ASSESSMENT AND ANALYSIS OF PIPLINE BUCKLES

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ABSTRACT

Geometric anomalies in pipelines are mainly represented by dents, ovalities and buckles. Dents can occur either during pipeline construction or in-service. Buckles and wrinkles may result from cold bending or from loss of stability during offshore pipe-laying. The challenge to the pipeline operator is the identification of those defects that may threaten the future integrity of the pipeline from those defects that are dormant and require no further action.

Codes and regulations contain limit state criteria to prevent buckles from happening during construction and in service; however, there is practically no acceptance guidance. In cases when buckles and wrinkles are identified, pipeline operators seek expert opinion.

The current industry thinking and research supports the use of advanced assessment techniques (beyond the depth-based rules). These enhanced assessment techniques make use of the detailed profile of a geometry anomaly. Such information is obtained from high-resolution geometry tools and other supporting information on the presence and severity of stress risers from ILI tools.

This paper describes how strain-based and stress-based assessment of geometric anomalies can be utilized to assess their significance and need for remediation. Examples are discussed to demonstrate application of the enhanced methods for the assessment of buckles.

INTRODUCTION

The main part of terminology, used in this paper, was summarized in Dawson et al (2006):

- A **dent** is defined as 'a depression that produces a gross disturbance in the curvature of the pipe wall' (ASME B31.8 (2003)).
- **Dents** are caused by external impact either mechanically (*i.e.,* by excavation equipment) or by rocks in the backfill.
- **Smooth dents** are dents that result in a smooth change in the curvature of the pipe.
- By contrast a **kinked dent** is a dent that causes an abrupt change in curvature of the pipe wall.
- If the smooth dent does not contain any stress raising features such as metal loss defects, welds or cracks then it is defined as a **plain dent**.

Additional definitions, required here, include description of buckles as another form of geometric anomalies, found in pipelines. The following terminology, PDAM (2003), have been adopted:

Buckle: A buckle is a local geometric instability causing ovalisation and flattening of the pipe, and possibly abrupt changes in the local curvature, which may or may not result in a loss of containment.

Global buckle: Buckling of the pipe in a manner analogous to a bar in compression. A global buckle will typically involve several pipe lengths. The pipe may buckle downwards (as in free span), laterally (snaking on the sea bed), or vertically (as in upheaval bucking).

Local buckle: A buckling mode causing gross deformation of the pipe cross-section, also known as pipe wall buckling. Collapse, localized wall wrinkling and kinking are examples of local buckling.

Only a local form of pipe buckling is considered in this paper. Global buckling requires different assessment methods and is not part of the discussion.

BUCKLE AND DENT DIFFERENTIATION

An obvious difference between dents and buckles is contained in their origin. While denting of a pipe requires an external indenter, which can be represented by a pipe handling tool, a backfill rock or a working part of a digger, buckling usually results from pipe overbending during pipe laying process or is a result of a ground movement.

Geometric anomalies are classified on the basis of codes and standards, summarized in Table 1.

Table 1 – Classification of Geometric Anomalies According to the Codes

Codes	Dents	Buckles
ASME B31.8 (2003), Gas Transmission and Distribution Systems	Dents are indentations of the pipe or distortions of the pipe's circular cross section caused by external forces	Buckling is the form of wrinkling of the pipe wall or lateral instability
PD 8010-2:2004, Code of Practice for Pipelines Part 2: Subsea pipelines		Local buckling of the pipe wall may be due to external pressure, axial tension or compression, bending and torsion or a combination of these loads
OS-F101 (2000) Submarine Pipeline Systems	A dent is defined as a depression which produces a gross disturbance in the curvature of the pipe wall, and which results in a diameter variation of more than 2% of the nominal diameter	Local buckling implies gross deformation of the cross section, confined to a short length of the pipeline, under following conditions: system collapse (under external pressure) or combined loading, i.e interaction between external or internal pressure, axial force and bending moment; localized wall wrinkling and kinking are examples thereof.

In Dawson et al (2006) it was highlighted, that the most complete information on geometric anomalies and their association with other defects can be gained by running an in-line inspection tool (magnetic or ultrasonic) in conjunction with a multi-channel geometry tool. Engineering judgment is still required to make decisions about the origin of the geometric anomaly. This can be done on the basis of all the data, obtained from an in-line inspection, analyzed in combination with construction and operation records.

