STRAIN DEMAND AND CAPACITY ASSESSMENT BASED ON IN LINE INSPECTION OF AXIAL AND BENDING STRAINS

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Abstract

Strain-based assessment is an important part of integrity management of pipelines located in areas with unstable ground conditions. Strain-based integrity assessment is conducted by comparing pipeline strain capacity with strain demand (the level of elongation or compression produced in the pipe wall as a result of external and internal factors). While the bending component of the longitudinal strain is well understood and can be derived from routine IMU (Inertial Measurement Unit) in-line inspections, the pure axial part of the longitudinal strain has been a recognised gap in the knowledge of the strain condition of a pipeline. Now, the inline axial strain inspection tool (AXISS™) can be used to measure the pure axial strain component. The measured axial strain can originate from many sources, such as geotechnical hazards, temperature effects as well as from the combination of soil restraint conditions and internal pressure effects.

This paper describes an approach to combining bending strain, measured by IMU tool, with axial strain, measured by the AXISS™ tool, in order to determine total longitudinal strain demand. The total strain demand can be determined at the girth welds in the pipeline, and at anomalies, such as metal loss, dents, etc, reported by magnetic, ultrasound and deformation inspections. The strain demand is compared with the strain capacity to determine whether remedial action is required. The tensile and compressive strain capacity will not be constant along the length of a pipeline and is influenced by several factors including material properties and imperfections in the girth welds, corrosion and geometric anomalies such as dents, buckles, wrinkles. A case study is included in the paper showing how the axial and bending strain components are combined to determine the longitudinal strain demand and an approach for evaluating the strain capacity to assess the integrity of the pipeline.

1. Introduction

The as-laid position of a pipeline is not always constant and movement can occur for several reasons including settlement, wash-out/flooding, subsidence, landslides, earthquakes and human activity adjacent to the line. Pipeline movement and deformation redistributes the axial force in a pipeline, inducing longitudinal tension in some locations and compression in other areas. Thus, pipelines subjected to ground movement hazards can experience high longitudinal tensile and/or compressive stresses and strains. In addition, longitudinal strains can be present in a pipeline due to construction and operation, e.g. pipe roping, internal pressure and temperature effects.

Loading on a pipeline can be by directly applied loads or by applied displacements, or some combination of the two. In load-controlled situations (e.g., internal or external pressure, dead-weight loading etc) the magnitude of the load is not affected by the amount of deformation or displacement of the structure and a stress-based assessment using stress-based limits is the appropriate approach to apply. In situations that are largely displacement-controlled (e.g., axial and/or bending loads from ground movement) strain-based assessment and limits can be applied. Applying stress limits in such cases can be overly conservative or limiting for fully supported pipelines under largely displacement-controlled loading. Hence a strain-based assessment is the preferred approach to evaluating the integrity of pipeline segments that are subjected to tensile and compressive longitudinal strains. A strain-based integrity assessment is conducted by comparing the pipe strain capacity (capability to withstand a certain amount of relative deformation) with the strain demand, i.e., the actual level of elongation or compression, produced in the pipe wall as a result of external and internal loading conditions.

This paper describes how a strain-based integrity assessment can be conducted to assess the severity of longitudinal strain caused by external loading on a pipeline using the data available from ILIs and published pipeline strain capacity models.

2. IMU Bending Strain Measurement

Running an IMU tool as part of an ILI survey has become a routine practice for most pipeline operators. The IMU is used to provide mapping information which, aligned to the ILI data, provides a means to accurately and easily locate pipeline anomalies, features and fittings. Specialized assessment of data from a single IMU survey can be performed to calculate curvature along the full pipeline [1]. The approach used to determine the level of bending strain is based on the pipeline curvature data, i.e., on the measured pipeline shape. Bending strain in a deformed pipeline can be found from the change in curvature between the initial and the final pipeline position.

IMU inspections allow for the identification of areas of localized bending strains and run-to-run movement analysis, but do not detect either pure axial tensile or compressive strain. The IMU technology provides geometry-based measurements of the centerline curvature which can be directly converted to strain using established definitions. Any elastic, plastic, or residual strain that changes the centerline curvature can be detected by the IMU. Detection capabilities for low level bending strain are typically above 0.125% strain measurement or above 0.04% strain change between one ILI run and another run. However, IMU strain measurements alone cannot differentiate within which strain condition the bending strain exists. For example, using a subsequent inspection and run to run analysis is needed to determine whether a strain occurred during the operation of the pipeline (vs during construction) and if an increase/decrease in strain can be attributed to an active applied in-service load.

