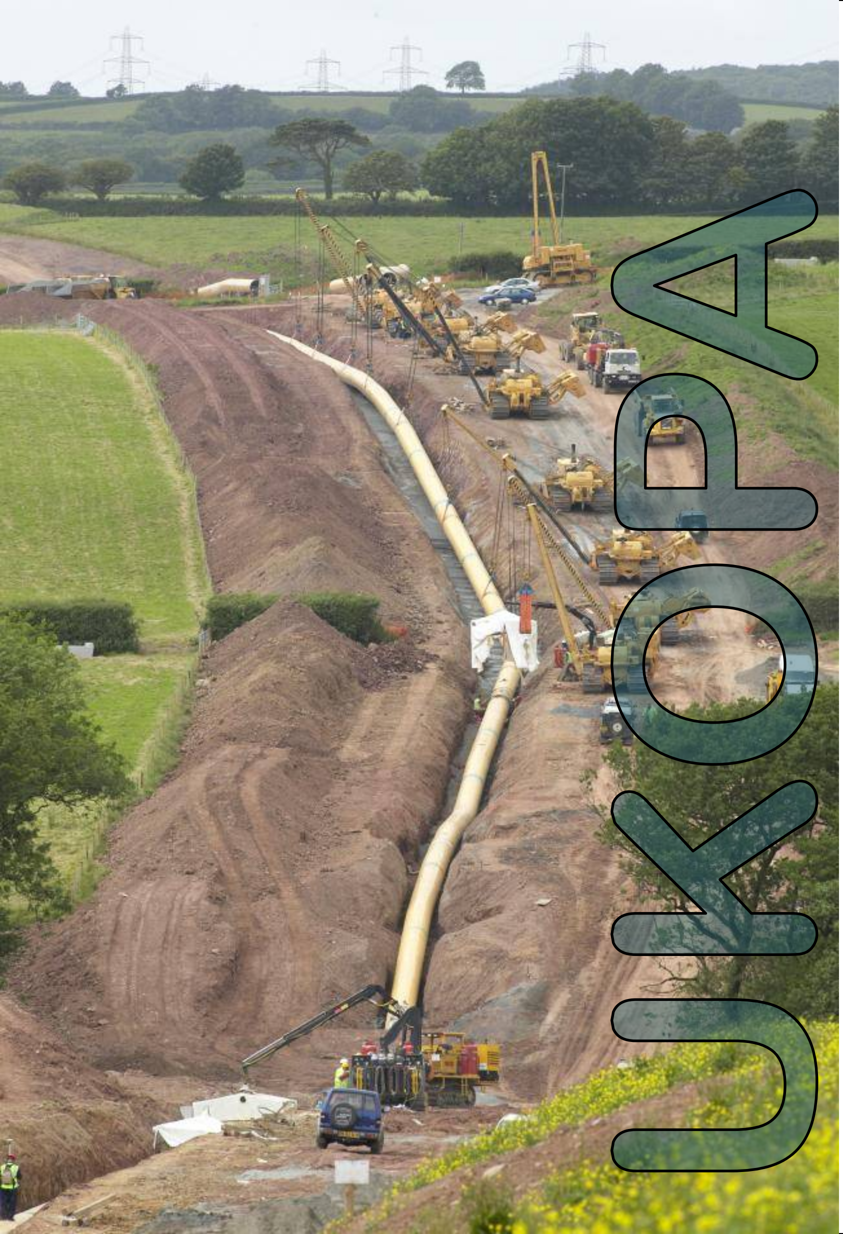
UKOPA

United Kingdom Onshore Pipeline Operators' Association



UKOPA Dent Management Strategy

Jane Haswell

UKOPA Dent Management Strategy – Background

- The majority of pipeline in-line inspections (ILI) are carried out using the magnetic flux leakage (MFL) inspection tools.
- MFL tools are capable of identifying and locating dents in the pipeline, but do not size dents.
- 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.
- Geometric ILI tools are capable of sizing the dent. However, where dents have been identified by MFL ILI only, there may be a time delay before geometric inspection can be scheduled.
- A Dent Management Strategy was therefore actioned which uses all available information and highlights critical actions.

Typical Pipeline Construction Dents

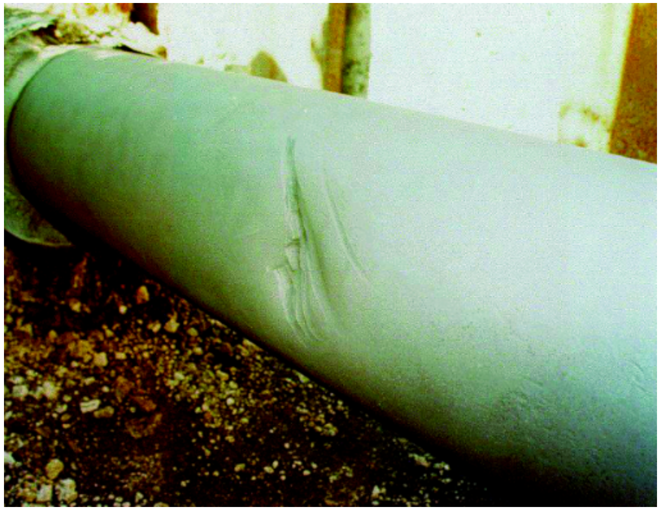
Construction Dents

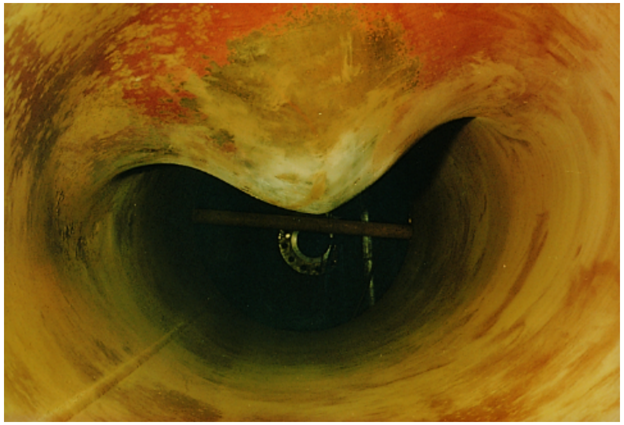
External Interference Dents

Smooth dent

Dent + gouge

Severe Pipeline Dents





Integrity Assessment of Construction Dents Subject to Fatigue Loading:

Shallow smooth construction dents are likely to be acceptable unless they are subject to fatigue.

A review for UKOPA was carried out by Dr Julia Race, Newcastle University:

- Code requirements and criteria
- Dent related pipeline failures
- Depth and strain based assessment approaches
- Static and fatigue assessment models
- Dent detection and measurement

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UKOPA Dent Management Strategy

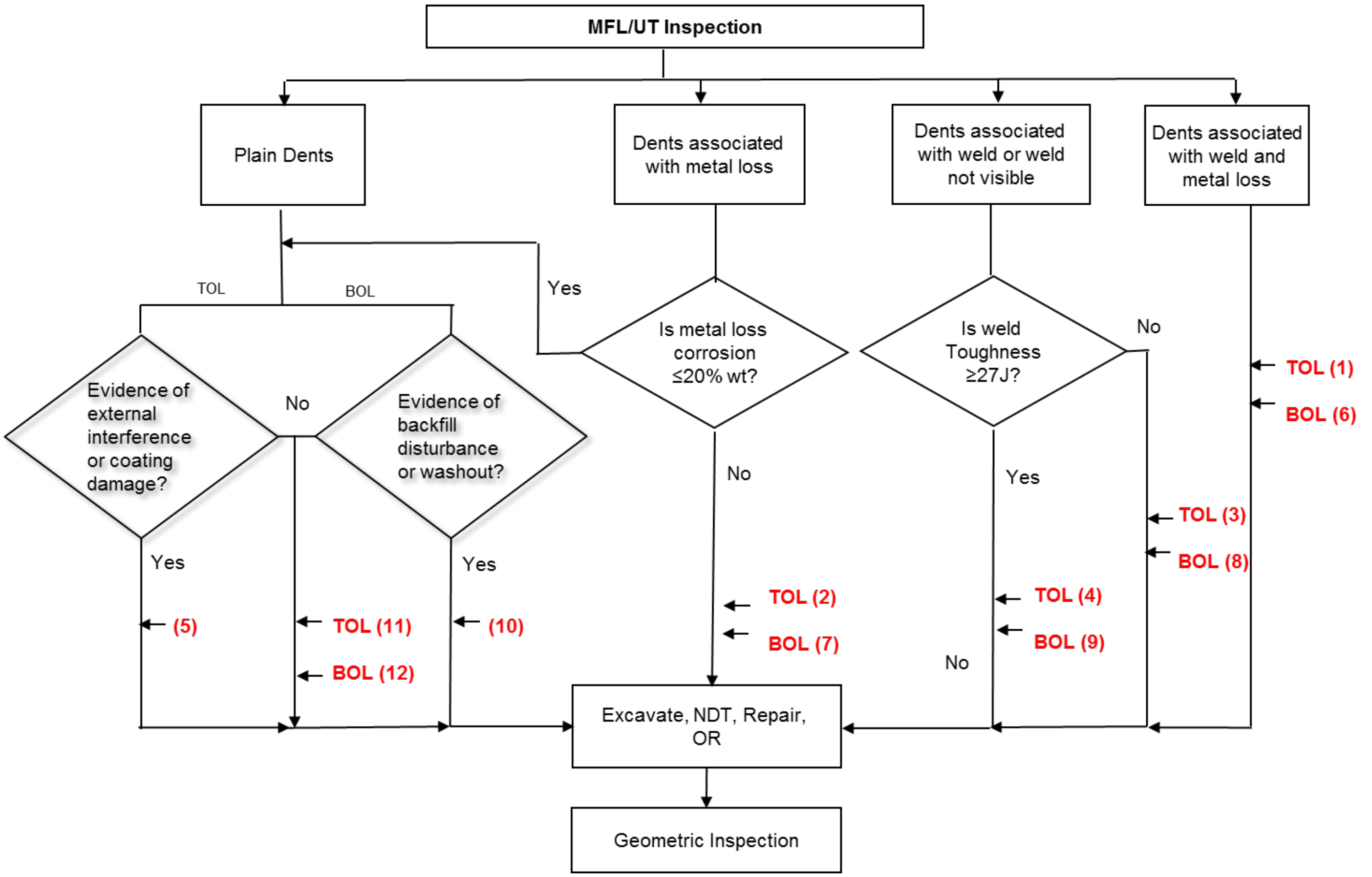
Following assessment of Julia Race's review, an initial work programme was initiated to develop:

- Prioritisation method for dent features detected by ILI for investigation based on:
    - Type of ILI tool
    - Feature location, characteristics, association with other damage & welds
- Assessment rules for dents subject to static and cyclic loading

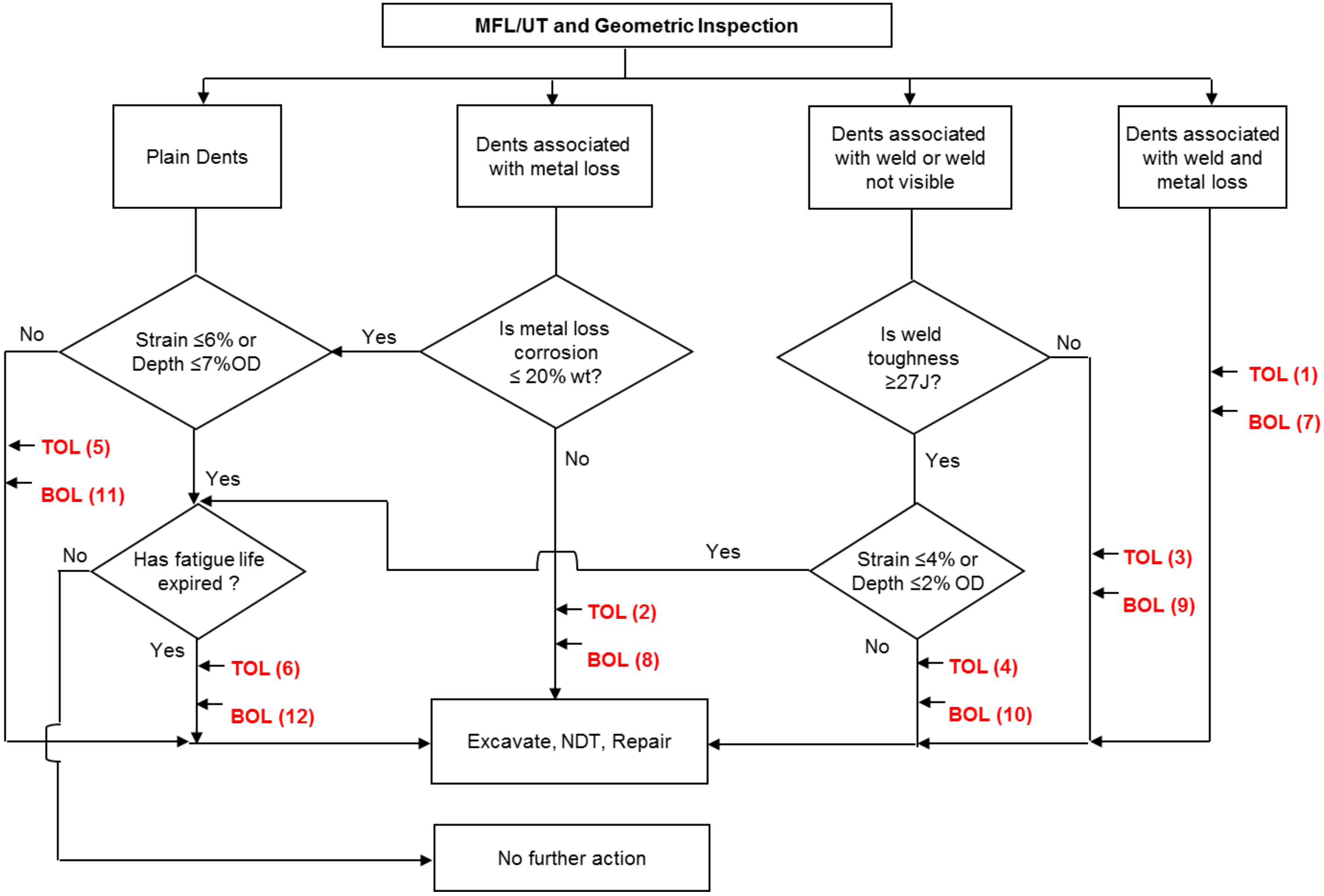
Initial Work Programme

- 3 operator workshops
- Review of operator data
- Development of prioritisation algorithms, simple assessment rules, dent assessment algorithm
- Review dent fatigue calculation model
- Operator review of above (2 gas and 2 liquid operators)
- External publication

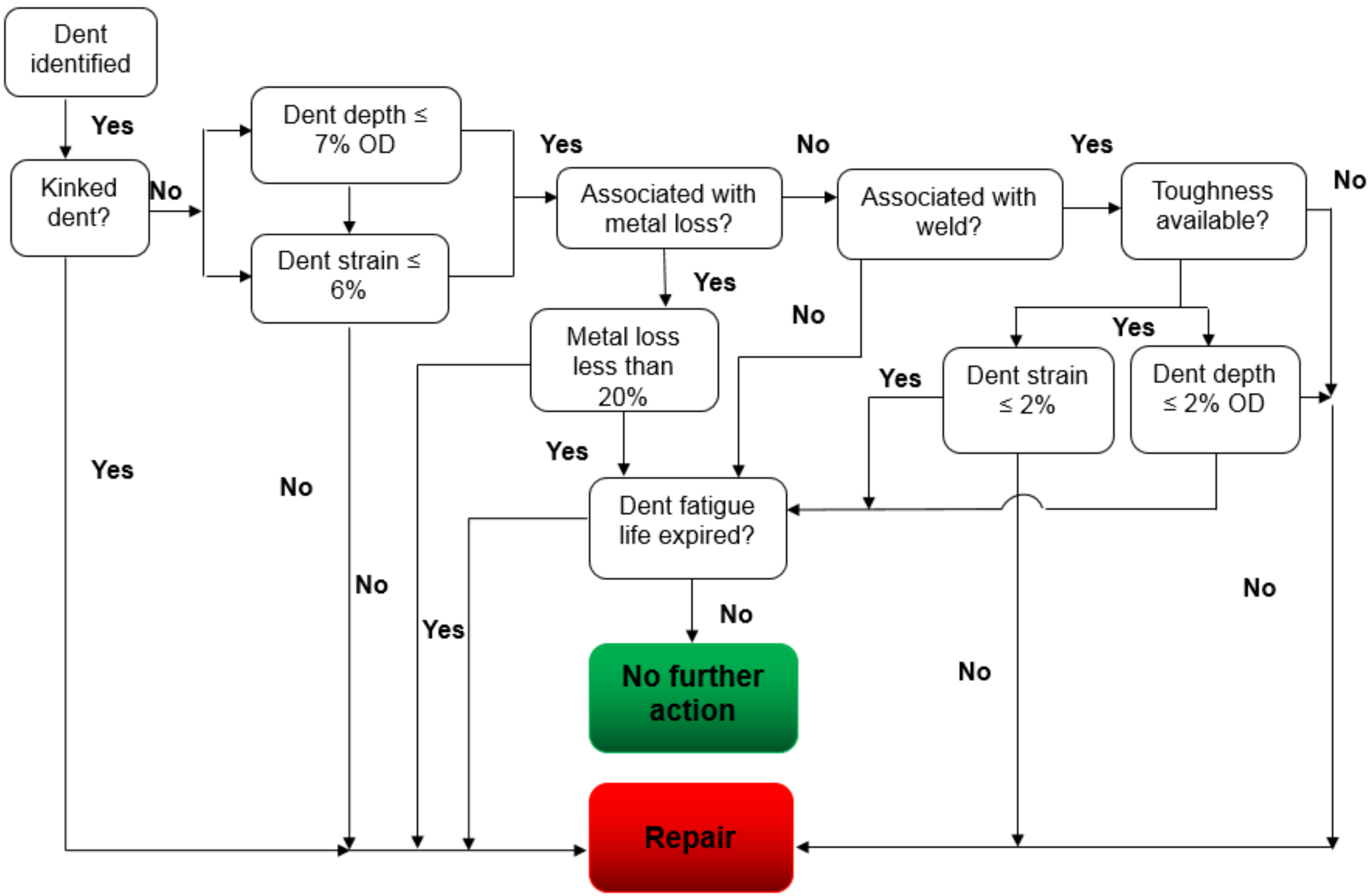
Prioritisation Algorithm – MFL/UT Inspection



Prioritisation Algorithm – MFL/UT + Geometric Inspection



Assessment Algorithm



Simple Dent Assessment Rules

- Kinked dents (e.g. wrinkles) – repair
- Static assessment of dents – depth/strain limits
- If pipeline is pressure cycled – assess dent location for damage:-
  - TOL – coating damage (DCVG/Pearson)
  - BOL – disturbance, washout etc.
- BOL dents in rocky locations should be monitored not excavated
- Dents associated with welds ≤ 2% dia. - acceptable if weld toughness & quality are acceptable
- New dent features identified between MFL/UT inspections - investigate