Differentiation between dents and local buckles in the pipeline is based on such characteristics as

- anomaly shape,
- location,
- predominant association with areas of lower rigidity (i.e. girth welds zones in a concrete coated off-shore pipeline),
- coincidence with free spans, etc.

BUCKLE AND DENT ASSESSMENT

As summarized in Dawson et al (2006), published guidance for the assessment of geometric anomalies is mostly based on depth and association with other imperfections of the pipe wall, such as metal loss, cracks, welds, etc. All of the codified depth-based criteria, for example a 6%OD acceptable plain dent size and a 2% OD size for a dent on a weld (ASME B31.8 (2003)) are applicable for dents only. There are no depth limits for local buckles (except for a tolerable wrinkle size stated for liquid lines in ASME B31.4 (2006)).

Pipeline codes do not provide acceptance criteria for buckles. Instead, codes contain recommendations how to avoid local buckling of the pipe by keeping various loads, to which the pipe is subjected, below characteristic values, stated in the code (for example PD 8010-2:2004, Code of Practice for Pipelines Part 2: Subsea pipelines).

The necessity to develop a buckle assessment method, described in this paper, originated from the fact that despite all efforts of construction companies and operators to prevent buckling on the stages of pipeline design, construction or operation, such form of a geometric anomaly can occur in pipelines. Operators, who face this problem, seek an answer to the question, whether the damage should be repaired and if yes, how much time do they have for making the decision and mobilizing the resources.

Current industry thinking on the assessment of dents (Baker (2004), Rosenfeld (2001)) suggests that the local strain in the dent may be a more relevant criterion for judging the dent severity (in terms of static behavior) and the susceptibility of the dent to cracking. Indeed, normal judgment would indicate, that a dent that is relatively deep for its length or width is worse in terms of the strains associated with the deformation than one with the same depth spread out over a greater length and width of pipe surface. The latest version of ASME B31.8 (2003) acknowledges this concept and provides strain acceptance criterion, as well as a method for estimating the strain in dents using either in-line inspection geometry tool data or field collected NDE data. Buckles are usually short and kinked in comparison with dents; therefore their depth alone is not the most reliable parameter for determining if the buckle presents a threat to pipeline integrity.

The strain–based method described in ASME B31.8 (2003) could be used in an assessment of buckle criticality in terms of an immediate static integrity of the pipeline. The accumulated strain $\varepsilon_{accumulated}$) in a buckle (due to the associated curvature) is calculated and then, if the buckle is not associated with any welds, it is compared with the strain 6% acceptance level (codified for plain dents). The basis for this value is explained in a recent report written for the Michael Baker Jr., Inc. study, Baker (2004). Essentially, the 6% limit was chosen as lying between the 3% strain limit for field bends (allowed in ASME B31.4 (2006) and ASME B31.8 (2003)) and the material strain level (12%) at which the likelihood of cracks in deformations appears to increase Rosenfeld (2001).

The accumulated plastic strain can also be determined by means of Finite Element (FE) modeling; in that case it will be defined as the sum of all plastic strain increments (regardless of their sign) on all stages of pipe construction and operation.
The calculation will result in a subsequent comparison of $\varepsilon_{accumulated}$ and $\varepsilon_{material}$ (a suitable strain limit of the pipe material determined from pipe mill certificates or other relevant information)

When $\varepsilon_{accumulated} \geq \varepsilon_{material}$, an obvious decision is to repair the geometric anomaly immediately. In case $\varepsilon_{accumulated} < \varepsilon_{material}$, additional failure mechanisms should be taken into consideration, such as fatigue, progressive pipe movement, etc. Stress concentration due to a buckle may be high and may lead to a failure even at a design level of internal (product pressure) and external (wave, hydrostatic, temperature, etc) loading. A possible failure scenario may involve either fatigue or a situation, when a pipeline, normally working at low operating parameters is subject to a peak load of any kind.

PRACTICAL STRAIN ASSESSMENT OF A BUCKLE

Practical implementation of strain assessment in geometric anomalies, irrespective of their classification as dents or buckles, faces its challenges at the stages of data analysis.

