

Development of Guidance for the Prioritisation of Dents

Validation of Dent Fatigue Life Estimation Method

UKOPA

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1. EXECUTIVE SUMMARY

1.1 Background

Modern in-line inspections report large numbers of shallow dents. The existing UKOPA dent management strategy 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 objective of the present project is to provide additional guidance to pipeline operators for inclusion in the UKOPA dent management strategy. This guidance will define the options for dent assessment for shallow dents affecting welds where the existing strategy requires excavation and possible repair.

It is becoming common practice to use finite element analysis in the assessment of stress concentration and fatigue life of dents. Methods based on finite element analysis can give more accurate estimates of fatigue life than the existing best practice methods such as the EPRG method, primarily because they take full account of the dent shape.

1.2 Objectives

Finite element methodologies have not yet been thoroughly validated against full scale tests. It is therefore currently inappropriate to include them in general guidance such as the UKOPA dent management strategy.

The objective of the present phase of the project is to validate against full scale test data an approach to fatigue life estimation using finite element analysis and SN curves for unrestrained plain dents and unrestrained dents on welds.

1.3 Conclusions and Recommendations

Use of a dent fatigue life estimation methodology based on elastic finite element analysis and the PD5500 SN curves is shown to be safe compared to the results of full scale tests. This applies to smooth dents with depth of up to 4.8% of the pipe diameter at zero internal pressure, which do not interact with any other defects or stress raisers except girth welds or seam welds.

It is therefore recommended that guidance on the use of this methodology should be included in the revised UKOPA dent management strategy. The guidance should contain four key elements, as described in the present report:

1. The dent shape should be measured using by high resolution geometry in-line inspection or field measurements of equivalent accuracy;
2. The measured dent shape should be smoothed using the method based on moving high-order polynomials described in Section 6.1;
3. The dent shape may be measured when the pipe is pressurised, but the finite element methodology presented here uses the dent shape at zero internal pressure; the depressurised dent shape should therefore be estimated using the iterative method described in Section 6.2;

4. A finite element model with a linear elastic material should be used to calculate the cyclic stress in the dent;
5. An appropriate SN curve from PD5500 should be used to predict the dent fatigue life. The 'C' curve should be used for plain dents. The 'D' curve may be used for dents on longitudinal seam welds with no weld cap (particularly ERW welds). The 'E' curve should be used for dents on all other welds. Any dented weld must meet the quality criteria described in the Penspen technical note "Proposed Changes to the UKOPA Dent Management Strategy".

2. INTRODUCTION

2.1 Background

UKOPA members have identified that modern in-line inspections report large numbers of shallow dents. The existing UKOPA dent management strategy [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 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 [2,3,4].

The objective of the present project is to provide additional guidance to pipeline operators for inclusion in the UKOPA dent management strategy. 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.

It is becoming common practice to use finite element analysis in the assessment of stress concentration and fatigue life of dents [5]. Methods based on finite element analysis can give more accurate estimates of fatigue life than the existing best practice methods such as the EPRG method [5,6], primarily because they take full account of the dent shape.

2.2 Objectives

Finite element methodologies have not yet been thoroughly validated against full scale tests. It is therefore currently inappropriate to include them in general guidance such as the UKOPA dent management strategy.

The objective of the present phase of the project is to validate against full scale test data an approach to fatigue life estimation using finite element analysis and SN curves for unrestrained¹ plain dents and unrestrained dents on welds.

The methodology developed in the present report does not use detailed material data, since this is often unavailable for operational pipelines.

The present study covers unrestrained dents only, because no reliable method exists to determine whether a dent detected by in-line inspection is restrained. It is conservative to assume a dent is unrestrained for the purposes of fatigue life prediction.

¹ A restrained dent has the indenting object (often a rock left in the construction trench) remaining in place, which prevents the dent re-rounding when internal pressure is applied. An unrestrained dent does not have an indenter present and is free to re-round.

3. PUBLISHED FULL SCALE TESTS

3.1 Sources

It was intended to base the present study on ring tests carried out by British Gas in the 1980s [7], which would have allowed simple two-dimensional finite element modelling. It proved difficult to determine the exact experimental setup for this work, so more thoroughly documented experimental work was sought.

The full scale test data supporting the validation work in the present study is provided by three International Pipeline Conference papers from 2008 [2], 2010 [3], and 2012 [4]. These describe PRCI sponsored work by BMT Fleet and SES to produce a validated finite element model for dent fatigue modelling. The main output of the project was a simplified method of dent fatigue life assessment based on dent geometry, but this has not been published in the open literature.

The 2008 paper describes 12 full scale fatigue tests on modern grade X52 and grade X70 pipes (called batch A and batch B respectively). 6 tests were restrained plain dents; the remaining 6 were unrestrained plain dents. Material testing and the resulting measured material properties are described for both material batches.

The 2010 paper describes 18 full scale fatigue tests on plain dents (including the 12 tests from the 2008 paper), using the same batch A and batch B pipe materials. 6 tests were restrained plain dents; the remaining 12 were unrestrained plain dents. A further 16 full scale fatigue tests on dents on welds are described, again using the batch A and B pipe materials. 6 tests were restrained dents on welds; the remaining 10 were unrestrained dents on welds. 2 of the restrained dents were located on the seam weld; the remaining 14 dents were located on or within 2 inches of a girth weld.

The 2012 paper describes 17 full scale fatigue tests on plain dents. 1950s era grade X52 pipe was used, after being removed from pipeline service. This is referred to in the present report as batch C material. Detailed material data were not given. 8 tests were restrained plain dents; the remaining 9 tests were unrestrained plain dents.

3.2 Test Parameters

The restrained dent tests are not considered in the present study. The unrestrained dent tests are summarised in Table 1. The basic pipe properties are summarised in Table 2.

