Learning to accept your wrinkles

Christopher Holliday and Alasdair Clyne, ROSEN Group, Canada, outline an integrated approach applied to a pipeline to demonstrate the acceptability of non-compliant wrinkles.

Improvements in inline inspection (ILI) technology have led to an improvement in the probability of detection and ability to characterise geometric features such as wrinkles. Guidance and limits for the assessment of wrinkles were introduced into CSA Z662, ‘Oil & Gas Pipeline Systems’, in the 2015 version.

The CSA wrinkle acceptance limits are largely based on fatigue assessment criteria; part of the assessment process is confirmation that associated cracking is absent. In practice, this can restrict the assessment to wrinkles where the absence of cracking has been confirmed by non-destructive examination (NDE).

This article describes an approach that was applied to a Canadian pipeline in order to demonstrate the acceptability of non-compliant wrinkles, i.e. peak-to-trough heights that exceeded the acceptance limits detailed in CSA.

A wrinkle (Figure 1) is defined as a localised deformation of the pipe wall, usually characterised by a dominant outward bulge. They can be purposely introduced to the pipe to shorten the intrados of a pipeline bend but can also be unintentionally formed during field bending, which is a particular challenge for pipe that is thermally insulated, where it is not readily possible to visually inspect the pipe bend for wrinkles.
To demonstrate an acceptable fatigue life, CSA Z662-15 Clause 10.10.8.3 stipulates an allowable peak-to-trough height that would be associated with a design fatigue life of 100 years, based on the generally conservative assumption that the pipeline is pressure cycled from the maximum operating pressure (MOP) to 0 psi every other day for liquid product pipelines and cycled once a month for gas pipelines (Figure 2).

If a wrinkle or ripple is not acceptable according to the criteria defined in CSA, then an engineering assessment can be used to demonstrate the acceptability of the anomaly. The engineering assessment must address CSA Z662-15 Clause 10.10.8.3, which defines two assessment criteria:

1. Demonstrate that the wrinkle is free from other interacting anomalies such as corrosion, gouges, cracks, etc.
2. Demonstrate an acceptable fatigue life of the wrinkle.

Furthermore, CSA states that wrinkles that are expected to grow in size over time (e.g. due to ground instability), if not removed or repaired, shall be periodically monitored.

A Canadian crude oil pipeline was inspected with an axially orientated MFL and high-resolution caliper dual technology ILI tool. 20 wrinkles were reported that were non-compliant (the peak-to-trough height was too large) according to the acceptance limits (Figure 2) given in CSA for the MOP. Therefore, to establish the acceptability of these wrinkles, an engineering assessment that included a strain check and stress-based fatigue was performed. Strain-based analysis was used to imply the likelihood of cracking, allowing for a fatigue life to be established on the basis of a crack-free wrinkle.

**Static strain-based assessment**

ASME B31.8 (2016) offers the option of using strain-based methods to assess the severity of mechanical damage. This method is primarily intended for dents; however, it is reasonable to apply a consistent methodology to wrinkles if the individual effect of the three strain components is considered.

The three strain components considered by ASME B31.8 are two bending strains (longitudinal and circumferential) and one membrane strain (axial extensional strain).

Extensional strain is the component of elongation experienced by a material that is pinned at both ends when plastically deformed by bending. This definition is appropriate for dents, but it is not wholly valid for wrinkles. In the case of wrinkles, the extensional strain component is considered to be negligible, relative to strain due to bending.

There are no standard industry-wide critical strain limits for wrinkles. However, the strain acceptance criteria in ASME B31.8-2016 and referenced in CSA Z662-15 are based partly upon the strain at which cracking initiates in buckles and includes an element of safety; therefore, these limits are reasonable for the strain-based assessment of wrinkles, i.e. 6% strain limit for wrinkles in the pipe body and 4% for wrinkles associated with welds. If wrinkles can be shown to

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**Figure 1. Exposed wrinkle bend**

**Figure 2. Recommended maximum allowable ripples, wrinkles and buckles for steel pipe.**

**Figure 3. Axial wrinkle profile vs bending strain in the longitudinal direction.**
be associated with curvature strains less than a critical limit, then it can be implicitly concluded that they are at a low likelihood of associated cracking.

Of the 20 wrinkles identified for further assessment, 13 within seven field bends had calculated curvature strains greater than the 6% critical limit (maximum of 12.1%, shown in Figures 3 and 4); they were therefore considered to have an increased risk of associated cracking.

The operator made the decision to investigate a bend containing seven wrinkles, including the wrinkle with the maximum strain of 12.1%. The objective of the excavation was to confirm the absence of cracking, maximum wrinkle height (peak-to-trough) and length (trough-to-trough), and to measure the shape (in particular the minimum radius of curvature), enabling a comparison with the ILI data and, therefore, the drawing of conclusions regarding the accuracy of the ILI.