In the example, Caliper deflection data was recorded at discrete intervals and as is typical for this type of data, was subject to a significant quantisation error and noise from pipe surface roughness and tool vibration as indicated in Figure 1. Noise and quantisation prevented the data from being used to estimate stress and strain directly, so a filtering algorithm was needed. Filtering was accomplished in two stages. First a smoothing filter was applied to the data to mitigate the impact of noise and quantisation. Secondly a proprietary algorithm was used to provide a best fit for each data section and a continuous axial deflection function for each Caliper channel calculated. This, subsequent to two derivations, was used to compute the longitudinal bending strain.

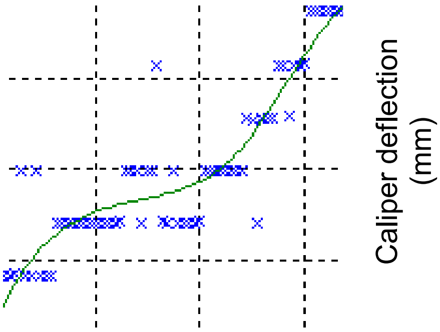

Figure 1– Example of a Caliper measurement, demonstrating significant quantization of signal and noise.

Filtered data is visualised in Figure 2. The worst affected area of the pipe was located over about 25% of the pipe circumference.

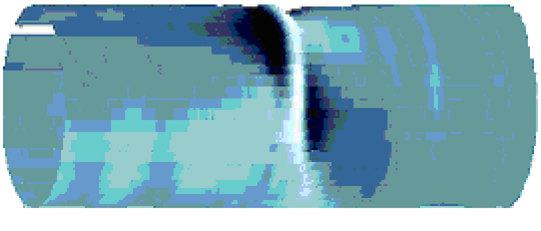

Figure 2 – Example of a Buckled Pipe

Figures 3 and 4 indicate the results of running the filter and fitting algorithms with a wide and with a narrow window respectively. The window was characterised by a filter span and a width of the data section, used to perform the least square fit.

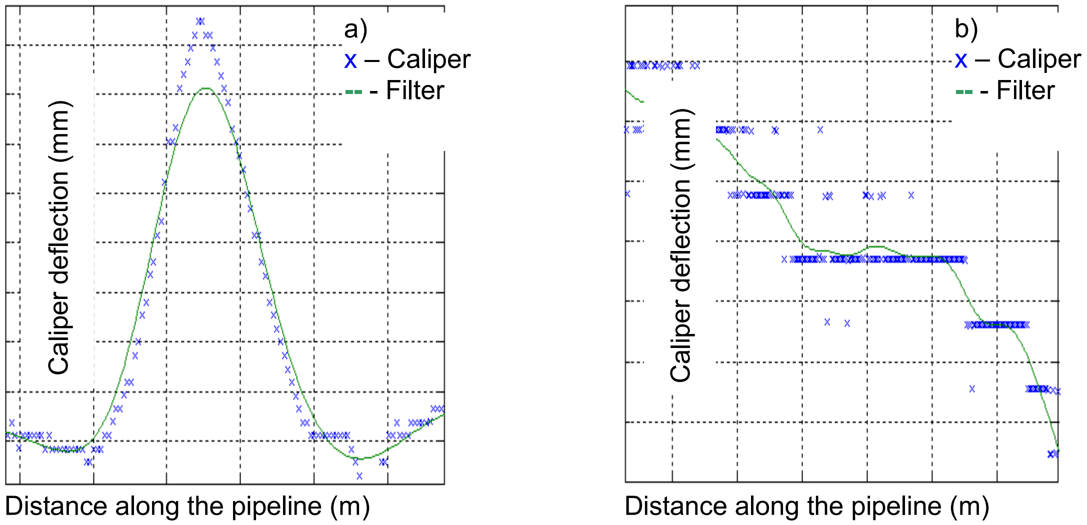

Figure 3 – Geometric Data Filtering and Fitting, Using a Wide Window.
a) around the top of a buckle, b) at a distance from the buckle top

