Technical Note

Client:	UKOPA		
Project title:	Development of Guidance for the Prioritisation of Dents		
Subject:	Analysis of Test Cases		
Prepared by:	Aaron Lockey	**Checked by:**	Roland Palmer-Jones
Authorised by:	Phil Hopkins		
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1. BACKGROUND

UKOPA members have identified that modern in-line inspections report large numbers of shallow dents. The existing UKOPA dent management strategy (DMS) [1] sometimes categorises these dents as requiring repair, particularly when the dent affects a weld and weld toughness data is not available, or pressure cycling is significant. This can lead to an onerous repair schedule.

The use of high resolution geometry tools means that even shallow dents with depths less than 2% of the pipe diameter can now be measured and reported with reasonable accuracy. The methods available to analyse dents, and particularly dents on welds, have not kept pace with the developments in inspection technology. There is research work underway that should enable the industry to better understand the behaviour of dent damage in pipelines.

The objective of the present project is to provide additional guidance to pipeline operators for inclusion in the UKOPA DMS. This guidance will define the options for pipeline specific dent assessment for shallow dents affecting welds where the existing strategy requires excavation and possible repair.

Penspen has completed a review of published work and international best practice covering dents on welds, in particular welds of unknown quality, which is set out in the literature review report [2]. The proposed changes to the UKOPA DMS were based on the literature review and covered in a technical note [3]: the present technical note should be read alongside the proposed DMS changes.

The proposed DMS changes allow the prediction of dent fatigue life using a methodology based on Finite Element Analysis (FEA). This methodology is thought to be accurate, but has not yet been fully validated against full scale tests. It was recommended in the previous technical note [3] that UKOPA should carry out this validation work.

1.1 Objectives

This technical note describes the application of the proposed DMS guidance [3] to three test cases, covering a variety of shallow dents in UK liquid pipelines.

The assessments in the present technical note are intended to be illustrative examples, and should not be taken as thorough formal assessments of the dents concerned.

2. EVALUATION OF TEST CASES

2.1 Dent and Pipeline Properties

Information about three dents has been provided by UKOPA members. The dent properties and pipeline properties at the dent locations are given in Table 1.

Units 7&8, Terrace Level, St. Peter's Wharf, Newcastle upon Tyne, NE6 1TZ, UK
Tel: +44 (0) 191 238 2200, integrity.ncl@penspen.com, www.penspenintegrity.com

Dent number	1	2	3
Pipeline	Crude Oil	Multi Product	Multi Product
Outer diameter	711.2 mm	273.0 mm	323.8 mm
Wall thickness	7.1 mm	4.77 mm	6.41 mm
Year of construction	1966	1981	1962
Linepipe type	SAW	ERW	Seamless
Material grade	X52	X52	X42
MAOP	46.2 bar	79 bar	71.5 bar
Reported dent depth	1.4% diameter	1.59% diameter	2.5% diameter
Dent orientation	Bottom of line	Top of line	Bottom of line
Dent interacts with weld	No, orientation of seam weld is known	Unknown	No
Pressure cycles	Estimated 399 cycles per year of 20 bar before Jan 2012, 44 bar thereafter	Equivalent to 26.4 cycles of MAOP per year	Equivalent to 23.2 cycles of MAOP per year
Dent has failed	Yes, in 2013	No	No

Table 1: Dent properties and pipeline properties at dent location

2.1.1 Dent Causes

Dent 1 has been excavated, and was caused by an object left in the pipe trench. Dent 2 has a shape and orientation consistent with damage caused during construction. Dent 3 is located on the bottom of the line, and cannot have been disturbed since construction. Therefore it is assumed that all three dents have been present since the date of construction.

2.1.2 Failure of Dent 1

Dent 1 failed by leaking through a crack in the dent in May 2013. The indenting object had been removed in 2010, so the dent was unconstrained. The proposed DMS includes a new guidance note stating that any excavated dent of any size, on a pipeline subject to significant cyclic loading, should be repaired: this guidance would now apply to Dent 1.

2.1.3 Surface Damage in Dent Locations

No damage to the pipe surface (such as gouging or corrosion) was reported during the excavation of Dent 1, or after Magnetic Flux Leakage (MFL) in-line inspections of Dents 2 and 3.