Dent type	Material batch	Number of tests
Plain	A	6
	B	6
	C	9
On weld	A	4
	B	6
Total		31

Table 1: Summary of full scale tests on unrestrained dents

Batch name	Era	External diameter (mm)	Wall thickness (mm)	Grade	SMYS (MPa)	Detailed material properties
A	Modern	609.6	7.9	X52	360	Yes
B	Modern	609.6	8.9	X70	485	Yes
C	1950s	457.2	7.9	X52	360	No

Table 2: Basic pipe properties

In each test, the pipe was supported from below, and indented using a hydraulic ram. Ellipsoidal pipe end caps were used as indenters. Some dents were introduced with internal pressure in the pipe. After indenting, an initial pressure cycle was applied to the dent to cause re-rounding. Between zero and ten pressure cycles from zero to 80% SMYS² were applied manually, followed by automatic pressure cycling from 10% to 80% SMYS until failure occurred.

The groups of full scale tests included variations of the following parameters:

- Indenter travel, and therefore dent depth at indentation pressure before the indenter is removed (2.5% to 10% of outer diameter reported – see note below);
- Indenter diameter (60.3 mm to 323.8 mm);
- Hoop stress caused by internal pressure in the pipe during indentation (zero to 80% SMYS);
- Initial hoop stress cycle caused by internal pressure (80% to 100% SMYS).

The reported indenter travel is between 5% and 20% of outer diameter. For example, the indenter travel reported for all the unrestrained plain dents in the 2010 paper is approximately 15% of outer diameter. The reported ‘residual’ dent depth at zero pressure, after indenter removal, mostly varies between 5% and 6% of outer diameter. Such a degree of spring-back has not been observed by other full-scale test programmes [8,9], where generally only 20% to 30% of dent depth is lost during spring-back of similarly sized dents.

All reported measurements of indenter travel have been halved in the present study. This gives consistent modelling results (discussed in Section 4.5), and makes the measured spring-back agree with previous studies. Other reported measurements of dent depth (such as before and after pressure cycling) appear to be reported correctly.

The test parameters for all tests included in the present study are given in Appendix A.

3.3 Material Testing

The 2008 paper details the material testing carried out on the batch A and batch B materials. The 2010 paper covers the material model developed for these materials. The basic material properties are given in Table 3.

² Where a percentage of SMYS is used as a measure of internal pressure, it is the hoop stress as a proportion of SMYS, calculated as follows:

$$\%SMYS = \frac{\text{Pressure} \times \text{Outer diameter}}{2 \times \text{Wall thickness} \times SMYS} \times 100\%$$

The nominal outer diameter and wall thickness are used.

Batch	Average yield strength (MPa)	Average ultimate tensile strength (MPa)	Young's modulus (GPa)
A	436	499	200
B	522	649	

Table 3: Basic material properties determined by testing

The batch C material is not characterised in detail, so the present study uses the same properties as the batch A material, which is the same grade. It is noted that the yield strength of the batch A material exceeds the SMYS by approximately 20%. This may not accurately represent the vintage batch C material, but no better data is available.

A nonlinear kinematic plasticity model is described in the 2010 paper. This tracks material hardening by moving the centre of the yield surface as the strain state changes, using multiple 'backstresses'. It enables accurate modelling of cyclic loading effects. The material plasticity for the first loading cycle takes the following form (which differs from the form in the 2010 paper, but matches that used by the Abaqus FEA code):

$$\sigma = \sigma_y + \sum_{i=1}^n \frac{C_i}{\gamma_i} (1 - e^{-\gamma_i \epsilon_p})$$

where

- σ, ϵ_p are the true stress and true plastic strain
- σ_y is the stress at first yield
- C_i, γ_i are the fit parameters
- n is the number of backstresses in the model, in this case $n = 2$

The fit parameter values are not given in the papers, however Figure 11 in the 2010 paper shows the test data and fitted curves. These have been used to estimate the fit parameters given in Table 4. The resulting material curves are plotted in Figure 1, which are a close fit to those in the 2010 paper.

<i>i</i>	Batch A			Batch B		
	C_i (MPa)	γ_i	σ_y (MPa)	C_i (MPa)	γ_i	σ_y (MPa)
1	2551	16.17	218.8	2915	16.81	427.1
2	239100	2805		77860	510.9	

Table 4: Fitted material curve parameters

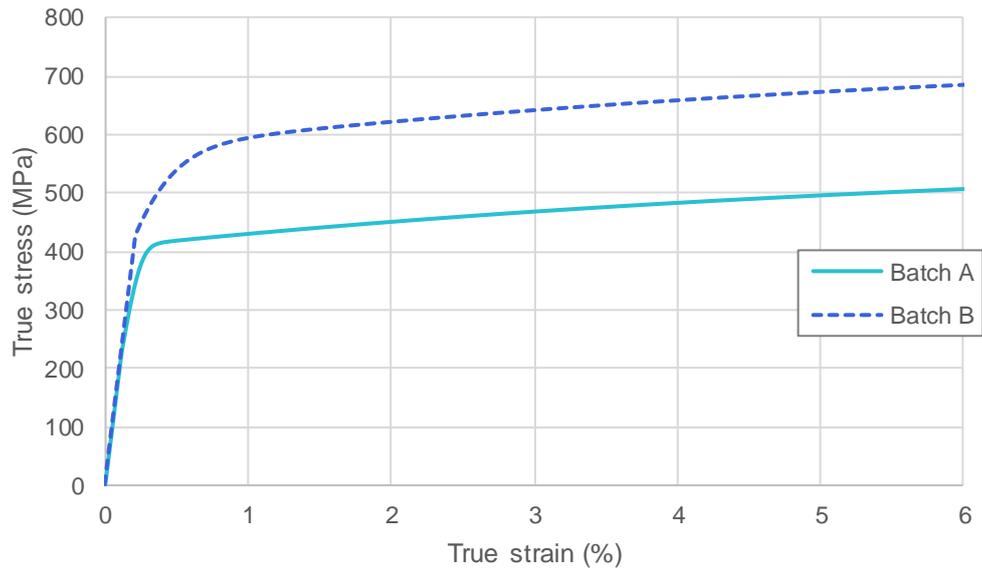


Figure 1: Fitted material curves

4. FINITE ELEMENT MODELLING

4.1 Modelling Methodology

Ideally, the detailed measured shape of each dent would be available. These shapes would be used to build simple elastic finite element models and determine the cyclic stress for each dent.

