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UKOPA DENT ASSESSMENT ALGORITHMS: A STRATEGY FOR PRIORITISING PIPELINE DENTS

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ABSTRACT

As in-line inspection tools improve, dents that would have been below the detection and reporting levels of previous inspections are now being detected and reported to pipeline operators. Consequently, operators are being faced with large numbers of dents in ILI reports that require further consideration and are left with the problem of how to prioritize these dents for further investigation and repair.

Although code guidance is clear on the relative severity of dents associated with other features or those based on a depth or strain criteria, this may still leave a significant number of dents in the pipeline which fall within codified static dent assessment criteria, but which may still pose a threat, particularly from fatigue. Many transmission pipelines in the UK are now 30-40 years old and fatigue failures at dent locations are starting to be reported. Such occurrences have raised technical concerns with regulators regarding the perceived conservatism of current dent assessment methods as the dents in question were within the code limits and were reported through standard ILI technologies, however, they were not identified as significant. There is therefore a requirement to develop best practice guidance for the safe and economic operation of dented pipelines.

The UK Onshore Pipeline Association (UKOPA) recognized that further guidance was needed in order that operators could identify dents which can be safely left in the pipeline and those for which further excavation is required. They have consequently developed a series of algorithms to allow pipeline operators to prioritize the dents for repair based on ILI results. This paper describes the background research to these

algorithms as well the algorithms themselves, demonstrating their use with ILI dent data from operators of onshore oil and gas pipelines. The paper concludes with comments on the current conservatism in the analysis of dent fatigue and proposes a way forward to allow pipeline operators to manage large numbers of dents for which the dent fatigue life is critical.

INTRODUCTION

Dent damage in pipelines may result from either impact damage caused by third parties or construction damage.

Third party damage or external interference generally occurs on the upper half of the pipe (between the 8 o'clock and 4 o'clock positions) and has historically contributed to the highest number of pipeline failures. Dents of this type are likely to be significant as they could also contain gouges or cracking and therefore these defects generally require immediate investigation and possible repair. In addition, dents caused by third party damage are unconstrained and therefore able to flex or reround during changes in pressure. Therefore, if failure as a result of third party damage is not immediate, it is possible that induced defects can grow in service and cause failure some time after the initial impact.

Dents caused during construction generally occur on the bottom half of the pipe and tend to be constrained by the indenter causing the dent, *i.e.* a stone or rock in the pipeline bed/backfill. Dents on the bottom of the pipeline are generally not considered significant as the dent has survived the pre-service hydrotest and is unable to move or reround due to changes in pressure.

All dents have the potential to cause an increase in stress in the pipeline, and consequently increase the pipeline sensitivity to fatigue damage caused by pressure cycling. Many transmission pipelines are now 30-40 years old and fatigue failures at dent locations are starting to be reported. Such occurrences have raised technical concerns with regulators regarding the perceived conservatism of current dent assessment methods as the dents in question were within the code limits and were reported through standard ILI technologies, however, they were not identified as significant [1-3].

Guidance is therefore needed in order that operators can identify dents for which excavation and inspection is not required and could potentially be damaging to pipeline safety and dents for which further action is required.

In this paper, the definition of a dent is taken as “a permanent plastic deformation of the cross section of the pipe caused by external forces [4]”. A dent that varies smoothly in cross section and contains no stress raisers, such as gouges, cracks or welds is defined as a plain dent. A kinked dent is a dent which contains rapid changes in contour and a constrained dent is one that will not move or reround as a result of changing internal pressure.

REVIEW OF CODE GUIDANCE FOR DENT ASSESSMENT

Historically, the acceptability of dents introduced during service has been based on the dent depth, although recent code revisions and guidance documents have recognized that the strain in the dent and the effects of fatigue should be considered. Although ASME B31.8 Appendix R [5] does provide a procedure for assessing the strain in dents, there is no codified methodology for conducting fatigue assessments. A summary of the code and best practice guidance for the assessment of dents in pipelines is provided in Table 2 (Annex A).

As well as guidance on acceptable dent depths, there is also information provided in the literature on the effects of re-rounding on dent depth. In gas pipelines operating at ‘moderate hoop stress levels’, unconstrained dents can re-round under the applied internal pressure [6]. Indeed Rosenfeld [6] states that any dent indicated by ILI to be deeper than 2%OD is almost certainly constrained by soil or rocks. Therefore, dents less than 2%OD may be unconstrained, re-rounded from an initially greater depth or very shallow constrained dents.

One of the key findings of the work conducted as part of API 1156 was that, for rock dents, the primary mode of failure if the rock remained in place was a puncture if the rock was sharp enough. In addition, from a fatigue point of view, it would be preferable to leave the rock in place, although it is recognized that this could increase the risk of corrosion.

Dents associated with welds are susceptible to cracks at the internal weld toe during denting, particularly in low toughness material. Historically therefore, dents on welds were not allowed in the pipeline codes, however, Rosenfeld [6] and API 1156 [7-8] suggest that smooth dents up to 2%OD on ductile (*i.e.* moderate to high toughness) welds can safely remain in gas and liquid pipelines and this has been incorporated into the latest codes.

