UKOPA/GP/004

# UK ONSHORE PIPELINE OPERATORS' ASSOCIATION - INDUSTRY GOOD PRACTICE GUIDE

## MANAGING PIPELINE DENTS

**Guidance Issued by UKOPA:**

The guidance in this document represents what is considered by UKOPA to represent current UK pipeline industry good practices within the defined scope of the guide. The document does not specify prescriptive requirements, should be considered guidance and should not be considered obligatory against the judgement of the Pipeline Owner/Operator. Where new and better techniques are developed and proved, they should be adopted without waiting for modification to the guidance in this document. The term 'shall' has been used to identify any requirement of UK law in Great Britain at the time of publication.

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This document was approved for publication by the UKOPA Board on 24th February 2016.

| **Document History** | **Date** |
|---|---|
| Edition 1 | January 2016 |

Planned revision date December 2021

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# 1 INTRODUCTION

Pipelines are thin shell structures which are susceptible to geometric distortions and dents during handling, construction and operation. These dents and distortions, particularly when associated with other forms of damage such as gouges, or which are associated with welds, can lead to failure of the pipeline. Consequently, rigorous assessment is required. The identification of the damage mechanism which has caused the dent, the severity of the dent and an assessment of the potential for failure is essential. The severity of the dent and the assessment of the impact on pipeline integrity is dependent upon its location, the size and shape of the dent, the line pipe mechanical properties, and the applied static and cyclic stresses.

The majority of pipeline in-line inspections (ILI) are carried out using the magnetic flux leakage (MFL) inspection tools. These tools are capable of identifying and locating dents in the pipeline, but most cannot currently size the dent. As a result, large numbers of dent features are reported by ILI companies for further consideration by the operator with little or no information for identifying any critical features which require investigation.

This document has been developed to provide UKOPA members with practical guidance to assess whether a dent identified through an MFL inspection could potentially result in a pipeline failure, resulting in a loss of containment of the fluid being transported or leak within the lifetime of the pipeline. The document also provides some rules that will assist pipeline operators in prioritising the repair of dents that are assessed as requiring further investigation or repair. This document is based on technical work sponsored by UKOPA which is summarised and reported in Reference 14.

# 2 SCOPE AND APPLICATION

## 2.1 Scope

The guidance in this document is applicable to all buried steel pipelines operated by the UKOPA member companies. These pipelines can be categorised as:

- Natural gas transmission and distribution pipelines;
- Petrochemical liquids and gas pipelines;
- Oil and refined liquid pipelines.

For gas pipelines the guidance is generally applicable to steel pipelines with maximum operating pressures above 7 bar, however the principles of the document can be equally applied to gas pipelines operating at lower pressures.

## 2.2 Application

The guidance in this document is considered by UKOPA to represent current UK pipeline industry good practice within the defined scope of the document. All requirements should be considered to be guidance and should not be considered to be obligatory against the judgement of the Pipeline Owner/Operator. Where new and better techniques are developed and proved, they should be adopted without waiting for modifications to the guidance in this document.

# 3 DEFINITIONS

The relevant definitions applied in this document are detailed below:

| | |
|---|---|
| Dent - | a depression which produces a gross disturbance in the curvature of the pipe wall, caused by contact with a foreign body, resulting in plastic deformation of the pipe wall. |
| Plain (or smooth) dent - | a dent which causes a smooth change in the curvature of the pipe wall, causing depression on external surface, with no metal loss, no change of curvature at any adjacent seam or girth weld. |
| Dent associated with weld - | a dent that changes the curvature of a seam or girth weld. |
| Kinked dent - | a dent which causes an abrupt change in the curvature of the pipe wall. An abrupt change in curvature is defined as one where the radius of curvature (in any direction) of the sharpest part of the dent is less than or equal to five times the wall thickness.<br>*Note – this definition is based on the guidance in the EPRG recommendations for the assessment of mechanical damage.* |
| Unconstrained dent - | a dent that is free to rebound elastically (spring back) when the indenter is removed, and is free to reround as the internal pressure varies. |
| Constrained dent - | a dent that is not free to rebound or reround, because the indenter is not removed. A rock dent is an example of a constrained dent. |
| Shallow dent - | a dent with depth < 2% of pipeline outside diameter. |
| Spring back - | (also referred to as rebounding) the reduction in dent depth due to the elastic unloading that occurs when the indenter is removed from the pipe. |
| Rerounding - | the change in dent depth under internal pressure. |
| Position - | Top of line (TOL) - 8 O’clock to 4 O’clock |

Bottom of line (BOL) - 4 O'clock to 8 O'clock

Note: *Top of line dents should be considered unconstrained. Bottom of line dents should be considered constrained, except where there is evidence to the contrary. In particular, bottom of line dents should be considered unconstrained where there is evidence of backfill disturbance or washout which could remove support to the dent.*