2.1.4 Pressure History of Dents

The magnitude of pressure cycles applied to Dent 1 became greater in January 2012, but detailed pressure data has not been made available for the current study. Estimates of pressure cycle magnitude and frequency are therefore used.

Pressure data recorded at the ends of each pipeline over a period of 9 years are used for Dents 2 and 3. These data may over-estimate the magnitude of pressure cycles at the dent locations.

2.1.5 Weld Quality at Dent 2

Dent 2 is located in Electric Resistance Welded (ERW) pipe, and the location of the seam weld cannot be determined from the inspection data. It is therefore assumed that the dent is located on the weld.

The ERW weld is assessed against all the proposed weld quality criteria in Table 2 and Table 3.

Item	Criterion	Weld meets criterion
1	The welds have a Charpy toughness of greater than 30 J minimum and 40J on average from three specimens, at the pipeline's minimum operating temperature.	No
2	The line pipe was manufactured to API 5L Edition 25 (1970) or later, or equivalent.	Yes
3	The weld was fabricated to a recognised pipeline welding standard such as API 1104, or equivalent, or as defined in API 5L.	Yes
4	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) shows a good quality weld with a clean cap, no spatter, no surface-breaking planar flaws, and no undercut.	No
5	Non-destructive testing of a sample of welds (at least 0.1% of the pipes 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.	No
6	Records show, or it is considered likely that, a high level 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.	No

Table 2: Indicators of a 'good quality' weld and assessments of Dent 2 ERW weld

Item	Criterion	Weld meets criterion
1	Welds of known low toughness (Charpy toughness less than 30 J minimum and 40 J on average from three specimens).	Yes
2	Pipe not manufactured to API 5L or equivalent.	No
3	An operating temperature less than the line pipe's drop weight tear test transition temperature.	No
4	The 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).	No
5	The weld is likely to contain cracks or defects.	No
6	Welds not fabricated to a recognised pipeline welding standard such as API 1104, or equivalent, or as defined in API 5L.	No
7	Low frequency electric resistance welds, induction welds, flash welds or oxyacetylene welds.	No
8	Welds with a history of causing hydrotest failures.	Yes
9	Non-destructive testing of a sample of 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.	No

Table 3: Indicators of a 'poor quality' weld and assessments of Dent 2 ERW weld

The ERW weld in the pipeline containing Dent 2 does not meet all the criteria of a 'good quality' weld (Table 2), and does meet some of the criteria for a 'poor quality' weld (Table 3). Low Charpy toughness has been recorded in tests, hydrotest failures were attributed to failure of the ERW weld, and the required level of non-destructive testing has not been carried out. On this basis, it is credible that the weld could have cracked when the dent was introduced, regardless of the applied strain.

The weld is assigned to the 'poor quality' level in the proposed DMS. Repair is recommended with priority level 4 as defined in the proposed DMS.

A full expert assessment has been completed of Dent 2 and similar dents in the same pipeline. It concluded that cracking when the dent was introduced was not credible for strains less than 2%, based on (briefly):

- The results of an in-line ultrasonic crack detection inspection showed no cracks in any of the dents, and no widespread ERW weld cracking problem;
- No cracking has been observed in other similar and deeper dents in the same pipeline, which have already been excavated and repaired.

The strain in the dent was calculated, and the fatigue life was predicted using the FEA method. The dent was found not to require repair.

The proposed DMS is intended to provide conservative general guidance. The expert assessment described above is specific to the pipeline concerned, and is not generally applicable. The present Technical Note describes the direct application of the proposed DMS guidance only, so the weld is treated as 'poor quality'.

2.2 Dent Assessments using Flow Diagrams

The route through the assessment flowchart in the updated DMS is shown for each dent in Figures 1 to 3. Red lines represent use of the FEA fatigue life estimation method where appropriate. Blue lines indicate the route followed when the EPRG fatigue life estimation method is used, where this is different. The FEA and EPRG methods are explained in Appendices A and B.

The calculated strain, predicted fatigue life, and assessment outcome for each dent are shown for the FEA method in Table 4, and for the EPRG method in Table 5. The repair priority levels are as defined in the proposed DMS, with lower priority numbers indicating a higher priority for investigation and repair.

