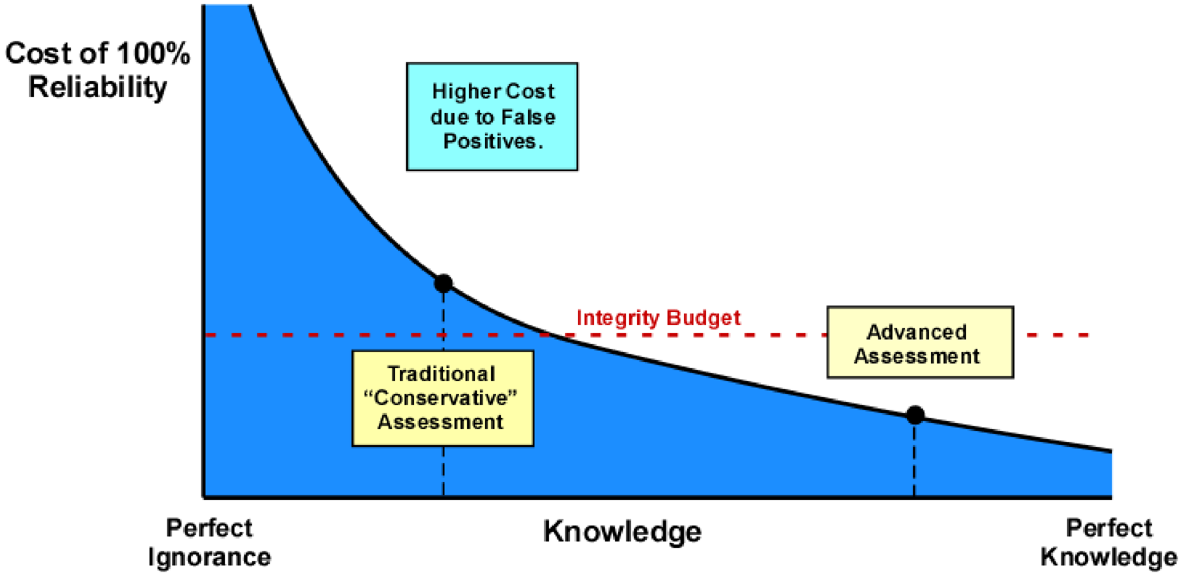

FIGURE 1. The relationship between the cost of achieving nearly 100% reliability and knowledge about the condition of the pipeline [2]. The hypothetical (and unachievable) extreme of “perfect knowledge” corresponds to the case where the operator knows the precise time and location of each future failure, and remediates immediately before each incident. The opposite extreme corresponds to the case where the operator knows nothing about the condition of the pipe and whose integrity management program consists of random digs. The traditional so-called conservative assessment leads to a significant number of false positives, which consume the integrity budget without achieving the desired level of reliability. When applying more accurate advanced models, a high level of reliability can be achieved at a lower cost.

This paper builds on the previous articles and presents four case studies where advanced flaw assessment technology has been applied to real pipelines. The cases are as follows:

1. Automated pressure cycle fatigue analysis (PCFA).
2. Advanced analysis of dents and wrinkle bends using ILI data.
3. Finite element modeling of overpressure events.
4. Virtual burst test simulation.

CASE STUDY 1: AUTOMATED PRESSURE CYCLE FATIGUE ANALYSIS (PCFA)

Pipelines that are subject to pressure cycling (i.e. the pressure fluctuates rather than remaining steady) can develop fatigue cracks in service. Pressure cycling is primarily a problem in liquid lines, but fatigue failures have occurred in gas lines. Fatigue cracks typically initiate at pre-existing weld flaws, so ERW pipe with hook cracks and lack of fusion flaws is particularly susceptible.

Pressure cycle fatigue analysis (PCFA) is an important part of integrity management of pipelines in cyclic service. The traditional approach to PCFA is labor intensive, and typically takes from one to three calendar months to issue a report. Consequently, most operators perform PCFA on susceptible lines no more often than annually.

Quest Integrity has recently developed a software system for automating pressure cycle fatigue analysis. The Pacifica^{TM} software system can run unattended on the operator's network and perform PCFA in nearly real time. Figure 2 illustrates the architecture and work flow in Pacifica. Initial setup is required for each pipeline that is added to the system. The user must enter the pipeline properties, dimensions, pumping station locations, and the elevation profile. The user must also populate a flaw table with initial sizes and locations. The flaw table can be calculated based on hydrostatic testing, or it can be based on ILI data. After initial setup, Pacifica accepts pressure data from the SCADA system. These data are processed through a rainflow cycle counting algorithm to compute cyclic pressure, which can be displayed as a histogram or exceedance diagram. The cyclic pressure data are then input into a crack growth analysis. End of life is defined by a fracture model. The software uses the API 579 fracture model [4] as a default, because it has been shown to give superior results to traditional models [2].