Mechanical damage is viewed as one of the most severe forms of pipeline damage as it is often accompanied by cracking and gouging. This combination of a loss of wall thickness (*i.e.* a gouge or a crack) and a dent is the severest form of pipeline defect and can record very low burst pressures and fatigue lives. It is highlighted that for dents containing corrosion, the two defects can be assessed separately *i.e.* the corrosion is assessed to the corrosion assessment codes and the dent is assessed to the appropriate code limits.

Anomaly	49 CFR 192	49 CFR 195
A dent that has any indication of metal loss, cracking or a stress raiser	Immediate	Upper 2/3 of the pipe – immediate Lower 1/3 of the pipe – 60 day
A dent with depth greater than 6%OD	Upper 2/3 of the pipe – one year* Lower 1/3 of the pipe – monitored	Upper 2/3 of the pipe – immediate Lower 1/3 of the pipe – 180 day
A dent with depth greater than 3%OD on the upper 2/3 of the pipe	Not defined	60 day
A dent with depth greater than 2%OD on the upper 2/3 of the pipe	Not defined	180 day
A dent with depth greater than 2%OD that affects pipe curvature at a weld	One year*	180 day
* can be downgraded to a monitored condition providing engineering analyses of the dent demonstrate that critical strain levels are not exceeded. In the case of a dent affecting a weld, the weld properties must also be considered		

Table 1 – Comparison of Dent Assessment Requirements in 49 CFR 192 [9] and 49 CFR 195 [10]

In the United States, operators of oil and gas pipelines have to comply with the Federal Regulations 49CFR192 [9] and 49 CFR195 [10] for pipelines operating in High Consequence Areas (HCAs). These recommendations specify response times for different dents depending on location and depth and are summarized in Table 1.

One of the assumptions of these requirements is that dents on the top of the pipeline are more likely to have been caused by

third party damage, whilst those on the bottom of the pipeline are more likely to be rock dents. Consequently, the remediation actions for rock dents are less immediate than for potential mechanical damage.

REVIEW OF DENT MANAGEMENT STRATEGIES

The issue facing pipeline operators is that a large number of dents are being reported by ILI tools. Many of the dents can be readily prioritized using the codes and guidance documents described previously on the basis of their association with other features, such as welds or metal loss, their depth or their position on the pipeline (i.e. at the top or bottom of the pipe). However, this may still leave a significant number of dents on the pipeline which fall within the dent criteria but may still pose a threat, particularly from fatigue. Consequently pipeline operators require a robust methodology for screening ILI results and determining appropriate and manageable dig and repair strategies, particularly for plain dents. The key requirements of such a strategy are that it should:

- be easy to use with measurements that can be readily made in the field or with ILI tools,
- not require intensive and expensive FEA to be conducted on every dent,
- recognize the key parameters that contribute to stress and strain concentration in the dent,
- relate to the pressure cycling regime of the pipe.

Many such strategies have been published in the open literature and the first stage in the development of the UKOPA dent management strategy was to review the published strategies against the key requirements listed above.

Fleet Technology (BMT) Dent Assessment Model

Fleet Technology developed their dent characterization model to rank dents on factors that could be readily quantified and were considered to affect the service life of the pipeline. The model was published in two stages [11-12] and the outcome of the research was a dent relative ranking parameter given by:

$$\text{Dent Factor} = \text{Pressure Factor} \times \text{Dent Geometry Factor} \quad (1)$$

The dent geometry factor is a combination of non-dimensional geometric parameters such as dent depth (as a %OD), D/t ratio and parameters relating to the transverse and axial shoulder sharpness. The pressure factor allows the severity of the pressure cycling that each dent experiences to be taken into account using cycle counting methods and applying Miner's rule to the resultant series of pressure range frequencies. This allows the data to be normalized for each pipeline section and the equivalent annual number of cycles to be calculated for each dent. The dent factor in equation (1), which has a unit of "years", is determined for each dent and the most severe dents are excavated.

The strength of this model is that it ranks the dent shape factors that affect stress concentration and dent rerounding (i.e. dent depth, length and width) and combines them with a pressure factor to indicate the likelihood of fatigue cracking. Unfortunately the published details are not sufficient to allow the model to be applied.

Enbridge Pipelines/Fleet Technology Rapid Characterization Method

In association with Fleet Technology, Enbridge pipelines developed a 'rapid characterization' process that could be used with ILI results to identify dents for excavation without the requirement to conduct expensive FEA on each dent [2]. The methodology is based on the premise that the shape characteristics of the dent are important in determining whether a dent will fail. Enbridge used three shape factors to determine an 'estimated severity factor' by which they could prioritize the dents for repair; the dent depth (as a % OD), the dent shoulder angle and the ratio of dent width to the width of the deformed area. Although the published details of the model are sufficient to allow it to be applied, it was considered that the shape parameters that are used would be difficult to measure accurately and repeatably either from the ILI data or in the field.