Extension of Assessment Rules

- Assess dents in conjunction with corrosion damage in order to define an acceptable limit for corrosion which does not impact on the static assessment and which can be accounted for in the fatigue assessment
- Develop dent SCF equations and assess the application of standard SN fatigue rules for the assessment of dent
- Review the dent depth and toughness limits for the acceptability of dents associated with welds

Extension of Assessment Rules

Assessment Rule	Study by:
Dent + corrosion	DNV GL
Dent Fatigue – SCF equations for dents and dents + corrosion	DNV GL
Literature review - dents associated with welds	Penspen
Review and update of UKOPA dent management strategy	Penspen
Analysis of test cases	Penspen
Validation of dent fatigue life estimation method	Penspen

Dent + Corrosion, Dent Fatigue

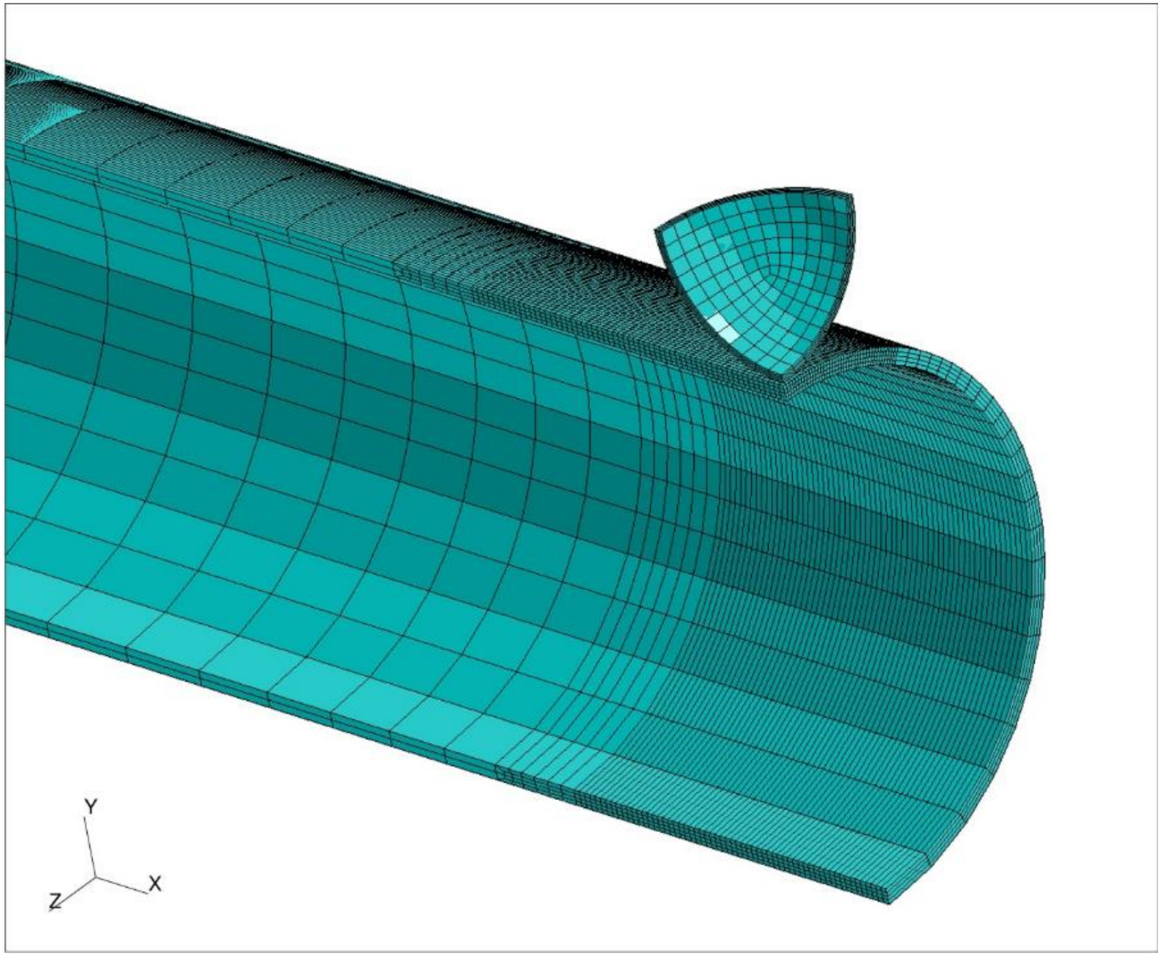
DNV GL Report 11631 –

Study to Investigate the Acceptability of 20% Corrosion Metal Loss Associated with a Plain Dent in a Pipeline