Both incoming data and calculated values are stored in a database. Multiple pipelines can be managed by a single installation of Pacifica. Reports can be generated on a scheduled basis, or custom reports can be created on demand.

Figure 3 is a plot of a typical exceedance diagram that shows 4 years of pressure cycle data for a crude oil pipeline. Note that the operation changed during after the 2006-07 period and the pressure cycling became more aggressive. One of the advantages of the Pacifica platform is that it provides notification of operational changes shortly after they occur. It is also possible to discern differences in pressure cycling over short periods. Figure 4 shows the monthly variation of pressure data from Fig. 3. In this case, the severity of the pressure cycling was quantified in terms of the growth rate of a hypothetical crack. The pattern appears random, although some of the slow periods in spring and autumn months may be associated with the refinery turnaround season.

Pacifica may also be used to perform sensitivity studies. Figure 5 is a plot of remaining life versus crack size and location between two pumping stations. The estimated life is considerably shorter near the pumping station discharge, as one would expect. The software can accommodate changes in flow direction. The corresponding remaining life plot for such a scenario would look considerably different from Fig. 5.

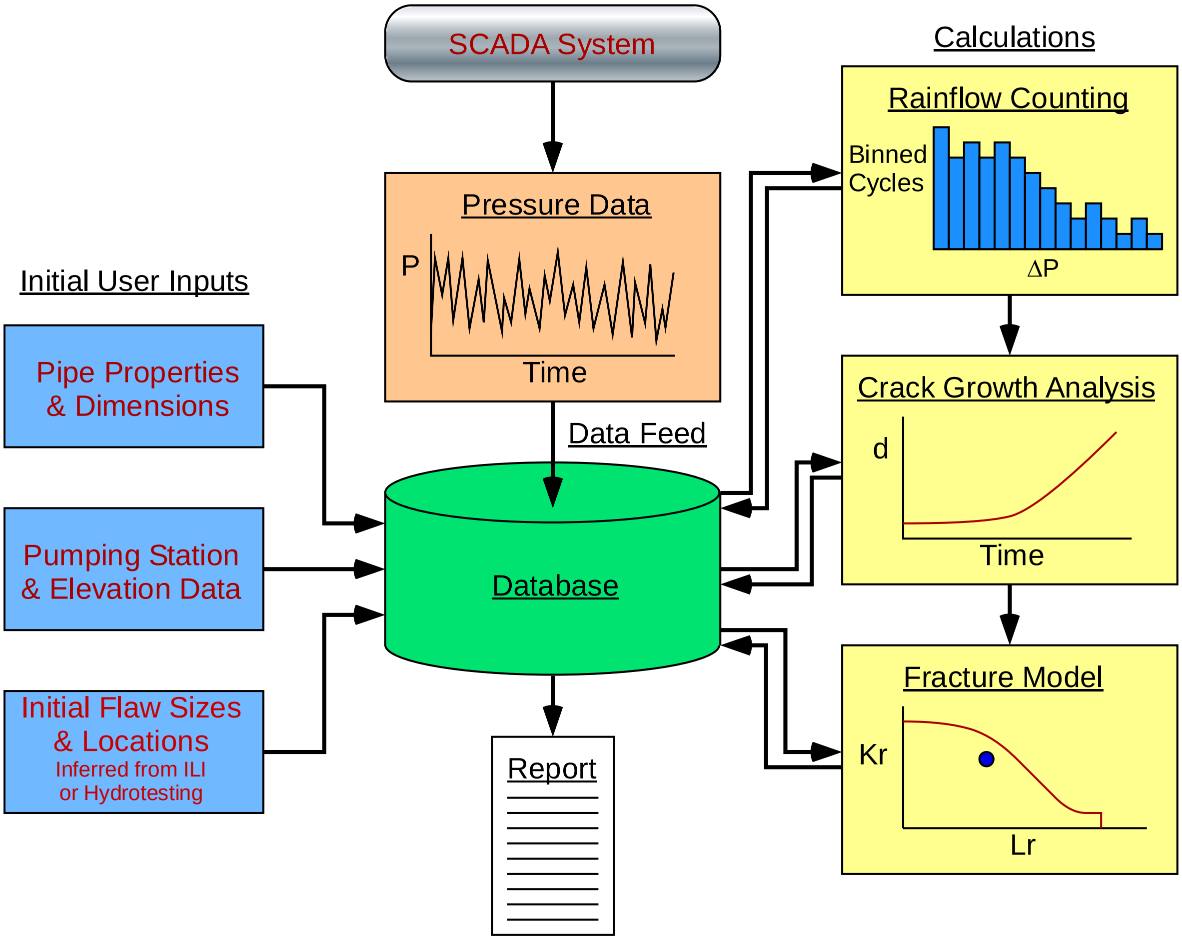

FIGURE 2. Architecture and workflow of the PACIFICA software for pressure cycle fatigue analysis.