# 4 DENT ASSESSMENT PROCESS

The dent assessment process detailed in this document has the following key steps:

1. **Gather all data** relevant to the assessment of the significance of the pipeline dent **(see Section 5.1)**
2. **Apply the specified dent assessment rules** in order to determine whether any further action needs to be taken **(see Section 5.2)**
3. For dents where further action is required to be taken **apply the appropriate algorithm** to determine the suggested priority for further assessment or repair **(see Section 5.3)**
4. For each prioritised category **determine whether excavation is recommended or a reassessment** using a high resolution geometry tool **(see Section 5.4)**

In addition guidance is provided within the document on assessment of weld quality (see Section 6.0) and assessment of Fatigue (see Section 7.0 and Appendix 1).

# 5 ASSESSMENT OF DENTS

## 5.1 Data Gathering

In order to undertake an appropriate assessment of any dents identified through ILI, all relevant pipeline data should be collected and documented. This would normally include collection of the following data:

- Details of the product transported through the pipeline and, for pipelines that have transported different products, the pipeline product history;
- Pipeline dimensions, i.e. diameter and wall thickness;
- Year of construction;
- Linepipe weld type, e.g. SAW ERW Seamless, etc.;

- Material grade;
- Current pipeline MOP (and MOP history if this was different in the past);
- The dent depth reported by the ILI company;
- Dent orientation, e.g. on bottom half of the pipeline or on top half of the pipeline;
- Whether the dent is known to interact with a weld;
- Orientation of the pipeline seam;
- The pipeline pressure history;
- Pipeline pressure test details;
- Any known information regarding the quality of the pipeline welds (see Section 6.0);
- Details of previous ILI inspections including construction footprint ILI run if available;
- Any known construction issues that might have increased the potential for a dent to have occurred, e.g. pipeline known to have been laid in rocky soil;
- Any known integrity issues, e.g. known CP or coating issues;

## 5.2 Apply Dent Assessment Rules

The rules in Table 1 below should be applied in order to determine whether any further action needs to be taken to further assess and/or repair a dent identified through ILI.

| **If any one or more of the requirements detailed below are not met for any one dent then further assessment will be required. If all of the relevant requirements are met then no further action need be taken.** |
|---|
| Any kinked dents must be repaired. See Section 3 for definition of a kinked dent. |
| For plain dents (see Section 3) the maximum dent depth must be less than 7% of the pipeline Outside Diameter (OD) unless the strain in the dent can be calculated, in which case the maximum calculated strain must be less than 6%. |
| For any dents associated with welds that are known to be of good quality, then the maximum depth of the dent must be less than 2% of the pipeline Outside Diameter (OD) unless the strain in the dent can be calculated, in which case any plain dent associated with a weld of good quality must have a calculated strain which is less than 4%. |
| Where the weld is believed to be of probable good quality (see Section 6) then and the strain in the dent can be calculated then then the calculated strain must be less than 2%. |
| Where the dent is associated with metal loss, the level of corrosion must be ≤ 20% wall thickness and the maximum dent depth must be less than 7% of the pipeline Outside Diameter (OD) or the calculated maximum strain must be less than 6%. If either the dent depth or the corrosion depth exceeds these limits then the combined effect of the dent plus the metal loss must be subject to detailed assessment. |
| Any dents associated with welds of unknown or poor quality must be repaired. |
| For pipelines which are cycled, the fatigue assessment must confirm that the cumulative damage over the operating life is acceptable, or the cumulative damage over the length of time up until a repair when a repair will be made is acceptable. |

**Table 1 – Criteria applied to Assessment of Dents in Gas and Liquid Pipelines**

*Notes:-*

1. *Where both dent depth and depth strain are available, dent strain should be used to prioritise dents.*
2. *If a dent strain assessment has not been completed, dents greater than 7% depth should not be allowed without seeking expert advice. This limit is reduced to 2% depth for dents on welds.*

In developing the above criteria it has been assumed that the integrity criterial in ASME B31.8, which addresses gas pipelines, apply to all products.

The peak strain in a dent may be calculated using high resolution geometry ILI data with the method described in ASME B31.8 Appendix R. Most geometry inspection data contains irregularities, for example due to sensor lift-off or debris in the pipeline, which cause large over-estimates in the calculated strain values. Some smoothing of the geometry data is usually required, but this must be done carefully to preserve the essential features of the dent shape. No particular smoothing method has been widely accepted by the pipeline industry but methods using B-splines and local polynomial regression have been used.

Dents which cannot be assessed and sentenced using the criteria in Table 1 must be investigated and repaired.