Such detailed measurements are not available. For each dent, an initial finite element model must therefore be used to reproduce the dent formation process and thereby determine the dent shape. The initial model will be referred to as the 'formation' model. The dent shape is then used in a second finite element model to determine the cyclic stress. This is used with an SN curve to predict the dent fatigue life. The second model will be referred to as the 'fatigue cycle' model.

The developed finite element models use the Abaqus FEA code. The formation model uses the detailed material model described in Section 4.3, and includes the following stages of dent formation:

- Indenting, with internal pressure if this was present in the corresponding full scale test;
- Removal of indenter (spring-back);
- Initial high pressure cycle (re-rounding);
- Subsequent pressure cycles between 10% and 80% SMYS until the material achieves a constant stress-strain cycle (shakedown), and the dent shape is stable.

The fatigue cycle finite element model uses a simple elastic material and a single application of internal pressure to determine the cyclic stress in each dent. This is the part of the approach being validated in the present study. It is effectively the same method that would be used if high-resolution in-line inspection geometry data were used to provide the dent shape as described in Section 6.

An automated process is used to execute the finite element models for multiple dents.

4.2 Model Geometry

A quarter shell model of the pipe is used with appropriate symmetry constraints. An element size equal to approximately half the wall thickness is used around the indenter for greater accuracy. The element size is increased away from the dent to reduce the number of elements and improve the calculation run-time. First-order elements (Abaqus type S4) are used, since these are most accurate for strains above approximately 1% which occur during indenting.

A rigid ellipsoidal indenter is used, defined using the diameter used in the appropriate full scale test. The minor diameter is half the major diameter, in accordance with specifications for ellipsoidal end cap geometry [10].

The pipe is supported on a rigid surface representing the 10 inch wide beam running perpendicular to the pipe axis. Vertical support is also provided at the end of the model to simulate the arrangement in the full scale tests. No gravity load is applied to the model, because its effects are small compared to internal pressure and indenting.

When internal pressure is applied to the model, a corresponding tensile axial force is applied at the end to simulate the end cap used in the full scale tests.

The model geometry is illustrated in Figure 2.

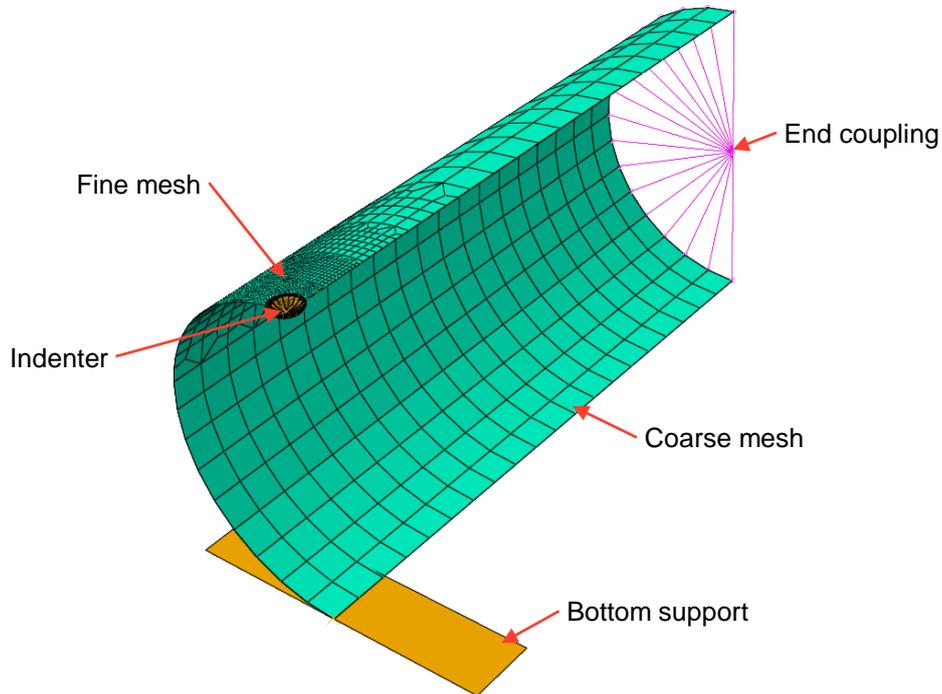


Figure 2: Illustration of model geometry

4.3 Material Modelling

The formation model uses a nonlinear kinematic material model with the parameters described in Section 3.3. This enables realistic tracking of the yield surface and hardening behaviour when stress reversals are applied, which means effects such as shakedown can be modelled accurately. This is not possible with conventional linear hardening models.

After multiple pressure cycles are applied to a dent, material shakedown will occur and a stable stress and strain cycle will be achieved. This may not be completely elastic, although plastic strains will be small. SN curves require this behaviour to be linearised, using a cyclic stress equal to Young's modulus multiplied by cyclic strain. The cyclic stress reported by the finite element model should not be used directly.