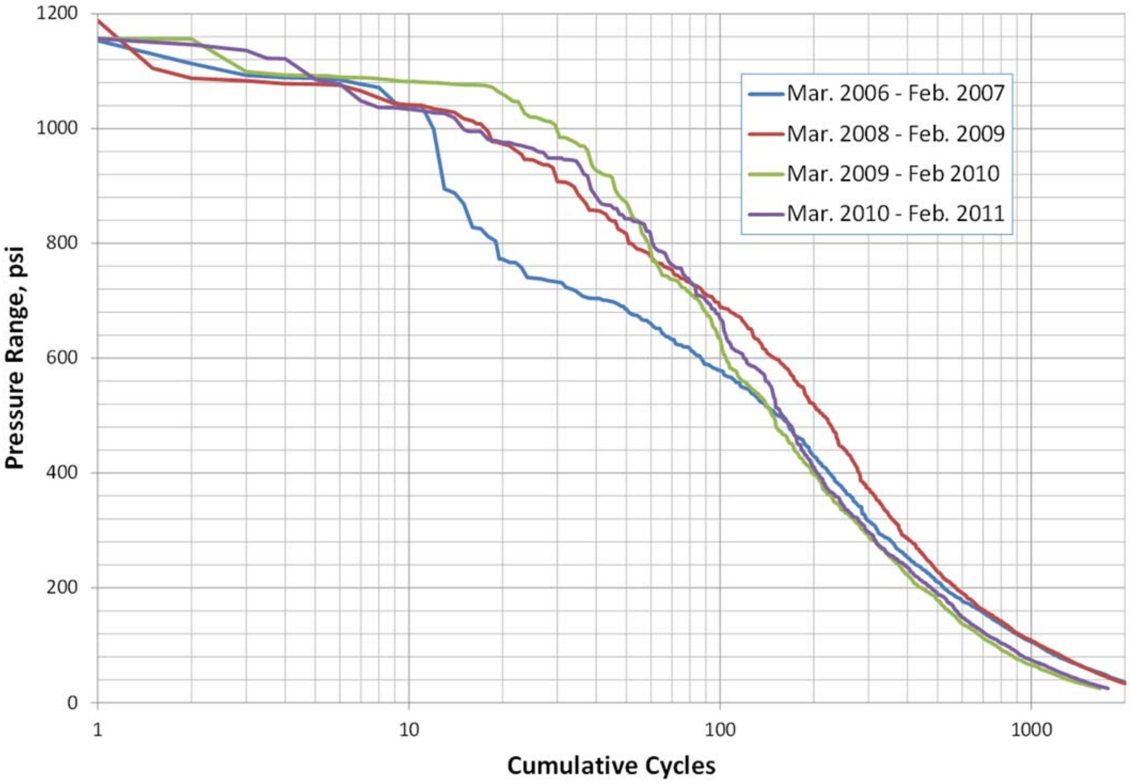

FIGURE 3. Exceedance Diagram showing annual pressure cycles for four 12-month periods.