3. Axial Strain Measurement

The axial strain measurement technology provides a measurement of the linepipe material magnetic properties which can be converted to an absolute strain value based on the calibration factor for the pipe material. Axial strain sensors are designed and calibrated to operate in the elastic strain region of steel.

AXISS has been developed specifically to detect and monitor areas of increased axial strain. Operators now can measure and monitor axial strain in pipelines without the need to expose the pipeline for the installation of strain gauges.

A key benefit of the axial strain sensing technology is that it can be retrofitted to standard Magnetic Flux Leakage (MFL) tools. This means that whilst dedicated inspections can be performed to determine the axial strain condition of the pipeline, in most cases, inspections can be conducted during scheduled corrosion inspection surveys, which is operationally efficient and cost effective. Axial strain tool contains an array of small footprint sensors that measure elastic axial strain (tensile and compressive) at discrete locations around the pipe circumference.

The values reported are the pure axial strain variation about the axial strain mean along the entire pipeline. The variation refers to the amplitude of the change in axial strain reading compared to the mean. When using a calibration factor based on a representative pipeline sample of the inspected section or predicted by the analytical calibration model, the axial strain will be absolute as opposed to relative. The recently developed analytical strain calibration methodology enables delivering absolute axial strain if the operator can provide Mill Test Reports (MTR's) or equivalent NDE material reports for the inspected pipeline materials.

Currently, AXISS can be run with both Baker Hughes MFL platforms, VECTRA/GEMINI: for sizes 12" to 42" and MagneScan™: for sizes 12" to 20". AXISS will be available on MagneScan for sizes 24", 26", 30" and 36" in 2021. The development of AXISS plans to complete deployment of the tool on the MagneScan fleet for all sizes 6" to 48" in 2023.

4. Evaluating Strain Demand

Strain demand is defined as the magnitude of strain acting on the pipeline and will vary along its length depending on the loads acting on the pipeline and the pipe geometry. This paper focusses on strains in the longitudinal pipeline direction that are the result of possible external loading and include the presence of internal pressure and thermal effects. The strain demand comprises both the longitudinal bending strain component (derived from the IMU data) and the pure axial strain component (measured using the AXISS technology). By using both technologies in the same inspection, it is possible to firstly identify geohazard threats (acting in both transverse and longitudinal directions respective to the pipeline) and secondly, to account for the presence of internal pressure and thermal effects as well as for non-intentional longitudinal strains induced by the pipeline construction activities, e.g. pipeline roping.

The strain demand information is a required input into a strain-based integrity assessment of a pipeline section that is subject to a strain from external loads. Strain demand is determined along the pipeline including specific susceptible locations such as girth welds, geometric anomalies (dents, buckles) and pipeline defects (e.g., corrosion, gouging).

It is highlighted that only strain values reported within identified bending or axial strain events characterise real strain demand acting on the pipeline (i.e., strain which can impact the pipeline integrity and has to be counteracted by sufficient pipeline strain capacity). Any other strain value, recorded by IMU or/and AXISS tools above the strain reporting threshold and outside of reported strain events, either represents the curvature at intentional construction bends or is caused by tool dynamics as the tool passes over internal surface protrusions i.e., at pipeline fittings, dents, girth welds etc. The latter can be (but not necessarily are) caused by wall thickness changes, mitre bends or girth weld misalignment.

Both IMU and AXISS technologies provide information regarding the presence of strain due to geotechnical events but neither can independently provide the full total strain information. Indeed, the technologies complement each other, and the real benefit comes in using and combining the information from both IMU and ILI axial strain tool technologies together enabling a fuller understanding of the total strain condition at any point along the pipeline. The benefits of combining the information from both strain measurement technologies include:

- Identification of the pure axial tensile and compressive strain as well as the bending strain.
- The electromagnetic AXISS tool sensor reacts to longitudinal strain actually acting in the pipe wall. Therefore, strain values recorded by the AXISS tool help the discrimination of pipeline strain induced by external loads vs curvature intentionally introduced during pipeline construction.

The total longitudinal strain i.e., the strain demand information is required to perform a strain-based integrity assessment of a pipeline section, to assess strain event severity and to determine remediation needs.