The fatigue cycle model uses an elastic material model, primarily because this part of the model is intended to be applied to in-line inspection geometry data from pipelines in service. SMYS or material grade is often not a good indicator of actual yield strength, and detailed material data are often not available. The strain history of a dent will also cause local hardening, which cannot be determined from in-line inspection data alone. An elastic material model is appropriate because material shakedown will have occurred, linearised stress is required, and no detailed knowledge of the material yield strength is available.

4.4 SN Curve Selection

The lower bound design SN curves from PD5500 [11] are used, because the situations these curves are specified for are a close match for those required here. Plain dents do not involve

a weld, and the ‘C’ curve is used – note that there is a kink in the ‘C’ curve where it would otherwise fall below the ‘D’ curve. For dents on girth welds, the ‘E’ curve is used. For dents on some longitudinal seam welds, use of the ‘D’ curve may be justified, however none of the dents considered in the present study are on a line pipe seam weld. The form of the PD5500 SN curves is given below, and the parameters are given in Table 5. The use of other SN curves is considered in Section 5.3.

$$S^m N = A$$

where

S is the cyclic stress

N is the predicted number of safe cycles before failure may occur

A, m are the curve parameters

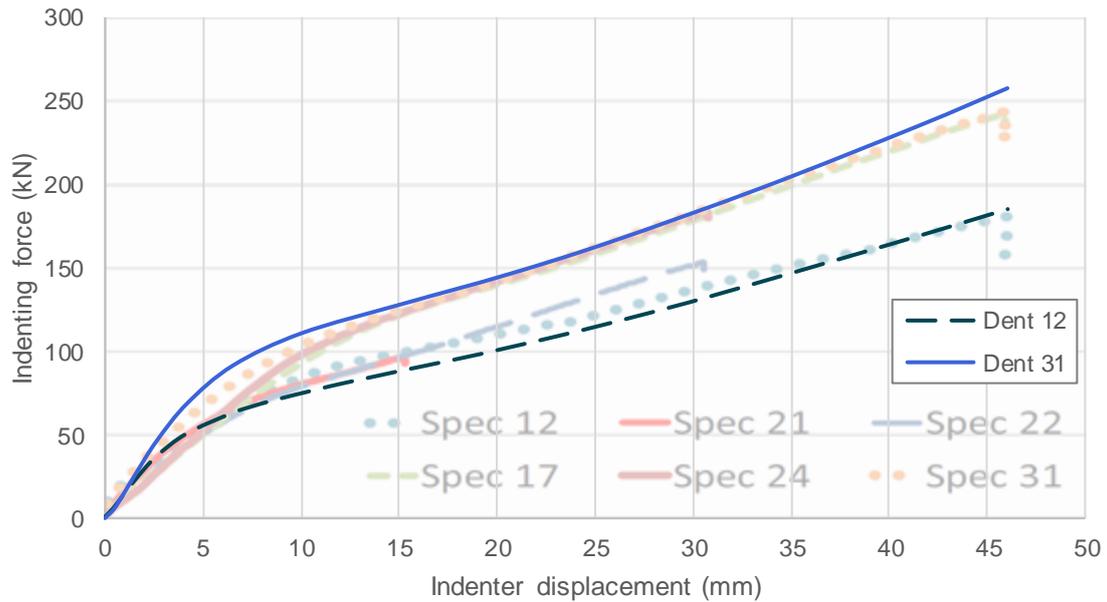
Curve name	Stress range	A	m
C	< 767 MPa	4.22×10^{13}	3.5
	> 767 MPa	1.52×10^{12}	3
E	All	1.04×10^{12}	3

Table 5: Lower bound SN curve parameters

4.5 Benchmarking against Full Scale Test Results

It is necessary to benchmark the results of the formation finite element model against full scale test results to give confidence that the process and material are modelled correctly. The papers include several plots showing results that can be used for comparison.

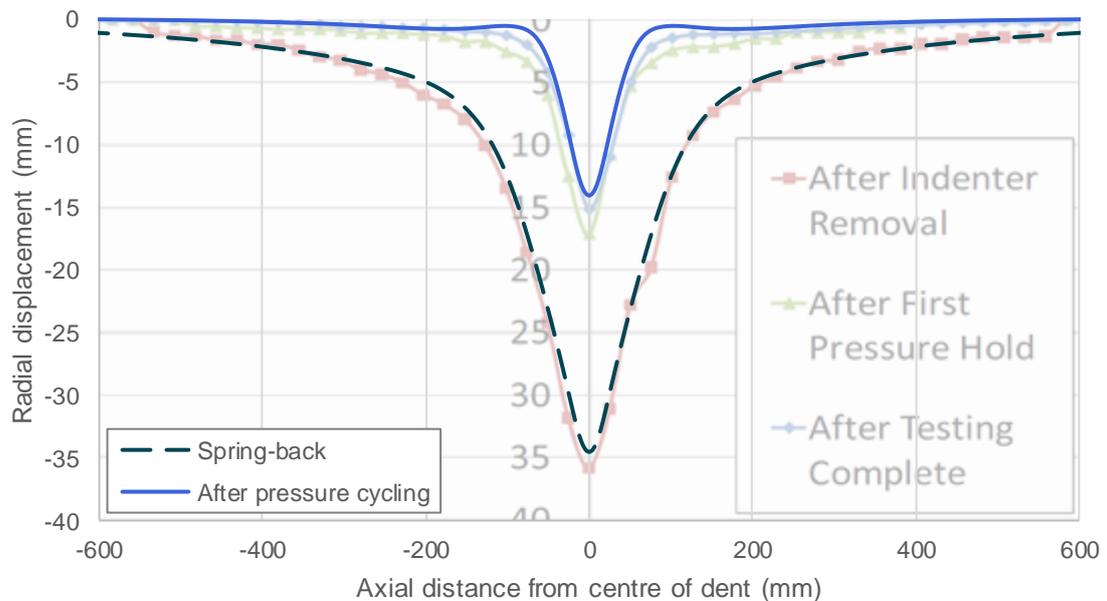
Figure 3 shows the force applied to the indenter as the dent is formed. Dents 12 and 31 are selected for comparison with the full-scale test data, which is shown in faded colours in the background. The displacement scale of the full-scale test data has been halved, as discussed in Section 3.2 (the original figure goes from zero to 100 mm displacement). This gives good agreement between the finite element results and the full scale test results.