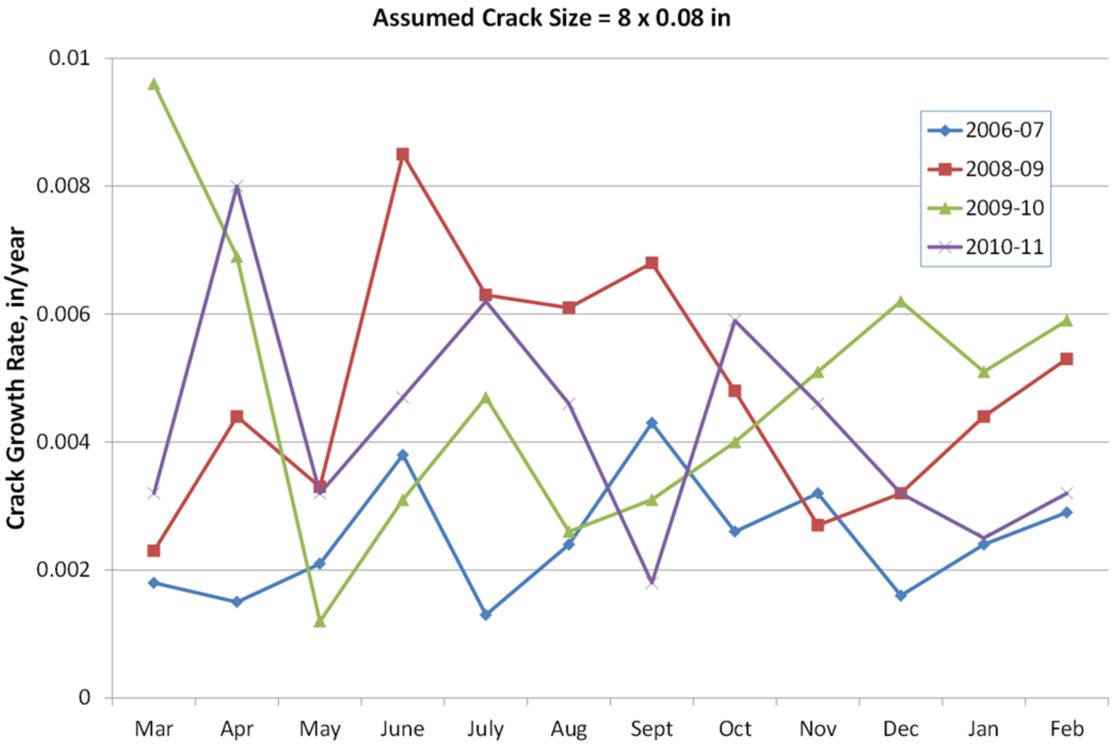

FIGURE 4. Monthly crack growth variation based on variations in pressure cycling

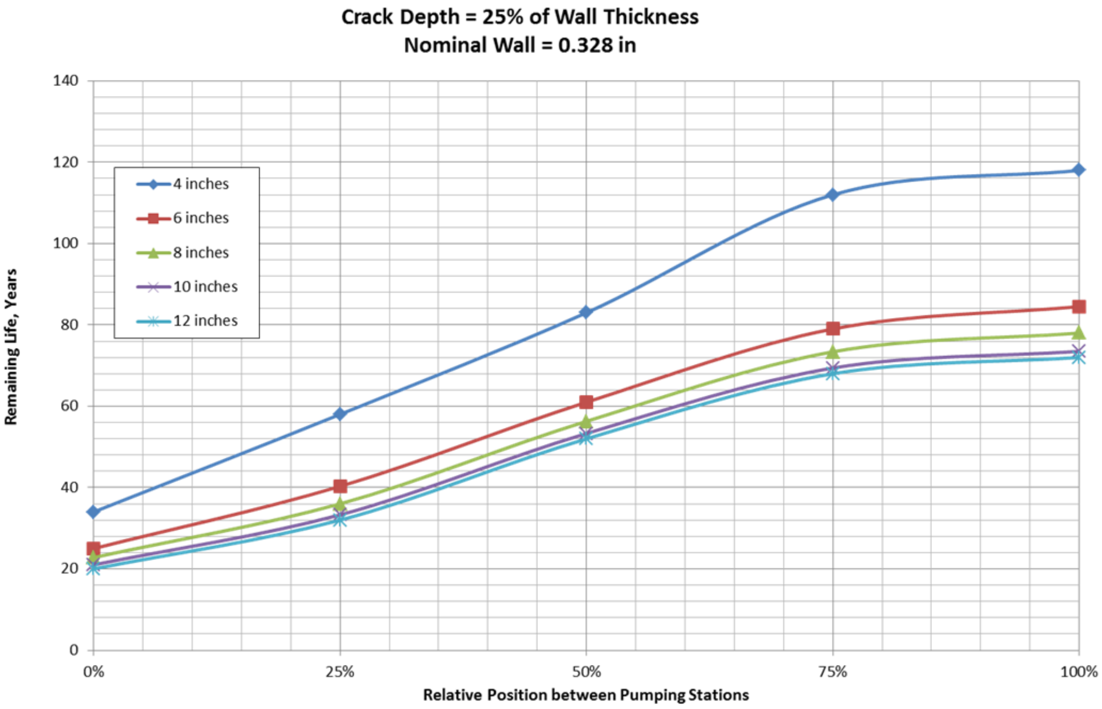

FIGURE 5. Remaining life versus the relative distance between pump stations

CASE STUDY 2: ADVANCED ANALYSIS OF DENTS AND WRINKE BENDS USING ILI DATA

Geometric flaws, such as dents and wrinkle bends, are perhaps the most commonly observed pipeline anomaly, and have led to a significant number of incidents. When the pipe shape deviates from a perfect cylindrical shell, internal pressure loading can generate significant stress concentrations. Pressure cycling can lead to fatigue failure at geometric flaws. Because of the potential threat from geometric anomalies, ILI tools that measure the internal geometry of the pipe are commonly deployed. Case Study 2 presents two examples of the application of ILI geometry data.

Automated Strain Calculation from ILI Data

Appendix R of B31.8 contains a calculation method for strain in dents. The formulae in this Appendix require that the circumferential and axial radii of curvature be computed at the feature in question. However, the radius of curvature at a dent or wrinkle is generally not a single number. Rather, radius and thus strain vary throughout the feature.

Quest Integrity has developed an automated procedure for calculating strain on a point-by-point basis using ILI geometry data. Determining the radius at a point on a curve (or the curvature, κ, which is the reciprocal of radius), requires evaluating the second derivative of the curve at the point of interest. Our algorithm entails fitting a spline curve to the ILI data, which directly leads to the required derivatives. Figure 6 shows an example of axial strain calculation for wrinkle.