## 5.3 Prioritisation of Dents

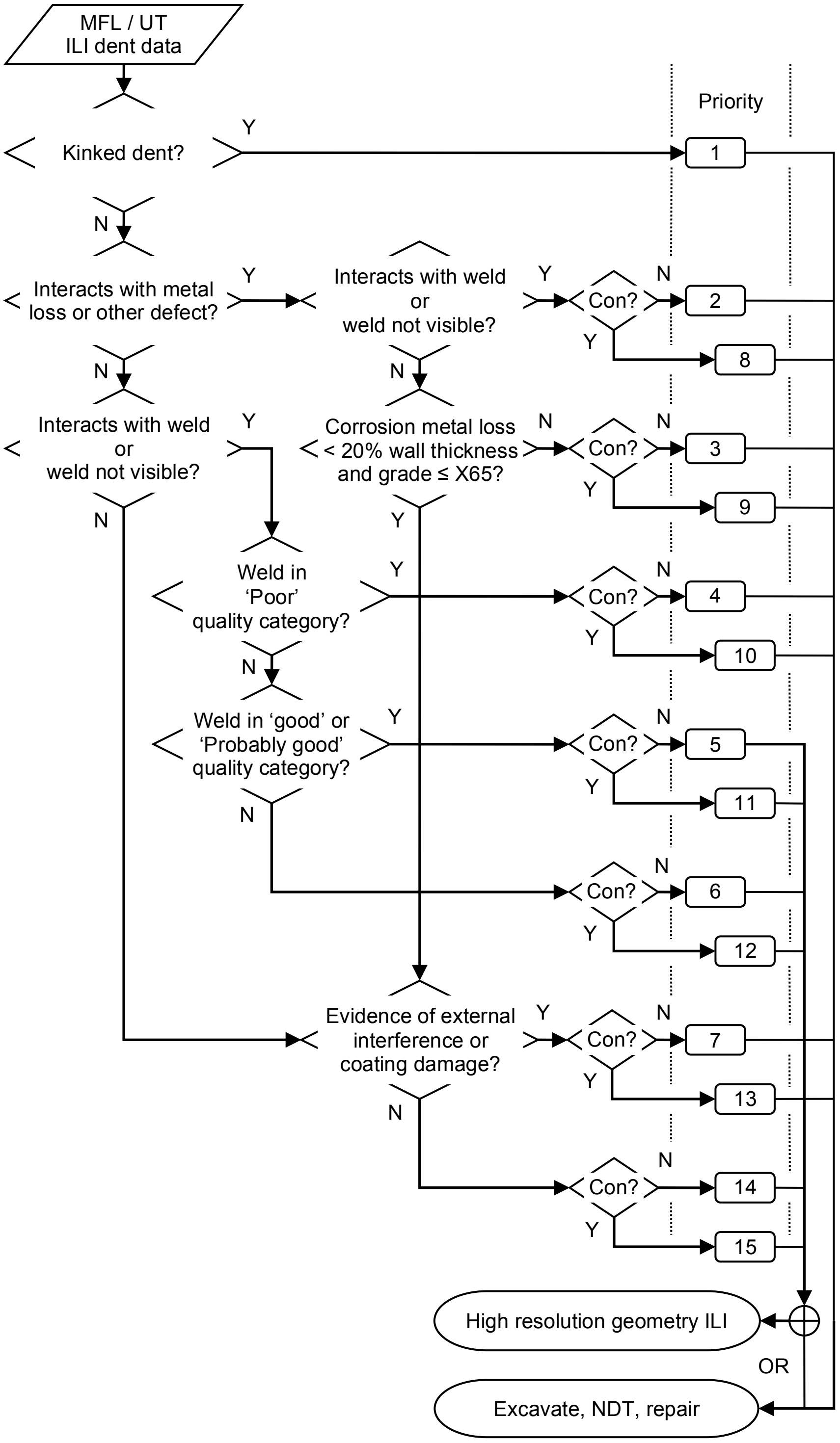
Dent features detected by ILI should be prioritised for investigation using the algorithms in Figures 1 and 2.

Figure 1 should be used where MFL/UT Inspection results are available but no Geometeric Inspection results are available. The algorithm identifies where dent features require immediate investigation and repair and where further inspection with a geometric inspection tool is suggested.

Table 2 provides a summary of the ranking provided by the algorithm in Figure 1 and identifies where a geometric inspection is suggested.

Figure 2 should be used where both MFL and Geometric Inspection results are available.

Table 3 provides a summary of the ranking of dents requiring repair provided by the algorithm in Figure 2.