Overlaid on Figure 1 from the 2010 paper – horizontal scale adjusted

Figure 3: Comparison of FEA predicted indenting force with test results

Figure 4 shows the predicted shape of dent 8 after spring-back (indenter removal), and after several pressure cycles when the dent shape has stabilised. A similar plot of full scale test measurements is shown in the background. There is good agreement between the finite element results and full scale test measurements, including the maximum depth and the overall dent shape.



Overlaid on Figure 5 from the 2010 paper

Figure 4: Comparison of FEA predicted dent shape with test results

Figure 5 shows a unity plot comparing the predicted and measured dent depths after pressure cycling. There is good agreement for the modern pipe, but poorer agreement for

5. PREDICTED FATIGUE LIFE RESULTS

5.1 Fatigue Life Predictions

The fatigue life of each dent has been predicted using the selected SN curves and the results from the fatigue cycle finite element model. Detailed results are presented in Appendix A. The predicted fatigue life is compared with the measure life in the unity plot in Figure 6.

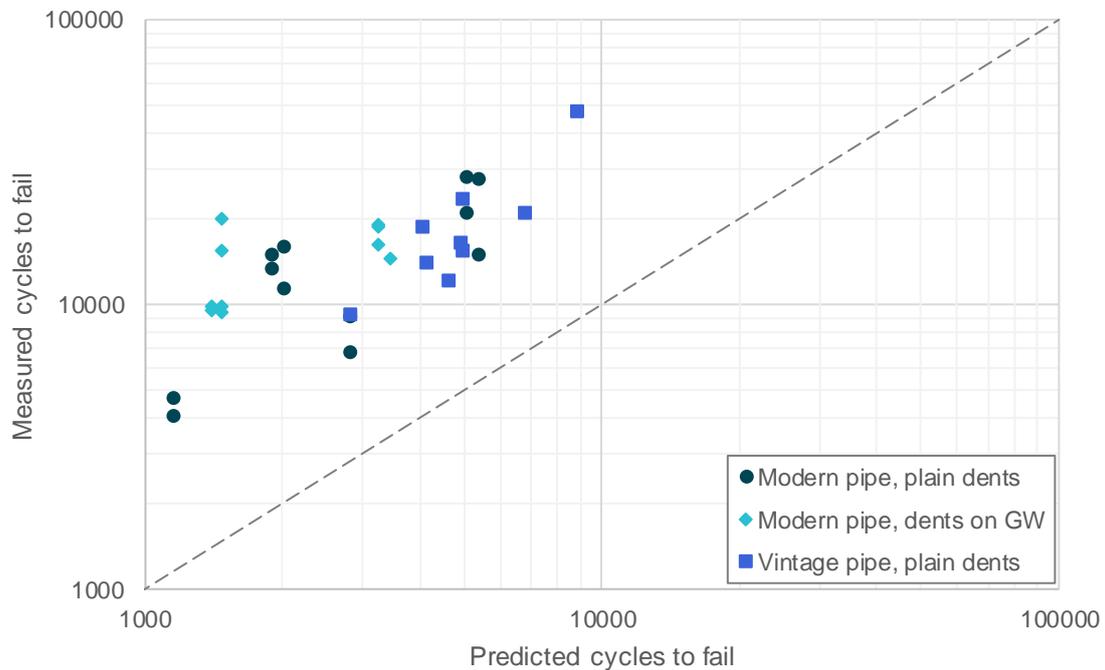


Figure 6: Comparison of predicted fatigue life with test results

The predicted fatigue life is conservative for all dents. The minimum factor of safety for plain dents is 2.4, and for dents on welds is 4.2. There is a clear correlation between the predicted and measured fatigue life.

5.2 Safety Factors

A statistical analysis is needed to determine any additional safety factors required to achieve a sufficiently low probability of failure.

Figure 7 plots the predicted cyclic stress in each plain dent against the measured number of cycles to failure. This is repeated in Figure 8 for dents on welds. The mean regression line through the data effectively represents the 'ideal' SN curve for the data. The lower bound line is offset from the mean line by three times the standard deviation of the data, and thus represents approximately a 99.87% probability of survival.

The PD5500 [11] 'design' SN curves are defined as a two standard deviation lower bound to test data. Two standard deviations is therefore considered a sufficient margin of safety for fatigue life. The relevant PD5500 SN curves are plotted in Figure 7 and Figure 8. They lie below the lower bound line for all but the highest stresses. They can therefore be used safely

without further safety factors to predict the fatigue life of dents using stresses from finite element analysis.