Strain values determined from the B31.8 curves have traditionally had limited value. For example, a strain value does not equate directly to the remaining life of the geometry flaw. However, strain values can used to rank relative severity for pipelines that contain a large number of dents or wrinkle bends. Moreover, finite element models constructed from geometry ILI data (see below) below have demonstrated that there is a good correlation between calculated strain and the stress concentration factor. The latter can be used in a fatigue analysis.

Creating Finite Element Models from ILI Data

Figure 7 shows a finite element model of a dented pipe that was created from ILI geometry data. The colors represent a contour map of stress, analogous to the USA Today weather map. Referring to the color bar on the right-hand side of Fig. 7, red represents the highest stress, which blue and purple correspond to low stress. As discussed above, a dent or other geometry anomaly can result in a significant stress concentration. Stresses obtained from finite element analysis can be used to compute remaining life in a fatigue analysis.

If a pipeline contains thousands of dents or wrinkle bends, it is not practical to perform finite element analysis on all such features. However, the strain calculation algorithm described above can be used to rank the features, and finite element analysis can focus on the most severe anomalies. Note that traditional methods to categorize dents, such as the depth/diameter ratio are ineffective. Two dents of the same depth can behave vastly different. If the dent is smooth and gradual, it is likely benign. If, on the other hand, a dent of same depth is an abrupt deviation from the original pipe cross section, it will fail much sooner than the smooth/gradual case. The strain calculation and finite element analysis can discern the difference between these two cases.

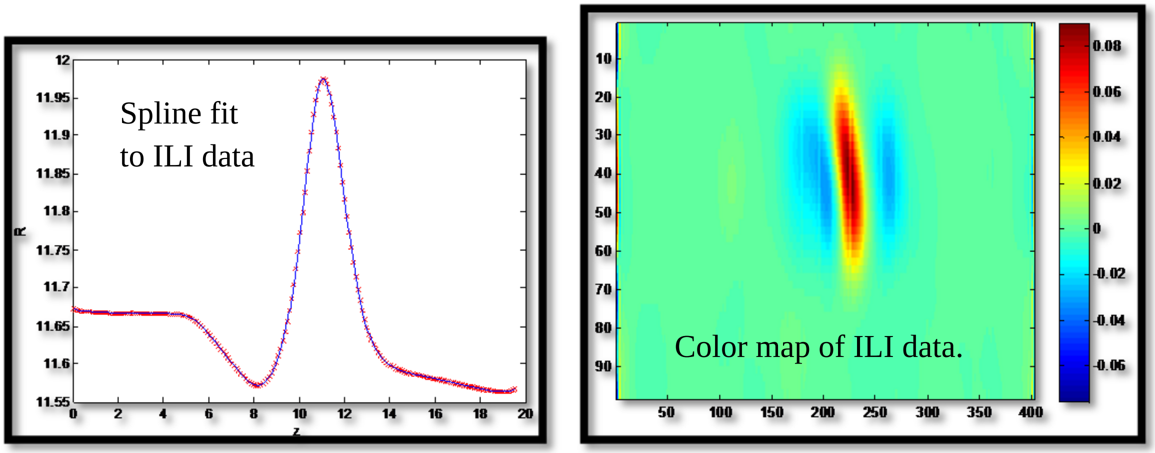

FIGURE 6. Axial strain calculation of a wrinkle bend based on ILI data.