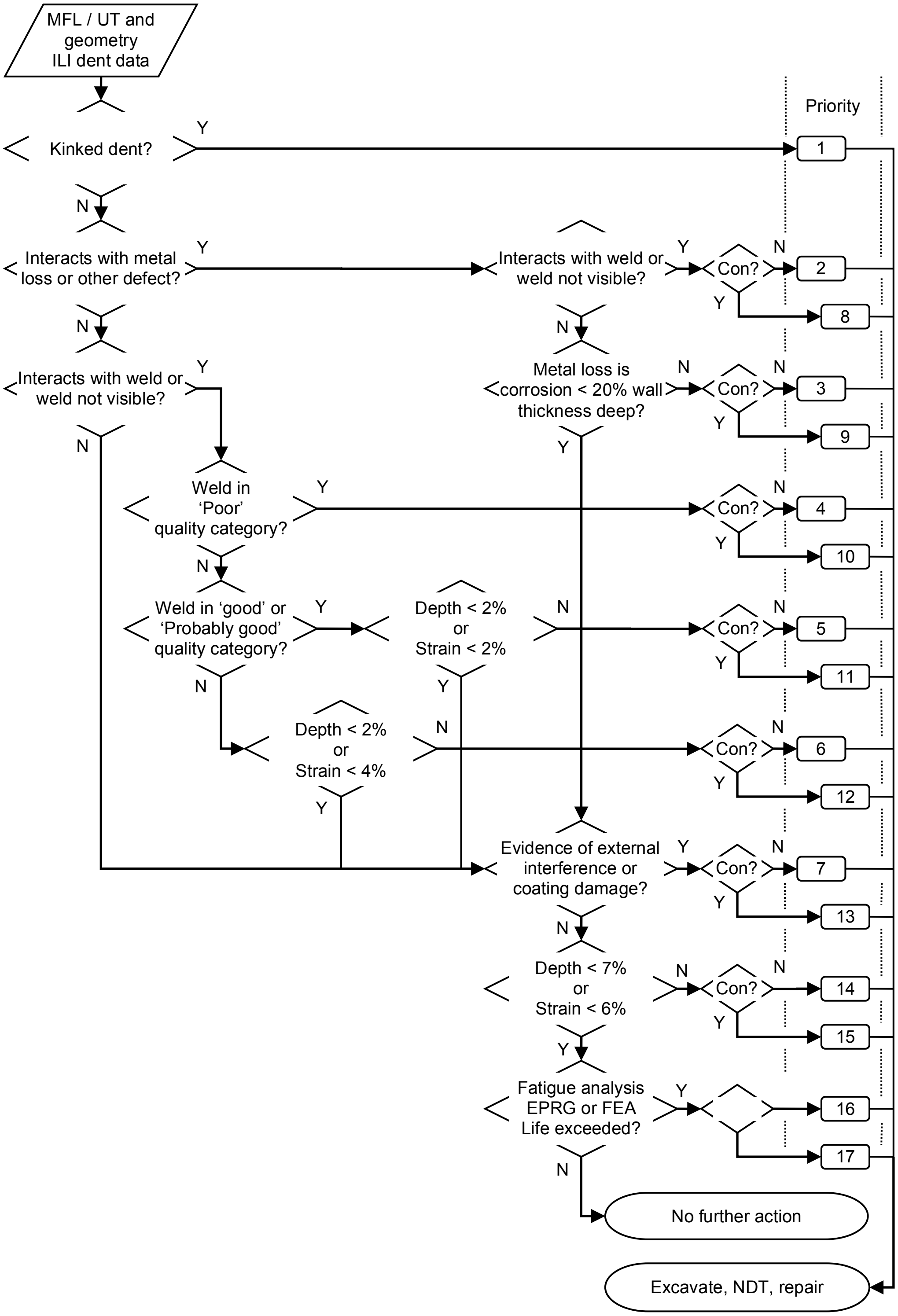


Note: 'Con' means 'constrained', as defined in Section 2.

**Figure 1: Dent Prioritisation Algorithm Where No Geometric ILI Data Is Not Available**

| Priority | Description | Action |
|---|---|---|
| 1 | Kinked dent | 1 |
| 2 | Unconstrained + associated with metal loss + associated with weld | 1 |
| 3 | Unconstrained + associated with metal loss (except corrosion less than 20% of wall thickness in depth in grade X65 material or lower) | 1 |
| 4 | Unconstrained + associated with weld in ‘Poor’ quality level | 1 |
| 5 | Unconstrained + associated with weld in ‘Probably good’ quality level | 1 or 2 |
| 6 | Unconstrained + associated with weld in ‘Known good’ quality level | 1 or 2 |
| 7 | Unconstrained + evidence of external interference or coating damage from CIPS / DCVG | 1 |
| 8 | Constrained + associated with metal loss + associated with weld | 1 |
| 9 | Constrained + associated with metal loss (except corrosion less than 20% of wall thickness in depth in grade X65 material or lower) | 1 |
| 10 | Constrained + associated with weld in ‘Poor’ quality level | 1 |
| 11 | Constrained + associated with weld in ‘Probably good’ quality level | 1 or 2 |
| 12 | Constrained + associated with weld in ‘Known good’ quality level | 1 or 2 |
| 13 | Constrained + evidence of external interference or coating damage from CIPS / DCVG | 1 |
| 14 | Unconstrained | 1 or 2 |
| 15 | Constrained | 1 or 2 |

**Table 2 – Prioritisation Rationale – MFL/UT Inspection**



Note: 'Con' means 'constrained', as defined in Section 2.