Dent number	Calculated peak strain (%)	Reported dent depth (% diameter)	Predicted fatigue life using FEA method (years)	Predicted date of failure	Outcome
1	0.99	1.4	40.3 (Note 1) 5.6 (Note 2)	2006 (Note 1) 2017 (Notes 2, 3)	Repair priority 16
2	-	1.59	-	-	Repair priority 4
3	4.74	2.5	221.9	2183	No further action

1. Using assumed pressure history for before January 2012.
2. Using assumed pressure history for after January 2012.
3. Assuming no fatigue damage prior to January 2012.

Table 4: Results and assessment outcome using FEA method

Dent number	Calculated peak strain (%)	Reported dent depth (% diameter)	Predicted fatigue life using EPRG method (years)	Predicted date of failure	Outcome
1	0.99	1.4	54.0 (Note 1) 1.8 (Note 2)	2020 (Note 1) 2013 (Notes 2, 3)	Repair priority 16
2	-	1.59	-	-	Repair priority 4
3	4.74	2.5	17.0	1979	Repair priority 17

1. Using assumed pressure history for before January 2012.
2. Using assumed pressure history for after January 2012.
3. Assuming no fatigue damage prior to January 2012.

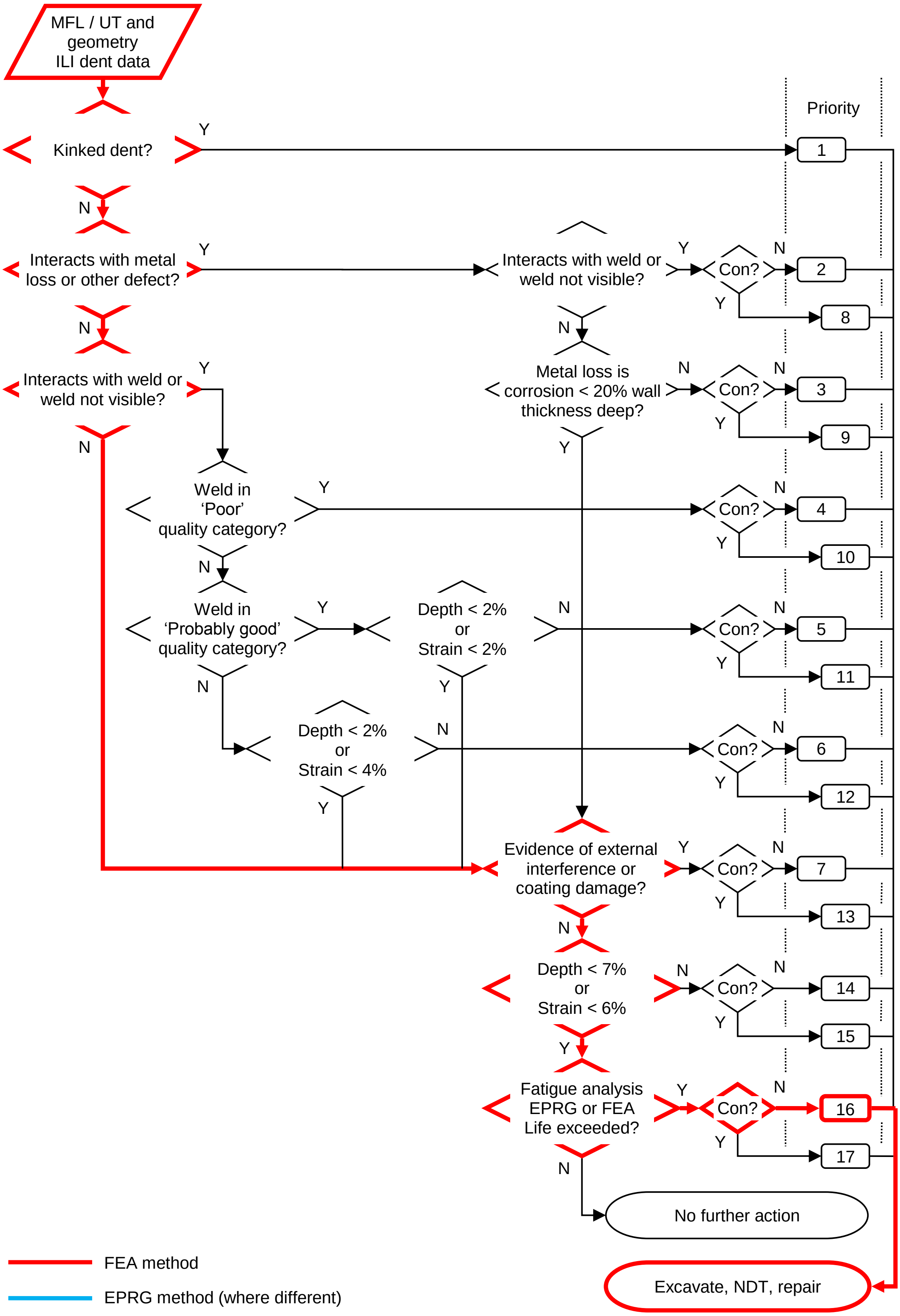
Table 5: Results and assessment outcome using EPRG method