4.1 Calculating Total Longitudinal Strain

The total longitudinal strain (the strain demand) along the pipeline is calculated by aligning and combining results of the bending strain assessment and the axial strain assessment as described below.

Total longitudinal strain	The strain at any point on the pipe cross-section acting in the longitudinal direction. Total longitudinal strain results from bending moments, axial loading and includes the effect of internal pressure. Positive and negative signs of the bending strain represent extended and compressed fibers of the pipeline respectively. $\varepsilon_L = \pm\, \varepsilon_b + \varepsilon_a$

Axial strain	The uniform strain (change in pipeline length over original length) component acting over the pipe cross-section due to external loading; includes pressure and thermal effects, if present. $\varepsilon_a = \varepsilon_{a\ ext} + \gamma\ \varepsilon_h$
Axial strain from external loading	The uniform strain component, acting over the pipe cross-section due to geotechnical, construction, in-operation loading, etc.; includes thermal effect, if present $\varepsilon_{a\ ext}$
Bending strain	Bending strain (change in length over original length) that is caused by bending deformation. Bending strain is directly proportional to change in curvature, K: $\varepsilon_b = K \times D / 2$
Hoop strain	$\boldsymbol{\varepsilon_h = \frac{pD}{2Et}}$
Where	Internal pressure, p Elasticity modulus (Young's factor), E Poisson factor, γ

5. Strain Capacity

Pipelines experiencing elevated longitudinal strains can potentially fail by tensile leak or rupture or by compressive buckling. The strain capacity is defined as the strain level a pipe segment can sustain without experiencing negative consequences. The negative consequences could be a leak, a rupture, or any other unacceptable change of the physical characteristics of the pipeline e.g., buckle or wrinkle. The tensile strain capacity (TSC) represents the pipe segment strain capacity under tensile loading conditions and the compressive strain capacity (CSC) under compressive loads.

- Under tensile longitudinal strain, the main integrity concern is a leak or rupture at an affected girth weld or other weakened location i.e., an area of reduced wall thickness (e.g., wide area of corrosion).
- Compressive longitudinal strain may cause the formation of wrinkles or buckles in the affected pipe segment leading to a structural integrity concern. The presence of girth weld anomalies, metal loss defects and dents can also affect capability of the pipe to sustain longitudinal loading.

5.1 Assessing Strain Capacity

The TSC of modern defect-free pipe body material is expected to be relatively high. But at girth welds (even where compliant with API 1104 [2]) it can be low; weld TSC can vary from as low as 0.2% to more than 2% [3, 4, 5]. A conservative strain demand limit of 0.4% [6] can be applied to modern pipelines with good quality girth welds. However, it is highlighted that this limit is NOT applicable to vintage pipelines; defective or poor-quality girth welds; or in modern high strength pipelines where girth weld under-matching is a possibility. If any of these conditions are applicable, a specific strain-based assessment is recommended to evaluate the severity of the reported strain features in relation to the strain capacity of the affected pipeline segment.

Onshore transmission pipelines are usually designed on a "stress" basis, where the allowable longitudinal stresses are limited to a percentage of SMYS to prevent yield. Guidance on acceptable longitudinal loading for a pipeline, designed using stress-based principles, i.e., ASME B31.8[7] and ASME B31.4[8] allows the following:

- tensile longitudinal stress $s_L \leq 0.9$SMYS and
- compressive longitudinal stress based Tresca or von Mises stress criteria

In addition, the ASME B31.8 and ASME B31.4 codes do have a proviso for strain-based assessment: “a) the longitudinal stress limits can be exceeded where due consideration is given to the ductility and strain capacity of seam weld, girth weld, and pipe body materials; and to the avoidance of buckles, swelling, or coating damage. b) The maximum permitted strain is limited to 2%.”

However, it is highlighted that the 2% limit should not be used to estimate the actual strain capacity of a pipeline, instead this proviso means that the predicted strain capacity should not exceed this value.