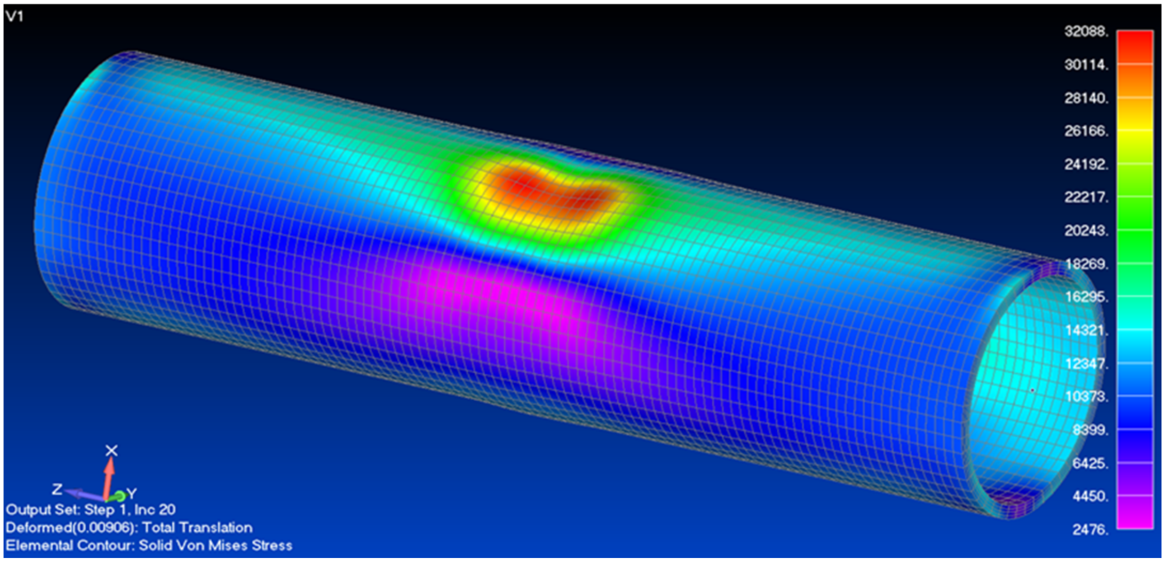

FIGURE 7. FEA Model of dented pipe created from ILI data

CASE STUDY 3: FINITE ELEMENT MODELING OF OVERPRESSURE EVENTS.

A flange connection at a terminal, owned by a major pipeline operator, was recently subject to an over-pressure event. The pipe and flange were subjected to 550 psi in the event, which is double the 275 psi pressure rating of the flange. As the flange had failed a simple code based assessment, the pipeline operator asked Quest integrity to perform an in depth assessment of the flange joint to determine whether or not it was fit for continued service.

We performed a series of elastic-plastic finite element analyses of the flange joint. These analyses incorporated the bolt preload, along with pressure corresponding to both the 275 psi rated load and the 550 psi overload. Figure 8 shows finite element results for two bolting scenarios. The bolt torque was held constant at 660 ft-lb. In one case, a dry nut was assumed, which resulted in a bolt preload of 24,600 lb. The other load case assumed a lubricated nut, corresponding to a preload of 35,200 for the same torque.

Stresses in the flange exceeded yield, resulting in a small permanent deformation. In order to assess the effect of this permanent deformation, it was compared with the deformation that occurs when the bolts are tightened. Figure 9 is a plot of rotation angle in the flange face as a function of bolt preload. The blue line represents the case where the flange joint has been made up, but not pressure has been applied. The green line corresponds to the rated pressure and the red line is the overpressure. Finally, the black line corresponds to the flange with the permanent deformation that resulted from the overpressure event. The black and green curves are close to one another, which indicate that the permanent deformation is small relative to the expected deformation that occurs from bolt torque. Thus the flange did not sustain significant damage, and it is fit for service.