The peak calculated strain at Dent 1 is less than the acceptable limit of 6% for a dent not located on a weld. The predicted fatigue life of 40.3 years (using the FEA method) expired in 2006 (before the pressure regime changed in 2012). It is also predicted that failure would occur 5.6 years after introduction of the dent if the revised pressure regime was applied (assuming no prior fatigue damage, which is unlikely to have been the case). Repair is therefore recommended.

The FEA method predicts a shorter fatigue life for Dent 1 than the EPRG method for the pressure history before 2012. The FEA method predicts a longer life than the EPRG method for the pressure history after 2012. This indicates that a detailed consideration of dent shape is important to accurately determine stress concentration in a dent, and that depth alone is not sufficient to characterise a dent.

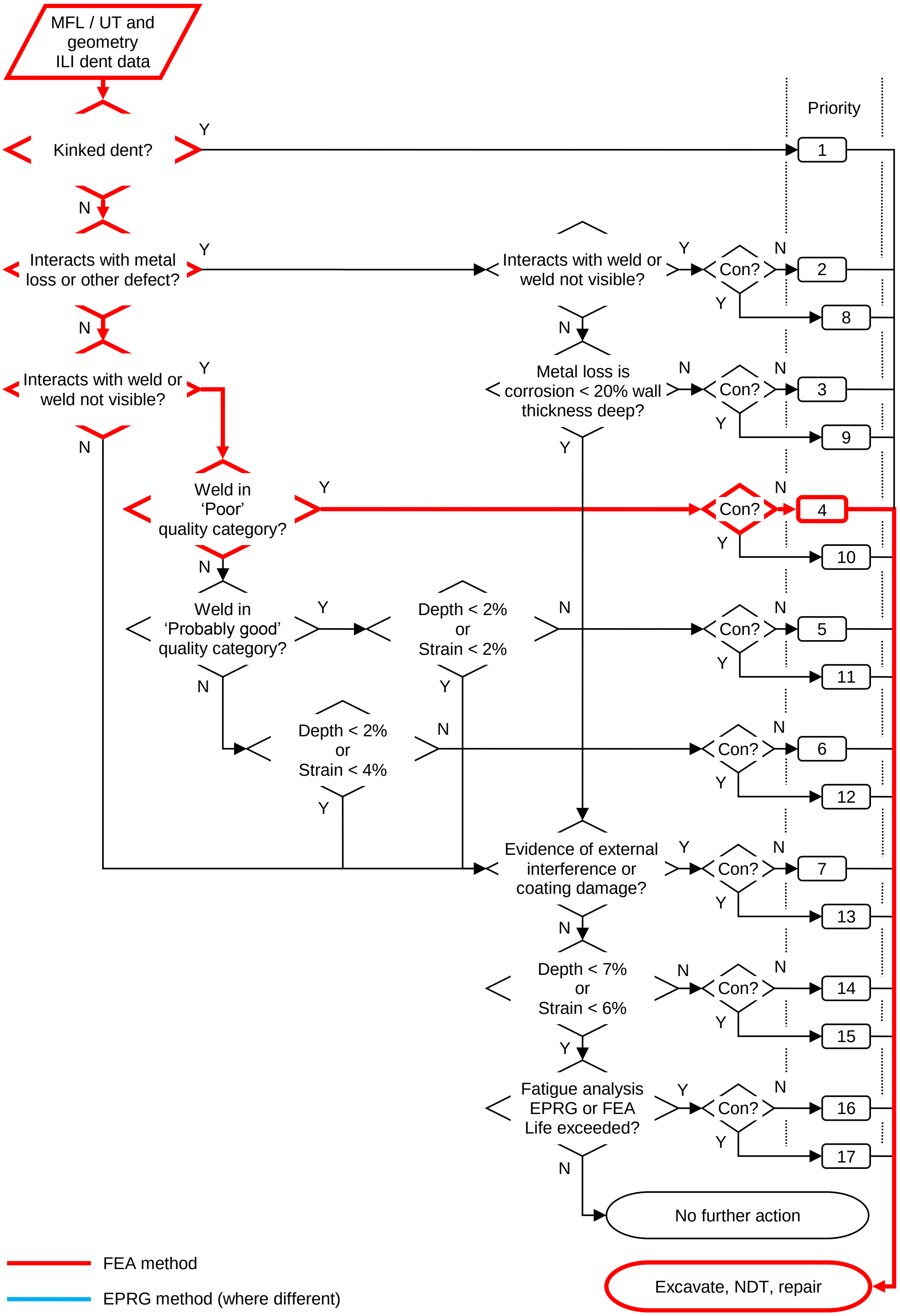
Repair of Dent 2 is recommended due to the poor quality weld.