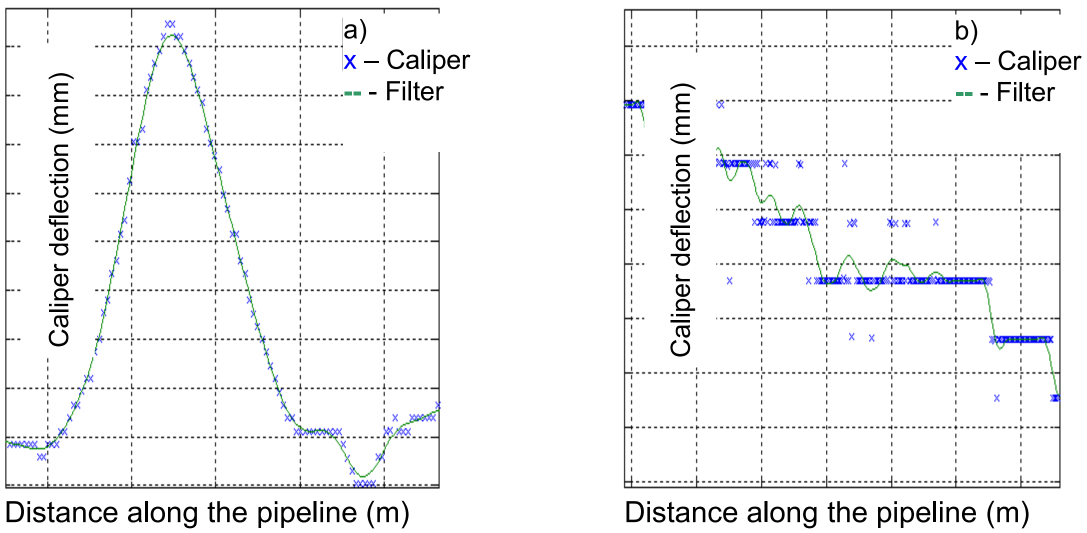

Figure 4 – Geometric Data Filtering and Fitting, Using a Narrow Window.
a) around the top of a buckle, b) at a distance from the buckle top

It can be seen that a wider filter smoothes the data better than a narrower one. However, when a wider filter is used, a maximum value of strain can be underestimated. A narrower filter better fits to the peak of the dent, but leaves some noise in the measurements, which can mask the actual answer.

The maximum values of a longitudinal bending strain ε_2, calculated following the procedure outlined in ASME B31.8 (2003) and according to Equation 1, were 9% and 25% with the wide and with narrow data filtering and fitting windows correspondingly.

$$\varepsilon_2 = \frac{-t}{2R_2}, \qquad (1)$$

where t = wall thickness and R_2 = radius of curvature in longitudinal plane, negative for reentrant dents.

In this example the buckle is not acceptable (ε_2 >6%) both using the wide and the narrow windows, however it can be seen that in other less obvious cases, the choice of data analysis parameters can make a significant difference in a decision whether to repair a geometric anomaly.

The choice of filters and smoothing models and the selection of input parameters, optimal for the task, are highly dependent on the Caliper tool measurement interval (axial pitch and the number of channels) as well as on quantization level of the geometric tool.

FINITE ELEMENT ANALYSIS OF A BUCKLE

In cases when a decision, whether to repair the geometric anomaly, requires consideration of additional loading and dynamic effects, the only way forward is to conduct a finite element (FE) analysis of the anomaly. An FE modeling of the geometric anomaly enables calculation of stress concentration factors and helps predict stresses, generated in the deformed pipe by the internal pressure and external loading. With an FE model, fatigue assessments of the pipe with a geometric anomaly can be performed as well.

It is highlighted that FE analysis of a geometric anomaly is prone to the same problems with data as it was discussed above. If raw data, recorded by a geometric tool, is filtered and smoothed incorrectly, an FE model inherits the behavior of the mathematical model and either generates a "noisy" solution or underestimates strains and stresses. The sections below describe the FE analysis of the same example buckle that is used to illustrate the strain-based approach in Section 4 above.

The buckle in the pipeline is modeled by applying displacement boundary conditions on the nodes in the radial direction corresponding to the depth of the buckle. To do this, filtering and smoothing of the data is performed (as described in Section 2 of this paper). Since the channel spacing and axial sampling distance of the tool are not equal to FE mesh size, mathematical interpolation techniques are used to obtain the displacements corresponding to the mesh nodes.

The axial strains at the end of the buckling process for a typical buckle are shown in Figure 5. In the example shown below, where wide filtering and fitting windows have been used, the maximum strain in the outer surface is 13%, so it exceeds the 6% limit and the buckle is unacceptable.