PII Ltd Dent Strategy

The dent strategy developed by PII [13] recognized that in order to conduct dent assessments using ILI data the limitations of the inspection tools had to be understood and the data interpreted in combination with code limits, additional pipeline information and the application of engineering judgment. Three strategies were developed as a series of flow charts to allow assessments to be made where only caliper or metal loss data was available and also for cases where both sets of data were available. As a result of the case study analysis conducted in the paper, a number of cautionary recommendations were made which are pertinent in the review of dent strategies:

- i) In order to make a full assessment of dents using ILI data, both MFL/UT and caliper tool data is required. Caliper tools cannot locate dents on some seam welds and MFL/UT tools cannot measure the depth of dents.
- ii) Running a caliper tool in isolation could mean that injurious dents on seam welds and dents associated with metal loss could remain undetected and therefore pose a serious threat to the pipeline.
- iii) Care should be taken when considering constrained dents on the bottom of the pipe. It is possible that rocks could move in service due to wash-out of the backfill or ground movement. Although this does mean that the dent size could be reduced due to rerounding, they would also be prone to fatigue.
- iv) A fatigue study should be conducted on all dent sizes, not just those greater than 2%OD, as it was shown in the analysis that even small dents can have low fatigue lives.

One of the attractions of this approach is the development of flow charts which make the strategy easy to apply, however, the paper does not address the issue of prioritization if a large number of dents are recommended for repair.

API1156 – Field Guide for Assessing Dents and Buckles

In the second phase of API 1156, Kiefner and Alexander [8] developed an approach for determining the severity of dents and provided a methodology for determining whether a dent requires repair or can safely remain in the pipeline.

The model is based on a risk-ranking methodology that takes into account the material properties and operational characteristics of the pipeline, the location of the dent around the pipe circumference, whether it is associated with metal loss or stress raisers and the depth of the dent.

This field guide is attractive in that it is easy to use and the data that is required is, in general, readily available from ILI tools or can be easily measured in the field. However, in essence, the ranking parameters are simply applying code guidance and, apart from the multiplier of the dent depth, are not taking into account dent shape to determine severity. Therefore this method does not allow plain dents to be ranked in terms of relative risk, other than on depth and location.

Duke Energy Gas Transmission (DEGT) Dent Strategy

DEGT have developed a dent management strategy using dent depth and dent strain as the governing criteria [14]. The process has been developed for a natural gas pipeline for which it was known from an analysis of the pressure cycling data that fatigue was not a concern.

The first stage of the strategy is an analysis of high resolution MFL data to identify dents with metal loss, dents on welds, dents with particularly significant signal response, particularly if they are located on the top of the pipe and dents that contain multiple sharp peaks. These dents are then prioritized based on the risk that they pose to the pipeline. If there are a significant number of high risk dents then DEGT will run a high resolution caliper inspection tool to measure the dent geometry and calculate dent strain. DEGT have adapted this approach to be used in the field by producing a series of radius of curvature plots at given strain levels for each wall thickness. When a profile measurement of the dent is taken in the field the radius plots can be matched to the profile and the strain read directly from pre-calculated charts.

In the strain analysis, using either ILI or field measurements, only the longitudinal bending strain is calculated and compared to the 6% criterion. Therefore no account is taken of the circumferential strain or the bending strains as required in the calculation provided in ASME B31.8 Appendix R [5]. In theory this will yield an unconservative strain result [15] and could lead to critical dents remaining in the pipeline if the 6% strain

criterion is adopted. However, based on their analysis, Dawson *et al* [16] have proposed that the total strain in the dent could be approximated to the longitudinal bending strain for the purpose of ranking dents for excavation.

DEGT have also developed a series of flow charts which they use to develop strategies for their response to dents reported in ILI and in the field [14]. In this approach, strain assessments are only conducted on dents with depths greater than the code depth criteria (2%OD for dents on welds and 6%OD for plain dents). However, it has been shown that dents that are below the 6%OD depth criteria can have strains greater than 6% [17]. Baker [15] who adopts a similar approach in the dent evaluation process recommended in the OPS Dent Study, recognizes that the strain criteria could be exceeded for shallow dents and therefore suggests that the strain criteria should be considered for all pipeline dents.

The DEGT approach is attractive in that the templates enable strain measurements to be taken effectively in the field. However, the limitations described above, in terms of the neglect of other strain components in the assessment and the restriction of the strain assessment to dents with depth > 6%OD, would need to be addressed to determine whether critical dents are being missed in the analysis.

GE Energy Dent Strategy

The dent management strategy developed by GE applies a dent strain criterion to pipelines that are not heavily pressure cycled and a fatigue risk assessment for pipelines that are heavily pressure cycled [16].

The dent strain assessment is similar to that applied by DEGT and uses ILI profile results to determine the strain in the dent using the equations in ASME B31.8 [5]. For the dents analyzed, GE found that the longitudinal and circumferential profiles of the dents were similar when plotted on the same co-ordinate system (*i.e.* the dents were essentially symmetrical) and therefore they used the profile with the best resolution (the longitudinal profile) to represent the data and consequently, essentially only the longitudinal bending strain is used to rank the severity of dents on the pipeline.