**Figure 2: Dent Prioritisation Algorithm Where No Geometric ILI Data Is Available**

| Priority | Description | Action |
|---|---|---|
| 1 | Kinked dent | 1 |
| 2 | Unconstrained + associated with metal loss + associated with weld | 1 |
| 3 | Unconstrained + associated with metal loss (except corrosion less than 20% of wall thickness depth in grade X65 material or lower) | 1 |
| 4 | Unconstrained + associated with weld in 'Poor' quality category | 1 |
| 5 | Unconstrained + associated with weld in 'Probably good' category + depth≥2% or strain≥2% | 1 |
| 6 | Unconstrained + associated with weld in 'Known good' category + depth≥2% or strain≥4% | 1 |
| 7 | Unconstrained + evidence of external interference or coating damage from CIPS / DCVG | 1 |
| 8 | Constrained + associated with metal loss + associated with weld | 1 |
| 9 | Constrained + associated with metal loss (except corrosion less than 20% depth in grade X65 material or lower) | 1 |
| 10 | Constrained + associated with weld in 'Poor' quality category | 1 |
| 11 | Constrained + associated with weld in 'Probably good' category + depth≥2% or strain≥2% | 1 |
| 12 | Constrained + associated with weld in 'Known good' category + depth≥2% or strain≥4% | 1 |
| 13 | Constrained + evidence of external interference or coating damage from CIPS / DCVG | 1 |
| 14 | Unconstrained + depth≥7% or strain≥6% | 1 |
| 15 | Constrained + depth≥7% or strain≥6% | 1 |
| 16 | Unconstrained + predicted fatigue life exceeded (further prioritise dents within this priority level by predicted remaining fatigue life) | 1 |
| 17 | Constrained + predicted fatigue life exceeded (further prioritise dents within this priority level by predicted remaining fatigue life) | 1 |

**Table 3 – Prioritisation Rationale – MFL/UT + Geometric Inspection**

## 5.4 Action Required

Where the assessment confirms the dent parameters are within the limits defined in Section 5.2 no further action is required. If the application of the criteria in Section 5.2 identify that remedial action is required then, depending on the outcome of applying the algorithms in Section 5.3, either Action 1 or 2 in Table 4 below should be taken as specified in the relevant algorithm.

| Action | Description |
|---|---|
| 1 | Excavate the dent, carry out NDT and repair if necessary |
| 2 | Carry out a high resolution geometry in-line inspection and re-assess dent |

**Table 4 - Actions required**

The actions for dents in higher priority levels should be given priority over those in lower priority levels where practical. Where two potential actions are suggested for a given priority level, the operator should choose the action he considers most appropriate to complete based on operational and cost considerations.

A constrained dent will become unconstrained, and should be re-assessed as such, if it is excavated and the constraining object (such as a rock) is removed. Additionally, a permanent repair should be considered for dented pipelines which carry liquids or are subjected to high fatigue loading. This is because there is evidence that fatigue failure can occur more quickly in these circumstances than would otherwise be expected for an unconstrained dent.

## 5.5 Applying the Specified Prioritisation

Section 5.3 provides a prioritisation for the dents that have been identified through ILI. It is outside of the scope of this guidance to provide a suggested timescale upon which the suggested remedial action needs to be taken. This timescale will be very dependent on the risks associated with individual pipelines which in turn will be dependent on a number of factors including the pipeline's age, operating history, fluid being transported, operating pressure, known pipeline condition and population around the pipeline at risk.

In line with UK health and safety legislation it is the responsibility of individual pipeline operators to ensure that risks have been made 'as low as reasonably practicable'. Pipeline operators must therefore schedule their remedial work taking all potential risk factors into account and the costs associated with any further inspection, assessment and remedial work.

Further guidance on undertaking ALARP demonstrations for hazardous pipelines can be found in IGEM/TD/2 (Reference 16) and PD 8010-3 (Reference 17). HSE's document 'Reducing Risks Protecting

People' (Reference 18) also provides guidance on the meaning of ALARP and how duty holders can demonstrate that risks have been made ALARP.