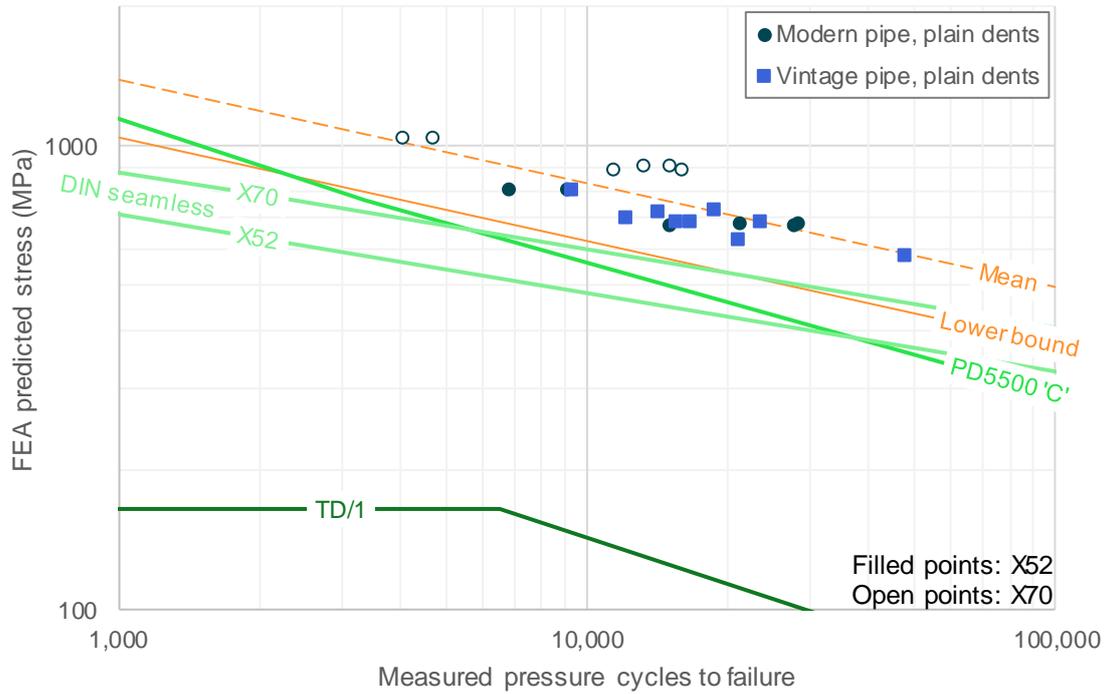


Figure 7: Comparison of FEA results with various SN curves for plain dents

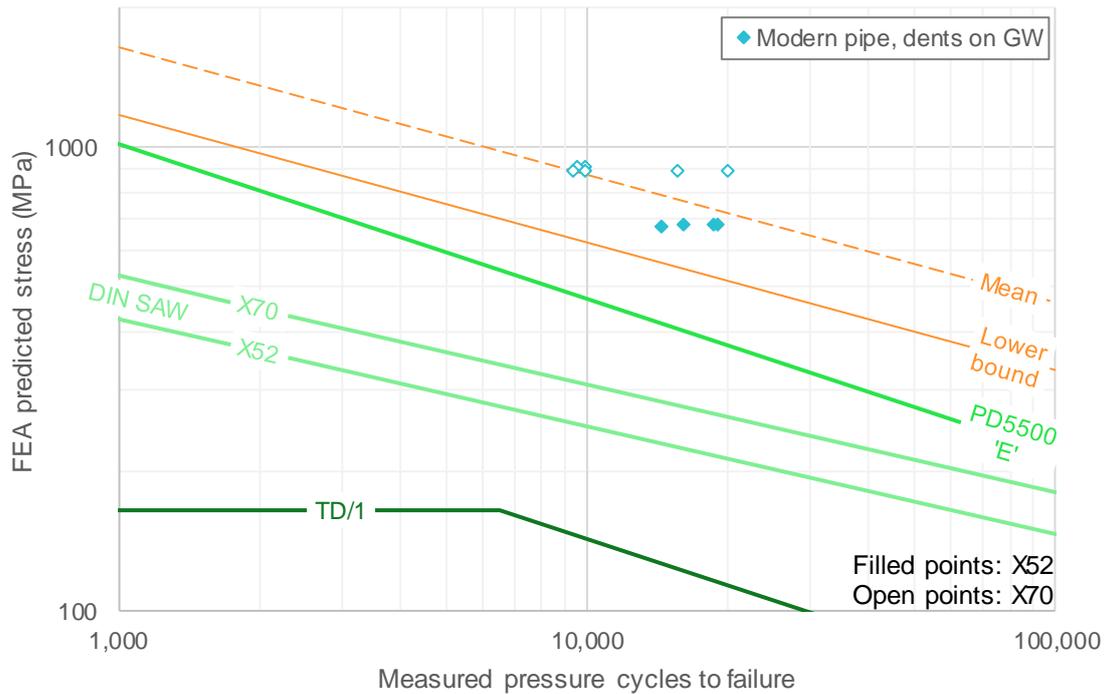


Figure 8: Comparison of FEA results with various SN curves for dents on welds

5.3 Other Possible SN Curve Selections

In Figure 7 and Figure 8, points representing grade X52 material are plotted differently to those representing grade X70 material. The X52 points generally lie below the mean line, while the X70 points generally lie above the mean line. This may indicate a material strength effect that is not considered by the PD5500 SN curves.

The existing best practice EPRG dent fatigue life estimation methodology [6] is based on an SN curve from DIN2413 [12]. The 'seamless' (plain pipe) curve is plotted in Figure 7 and the 'SAW' curve (girth welds) is plotted in Figure 8. These curves are dependent on the ultimate tensile strength of the material. Interestingly, the separation of the X52 and X70 curves approximately matches the separation of the groups of data points. However, the present study aims to validate a method that can be used when the material properties are unknown. Also the 'SAW' curve is very conservative. Therefore, although use of these DIN2413 curves would be appropriate, they are not recommended in conjunction with the finite element method considered by the present study.

Some design codes include SN curves for assessment of the effect of long term pressure cycling on seam welds. For example, the curve defined in TD/1 [13] is plotted in Figure 7 and Figure 8. It is very conservative compared to the other SN curves considered.