For pipelines that are heavily pressure cycled the methodology uses an S-N approach with FEA to determine the stress concentration factor (SCF) for the dent. This SCF can then be applied to appropriate S-N curves to calculate the fatigue life for the dent. In the GE work the DIN2413 S-N curve was used [18]. As mentioned previously, however, performing FEA on every dent on a pipeline may not be practical or economical and GE have found a positive correlation between a dent volume parameter proposed by Rinehart and Keating [19] and the hoop stress range and hence fatigue life. This finding could be used to predict fatigue lives for dents without extensive FEA analysis, although further work is required to confirm that the relationship holds across pipe geometries and properties.

Alyeska Pipeline System Strategy

Rosenfeld *et al* [20] has developed a mechanistic fatigue model which has been applied to minor mechanical damage features on the Alyeska Trans Alaska Pipeline System (TAPS). A stress concentration factor was calculated for each dent and then the fatigue life of the dent was calculated for a number of assumed crack depths using a fracture mechanics approach. One of the difficulties of using a fracture mechanics approach in fatigue assessment is the assumption that has to be made on initial crack size. However, in this work, Rosenfeld *et al* were able to use the data from the previous 436 investigations that had been carried out on the TAPS to estimate realistic initial crack sizes. One caution that the authors make is that, although the model has proved effective on the TAPS, the model cannot be directly applied to other pipelines as many of the parameters used (such as material properties, field data, pressure cycling information *etc.*) are specific to TAPS.

DEVELOPMENT OF UKOPA DENT ALGORITHMS

In the dent strategies that have been reviewed and are being used by operators and integrity consultants, the more robust methods will consider all of the key requirements discussed earlier in this paper. However, it was considered that no strategy could be immediately adopted by UKOPA members without further validation and the establishment of the range of validity for that approach. Although UKOPA have recognized this requirement and have built it in to their on-going work programme, a methodology needed to be established in the short-term which captured the guidance and recommendations and could be readily used by operators. The preferred methodology was therefore to develop a series of easy to use algorithms, building on the PII approach [13] and the internal approaches already adopted by individual companies.

Having reviewed the available dent management strategies and code requirements, the technical basis and methodology was established for the development of algorithms which would allow dents to be assessed and prioritized. These algorithms are based on the following simple assessment rules:

1. Kinked dents (*i.e.* dents with rapid changes in contour) should be repaired.
2. For static dent assessment:
 - a. Plain dents $>7\%OD$ or 6% strain should be repaired.
 - b. Dents $>2\%OD$ or 4% strain associated with welds should be repaired.
 - c. Dents $\leq 2\%OD$ or 4% strain associated with welds should be repaired only if the weld toughness¹ and quality are unacceptable.
 - d. If the dent is associated with corrosion and the corrosion is $\leq 20\%wt$, then the dent can be assessed as a plain dent. This limit has been proposed based on the corrosion

¹ In this rule, the weld toughness is considered to be acceptable if the Charpy Energy is $\geq 27J$.

limit applied by a number of UKOPA member companies and will be checked as part of the further work planned by UKOPA in developing the Dent Management Strategy.

3. If the pipeline is pressure cycled the pipeline should be assessed for associated damage which could enhance the risk of fatigue failure:
 - a. Top of line dent locations should be inspected for coating damage using DCVG or Pearson above ground surveys.
 - b. Bottom of line dent locations should be assessed for backfill disturbance or washout.
 - c. Bottom of line dents in rocky locations should be monitored not excavated.
 - d. Dents $>2\%OD$ should be subject to a fatigue assessment.
4. All new dent features identified between successive ILI inspections should be investigated.
5. If there is no indication of associated damage, the dent fatigue life should be assessed using a recommended dent fatigue S-N curve.

On the basis of these simple rules, two algorithms have been developed to represent the ILI data which may be available to a pipeline operator on which to make the assessment; MFL/UT data only (Figure 1) and MFL/UT and caliper data together (Figure 2). The algorithms are designed, not only to guide the user through the dent assessment codes, but also to provide a dig prioritization order based on the perceived risk of failure of that category of dent. These algorithms have been trialed by member companies of UKOPA on dents detected on their own pipeline systems and example assessments are illustrated in the following sections through consideration of two case study pipelines.

It is highlighted that an assessment algorithm was also developed for the situation where an operator may only have caliper data on which to make an assessment. However, during the trial of these algorithms it was considered that there was a high risk that dents that were unacceptable to code, such as dents on welds and dents associated with metal loss, could remain undetected in the pipeline. Consequently, in this situation, it is the recommendation of UKOPA that an MFL/UT inspection should also be conducted in order to make a full dent assessment.

It should be noted that the algorithms are currently based on either a strain limit or a depth limit being satisfied. However, it is noted that in other dent management strategies [14, 15] dents are only subject to a strain assessment if they exceed the depth limit. It is considered that this approach could result in dents that fail the strain criterion being left in the pipeline because they pass the depth criterion. It is the current recommendation of UKOPA, in line with that of Baker [15], that a strain assessment should be conducted if possible. If this is not possible then the assessment should be based on dent depth. If both dent and strain data are available for the dents on a

pipeline then the strain data should take precedence when using the algorithm. This recommendation is currently under review as part of a continuing programme of work to determine the validity and practicability of the approach.