The peak calculated strain at Dent 3 is less than the acceptable limit of 6% for a dent not located on a weld. The predicted fatigue life of 221.9 years (using the FEA method) is longer than the remaining useful life of the pipeline, so no repair is required. The predicted life using the EPRG method is less than the remaining pipeline life, so a repair is recommended when this method is used.



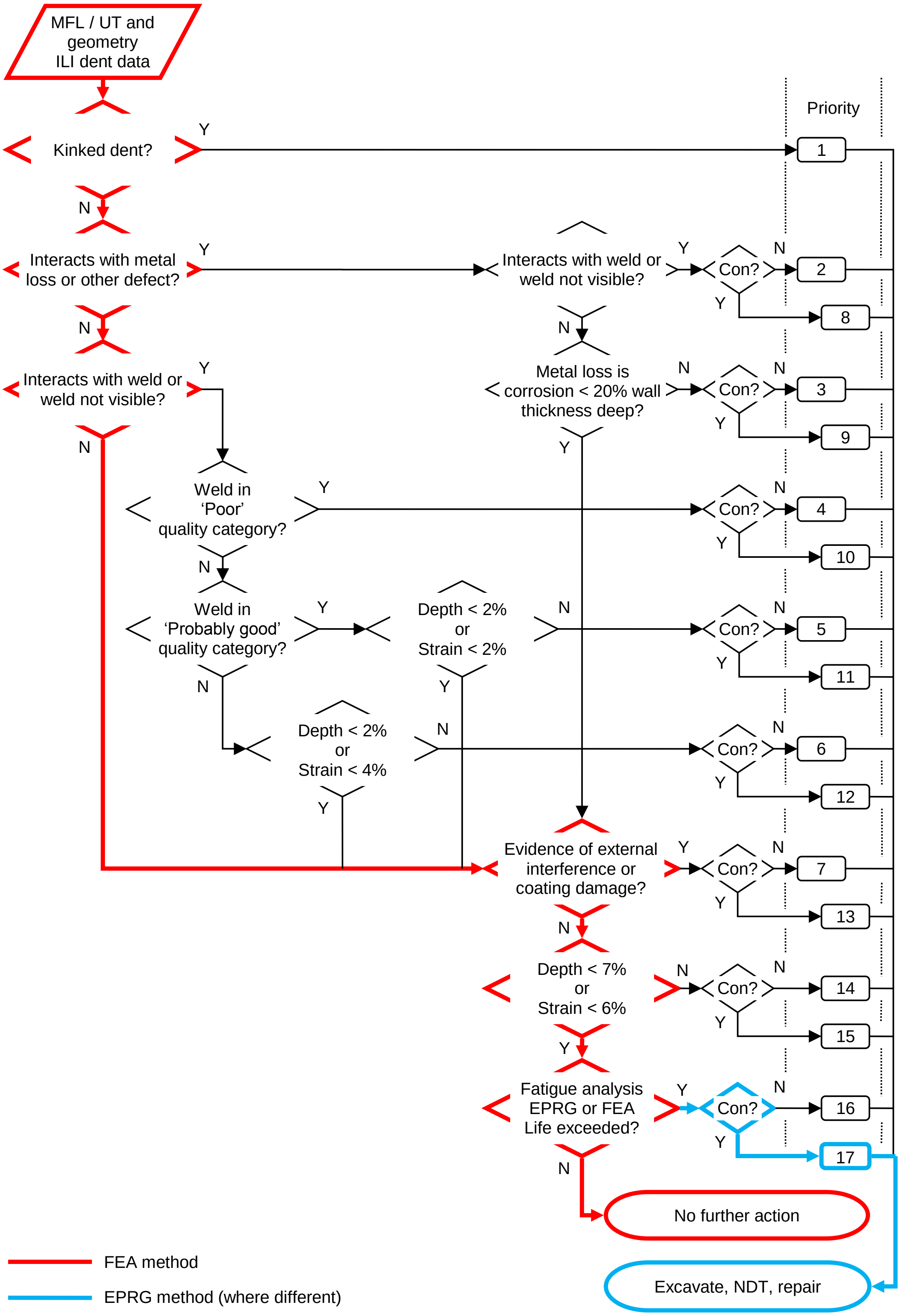
Note: 'Con' means 'constrained', as defined in the proposed DMS.