No wrinkles were apparent initially, however, upon removal of the insulation, the wrinkles were clearly visible (Figure 5). The wrinkle profiles were recorded using a portable 3D imaging system, and the strain associated with each wrinkle was calculated based on the radii of curvature measured by the 3D imaging. The wrinkles were also inspected using 0° and 45° UT probes and magnetic particle inspection (MPI); no wall thinning, metal loss or crack-like indications were identified.

The comparisons between the ILI and in-field measurements displayed good correlations for both dimensions and strain, demonstrating the accuracy of measurement that can be achieved by using the appropriate ILI tools combined with the necessary data evaluation. The wrinkle data evaluation exploited an optimisation process based on known limitations of caliper measurements.2 The absence of cracking associated with all seven wrinkles, including the wrinkle with a calculated curvature strain of 12.1%, suggests that a critical strain limit of 6% for this particular vintage of pipe contains an element of conservatism.

Of the 13 wrinkles not yet excavated, five had estimated strains >6%. Three of these (maximum strain of 8.0%) were located in the same vintage of pipe as the excavated bend, where the maximum strain of 12.1% was observed to be free of cracking. Therefore, the likelihood of cracking associated with these three wrinkles was considered low.

Two wrinkles were located in another bend with calculated strains of 10.6% and 6.5% – they were present in a different pipe vintage. For that reason, a low likelihood of cracking could not be implicitly demonstrated based on the findings of the excavated bend, which led to the NDE being recommended to confirm the absence of cracking. Therefore, with the exception of the two wrinkles where the absence of cracking could not be implicitly concluded, the findings of the strain-based assessment allowed for a fatigue life to be established on the basis of a crack-free wrinkle.

**Stress-based fatigue assessment**

If a wrinkle can be demonstrated to be free from interaction with other defects such as cracking, then CSA Z662-15 stipulates reviewing the wrinkle peak-to-trough against the wrinkle acceptance criteria derived from research undertaken by Kiefner & Associates.4 As all 20 wrinkles exceeded the CSA peak-to-trough height criteria, a more detailed fatigue assessment was conducted in accordance with the work performed by Kiefner & Associates, utilising cyclic pressure and temperature data representative of historical and anticipated future pipeline operation.

A stress concentration factor (SCF) associated with wrinkles can be determined by finite element analysis (FEA) based on the wrinkle geometry. An example of an FEA model is shown in Figure 8. Detailed FEA can also include corroded areas within the model.

It is possible to estimate the design fatigue life due to cyclic internal pressure by using the calculated SCF, an appropriate S-N curve, and historical and future pressure and temperature operating regime information.

The maximum cyclic stresses in the wrinkles were estimated based on the calculated SCFs and the cyclic....
pressure and temperature data. The wrinkle fatigue lives were subsequently estimated using a conservative stress-based S-N curve provided in BS 7608-2014. The fatigue assessment resulted in estimated fatigue lives (due to internal pressure and temperature cycling) in excess of 100 years for all 20 wrinkles. Therefore, having shown cracking to be unlikely by strain assessment, and evaluation of MFL data for the wrinkled areas showing no evidence of metal loss, and hence no corrosion, the fatigue lives of all the wrinkles were demonstrated to be acceptable.

CSA Z662-15 Clause 10.10.8.2 states that wrinkles that are expected to grow in size over time, if not removed or repaired, shall be periodically monitored. In practice, bends containing wrinkles can be monitored by routinely comparing repeat geometry inspections to monitor for changes in wrinkle dimensions. Geospatial data recorded by an inertial mapping unit (IMU) gives the curvature of the wrinkled section. An increase in curvature would likely be accompanied by an increase in wrinkle severity and a need for re-assessment. The pipe curvature data from the IMU can also be used to calculate bending strain. The bending strain assessment can be supported by a pipe movement assessment that compares bending strain estimated from repeat inspections. An increase (or reduction) in bending strain is generally associated with movement of the pipe. An area of pipe movement raises a number of integrity concerns: is the area stable? Is further movement a possibility? Have wrinkles or a buckle been introduced or made worse? What level of bending can the pipeline tolerate? How imminent is loss of containment, or loss of serviceability?

The findings of the bending strain and pipeline movement assessment can be reviewed alongside detailed geohazard surveys or slope analyses to make an engineering judgement on the likelihood of future ground movement.

Conclusions
In conclusion, the approach adopted as part of the case study described in this article applies the codified strain assessment of dents to wrinkles. Furthermore, it facilitates the refinement of existing conservative height-based methods with more accurate stress analysis-based methods of assessing wrinkles to determine their significance for the integrity of the pipeline and the need to remediate.

The fatigue assessment presented as part of this paper primarily considers cyclic loading based on pressure history data. However, some studies suggest that another failure mode of wrinkles is high-strain low-cycle fatigue, a mechanism which is particularly challenging to predict but was outside of the scope of this case study.

References