Case Study 1 – MFL/UT Inspection Data

The application of the algorithm in Figure 1 is illustrated through consideration of a 230km, 270mm diameter gas pipeline on which 55 dents were detected by an MFL inspection. These dents were categorized as follows:

- 30 plain dents of which 15 were at the top of the pipeline (between 8o'clock and 4o'clock),
- 2 dents associated with the seam weld and metal loss on the top of the pipeline,
- 1 dent associated with metal loss on the top of the pipeline,
- 22 dents reported as seam weld not clear, 12 of which were at the top of the pipeline.

The algorithm recommends that the 2 dents associated with the seam weld and metal loss and the dent associated solely with metal loss be excavated as a priorities 1 and 2 respectively. This leaves 52 dents for which no further information is available from the ILI data to prioritize the dents. However, 22 of these dents may be associated with the seam weld and therefore these are given higher priority in the excavation list. The algorithm therefore recommends that the top of line dents in this category (12 dents) are investigated as next priority.

For the plain dents, priority is given to any dents in locations which show evidence of interference, but the operator is then left with the decision either to excavate all of the remaining dents to determine their depth or to conduct a geometric inspection using a caliper tool. In this case there was no evidence of interference. Therefore, for this pipeline, the operator would need to excavate and repair the dents detected by the MFL inspection in the following priority order:

- 2 dents associated with seam weld and metal loss on the top of the pipeline,
- 1 dent associated with metal loss on the top of the pipeline,
- 12 dents potentially associated with the weld on the top of the pipeline
- 10 dents potentially associated with the weld on the bottom of the pipeline
- 30 plain dents – prioritizing those on the top of the pipeline first.

However, if a caliper run were to be made then, although the 3 dents associated with seam weld and metal loss and metal loss alone would still need to be investigated, the number of plain dents and dents which could be associated with the seam weld that may require excavation would be significantly reduced. Indeed for this pipeline the dig costs for the recommended dents were prohibitive and a caliper inspection was run.

Case Study 2 – MFL/UT Inspection and Caliper Inspection Data

The combined algorithm is demonstrated through consideration of a 914mm diameter, 9.52mm wall thickness pipeline which was inspected using both an MFL inspection tool and a high resolution caliper inspection tool. The pipeline is 213km long and 421 dents were detected by the MFL tool, of these only 262 were also detected by the caliper tool. As the caliper tool had a minimum guaranteed detection limit of 2%OD it could be assumed that all of the dents in the MFL inspection, not detected by the caliper, were less than 2%OD. 8 dents were associated with metal loss, 5 of which were confirmed as corrosion, and 3 dents were associated with the welds.

The algorithm in Figure 2 immediately recommends that the 3 dents associated with metal loss, not confirmed as corrosion, need to be repaired, prioritizing those on the top of the pipeline. The 5 dents associated with corrosion were assessed separately and found to be acceptable. The 3 dents associated with welds were subject to a strain assessment however the strain was calculated to be greater than the 4% limit and these 3 dents were also recommended for repair. The remaining 262 plain dents passed the strain assessment, but one subsequently failed the fatigue assessment and was recommended for investigation. Consequently, of the 421 dents detected, only 7 dents required excavation and repair.

Although not the situation in this case study, it is recognized that in some cases, operators are faced with the excavation of large numbers of dents. In these circumstances, one of the ways by which dents can be prioritized is through the fatigue life, which is discussed in the next section.

ASSESSMENT OF FATIGUE

As mentioned in the introduction to this paper, there is currently no codified guidance on how to conduct a dent fatigue assessment, although the requirement to consider fatigue is embodied in API1156. In addition, the algorithms presented in this paper also require an operator to consider fatigue when the depth of the dent is known and therefore further guidance is required in order that an operator can consider fatigue appropriately. As part of this research, therefore, a review was conducted of the current methodologies available for the assessment of dent fatigue.

Review of dent fatigue models

A number of semi-empirical and empirical models for predicting the fatigue life of plain dents have been developed using design fatigue curves. The basic methodology involves using published fatigue (S-N) curves from an appropriate design code and accounting for the stress concentration in the dent by the use of a stress concentration factor (SCF). The SCF is applied to the cyclic stress range and the number of cycles to failure can then be calculated from the design curve to determine the fatigue life. It is highlighted that this approach assumes that no initial crack is present in the dent and therefore

the fatigue life includes the time to initiate and propagate a crack.

The issue for operators faced with conducting a fatigue assessment is that there is not agreement in the literature regarding the most appropriate S-N curve to use for application to dent fatigue and there is no standard methodology for determining stress concentration factors, some of which are determined experimentally and some by FEA. A review of the literature indicated that there were six different fatigue design curves that have been used for the assessment of dent fatigue; DIN 2413 curves [18], Curve X' in API-RP2A [21], DOE-B curve [22], modified ASME B31.3 curves [23], ASME Section VIII Division 2 Appendix 5[24] design curve and the AWS A-curve [25].

The available dent fatigue assessment methods have been reviewed by Cosham and Hopkins [4] and compared against the published experimental dent fatigue data. The recommendation of their review was to use the original method published by EPRG (European Pipeline Research Group) [26], which is described in the next section, as this provided the best fit to the published full-scale test data.