Figure 1: Dent 1 analysis and priority selection



Note: 'Con' means 'constrained', as defined in the proposed DMS.

Figure 2: Dent 2 analysis and priority selection



Note: 'Con' means 'constrained', as defined in the proposed DMS.

Figure 3: Dent 3 analysis and priority selection

3. CONCLUSIONS

1. The updated DMS guidance has been applied successfully to three example dents.
2. The assessment outcomes using the FEA method were consistent with this method being conservative, because they recommended:
    a. Repair for the dent that had failed, in addition to new guidance requiring repair of this dent following the first excavation;
    b. Repair for one of the two dents that had not failed.
3. The method based on FEA reduced the number of repairs recommended compared to the EPRG method.

4. RECOMMENDATIONS

UKOPA should adopt the proposed updates to the dent management strategy once validation of the finite element fatigue calculation method has been completed as recommended by previous phases of the present study.

5. DISCLAIMER

6. REFERENCES

[1] Anon; *UKOPA Dent Management Strategy*; UKOPA/10/0051 Version 10; 2010.

[2] Anon; *Development of Guidance for the Prioritisation of Dents: Literature Review for Dents Associated with Welds*; Penspen Report number 13131-RPT-001 Revision 0; April 2014.

[3] Anon; *Development of Guidance for the Prioritisation of Dents: Proposed Guidance for Dents Associated with Welds*; Penspen Technical Note Number 13131-TN-001 Revision 0; April 2014.

APPENDIX A FATIGUE LIFE PREDICTION BASED ON FEA METHOD

A.1 Background

A.2 FEA Model

A generic Abaqus finite element model has been used to calculate the stress in the pipe wall when internal pressure is applied to a dented pipe. The model uses shell elements, which assume a linear variation in through-thickness strain. This approach is appropriate for pipes with a large diameter to wall thickness ratio.

Any dent geometry can be used in the model, and any internal pressure can be applied. An example model with illustrative stress results is shown in Figure A.1.