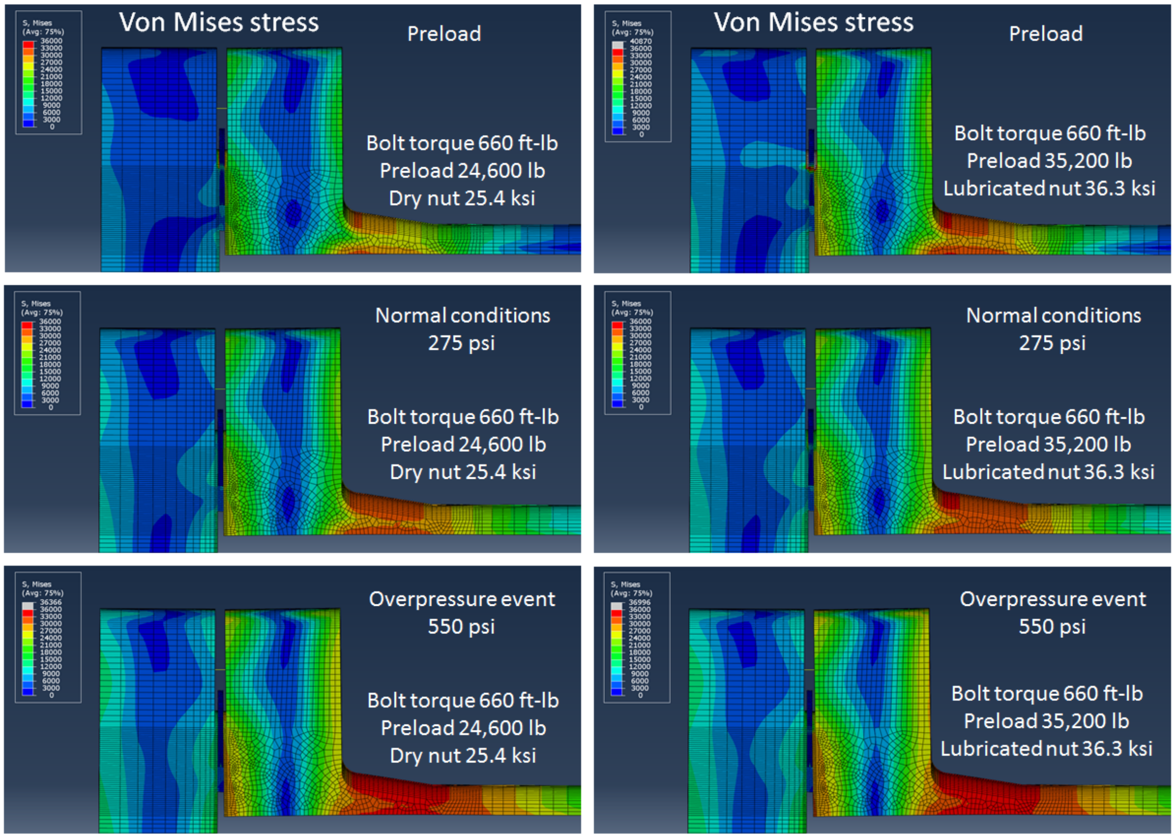

FIGURE 8. FEA Model comparing different bolt preloads during overpressure event

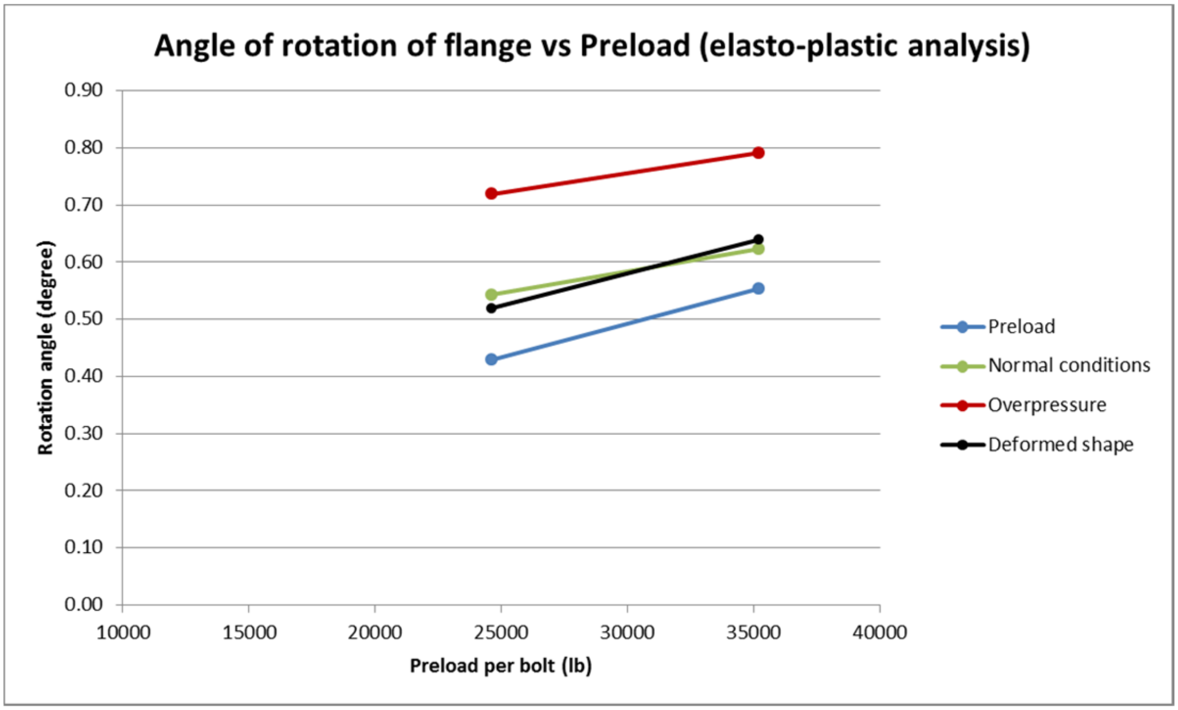

FIGURE 9. Results of the assessment determining the angle of flange rotation versus bolt preload

CASE STUDY 4: VIRTUAL BURST TEST SIMULATION

Reference [3] described a number of advanced crack assessment methods that are an improvement over traditional models. The most advanced such model is the virtual burst test, which is a special type of finite element analysis that simulates fracture. The finite element model incorporates a material model that causes and element to fail when certain stress and strain values are exceeded. The material model must first be calibrated to experimental data.

Figure 10 shows a typical fracture simulation of a compact tension specimen. This specimen geometry is commonly used in fracture mechanics testing. The location of the starting and final crack tips are labeled. Note that the corresponding experiment must be performed on the material of interest. Parameters in the material fracture model are adjusted until the simulation matches experiment. Then the calibrated material model is applied to a pipe rupture experiment.

Figure 11 shows a fracture simulation for a pipe with an OD crack. Initially the crack grows slowly as burst pressure is approached, but then rapidly accelerates at the moment of burst. In this case, the simulation was stopped during the rapid fracture event, when the burst pressure was reached.