Several methods exist for assessing pipeline strain capacity at the limit states of tensile rupture and compressive buckling (e.g., API 1104 Annex A [2], CSA Z662-11 Annex C [9], DNVGL-RP-F108 [6], CSA Z662-15 Annex K [10], BS 8010 Parts 1 [11] and 3 [12], PHMSA [3]). The pipeline strain capacity methodologies require various input parameters, e.g., the PHMSA guidance [3] is based on a set of strain capacity parametric equations that consider a wide range of influential attributes used to describe pipe strain hardening behaviour and including the:

- Type of the girth weld (manual (e.g., tie-in welds) vs mechanized/automatic)
- Girth weld strength mismatch (ratio of the weld metal tensile strength to the parent metal tensile strength)
- Pipe and weld fracture toughness
- Pipe and weld geometry and imperfections
- Anomaly dimensions.

This combination of attributes enables a rigorous assessment of the TSC and CSC limits.

The strain demand limit (SDL) is the permitted value of the strain demand determined by applying a safety factor to the predicted strain capacity. The use of a safety factor ensures a sufficient margin of safety between the load acting on the pipeline (strain demand) and the pipeline resistance (strain capacity). A safety factor should allow for uncertainties in strain capacity modelling, e.g. in the material property estimates used to predict the strain capacity and in the measurement of the strain demand itself. Appropriate safety factors may be chosen to reflect the uncertainty in the accuracy of the input attributes and also the risk tolerance level at the site of interest. The following sections summarise the published industry guidance.

5.2 Application of Safety Factor (SDL in tension)

PHMSA’s strain-based assessment guidance [3] and strain-based design special permit conditions [13] specify a safety factor of 0.60. CSA Z662 Annex C [9] on limit state design contains a resistance factor that is equivalent to a safety factor of 0.70. Recent industry best practices [5] recommend a safety factor of 0.67.

In strain capacity analysis of existing (vs designed) pipelines, many of the input parameters may not be available and have to be assumed based on near worst-case scenarios. This process leads to a lower bound estimate of the predicted TSC. Using a safety factor of 0.67 on such a TSC can be overly conservative. A safety factor greater than 0.67 may be used to determine the SDL when the predicted TSC is based on conservative assumptions and acceptable risk level is considered.

5.3 Application of Safety Factor (SDL in compression)

CSA Z662 Annex C [9] sets the safety factor for compressive strain capacity to 0.80. PHMSA’s strain-based design special permit conditions also use a safety factor of 0.80. A safety factor of 0.8 is recommended in the industry best practices [3, 4, 5].

6. Case Studies

Two strain-based integrity assessment case studies are discussed below.

6.1 Case Study 1

A large diameter, modern gas pipeline was inspected with a magnetic ILI tool equipped with AXISS sensors and an IMU unit. Several bending strain events and axial strain events were identified in the pipeline. After receiving the results of the inspection, bending strain assessment and axial strain assessment, the operator of the pipeline required additional support in determining the criticality of the reported bending and axial strain events.

There were several construction tie-in girth welds identified within the reported strain events. It is very important to understand the welding process (SMAW[1] vs GMAW[2]) used for the girth welds in the pipeline as this has a significant influence on the calculation of the strain capacity with manual girth welds typically having lower strain capacity than automated girth welds. Indeed, the tensile SDL for the girth welds were calculated using the methodology published by PHMSA [3] and varied between 0.2% and 0.93% (with the lowest 0.2% SDL applying to the manual, tie-in welds in the lowest pipe wall thickness and 0.93% being associated with the automatic welds in the thicker wall pipe). It is highlighted that these limits include a safety factor of 0.6 to account for uncertainties in the assumed mechanical and fracture properties of the manual and automated weld material. The compressive strain demand limit for girth welds varied between 0.43% and 1.17% depending on the pipe wall thickness and the magnitude of the measured axial strain and includes a safety factor of 0.8.

The total strain demand was evaluated by combining the axial and bending strain values reported in the pipe body and at the girth welds within the identified strain events. The maximum total strain demand was initially assessed as being 0.47% in tension and -0.27% in compression. Specific attention was given to the strain demand at the pipe girth welds (as the SDL's are lower in girth welds vs pipe body) and any artificial "spikes" in strain (caused by tool dynamics passing the raised weld geometry) were removed and the strain demand at the girth welds reassessed. Following this process, the maximum tensile strain demand acting on a girth weld was 0.46% at an automated weld and 0.15% at a manual (tie-in) weld. It was concluded that the total longitudinal tensile strain at any of the welds within the reported strain events was below the corresponding tensile SDLs. Similarly, the total longitudinal compressive strain identified within the reported strain events was shown to be below the compressive SDLs. Based on this assessment, the immediate integrity of the pipeline girth welds in terms of the identified total longitudinal tensile and compressive strain was established.