EPRG Fatigue Model

The EPRG approach [26] is based on S-N curves for longitudinal submerged arc welded pipe published in DIN 2413 [18]. The DIN code gives a series of S-N curves which are dependent on both the mean stress and ultimate tensile strength. The SCF used in the EPRG method has been derived empirically and is a function of the dent depth and the pipe geometry. The dent depth used in the model is the dent depth at zero pressure and therefore, if using dent depths measured at pressure (*i.e.* from a caliper inspection tool) the dent depth needs to be corrected for spring back. Cosham and Hopkins [4] in the Pipeline Defect Assessment Manual (PDAM) recommend that a safety factor of 13.3 is applied to the calculated fatigue life to ensure a 95% probability of conservative prediction of the test data.

However, industry experience suggests that the EPRG model gives very conservative estimates of dent fatigue life and predicts fatigue lives much lower than the service life of the dent even though no failure of the dent has been observed [16]. In fact, due to the conservativeness of this methodology, members of UKOPA who were using this approach were faced with hundreds of dents which required excavation on the basis of the algorithms, a situation that was proving impractical to manage. In addition, of the operators surveyed, none had found fatigue cracking present on excavating dents that were predicted to have exceeded their design lives. The conservatism of the approach is illustrated in the following example.

Assessment of Fatigue Life of Dented Pipelines

Consider a pipeline which is cycling at a base stress cycle of 125N/mm² per day. The effect on the design life of introducing

dents of different depths into this pipeline is illustrated in Figure 3. It can be seen that if the EPRG lower bound prediction is used (*i.e.* a factor of 13.3 is applied to the mean prediction), even a dent of 2.5% in this pipeline will reduce the life of the pipeline to 10% of the design life.

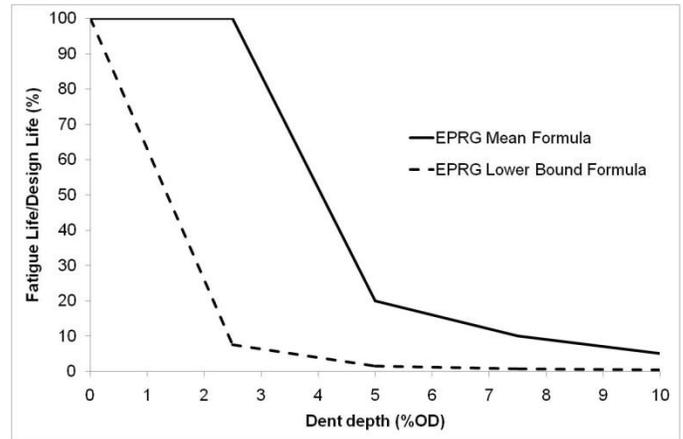


Figure 3 – Simple assessment of fatigue of dented pipelines

If the probability of finding a dent of these sizes on a pipeline is considered then the effect of this fatigue life reduction can start to be quantified. Members of UKOPA contribute to the maintenance of a fault database which includes records of all loss of containment failures, and in addition records details of part through wall faults recorded by pipeline operators. Of specific importance are faults recorded in relation to external interference incidents. This database was interrogated to determine the number of dents that were recorded as third party damage and the depths of those dents. Of the 110 dents reported, 80% were less than 50%OD and the smallest dent recorded in this database is 10%OD (Figure 4). It is highlighted that as well as posing a threat to the integrity of the pipeline, dents of this size also need to be removed to enable the passage of inspection vehicles.

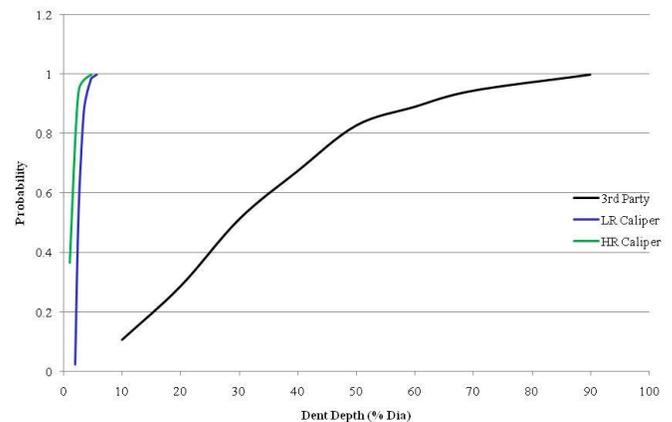


Figure 4 – Probability density plot for dents recorded in the UKOPA database and two case study pipelines

If these results are compared with dents reported on two typical caliper inspections, it can be seen that the size of dents being reported is much less than 10%OD. For example, for the high resolution (HR) caliper inspection, 80% of the dents are less than 2%OD and for the low resolution (LR) inspection 80% of the dents are less than 3.25%OD. However, the minimum guaranteed detection level on the caliper inspection was 2%OD.

On the basis of this preliminary analysis, it can be concluded that dents below the guaranteed reporting level of the caliper inspection could pose a serious fatigue threat to the pipeline if the EPRG lower bound fatigue model is applied. And yet, pipeline operators excavating dents of this size are seeing no signs of fatigue crack initiation through visual, MPI and ultrasonic inspection.