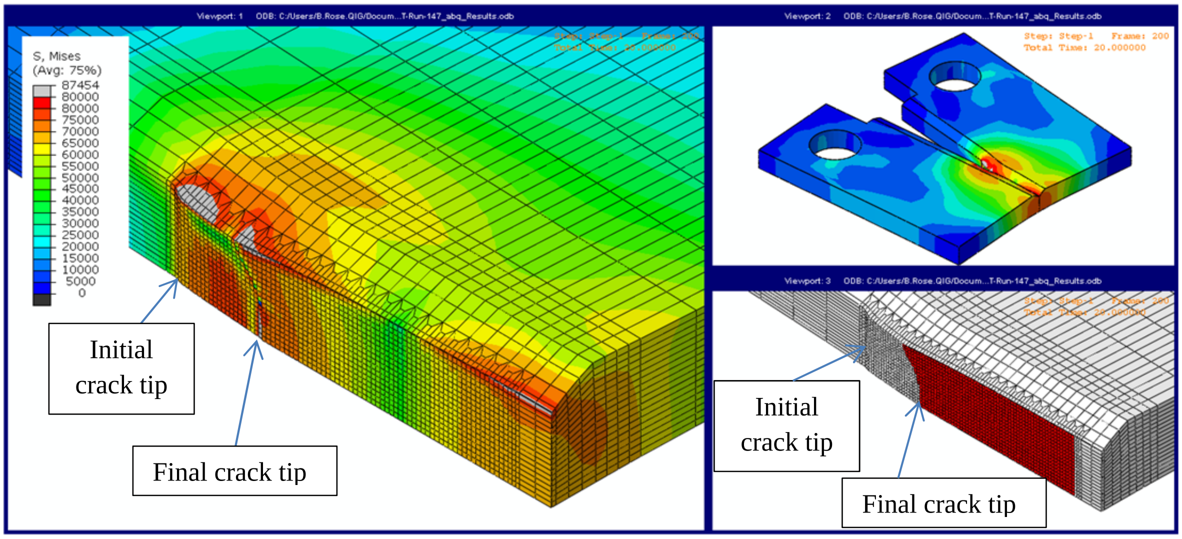

FIGURE 10. Fracture simulation in a compact tension specimen. This simulation was used to calibrate the material model to experimental results.

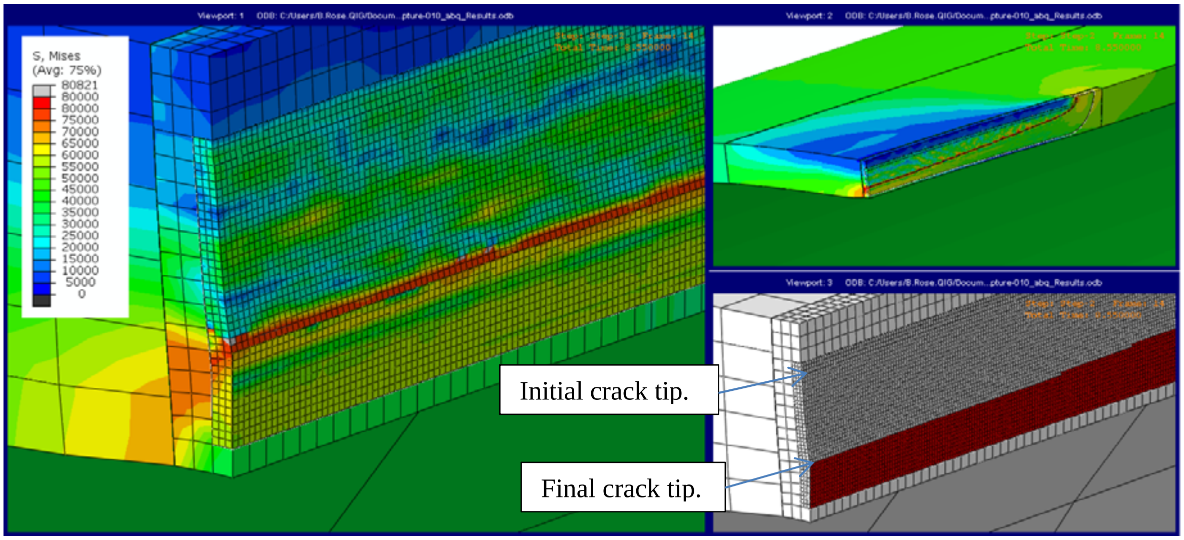

FIGURE 11. Burst simulation. The analysis was suspended at the onset of rapid crack propagation.

CONCLUDING REMARKS

The four case studies presented herein provide examples applications of advanced technology, but there are many other applications, both potential and already realized. Although advanced methods, including 3D computer models, are somewhat more expensive and time consuming than simple hand calculations, the investment is easily justified by avoiding both false positives and false negatives. The former is costly in monetary terms, and the latter is costly on many levels. The good news is that a growing number of pipeline operators are adopting advanced methods such as described in this paper.

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