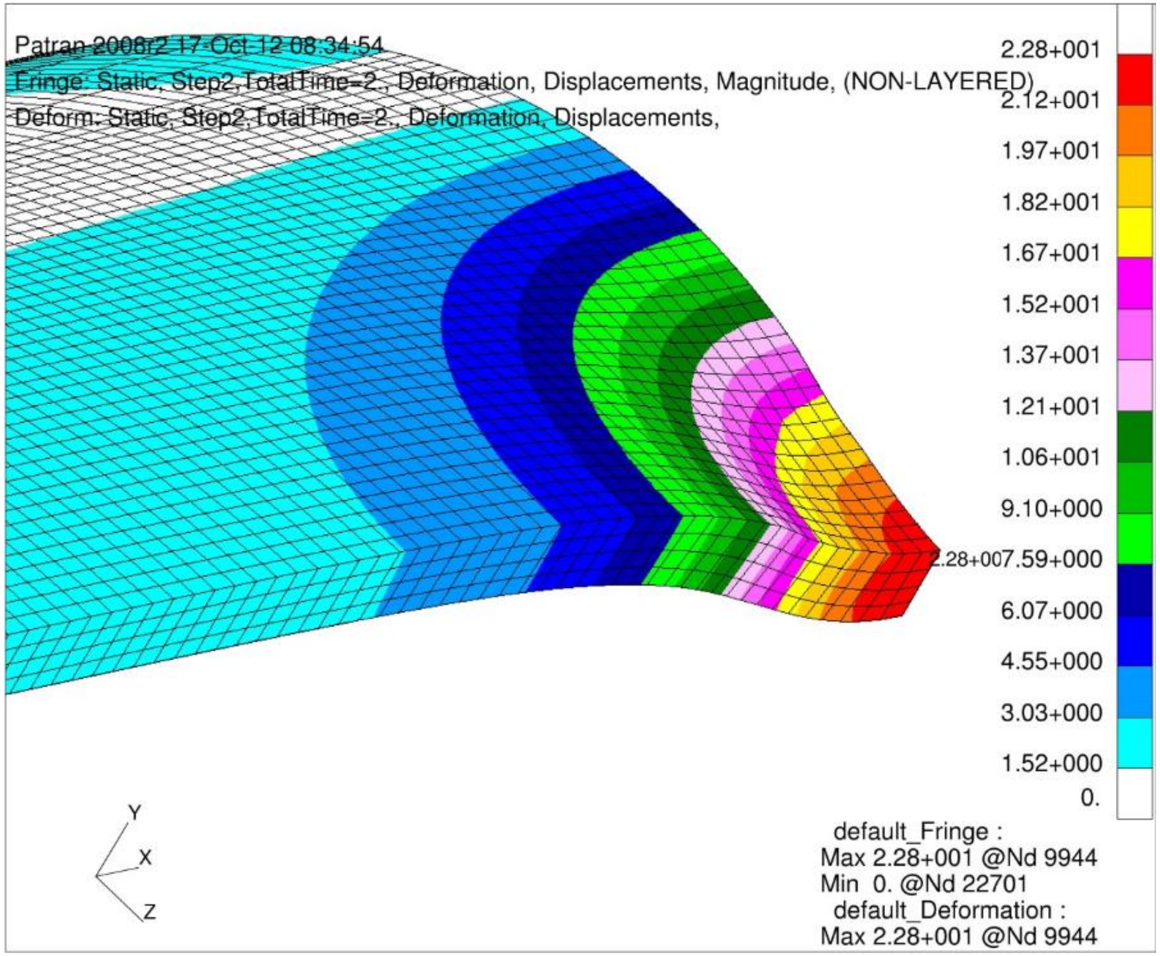
DNV GL Report 12505 –

Feasibility Study: Fatigue Assessment of Plain Dent Damage

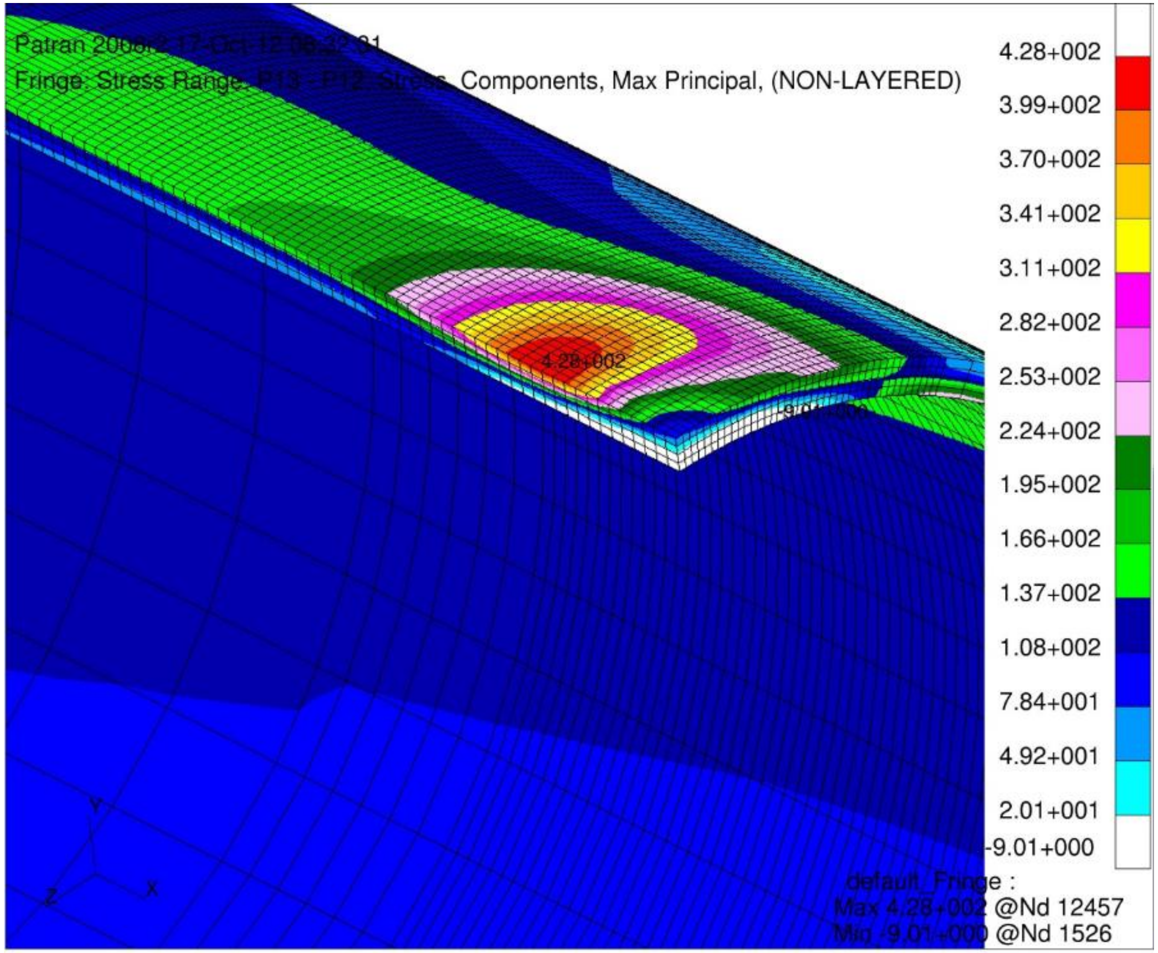
FEA Model



323.9x9.5mm - Displacement Predictions



323.9x9.5mm – Stress Range



Conclusions

- A review of a limited number of full-scale tests found in the literature support the UKOPA limits of 6% OD dents with corrosion up to 20% wt in depth in pipelines operating up to 72% SMYS.
- FEA of dents + 20% depth corrosion showed failure pressures were in excess of those for corrosion only.
- A model has been developed for predicting the remaining life of a dent plus corrosion feature, based on the EPRG dent model and a closed form equation developed for the DNV GL corrosion model.

Dent Fatigue Assessment

Study undertaken by DNV GL

Fatigue Assessment of Plain Dent Damage

The UKOPA Dent Management Strategy recommends use of the EPRG methodology for assessing dent fatigue life, this methodology is conservative, an alternative is required.

Preferred approach - Use dent SCF + standard fatigue SN curves in a generic fatigue life calculation procedure

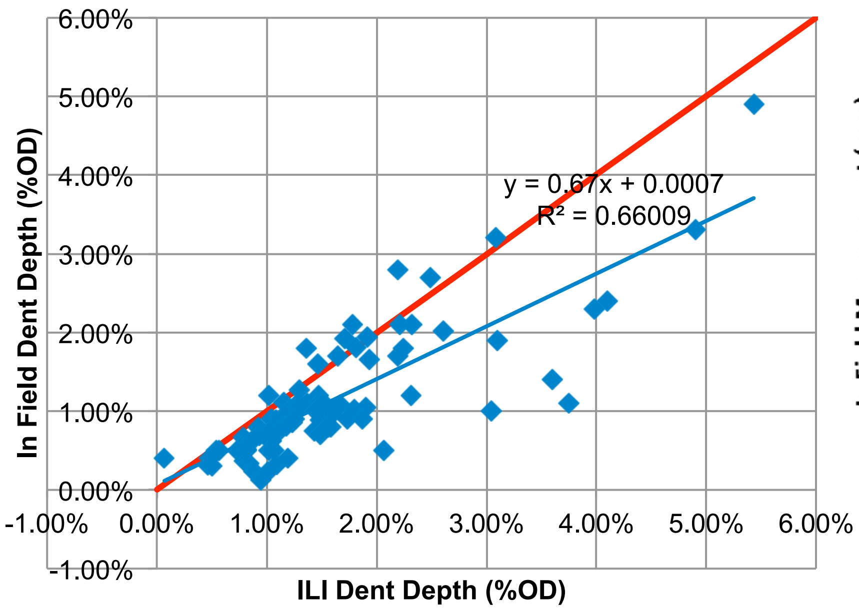
The study undertaken by DNV GL reviewed published dent SCF equations, compiled and compared SCFs calculated using FEA, and carried out fatigue calculations.

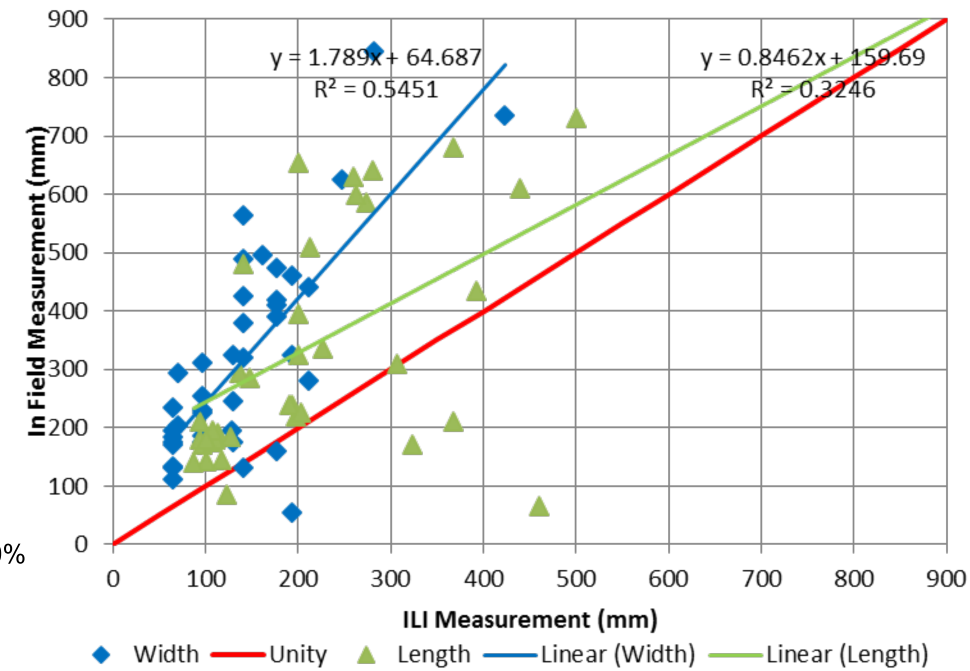
Conclusions

- A number of published dent fatigue methodologies have been reviewed and compared. The review confirms that the EPRG dent fatigue methodology is conservative, and predicts low fatigue lives in comparisons with other methodologies.
- The DNV GL dent fatigue methodology gives predictions which compare best with a full scale fatigue test.
- The UKOPA dent management strategy was updated to use the DNV GL dent fatigue methodology.

Dent Damage Data

Dent depth measured by ILI has been compared with depth measured in field investigations using data supplied by UKOPA members as part of the dent management work





ILI measurement 1.43 x field measurement

ILI measurement for width is 0.5 x field measurement
ILI measurement for length is 0.75 x field measurement

Dent Damage Data - Summary

- The results indicate that ILI measurements overestimate depth and underestimate width and length
- ILI measurements are recorded under operational pressure, whereas field measurements are recorded at reduced pressure, so field measurements would be expected to be greater
- The accuracy of dent size inspection data impacts on establishing the maximum acceptable dent parameters
- The majority of dent depths are ≤ 5% OD
- A significant proportion of top of line dents had associated metal loss damage (gouges)

Dent Damage Data – Current Database

Field Measurements Only

Product	Dents
Natural Gas	277
Ethylene	27
Spiked Crude	9
NGL	1
CO	1
	315

Cause of Dent	Number	%
External Interference	109	34.6%
Original Construction Damage	108	34.3%
External Corrosion	10	3.2%
Girth Weld Defect	13	4.1%
Ground Movement	12	3.8%
Pipe Mill Damage	8	2.5%
Pipe Defect	3	1.0%
Other / Unknown	52	16.5%
TOTAL	**315**	**100.0%**

Depth / Diameter Ratio	Number
Greater than 10%	19
Greater than 5%	42
Greater than 1%	134
Greater than 0.5%	187

Dent Depth and Toughness Limits for Dents Associated with Welds

Study undertaken by Penspen

Literature Review of recent international work covering dents on welds, in particular welds of unknown quality (analytical studies, testing and failures)

Development of additional guidance, update of UKOPA DMS

Test Cases – analysis of 3 cases

Literature Review - Conclusions

- Existing guidance is conservative
- Existing best practice is given in PDAM (requires weld quality and toughness)
- There is no assessment method for dents on welds of poor quality
- Future assessment methods are likely to be based on FEA

Key Findings for Additional Guidance

- Dents associated with welds have shorter fatigue lives
- The acceptable depth for a dent associated with a weld is less than a dent in plain pipe
- There is no evidence for changing the current depth acceptability limit of 2% OD for dents associated with welds
- Pipelines transporting liquids are more susceptible to fatigue at dents
- There is no assessment method for dents on welds of poor quality
- Future assessment methods are likely to be based on FEA
- The dent shape has a significant affect on SCF

Key Findings for Additional Guidance

From Kiefner and Lewis for PRCI:

- There is no single equation or expression currently available that is capable of predicting the safe operating pressure or time to failure of a dent or mechanical damage which is a) simple and b) accurate
- Simple models tend to be inaccurate and conservative as a result of excessive simplification of a complex problem
- Complex procedural approaches combining FEA and fracture mechanics will continue to evolve

Recommendations for Changes to DMS

- Weld Quality:
  - Good quality – allowable dent strain 4%
  - Probable good quality – allowable dent strain 2%
  - Poor quality - repair

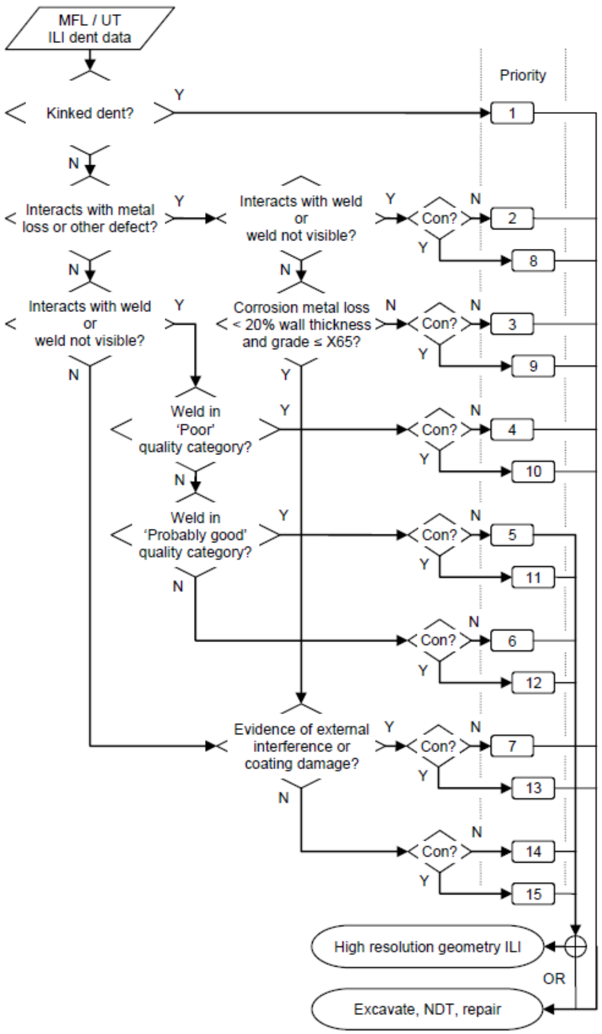
Indicators of Good Quality Welds

Item	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.
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	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.
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.
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.

Indicators of Poor Quality Welds

Item	Criterion
1	Welds of known low toughness (Charpy toughness less than 30 J minimum and 40 J on average from three specimens).
2	Pipe not manufactured to API 5L or equivalent.
3	An operating temperature less than the line pipe's drop weight tear test transition temperature.
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).
5	The weld is likely to contain cracks or defects.
6	Welds not fabricated to a recognised pipeline welding standard such as API 1104, or equivalent, or as defined in API 5L.
7	Low frequency electric resistance welds, induction welds, flash welds or oxyacetylene welds.
8	Welds with a history of causing hydrotest failures.
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.

Revisions to Prioritisation Logic – MFL/UT ILI



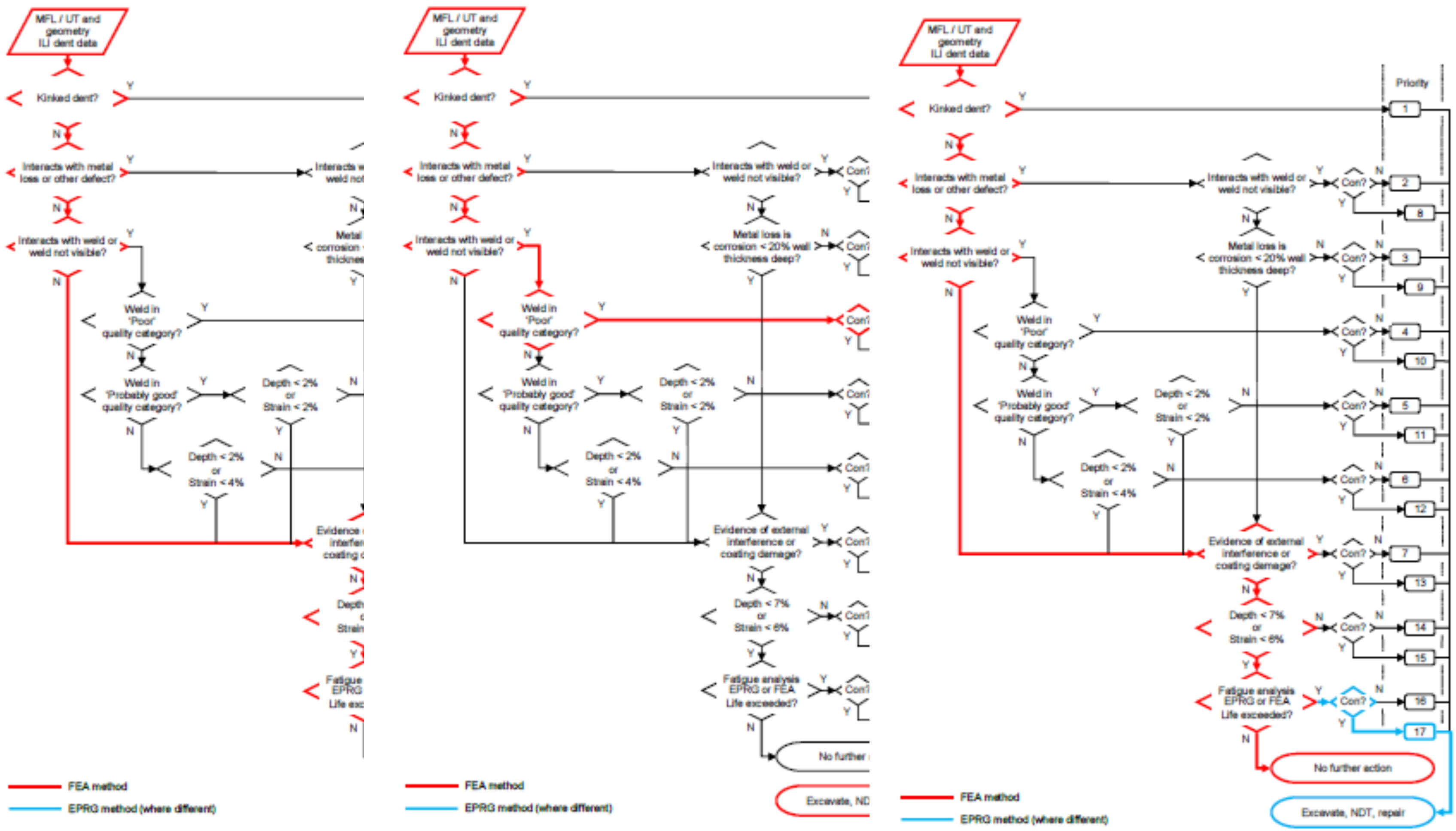
Priority	Description	Action
1	Kinked dent	1
2	Unconstrained + associated with metal loss + associated with weld	1
3	Unconstrained + associated with metal loss (except corrosion less than 20% of wall thickness in depth in grade X65 material or lower)	1
4	Unconstrained + associated with weld in 'Poor' 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

Case Studies – Analysis of 3 Dents

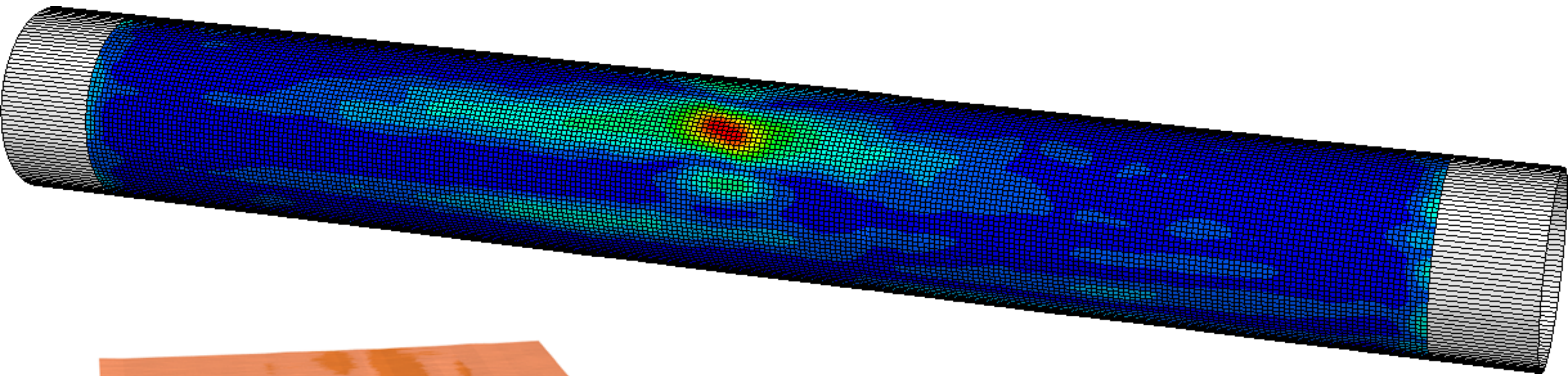
Dent number	1	2	3
Pipeline	Crude Oil	Multi Product	Multi Product
Outer diameter	711.2 mm	273.0 mm	323.8 mm
Wall thickness	7.1 mm	4.77 mm	6.41 mm
Year of construction	1966	1981	1962
Linepipe type	SAW	ERW	Seamless
Material grade	X52	X52	X42
MAOP	46.2 bar	79 bar	71.5 bar
Reported dent depth	1.4% diameter	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