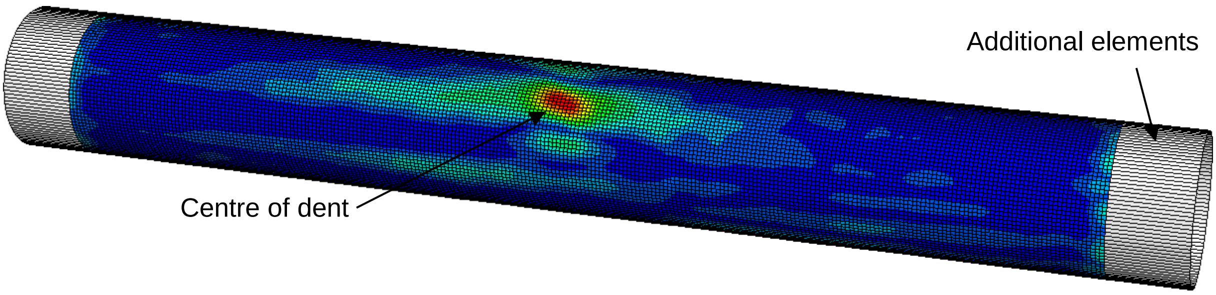


Figure A.1: Example of finite element model and stress results

The element size is chosen so that the stress results vary smoothly between elements, and the peak stress areas (shown as red in Figure A.1) are spread over several elements. This ensures the elements are sufficiently small to accurately model the peak stresses.

Additional elements are added to the ends of the model, and the outer edges are fixed. These elements provide restraint to model the effect of the adjacent pipe, without affecting the localised behaviour of the dent.

The internal pressure cycles since each dent was introduced will have caused shakedown of the pipe material as illustrated in Figure A.2. Shakedown is defined in IGE/TD/12 as “A condition of elastic system response once initial localised yielding has occurred under the limits of coincident pressure and temperature.”

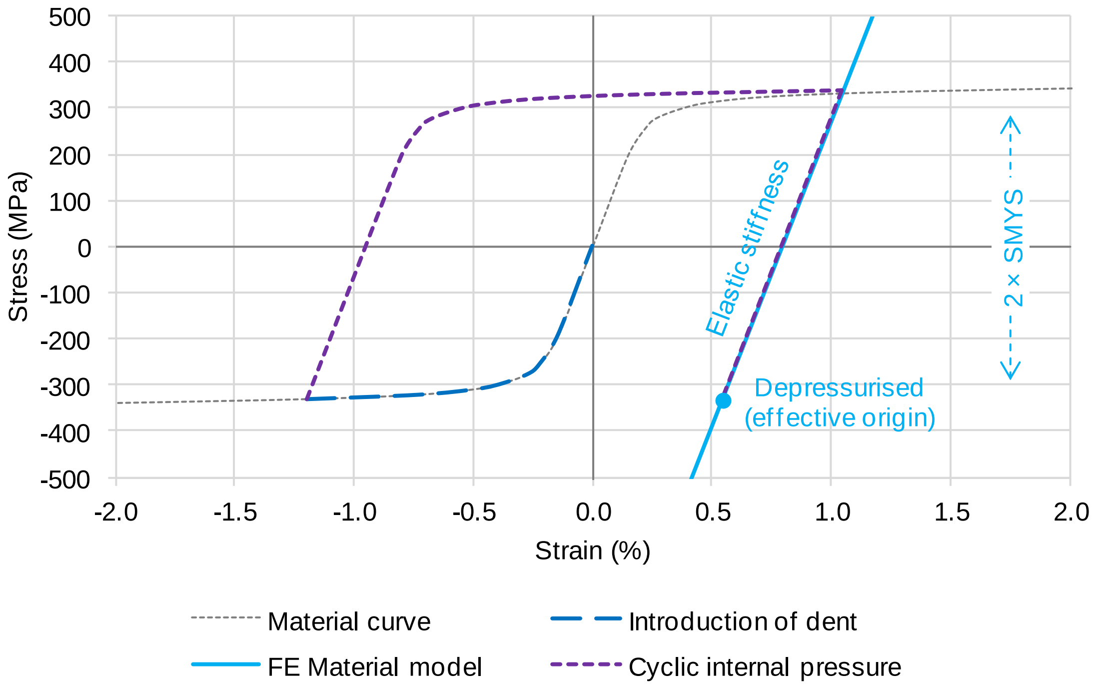


Figure A.2: Illustrative example of shakedown and finite element material model

A linear-elastic material curve is used in the finite element model. This will give accurate results for stresses less than double the material SMYS. The results will also be appropriate for use with an SN fatigue life curve, as explained in Section A.5.

A.3 Depressurised Shape

Applying internal pressure to a dented pipe causes the dent to re-round, and the centre of the dent moves outwards. The dent geometries in the current study were measured by an in-line inspection geometry tool while internal pressure was applied to the dent, and while re-rounding was present. The measured dent shapes are therefore shallower than the dent shapes when no internal pressure is applied.