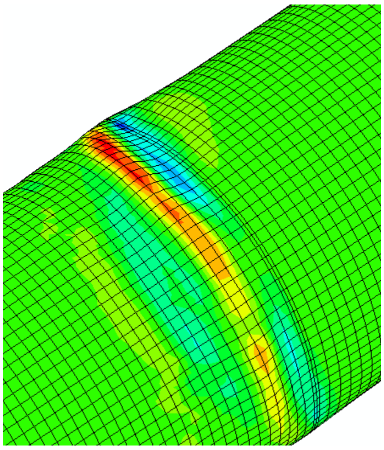

Figure 5 - Plastic Strain Contour Plot of a buckle at outer surface

AMPLICATION OF ENVIRONMENTAL LOADS BY A BUCKLE IN THE PIPELINE

Loads, equivalent to dynamic environmental conditions (wave loading of a pipe freespan), calculated in a separate study, were applied to the results of the FE displacement modelling of a buckle. An equivalent bending moment of 130 KNm and an equivalent axial load of 10 KN were used as well as an internal pressure of 10 MPa.

The results of the assessment can be seen in Figure 6. An equivalent stress, calculated for the combination of the geometric imperfection and the environmental loading is equal to 600 MPa, which is between the yield and the ultimate tensile stress for the pipeline, which means that the buckle is close to a failure and should be remediated. This also means that the stress concentration factor in the buckle exceeds 2.0 (the stress in the buckle is more than 2 times the stress in the undeformed pipe) and this factor should be taken into account when planning any work (inspection or repair) on the pipeline. Care must be taken not to further increase the loading (and stress) on the pipe during any remediation operations.

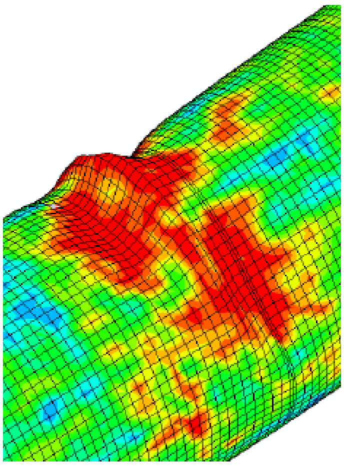

Figure 6 – Results of Environmental Loading of a Buckle

CONCLUSIONS

There are no codified acceptance criteria for local buckles, found in pipelines. The use of depth-based criteria alone is not applicable for assessing the severity of buckles. The assessment techniques discussed in this paper make use of the detailed buckle profile information obtained from high-resolution geometry tools and other supporting information on the presence and severity of stress risers from ILI tools.

The approach proposed in this paper for the severity assessment of a buckle is as follows:

1) Use the strain-based criteria to assess the acceptability of a buckle in terms of static behavior.
2) Prepare raw data, recorded by the geometry tool, for a strain assessment by filtering and smoothing it accordingly.
3) When additional factors of failure mechanisms should be considered in assessing an immediate and future integrity of the pipeline, conduct an FE analysis of the buckle to determine the stress concentration and estimate fatigue life of the geometric anomaly.

The outlined approach fills the gap in the codified assessment of geometric anomalies and provides a route to follow for operators, in-line inspection vendors and consultants, who face the challenging task of assessing buckle significance and its need for remediation.
Further work is being conducted to create procedures to optimize the choice of the parameters in the mathematical models used to filter and smooth the raw data recorded by multi-channel geometric in-line inspection tools.

DISCLAIMER

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REFERENCES

ASME B31.4 (2006) Pipeline Transportation Systems for Liquid Hydrocarbons and other Liquids (2006).
ASME B31.8 (2003) Gas Transmission and Distribution Piping Systems (2003).
BAKER (2004) Department of Transportation, Office of Pipeline Safety, TTO Number 10, Integrity Management *Program - Dent Study. Delivery Order DTRS56-02-D-70036, Final Report*, November 2004.
DAWSON, RUSSELL, PATTERSON (2006) Emerging Techniques for Enhanced Assessment and Analysis of Dents, *6th International Pipeline Conference*, September 2006, Calgary
DNV OS-F101 (2000) Submarine Pipeline Systems, 2000
PD 8010-2:2004, Code of Practice for Pipelines Part 2: Subsea pipelines

PDAM (2003) Pipeline Defect Assessment Manual (2003)
ROSENFELD (2001) Proposed New Guidelines for ASME B31.8 on Assessment of Dents and Mechanical Damage, *GRI*, May 2001.