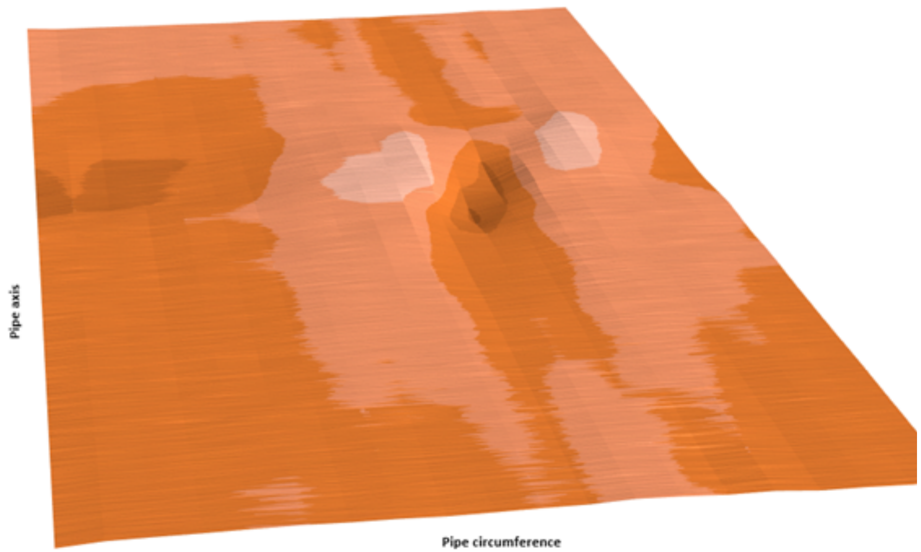
Table 1: Dent properties and pipeline properties at dent location

Case Studies



Case Studies - FEA model





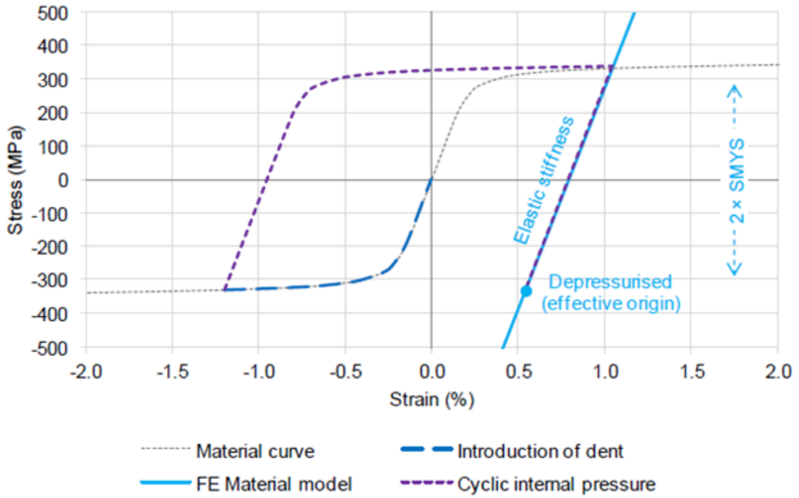


Figure A.2: Illustrative example of shakedown and finite element material model

Case Studies - Conclusions

- The updated guidance has been successfully applied to 3 example dents
- The assessment outcomes using the FEA method were consistent with the method being conservative:
  - Repair for the dent that had failed, new guidance would require repair of this dent on first excavation
  - Repair of one of the two dents that had not failed
- The method based on FEA reduced the number of repairs recommended compared to the EPRG method

Validation of Dent Fatigue Life Estimation Method - Penspen Report

- UKOPA Dent Management Strategy allows use of finite element analysis (FEA) for dent fatigue assessment
- FEA allows accurate assessment of the dent shape, the stress field and the stress concentration factor
- A study to validate the fatigue life of dents determined using FEA and published SN curves against full scale test data has been carried out by Penspen for UKOPA

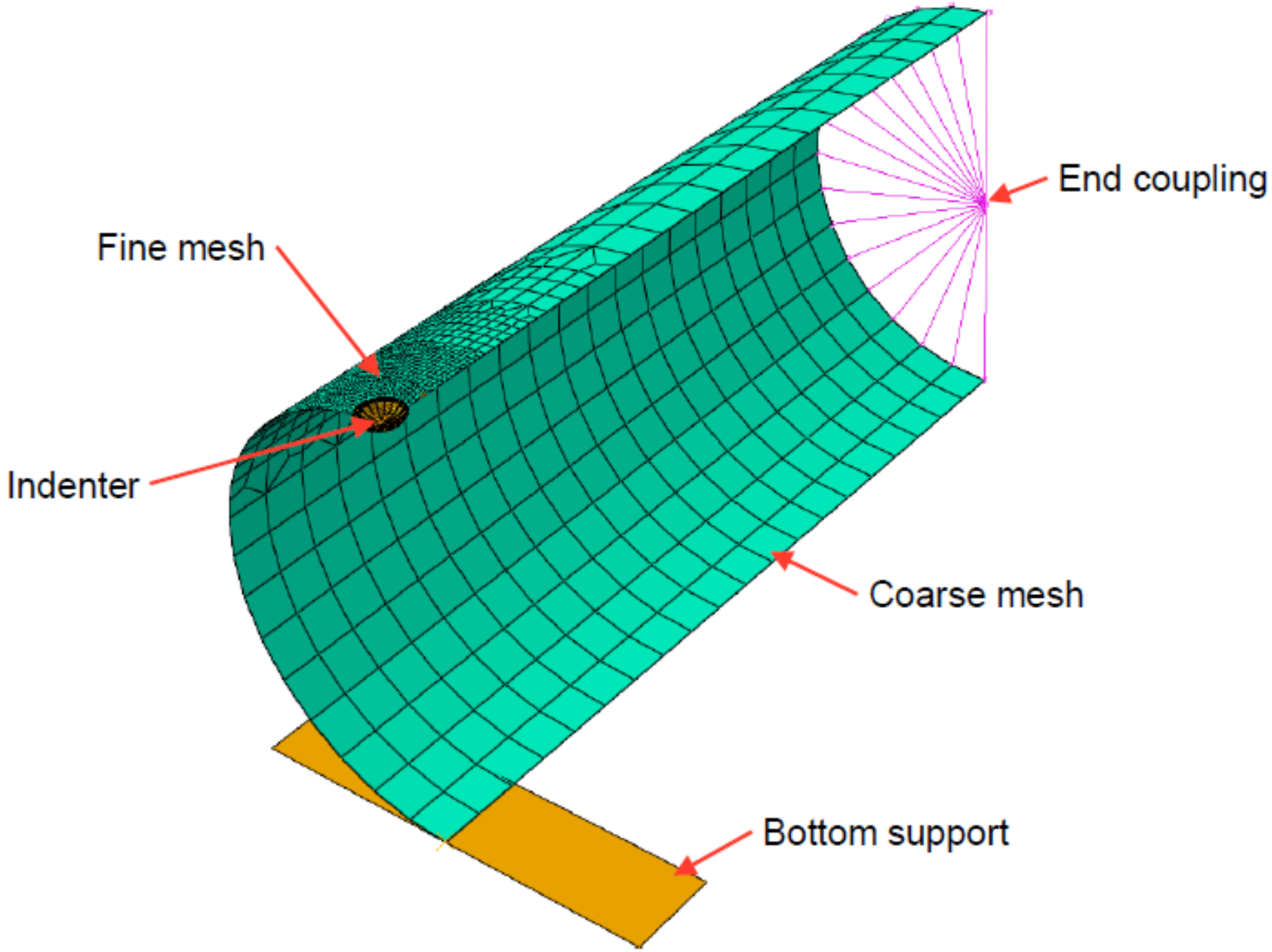
Full Scale Test Results

- Full scale test data obtained from PRCI sponsored work published at the International Pipeline Conference in 2008, 2010 and 2012:
  - 2008 12 full scale tests modern X52 & X70 pipelines, 6 restrained plain dents, 6 unrestrained
  - 2010 – 18 full scale fatigue tests(including 12 from the 2008 paper), 6 restrained, 12 unrestrained, + 16 full scale fatigue tests on dents on welds, 6 restrained, 10 unrestrained, 14 of these dents were located on or within 2” of a girth weld
  - 2012 – 17 full scale tests, plain dents, X52 material removed from service, 8 restrained, 9 unrestrained
- Errors in description of experimental work were identified and corrected through contact with IPC authors
- Material data for X52 pipe removed from service not available, modern pipe properties assumed