It was therefore perceived that alternative fatigue models were required that, whilst remaining safe, allowed pipeline operators to manage the threat of failure appropriately.

DEVELOPMENT OF UKOPA FATIGUE CRITERIA

UKOPA have initiated a work programme that is aimed at addressing the current conservatism in the dent fatigue criteria. This is a long term project that will involve the collection of dent investigation and pressure cycling data so that the threat of fatigue failure can begin to be quantified for onshore pipelines in the UK. In addition, the calculation of stress concentration factors and the impact of the application of S-N curves on the fatigue life will also be investigated in order that UKOPA can move towards a recommendation of an appropriate fatigue life assessment method for dents.

CONCLUSIONS

At the start of this research programme, UKOPA's aim was to develop a robust dent management strategy that could be applied to the UK onshore pipeline network.

Based on a review of dent management strategies available in the literature and the requirements of codes and industry best practice, UKOPA have developed a series of algorithms that can be used to assess and prioritize dents which have been detected with MFL/UT tools alone or caliper tools alone or situations where MFL/UT and caliper data is available for the pipeline.

It is highlighted from the demonstration of these algorithms based on case study pipelines, that using only one set of inspection data to make a dent assessment increases the risk of subsequent dent failure as not enough information is available to assess the dent completely. It is therefore the recommendation of UKOPA that MFL/UT and caliper data is collected for a pipeline.

Although pipeline codes recommend a fatigue assessment for dents, there is no codified methodology for calculating the fatigue life of a dent. The S-N method is the most widely used

approach for calculating fatigue life, however, the methodology for calculating the stress concentration factors (SCF) in the dents varies in the literature and there is no unified approach. In addition, there is no recommendation for the most appropriate design curve to be used.

Application of the current recommendations to use the EPRG approach have indicated that dents below the guaranteed reporting level could fail the assessment indicating that operators could have a latent fatigue problem in their pipeline. In any event, the current approaches are leaving some pipeline operators with an unfeasible number of dents to excavate. This conclusion has to be balanced against reports of dents beginning to fail by fatigue and highlights the requirement for a robust, safe and cost-effective fatigue assessment approach.

UKOPA are addressing these issues through a structured dent management research programme. These algorithms form the first stage of that programme and they will be updated as further industry experience is gathered from their use.

NOMENCLATURE

BOL	Bottom of line
D	Pipeline outside diameter
EPRG	European Pipeline Research Group
FEA	Finite element analysis
HCA	High consequence area
HR	High resolution
ILI	In line inspection
LR	Low resolution
MFL	Magnetic flux leakage
NPS	Nominal pipe size
OD	Outside diameter
PDAM	Pipeline defect assessment manual
SCF	Stress concentration factor
TOL	Top of line
UKOPA	United Kingdom Onshore Pipeline Association
UT	Ultrasonic
d	Dent depth
t	Pipeline nominal wall thickness

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Annex A

	Plain Dents		
	Constrained	Unconstrained	
ASME B31.8 [5]	Upto 6%OD or strain level upto 6%		
ASME B31.4 [27]	Upto 6% OD in pipe diameters > NPS 4 Upto 6mm in pipe diameters < NPS 4		
API 1156 [7] [8]	Upto 6%OD, >2% OD requires a fatigue assessment		
EPRG [26]	≤7%OD at a hoop stress of 72%SMYS		
PDAM [4]	Upto 10%OD	Upto 7%OD	
	Dents at welds	Dents with cracks or gouges	Dents with corrosion
ASME B31.8 [5]	Upto 2%OD or 4% strain on ductile welds Not allowed on brittle welds	Not allowed	Assess individually
ASME B31.4 [27]	Not allowed	Not allowed	Not allowed
API 1156 [7] [8]	Upto 2%OD on ductile welds Not allowed on brittle welds	Not allowed	Not considered
EPRG [26]	Not allowed	Not allowed	Not allowed