The depressurised dent shape is required to form the initial shape for the finite element models, so that accurate stresses can be predicted for the applied internal pressure variations.

An iterative algorithm has been used with the finite element model to determine the depressurised dent shape that, when the internal pressure at the time of the in-line inspection is applied, results in the measured dent geometry.

A.4 Stress due to Internal Pressure

The finite element model has been used to predict the peak stress in each dent as a function of internal pressure. Stress is generally predicted to increase non-linearly with internal pressure. As internal pressure increases, the dent re-rounds, and the stress concentration in the dent reduces.

A.5 Fatigue Life

The fatigue life of a dent can be estimated using a relationship between applied cyclic stress and the number of cycles to cause failure, called an SN curve.

PD 5500:2012 gives a series of lower bound SN curves relating cyclic stress S and a conservative estimate of the number of cycles to cause failure N; constant values m and A are defined for the curves:

$$S^m N = A$$

The SN curves in PD 5500 were developed as lower bounds to test data, and are appropriate for fatigue crack growth in pressure vessels. The curves remain acceptable lower bound relationships for post-yield stress cycles, provided an equivalent elastic stress is used. This means that the stress input to the SN curve should always equal the Young's modulus multiplied by the applied strain cycle. Thus an elastic material curve has been used in the finite element model, as discussed in Section A.2.

The appropriate SN curves from PD 5500 for the dents considered in the present study are given in Table A.1.

Curve	Description	Constants		Applied to dents
		m	A	
'C'	Parent plate (no weld)	3.5	4.22×10^{13}	1, 3
'D'	Seam weld	3.0	1.52×10^{12}	2

Table A.1: Selected SN curves

Multiple stress ranges are present in the pipeline due to fluctuating internal pressure, but the SN curve gives the fatigue life (as a number of cycles) for a single stress range. Therefore it is necessary to sum the fatigue damage caused by the different stress cycles. The applied stress is a non-linear function of the applied internal pressure (see Section A.4).

The fatigue life in years from the date the dent was introduced T is estimated using the annual number of pressure cycles f_i and the pressure cycle magnitudes p_i at each dent location:

$$T = \frac{A}{\sum_i [f_i \cdot S(p_i)^m]}$$

The pressure cycle counts and magnitudes at each dent location are described in the main Technical Note.

APPENDIX B FATIGUE LIFE PREDICTION BASED ON EPRG METHOD

B.1 Background

The original empirical model developed by the European Pipeline Research Group (EPRG) was described by Corder and Chatain in 1995. It is based on the S-N curve for the fatigue strength of (longitudinal) submerged arc welded pipe given in DIN 2413, combined with a calculation of the stress concentration due to the dent.

This method is recommended by PDAM for the assessment of plain dents (not containing welds) because it gives the best fit with published full scale test data.

B.2 Method

The number of internal pressure cycles required to cause fatigue failure of a dent can be estimated as follows:

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

where:

$$2\sigma_A = \sigma_U\left[B(4 + B^2)^{0.5} - B^2\right]$$

$$B = \frac{\dfrac{\sigma_{\max} - \sigma_{\min}}{2\sigma_U}}{\left[1 - \dfrac{\sigma_{\max} + \sigma_{\min}}{2\sigma_U}\right]^{0.5}}$$

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

and:

t	Pipe wall thickness (mm)
D	Outside diameter of pipe (mm)
H_o	Dent depth measured at zero pressure (mm)
σ_U	Steel ultimate tensile strength (MPa)
$\sigma_{\max}$	Maximum hoop stress in stress cycle (MPa)
$\sigma_{\min}$	Minimum hoop stress in stress cycle (MPa)

If required, the dent depth at zero pressure can be estimated from the dent depth measured at pressure:

$$H_o = 1.43H_r$$

where:

H_r	Dent depth measured at pressure (mm)

PDAM recommends that the predicted fatigue life should be divided by a ‘model uncertainty factor’ of 13.3 to account for scatter in the full scale test data. The fatigue life should be further divided by 10 for dents on welds to account for the reduced fatigue life of the weld compared to the parent plate.