In relation to future integrity, it is important to understand if any of the reported strain events could be active meaning that the strain demand could increase with time. There are several indicators that can be used to evaluate the likely cause of the strain acting on a pipeline (i.e., is it construction related and stable or associated with a geo-hazard and possibly active). The indicators associated with the presence of a geo-hazard for example can include, but are not limited to:

- A significant horizontal component of bending strain (from a review of in-field investigations, the presence of a geo-hazard was identified in 50% of cases where the horizontal bending component exceeded 0.14% and in almost 100% of cases where the horizontal bending strain exceeded 0.36% [14]).
- Presence of both bending strain and axial strain at the same location.
- Change in bending strain or axial strain identified from a subsequent ILI survey.
- Terrain susceptible to ground instabilities.

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[1] Shielded metal arc welding (SMAW), also known as stick welding is a manual welding process.

[2] Gas metal arc welding (GMAW), sometimes referred to as MIG welding is an automated welding process.

In this case study, it was concluded that the reported strain demand was related to the pipeline construction and therefore was very unlikely to progress with time. Nevertheless, a monitoring regime was recommended to reassess the identified strain demand on the pipeline in future ILI surveys, checking for any changes or new strain events occurring.

6.2 Case Study 2

This case study considers a small diameter, vintage (1950's) pipeline that had been inspected twice with a magnetic ILI tool equipped with an IMU unit. The bending strain assessment reported more than 20 strain and strain change events. In addition, there were metal loss features located inside the reported strain events, several features being adjacent to girth welds. A strain-based integrity assessment was conducted to determine the criticality of the reported bending strain and strain change events.

A strain capacity assessment methodology applicable to vintage girth welds [15] was adopted for this assessment. A tensile SDL of 0.34% was calculated for the girth welds (including a safety factor of 0.6). The presence of the metal loss features was accommodated in the strain capacity assessment. The maximum reported bending strain was 0.26% and well below the calculated SDL at all the girth welds.

It was concluded that the strain events were safe in terms of the immediate integrity of the pipeline.
On examination of the locations of the reported bending strain and strain change events it was identified that most were associated with pipe segments that had been subjected to excavation and repair activities and, therefore, were not considered to present a threat of progressive pipeline movement.

It is highlighted that the ILI survey did not include axial strain sensors, and therefore, only information from the bending strain assessment was available to use in this study. Accordingly, a conservative safety factor of 0.6 was used in the SDL assessment to account for the unknown axial strain component.

7. Conclusions

Strain-based assessment is an important part of the integrity management of pipelines located in areas with unstable ground conditions. This paper has described how the bending strain (measured by an IMU tool) can be combined with the axial strain (measured by the AXISS axial strain sensors) in order to determine total longitudinal strain demand along the length of a pipeline. The two ILI technologies complement each other, and it is beneficial to combine the longitudinal bending strain and axial strain together to enable a fuller understanding of the total strain condition at any point along a pipeline.

The strain demand is compared with the strain capacity in order to determine whether remedial action is required. The tensile and compressive strain capacity will not be constant along the length of a pipeline and is influenced by many factors. Pipeline strain capacity has been the subject of several research projects in recent years and although there is no single set of acceptable strain limits that can be applied, there are various published guidance documents available that provide methodologies to cover most pipeline scenarios. To determine which strain capacity methodology is applicable for a given situation, consideration must be given to the construction era, pipe and girth weld material properties, defective or poor quality welds, girth weld strength mis-matching, presence of corrosion or geometric anomalies and also selection of an appropriate factor of safety to account for uncertainties.

A complete strain-based pipeline integrity solution is presented in this paper involving the comparison of pipeline strain capacity with the strain demand to support geohazard risk management programs of pipeline operators.

8. Nomenclature

AXISS™	Axial strain sensing technology (a trademark of Baker Hughes Incorporated)
CSC	Compressive Strain Capacity

ILI	In-line Inspection
IMU	Inertial Mapping Unit
MFL	Magnetic Flux Leakage tool
MTR	Mill Test Reports
NDE	Non-Destructive Evaluation
SDL	Strain Demand Limit
TSC	Tensile Strain Capacity
SMYS	Specified Minimum Yield Strength

9. References

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