# 6 ASSESSMENT OF WELD QUALITY

Weld quality should be established through material and construction records. It may be difficult to determine weld quality, particularly for older pipelines. Weld toughness is a good indicator of weld quality, but older welding standards did not require toughness tests to be carried out, so other indicators are required.

Based on published industry practice (References 3, 4 and 5), the following quality levels are proposed for both seam and girth welds (based on work reported in References 8 and 9):

***Known good quality welds***

'Known good quality' welds meet all of the material and construction criteria or relevant inspection criteria (selected in relation to a specific dent assessment) in Table 5.

***Probable good quality welds***

Probable good quality welds are likely to have a sufficient Charpy toughness (greater than 30 J minimum and 40 J on average from three specimens), but do not have Charpy test data available. Probable good quality welds meet the material and construction criteria 2 to 4 or the relevant inspection criteria 5 to 6 in Table 5.

***Poor quality welds***

Poor quality welds are welds where cracking is credible during the denting process. This includes any of the material and construction or inspection criteria in Table 6.

If it is not clear which category applies to a particular weld, either the worst credible category should be assumed, or expert advice should be sought.

| Item | Criterion |
|---|---|
| 1 | The welds have a Charpy toughness of greater than 30J minimum and 40J on average from three specimens, at the pipeline's minimum operating temperature. |
| 2 | The line pipe was manufactured to API 5L Edition 25 (1970) or later, or equivalent. |
| 3 | The weld was fabricated to a recognised pipeline welding standard such as API 1104, or equivalent, or as defined in API 5L. |
| 4 | Records show, or it is considered likely that, a hydrotest has been completed at an internal pressure of at least 1.25 times Maximum Operating Pressure (MOP), and there is no evidence that hydrotest failures were caused by welds. |
| 5 | Visual and magnetic particle (or similar) inspection of a sample of seam or girth welds (at least 0.1% of the pipes or girth welds in the pipeline) shows a good quality weld with a clean cap, no spatter, no surface-breaking planar flaws, and no undercut. |
| 6 | Non-destructive testing of a sample of seam or girth welds (at least 0.1% of the pipes or girth welds in the pipeline) using manual shear wave ultrasonic technology (UT), time of flight diffraction (TOFD), or other suitable method shows a low density of anomalies, and no anomalies outside the workmanship limits in a current welding standard. |

**Table 5: Indicators of a 'good quality' weld**

| Item | Criterion |
|---|---|
| 1 | Welds of known low toughness (Charpy toughness less than 30J minimum and 40J on average from three specimens), or operating temperature less than drop weight tear test transition temperature, or weld is under-matched (the tensile strength of the weld is less than the line pipe, or the yield strength of the weld is less than the line pipe). |
| 2 | Pipe not manufactured to API 5L or equivalent. |
| 3 | Welds not fabricated to a recognised pipeline welding standard such as API 1104, or equivalent, or as defined in API 5L. |
| 4 | Low frequency electric resistance welds, induction welds, flash welds or oxyacetylene welds. |
| 5 | Welds with a history of causing hydrotest failures. |
| 6 | Visual and magnetic particle (or similar) inspection of a sample of welds (at least 0.1% of the pipes or girth welds in the pipeline) indicate poor quality weld. |
| 7 | Non-destructive testing of a sample of seam or girth welds using manual shear wave ultrasonic technology (UT), time of flight diffraction (TOFD), or other suitable method shows a high density of anomalies, or the presence of anomalies outside the workmanship limits in a current welding standard. |
| 8 | More than 0.1% girth welds have anomalies recorded using Magnetic Flux Leakage (MFL) inspection tool. |

**Table 6: Indicators of a 'poor quality' weld**

# 7 DENT FATIGUE ASSESSMENT

## 7.1 European Pipeline Research Group (EPRG) Model

The fatigue assessment of plain dents is carried out using the EPRG dent fatigue life estimation method, as recommended in the Pipeline Defect Assessment Manual (PDAM) Reference 3. PDAM recommends that a fatigue life reduction factor of 13.3 is applied to ensure a lower bound prediction is obtained for plain dents, and an additional fatigue life reduction factor of 10 is applied to dents associated with welds.

The EPRG model is detailed in Section A1.1, Appendix 1.

An approximate indication of the impact on fatigue life of plain dents is shown in Table 7, for dents associated with welds the fatigue life is reduced by factor of 10.