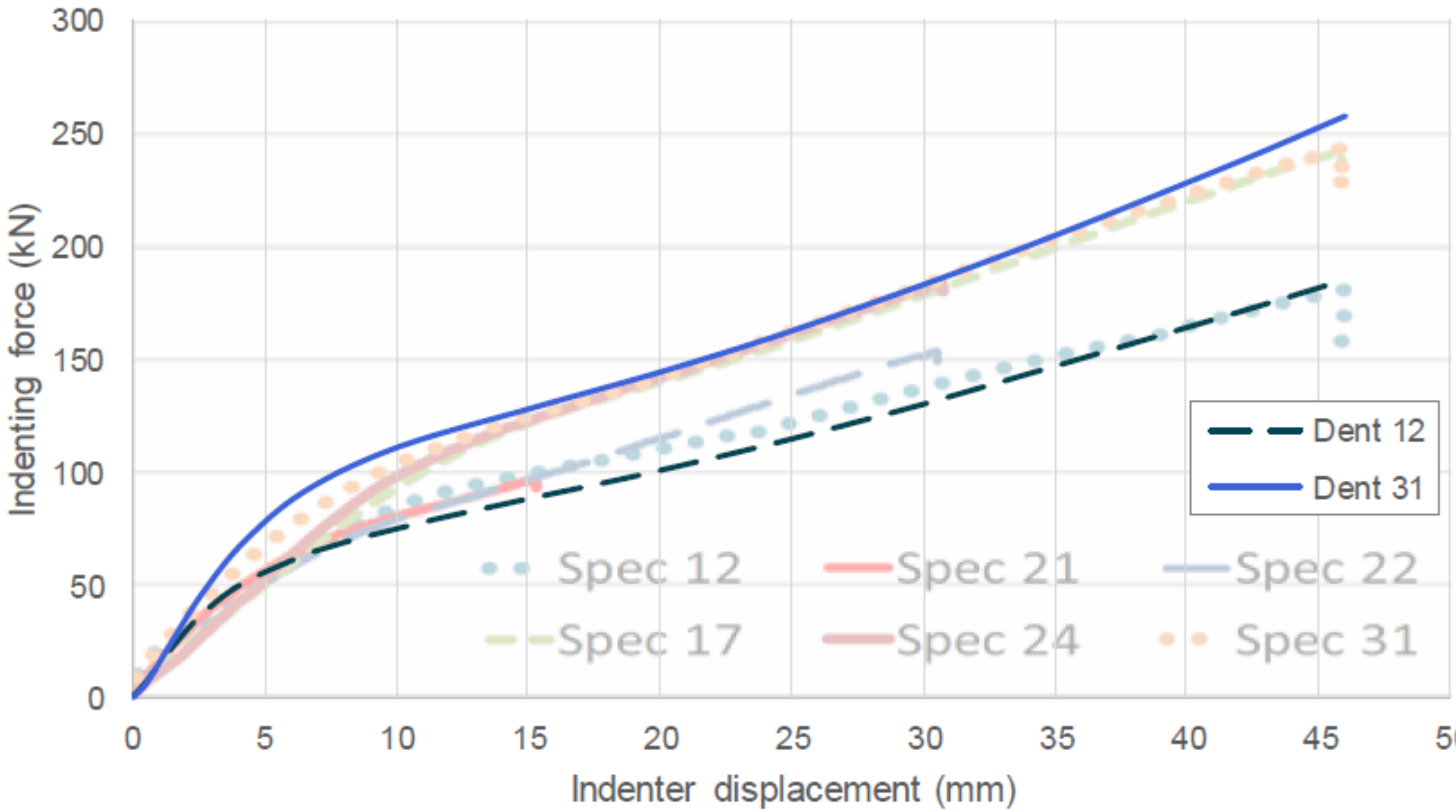
Modelling Methodology

- Indenting, with internal pressure if present in full scale test
- Removal of indenter (assessment of spring-back)
- Initial high pressure cycle (re-rounding)
- Subsequent pressure cycling between 10% - 80% SMYS to achieve material shakedown and stable dent shape
- Single application of internal pressure to model with elastic material to determine fatigue cycle in each dent (as would be applied in analysis of ILI data)
- An iterative approach for estimating the depressurised dent shape is described

FEA Model


End coupling
Fine mesh
Indenter
Coarse mesh
Bottom support

Results – Indenting Force



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

FEA Results

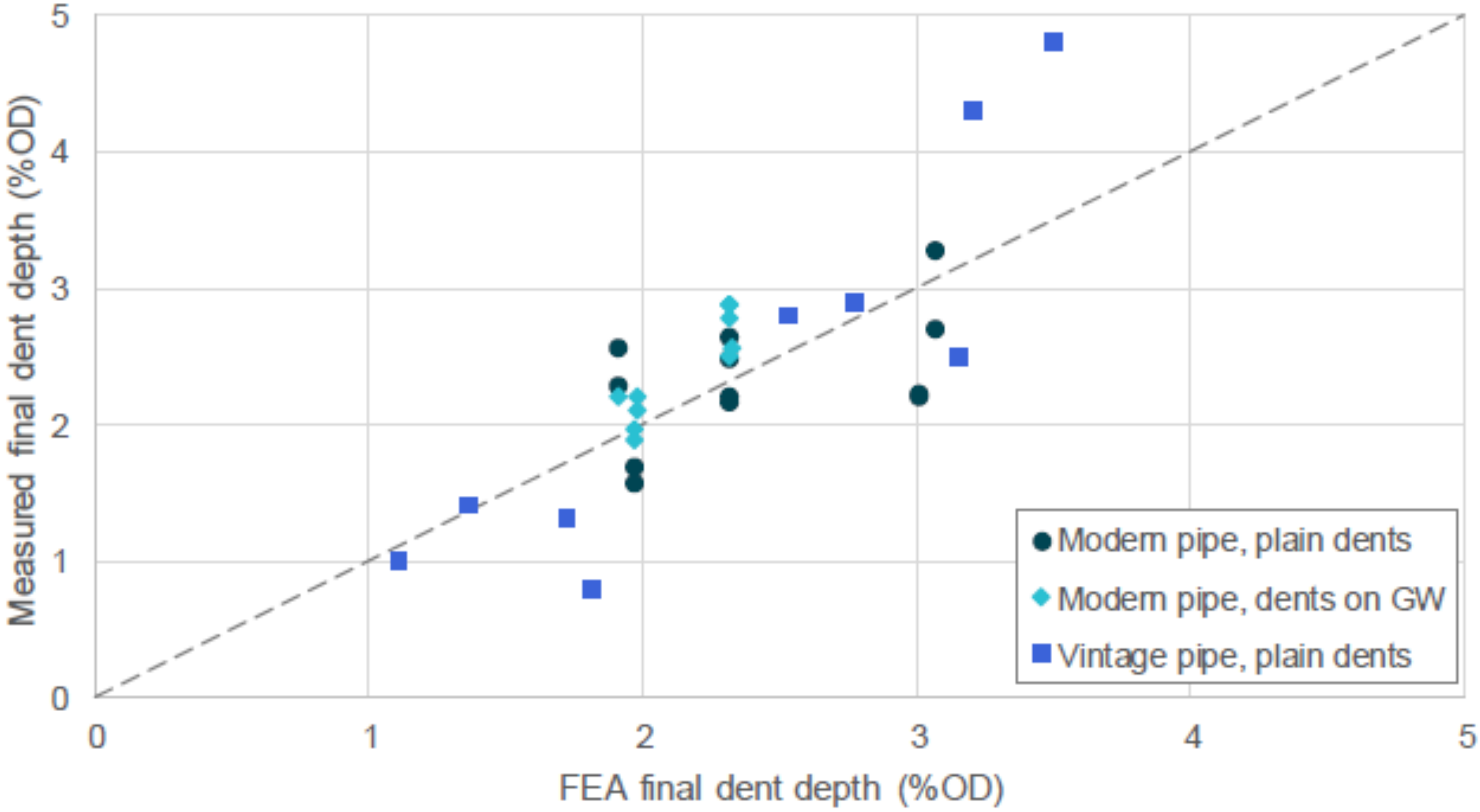


Figure 5: Comparison of FEA predicted dent depth after pressure cycling with test results