Table 2 - Summary of Dent Acceptance Criteria and Guidance

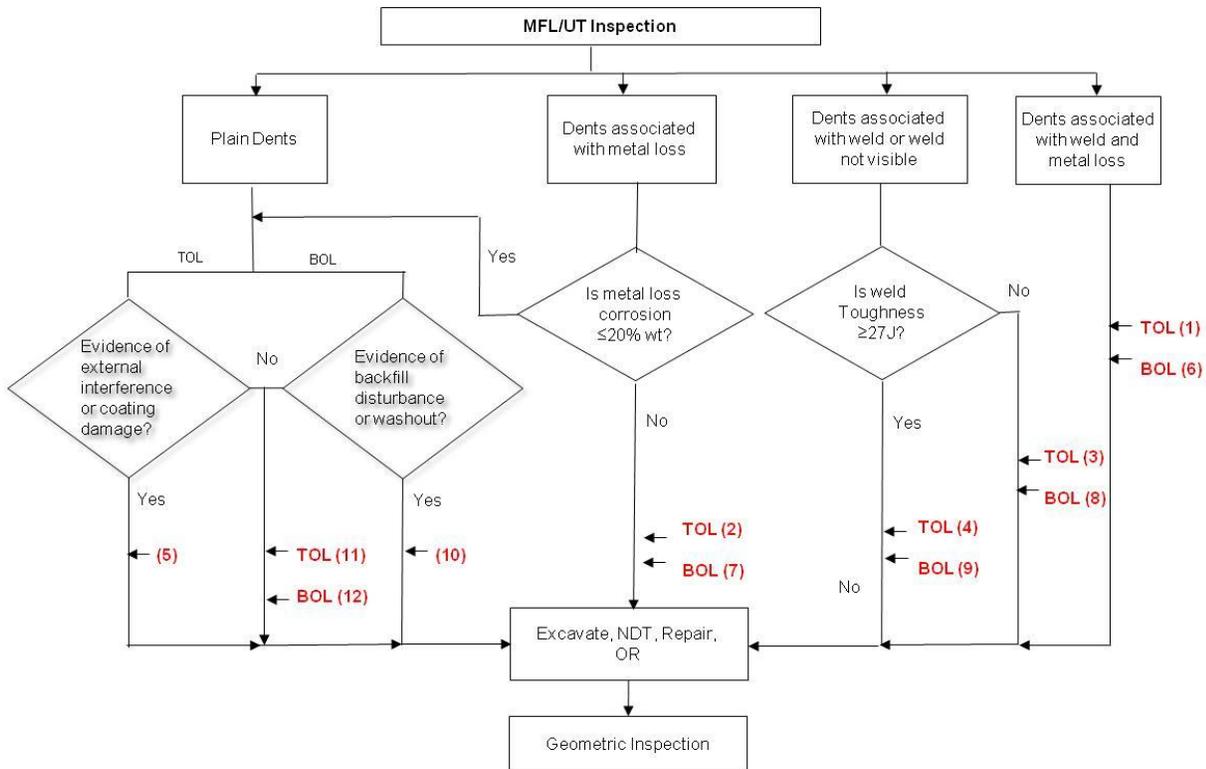


Figure 1 - UKOPA Dent Prioritization Algorithm 1 - MFL/UT Inspection Data

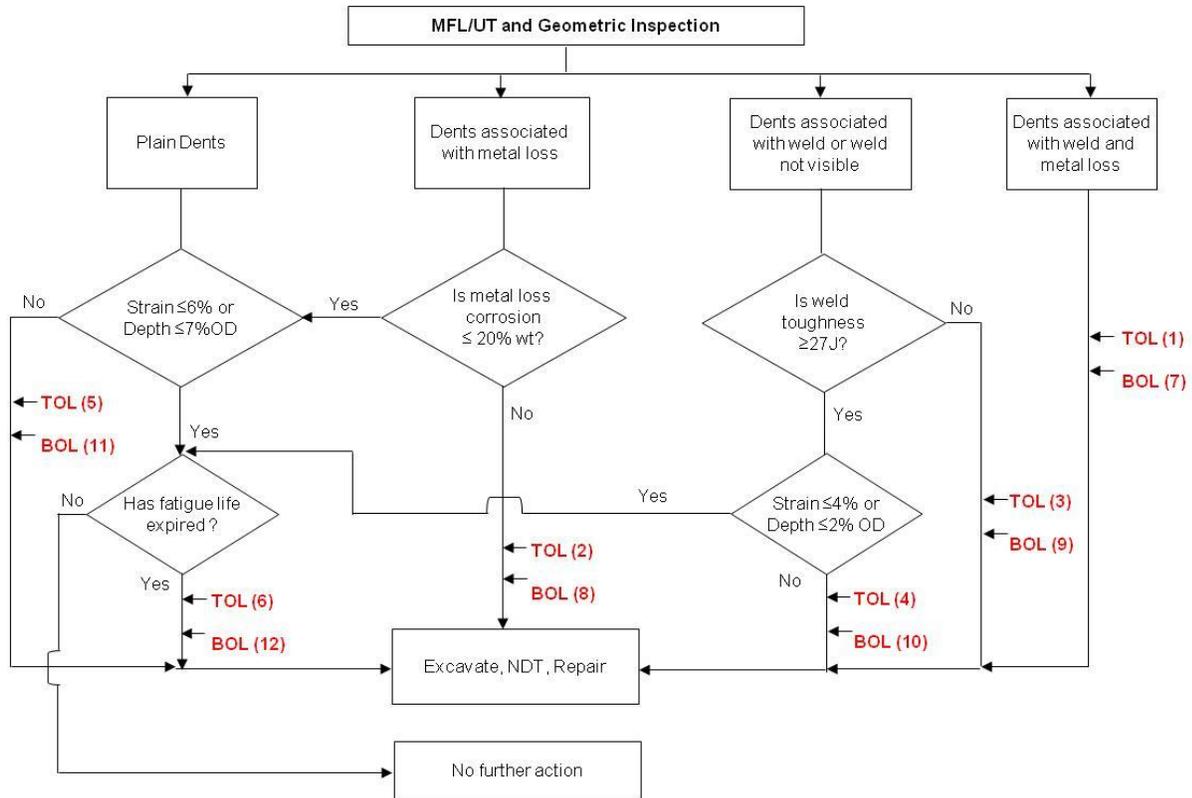


Figure 2 - UKOPA Dent Prioritization Algorithm 2 - MFL/UT and Geometric Inspection Data