Examples of SN curves for dented pipelines based on the EPRG formula are shown in Figure 3. These SN curves relate to dent depths of 2.5%, 5%, 7.5% and 10% OD at varying wall thicknesses assuming a base stress cycle of 125N/mm$^2$.

| Plain dent depth % dia | EPRG Fatigue Prediction as % of Fatigue life of Undented Pipeline |
|---|---|
| 2.5 | 10 |
| 5 | 2 |
| 7.5 | 1 |
| 10 | 0.5 |

**Table 7 – Impact of Dents on Pipeline Fatigue Life**

Table 7 and Figure 3 only give an indication of the reduction in fatigue life of dented pipelines and should not be used for specific dent fatigue assessments. Where a screening assessment carried out using the EPRG model indicates the fatigue life is exceeded, a more detailed dent fatigue assessment should be carried out or the dent feature should be investigated.

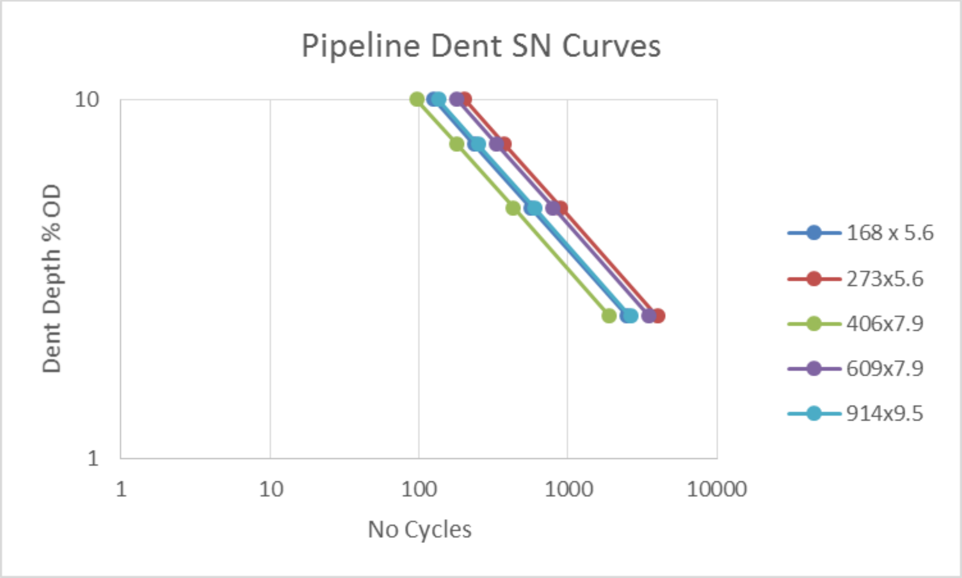


**Figure 3 – Examples of Plain Dent SN Curves based on EPRG Formula**

The above fatigue prediction methodology has been developed as an excel calculator for use by UKOPA members (Reference 11).

## 7.2 Fatigue Assessment of Dents with Associated Corrosion

For the fatigue assessment of plain dents with associated corrosion of depth up to 20% of wall thickness, it is recommended that the nominal cyclic hoop stress range required as input to the EPRG dent fatigue model is multiplied by the stress concentrations factors (SCF) given in A1.2 [6].

## 7.3 Dent Stress Concentration Factors (SCFs)

Recommended equations for dent stress concentration factors are given in Section A1.3 of Appendix 1. These are taken from Reference 12.

It is recommended that the EPRG model is used to establish a lower bound fatigue life, and the SCF equations given in Section A1.3 of Appendix 1 are used in conjunction with the Class B SN Curve from BS 7608 (Reference 13) to establish a more realistic fatigue life.

## 7.4 Fatigue life Assessment using Finite Element Analysis (FEA)

More accurate predictions of dent fatigue life can be achieved using a combination of FEA to calculate the stress concentration due to the dent, and an SN curve to estimate fatigue life. For these approaches it is recommended that expert guidance is sought. The methodology applied should include:

- Use of high-resolution geometry inspection data to produce a finite element model geometry;
- Use of an elastic material model to take account of shakedown of the dented material that would occur over many internal pressure cycles;
- Use of results for the maximum principal stress as a function of internal pressure;
- Application of a lower bound SN curve appropriate to the pipe material, and weld quality if the dent is located on a weld (for example from PD 5500, Reference 14);
- Calculation of the predicted fatigue life by summing predicted fatigue damage over a known internal pressure history.

# 8 RECORDS

It is important that accurate records of repaired dents are kept so that repaired dents can be excluded from future assessments and repair programmes.

Records should also be retained of any dent fatigue life assessments. These will need to be re-evaluated if the fatigue loading caused by internal pressure variations changes significantly during the future operation of the pipeline, for example due to changes in valve control systems or product batching arrangements. It is therefore important that all assessments are appropriately recorded and logged so that they can be re-assessed should the pressure cycling of the pipeline change significantly or if the anticipated lifetime of the pipeline is extended.