Fatigue Results

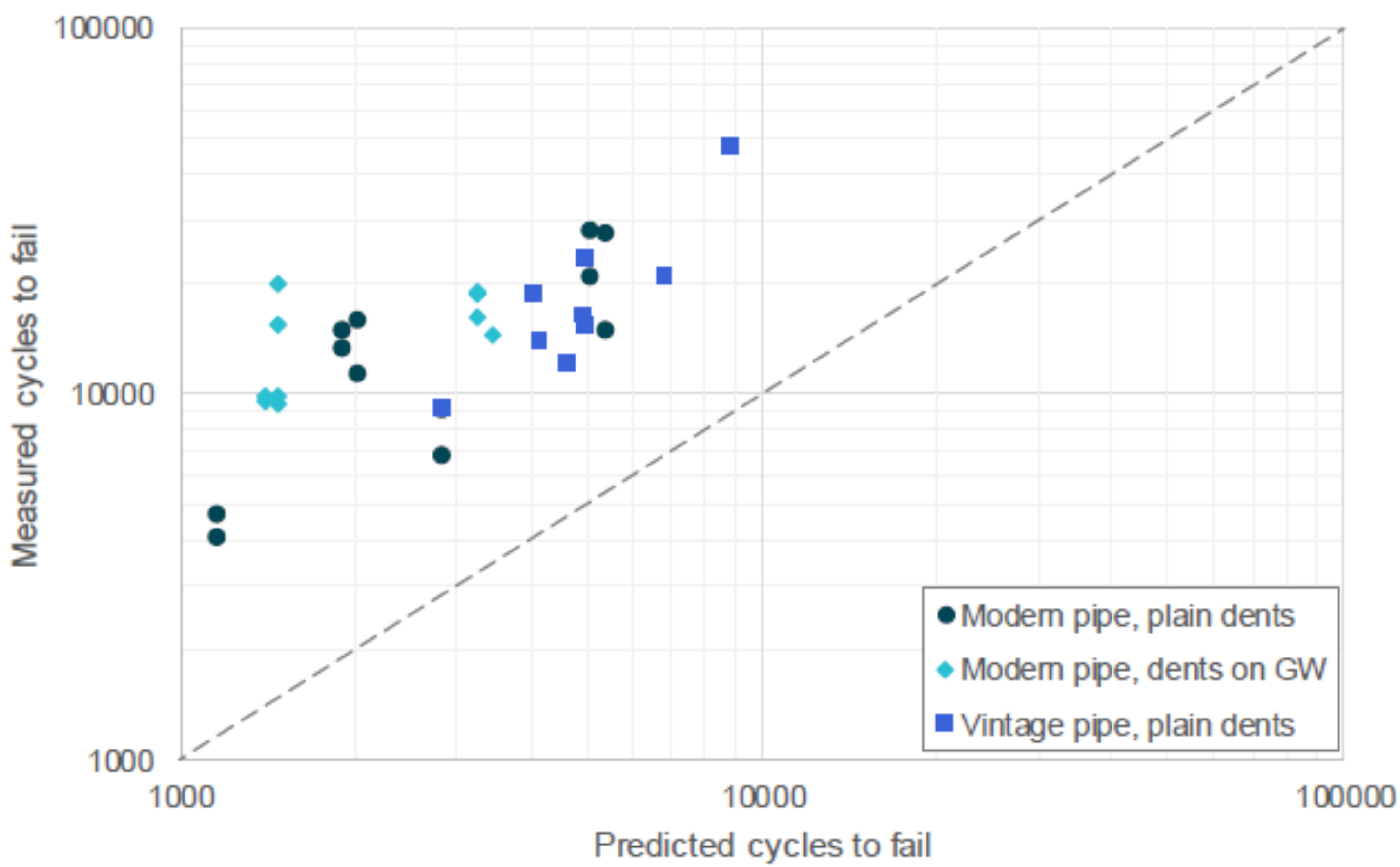
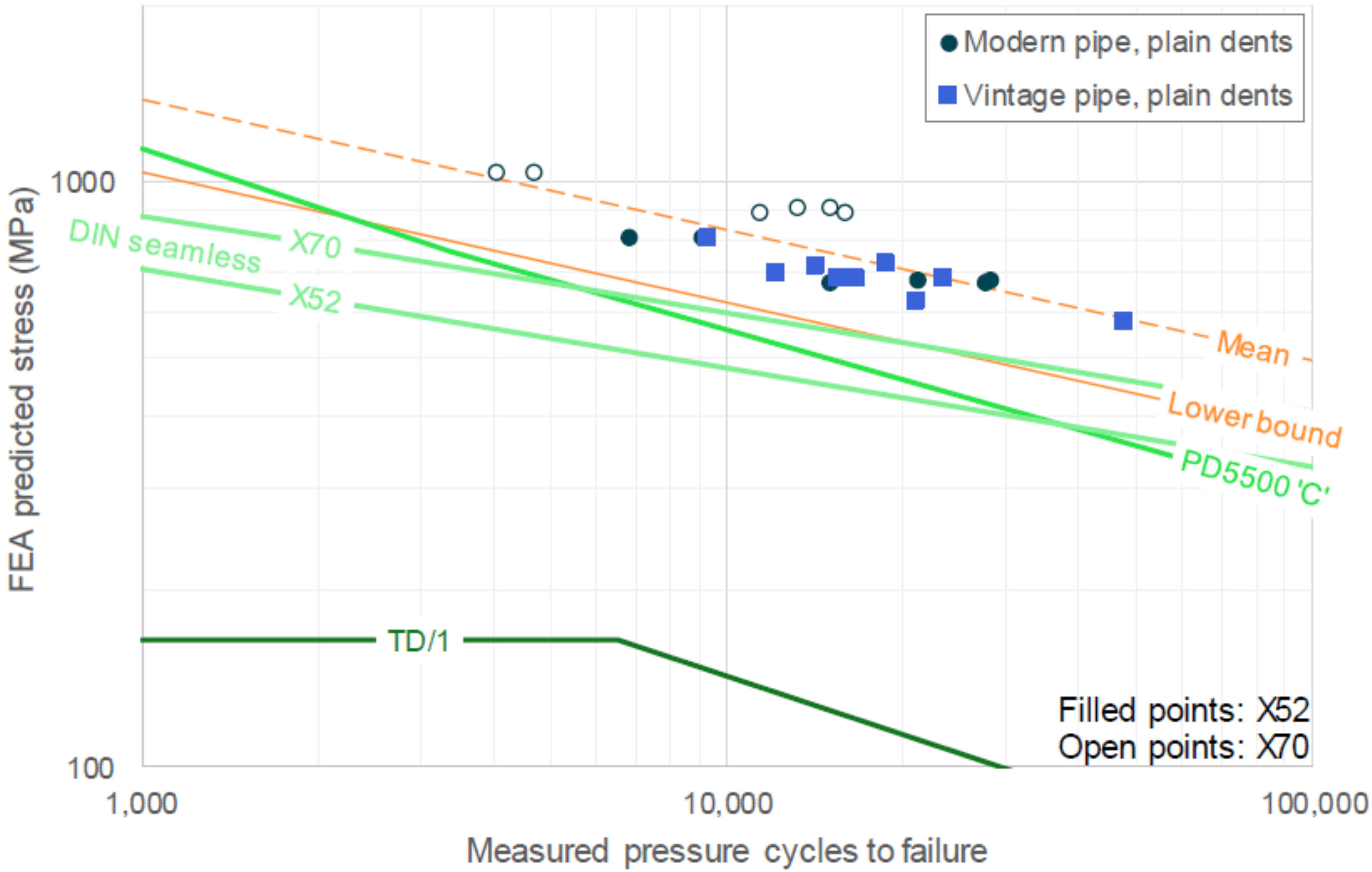
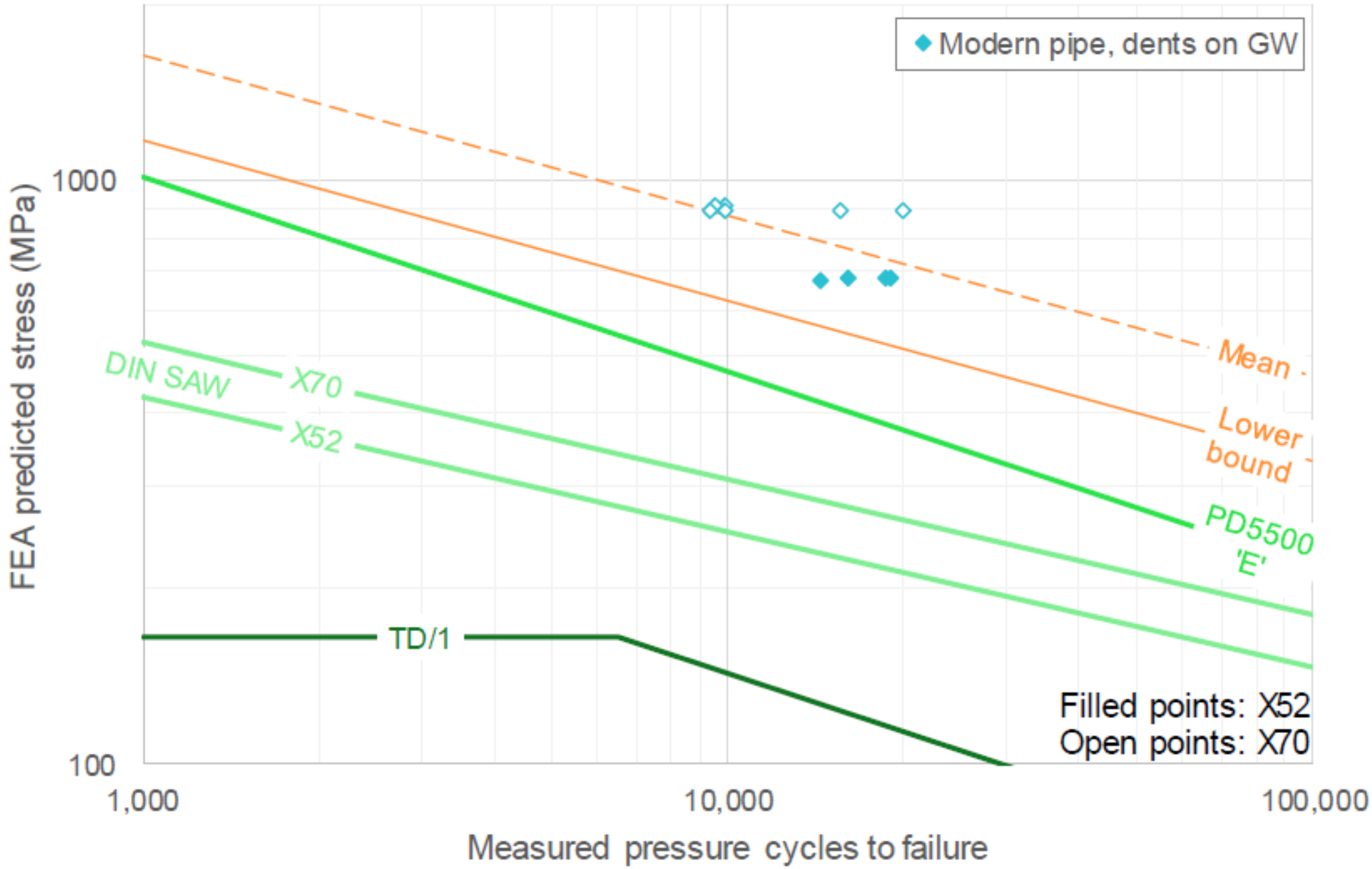


Figure 6: Comparison of predicted fatigue life with test results

Comparison with SN Curves – Plain Dents



Comparison with SN Curves – Dents on Welds



Findings:

- FEA results show good agreement with full scale test results for material behaviour and dent shape
- Predicted fatigue life is conservative for all dents
- PD 5500 SN ‘C’ curve should be used for plain dents, ‘D’ or ‘E’ for dents on welds
- No additional safety factor required

The work validates the application of FEA in the estimation of dent fatigue life

Need for a Calculation Tool

$$N_c = 1000\left[\frac{(\sigma_U - 50)}{2\sigma_A K_S}\right]^{4.292} \qquad 2\sigma_A = \sigma_U\left[B\sqrt{(4+B^2)} - B^2\right]$$

K_s is given by the equation:-

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

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

$$SCF = \frac{\Delta\sigma}{\Delta\sigma_{hoop}} = 1.8\ln\left(88\frac{H_r}{D}+1\right)+1 \qquad N = 1.01\times10^{15}(SCF\times\Delta\sigma)^{-4}$$

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