The PD5500 curves are considered the best for use with the finite element method considered by the present study, because they are sufficiently conservative but do not require detailed material properties. The 'C' curve should be used for plain dents. The 'D' curve may be used for dents on longitudinal seam welds with no weld cap (particularly ERW welds). The 'E' curve should be used for dents on all other welds. Any dented weld must meet the quality criteria described in the Penspen technical note "Proposed Changes to the UKOPA Dent Management Strategy" [14].

6. APPLICATION TO IN-LINE INSPECTION DATA

It is intended that fatigue life estimation by the combination of finite element analysis and SN curves should be applicable to dents measured by high resolution in-line geometry inspection.

6.1 Smoothing of Geometry Data

The shape of the dents considered in the present study has been determined by the formation finite element model. Thus they are very smooth, continuous shapes. Data from in-line inspection will contain measurement errors, and will not be smooth. If a measured shape is used directly to construct a finite element model, large stress concentrations are generally predicted at features that do not exist in reality, and the assessment can be very conservative.

Smoothing of the measured shape is required: increasing smoothing reduces conservatism until the real shape of the dent is reached. Too much smoothing can remove essential features of the dent shape, and thus can be non-conservative as shown in Figure 9. It is important that the smoothing technique preserves the peak dent depth, the shape of the dent centre, and the shape of the dent shoulders, since these areas are generally where the peak cyclic stress occurs.

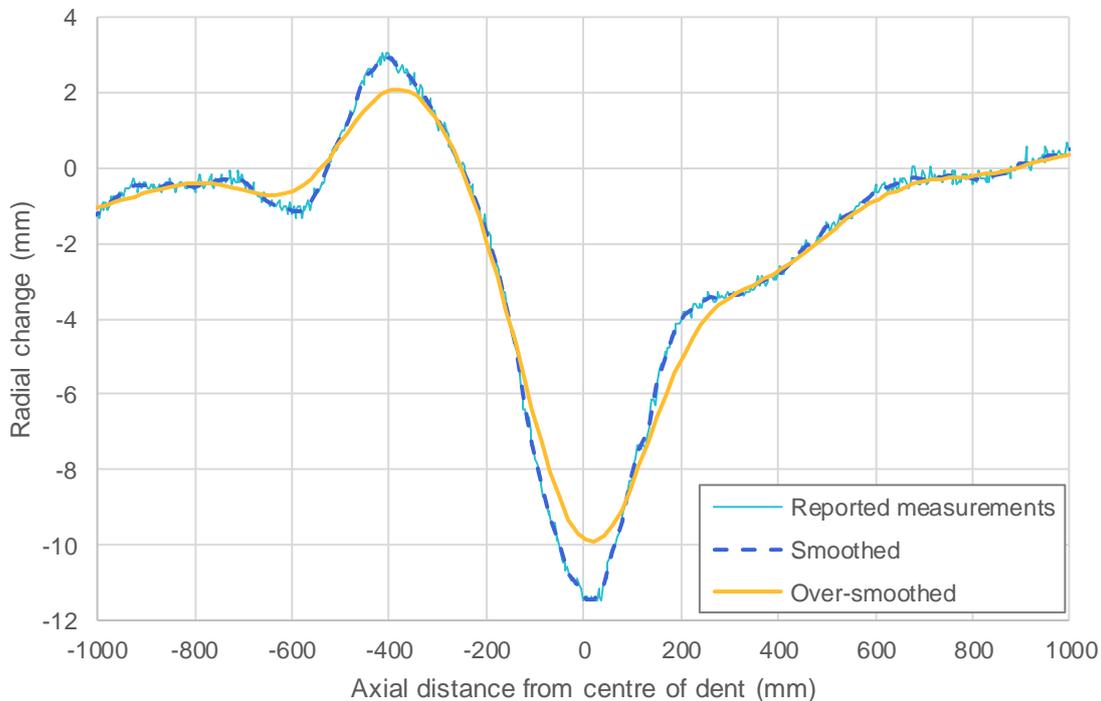


Figure 9: Illustration of excessive smoothing

A smoothing technique based on moving high-order polynomials has been found to be effective [15] at minimising measurement errors whilst maintaining the essential features of dent shape. Techniques based on lower-order polynomials (such as moving average or splines) can be difficult to balance between these objectives, and in particular can reduce peak dent depth if not used carefully.

6.2 Depressurised Dent Shape

The geometry of the finite element analysis model is defined with no internal pressure. In-line inspections are carried out with internal pressure applied, and therefore the re-rounded shape of dents is measured. The reported dent depth will be less than the depressurised dent depth. The reported dent shape must therefore be adjusted to provide an accurate starting geometry for the finite element model.

An iterative approach has been developed [15] and is recommended for estimating the depressurised dent shape, illustrated in Figure 10. It is based on finding the depressurised shape which causes the finite element model to predict the measured shape when internal pressure is applied.

1. Use the smoothed, measured dent shape as the initial guess of depressurised dent shape.
2. Generate a finite element model using the current shape guess, and apply the internal pressure at the dent location at the time of the inspection.
3. Calculate the difference between the resulting predicted dent shape and the measured dent shape with internal pressure applied. This estimates the error in the current shape guess.
4. If the error is small, the current shape guess is an accurate estimate of the depressurised dent shape.
5. Otherwise, generate a new shape guess by adding the error to the current shape guess.
6. Iterate by returning to step 2.