# 9 REFERENCES

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15 UKOPA/14/016, UKOPA Dent Management Strategy Guidance, Jane Haswell, August 2014.

16 IGEM/TD/2 Edition 2, Communication 1764, Assessing the Risks From High Pressure Natural Gas Pipelines

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# Appendix 1 - Dent Fatigue Assessment Models

## A1.1 EPRG Model for Plain Dents

The fatigue assessment of plain dents is carried out using the EPRG formula (Reference 3) as follows:-

$$N_c = 1000\left[\frac{(\sigma_U - 50)}{2\sigma_A K_S}\right]^{4.292}$$

Where:-

$N_c$ = Predicted number of cycles to failure

$\sigma_U$ = UTS

$2\sigma_A$ = equivalent cyclic stress at R = 0, N/mm$^2$

$t$ = wall thickness

$K_s$ = stress concentration factor

$2\sigma_A$, the equivalent stress at R = 0 is calculated as follows;

$$2\sigma_A = \sigma_U \left\lfloor B\sqrt{(4 + B^2)} - B^2 \right\rfloor$$

$$B = \frac{\dfrac{\sigma_a}{\sigma_U}}{\sqrt{1 - \left(\dfrac{\sigma_{\max} - \sigma_a}{\sigma_U}\right)}} = \frac{\dfrac{\sigma_a}{\sigma_U}}{\sqrt{1 - \dfrac{\sigma_a}{\sigma_U}\left(\dfrac{1+R}{1-R}\right)}}$$

$K_s$ is given by the equation:-

$$K_s = 2.871\sqrt{H_o \frac{t}{D}}$$

Where:-

D = Pipe outside diameter

t = pipe wall thickness

$H_o$ = dent depth at zero pressure

$H_r$ = dent depth at pressure

$$H_o = 1.43 H_r$$

NOTE:- PDAM recommends that a factor of 13.3 is applied to the calculated fatigue life to ensure a 95% probability of lower bound prediction of test data.

The fatigue life prediction obtained using the EPRG model for plain dents as detailed above should be reduced by a factor of 10 if the dent is associated with a weld.

## A1.2 EPRG Model Applied to Dents with Associated Corrosion

To assess the fatigue life of plain dents associated with corrosion of depth up to 20% of wall thickness, the nominal cyclic hoop stress range required as input to the EPRG dent fatigue model is multiplied by the following SCF [6]:

$$SCF_{HOOP} = A_1 + \left[ A_2 (CD)^2 \left( \frac{Ln(ACL)}{Ln(CCL)} \right)^2 \right] + \left[ A_3 \frac{CD^2}{\left( \frac{CCL}{\sqrt{Dt}} \right)} \right] + \left[ A_4 \frac{(CD)^2 ACL}{CCL} \right] + \left[ A_5 (CD)^2 Ln \left( \frac{CCL}{ACL(CD)} \right) \right]$$

The terms D and t are pipe diameter and wall thickness, ACL and CCL are the axial and circumferential half length of the corrosion respectively, and CD is corrosion depth (expressed as a decimal, i.e., 20%t is 0.2). The terms $A_1$ to $A_6$ are equation fitting constants, which for corrosion up to 20%t in depth are as follows;

$A_1$ : 1.47
$A_2$ : 8.91
$A_3$ : -0.23
$A_4$ : -0.72
$A_5$ : 0.67

## A1.3 Dent SCF + SN Models

The dent SCF is taken as the difference between the maximum principal stress range (corresponding to the minimum and maximum operating pressure) over the remote hoop stress range in the pipe, away from the dent region (Reference 12).

The SCF increases as the dent depth $H_o$ or $H_r$ increases, where

$H_o$ = dent depth at zero pressure after removal of indenter and after spring back

$H_r$ = dent depth at zero internal pressure after spring back and rerounding

For a dent depth ratio described by $H_o/D$ the SCF is given by;

$$SCF = \frac{\Delta\sigma}{\Delta\sigma_{hoop}} = 2.05\ln\left(65\frac{H_o}{D}+1\right)+1$$

For a dent depth ratio defined by $H_r/D$ the SCF is given by;

$$SCF = \frac{\Delta\sigma}{\Delta\sigma_{hoop}} = 1.8\ln\left(88\frac{H_r}{D}+1\right)+1$$

$\Delta\sigma$ = maximum principal stress range (units: N/mm$^2$)

$\Delta\sigma_{hoop}$ = hoop stress range in the pipe away from stress concentrations (units: N/mm$^2$).

Both equations give an upper bound SCF for a single smooth dent.

The fatigue life is then predicted using the Class B S-N curve from BS 7608 where the stress range is modified by the above SCFs for the dent as follows:

$$N = 1.01\times10^{15}\left(SCF\times\Delta\sigma\right)^{-4}$$