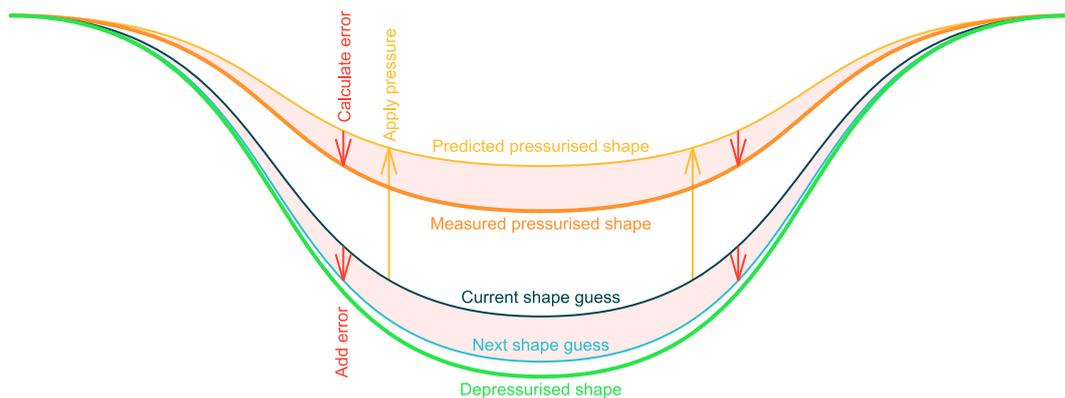


Figure 10: Iterative approach to estimating depressurised dent shape

7. CONCLUSIONS AND RECOMMENDATIONS

Use of a dent fatigue life estimation methodology based on elastic finite element analysis and the PD5500 SN curves is shown to be safe compared to the results of full scale tests. This applies to smooth dents with depth of up to 4.8% of the pipe diameter at zero internal pressure, which do not interact with any other defects or stress raisers except girth welds or seam welds.

It is therefore recommended that guidance on the use of this methodology should be included in the revised UKOPA dent management strategy. The guidance should contain four key elements, as described in the present report:

1. The dent shape should be measured using by high resolution geometry in-line inspection or field measurements of equivalent accuracy;
2. The measured dent shape should be smoothed using the method based on moving high-order polynomials described in Section 6.1;
3. The dent shape may be measured when the pipe is pressurised, but the finite element methodology presented here uses the dent shape at zero internal pressure; the depressurised dent shape should therefore be estimated using the iterative method described in Section 6.2;
4. A finite element model with a linear elastic material should be used to calculate the cyclic stress in the dent;
5. An appropriate SN curve from PD5500 should be used to predict the dent fatigue life. The 'C' curve should be used for plain dents. The 'D' curve may be used for dents on longitudinal seam welds with no weld cap (particularly ERW welds). The 'E' curve should be used for dents on all other welds. Any dented weld must meet the quality criteria described in the Penspen technical note "Proposed Changes to the UKOPA Dent Management Strategy".

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APPENDIX A: DENT PROPERTIES AND PREDICTED FATIGUE LIFE

Index	Material Batch	Indenter travel during indenting (%OD)	Hoop stress during indenting (%SMYS)	First hoop stress cycle (%SMYS)	Measured depth after fatigue failure (%OD)	FEA predicted depth after fatigue failure (%OD)	Measured fatigue life (cycles)	FEA/SN predicted fatigue life (cycles)	FEA predicted cyclic stress (MPa)
7	A	7.5	0	100	2.63	2.31	21103	5042	684.0
8	A	7.55	0	100	2.48	2.31	28211	5034	684.3
9	A	7.55	0	80	3.28	3.07	6825	2810	808.4
10	A	7.55	0	80	2.69	3.07	9116	2810	808.4
11	A	7.5	0	100	2.55	1.91	15063	5381	671.4
12	A	7.55	0	100	2.28	1.91	27575	5372	671.7
13	B	7.5	0	100	2.17	2.32	13262	1892	905.1
14	B	7.5	0	100	2.21	2.32	15065	1892	905.1
15	B	7.5	0	80	2.21	3.01	4035	1150	1043.5
16	B	7.5	0	80	2.22	3.01	4684	1150	1043.5
17	B	7.5	0	100	1.56	1.97	11415	2004	890.3
18	B	7.5	0	100	1.69	1.97	15949	2004	890.3
25	A	7.5	0	100	2.77	2.31	19063	3250	684.0
27	A	7.5	0	100	2.88	2.31	18633	3250	684.0
28	A	7.5	0	100	2.88	2.31	16107	3250	684.0
29	A	7.5	0	100	2.20	1.91	14472	3436	671.4
31	B	7.55	0	100	2.55	2.32	9890	1398	906.1
32	B	7.5	0	100	2.51	2.32	9506	1403	905.1
33	B	7.55	0	100	2.20	1.98	9386	1469	891.3
34	B	7.5	0	100	1.97	1.97	9871	1474	890.3
35	B	7.55	0	100	2.10	1.98	19959	1469	891.3

Index	Material Batch	Indenter travel during indenting (%OD)	Hoop stress during indenting (%SMYS)	First hoop stress cycle (%SMYS)	Measured depth after fatigue failure (%OD)	FEA predicted depth after fatigue failure (%OD)	Measured fatigue life (cycles)	FEA/SN predicted fatigue life (cycles)	FEA predicted cyclic stress (MPa)
36	B	7.5	0	100	1.88	1.97	15568	1474	890.3
48	C	7.5	0	100	2.90	2.76	23482	4974	686.6
50	C	7.5	40	100	4.30	3.20	16600	4897	689.7
51	C	7.5	80	100	4.80	3.50	12131	4617	701.4
52	C	7.5	0	80	2.50	3.15	9226	2822	807.4
53	C	10	40	80	1.30	1.72	18636	4049	728.3
54	C	7.5	0	100	1.00	1.11	47702	8824	582.9
55	C	10	80	105	1.40	1.36	21018	6782	628.5
56	C	10	0	100	2.80	2.53	15473	4933	688.3
57	C	10	0	80	0.80	1.81	14091	4150	723.1