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

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*GL Noble Denton  
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**Distribution**

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## Executive Summary

The United Kingdom Onshore Pipeline Operators' Association (UKOPA) Risk Assessment Working Group is developing a strategy for managing dents in pipelines. The strategy is based on industry guidance, UKOPA member companies best practice (where appropriate) and the results of pipeline inspections (as provided by UKOPA members).

The UKOPA 'Dent Management Strategy' specifies acceptance limits on dents in the body of the pipe and associated with welds (expressed as a percentage of the pipe outside diameter and as a percentage strain), and dents with combined defects, such as metal loss due to corrosion.

The dent plus corrosion acceptance limits specified in the Dent Management Strategy of 6%OD (dent depth expressed as a percentage of the pipe outside diameter) and 20%t (depth of corrosion expressed as a percentage of the pipe wall thickness) are greater than those specified in pipeline codes, such as ASME B31.8 and CSA Z662. However, they have been included in the strategy document as they are limits currently used by some UKOPA member companies.

To confirm the validity of the UKOPA limits for dent plus corrosion damage, UKOPA has requested GL Noble Denton to undertake a feasibility study to review the most up to date industry guidance and research work undertaken on combined dent plus corrosion work, with supporting finite element (FE) analysis if required, towards justifying the UKOPA limits.

UKOPA propose a method for predicting the remaining fatigue life of smooth dent damage, based on recommendations by the European Pipeline Research Group (EPRG). The presence of corrosion damage within the dent may impact on the predicted fatigue life due to the local stress raising effect of the metal loss area. In 2009 GL Noble Denton developed a new method for the Pipeline Research Council International, Inc (PRCI) and the US Department of Transportation (DOT) Pipelines and Hazardous Materials safety Administration (PHMSA) for predicting the remaining fatigue life of corrosion damage in pipelines that are pressure cycled. UKOPA has requested GL Noble Denton to investigate whether that work can be used in conjunction with the EPRG dent fatigue model to enable a prediction of the remaining fatigue life of dent plus corrosion damage (up to 20%t in depth).

The main conclusions and recommendations from the work undertaken are given below.

### Conclusions

1. The pipeline codes ASME B31.8 and CSA Z662 permit dents up to 6%OD in depth with corrosion up to 10%t in depth in the body of the pipe (not associated with a seam or girth weld). Corrosion up to 40%t is permitted, although any corrosion greater than 10%t in depth will be restricted by length.
2. A limited number of full-scale tests have been found in the public domain which considers dents plus machined metal loss defects and dents plus areas of metal loss due to grinding (simulation of defect removal by grinding). Those tests support the UKOPA limits of 6%OD dents with corrosion up to 20%t in depth in pipelines operating at hoop stress levels up to 72% SMYS.

3. A limited number of FE models were created of dents with corrosion up to 20%t in depth to investigate whether the general size and shape of the corrosion had a detrimental effect on the dented pipeline. The predicted failure pressures were found to differ, depending on shape, although the predictions were higher than the failure pressures predicted for the dent only model, and the corrosion only models. The results suggested that the geometrical constraint introduced by the dent had a beneficial effect on the failure behaviour of the damaged pipe.
4. There is no method available for predicting the fatigue life of a dent plus corrosion feature. There are methods available for determining the fatigue life of a dent (UKOPA recommend use of a model developed by EPRG) or corrosion damage (a model developed by GL Noble Denton for PRCI and the US DOT). A model is proposed 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 GL Noble Denton corrosion model. There is no experimental data to support this modification; hence further work will be required.

### Recommendations

1. The UKOPA limits for dent plus corrosion damage should be limited to pipelines constructed from line pipe up to and including grade X65. Dent only limits for pipelines constructed from grade X80 line pipe are currently being investigated by EPRG. Once the EPRG work is in the public domain it should be reviewed by UKOPA, and the limits extended if appropriate.
2. Consideration should be given to undertaking additional FE studies to further investigate the effects of pipe geometry, material grade and dent depth.
3. Consideration should be given to investigating the effect of dent shape on the behaviour of combined dent plus corrosion damage as the limited numerical studies undertaken in this work considered only spherical shaped dents.
4. To further support the proposed modification to the EPRG dent fatigue model it is recommended that UKOPA give consideration to undertaking a limited number of full-scale pressure cycle tests on combined dent plus corrosion damage.
5. Consideration should be given to including the method recommended in PDAM for estimating the fatigue life of a dented weld.

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## 1 Introduction

The United Kingdom Onshore Pipeline Operators' Association (UKOPA) Dent Management Strategy [1] states that, provided the depth of metal loss (due to corrosion) associated with a plain dent in the pipe body (i.e., not associated with a seam or girth weld) is not greater than 20% of the pipe nominal wall thickness (hereafter 20%t), then the combined dent plus corrosion feature can be assessed as a plain dent. There is a note accompanying this criterion stating that the validity of this limit is subject to further work, and that the accepted 'code' limit is 10%t<sup>1</sup>.

UKOPA has requested that GL Noble Denton (GL) undertake an investigation to confirm whether a 20%t limit can be recommended. Consideration is to be given to the resistance of the damaged pipeline to both static and cyclic internal pressure loading.

A brief overview of the UKOPA Dent Management Strategy is given in Section 2. The report then focuses on the assessment of a pipeline with plain dent damage and associated metal loss due to corrosion with a comprehensive review of industry guidance and applicable test data presented in Section 3, with supporting numerical analyses in Section 4. A method for predicting the fatigue life of a combined dent plus corrosion feature is presented in Section 5. The feasibility of adopting a 20%t corrosion limit for plain dent damage, and the proposed dent plus corrosion fatigue life model is discussed in Section 6, with conclusions and recommendations from the study given in Sections 7 and 8 respectively.

In this report, unless otherwise stated, dent depth is expressed as a percentage of the pipe outside diameter, %OD and the depth of metal loss/corrosion is expressed as a percentage of the nominal pipe wall thickness, %t.

## 2 UKOPA Dent Management Strategy

The UKOPA Dent Management Strategy [1] is being developed by the UKOPA Risk Assessment Working Group (RAWG). The strategy is based on industry guidance, UKOPA member company's best practice (where appropriate) and the results of pipeline inspections (from in-line inspection (ILI) and field investigations following excavation of the pipeline), as provided by UKOPA members.

The purpose of the Dent Management Strategy is to;

- 1) Allow prioritisation of dent features detected by ILI for investigation.
- 2) Take account of dent location, depth, strain and association with other defects, damage or welds.
- 3) Assess dents under static and cyclic loading.
- 4) Consider whether the dent features were present at commissioning, and the operational service to date and future operating requirements of the pipeline.

The criteria recommended by UKOPA for undertaking an assessment depends on whether the dent is in the body of the pipe, associated with a weld, or if it is associated

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<sup>1</sup> The UKOPA Dent Management Strategy states 12%t, which is incorrect. The 10%t limit is discussed further in Section 3.

with metal loss due to corrosion. The criteria are from different sources. The criteria used to assess dent damage subjected to static loading are given in Table 1.

For a pipeline subjected to pressure cycling, UKOPA recommends an empirical method developed by the European Pipeline Research Group (EPRG) [2] for predicting the fatigue life of a plain dent, in the body of a pipe. The fatigue life (N) of a plain dent is given by;

$$N = 1,000 \left[ \frac{\sigma_U - 50}{2\sigma_A K_s} \right]^{4.292} \quad [1]$$

Where,  $\sigma_U$  = tensile strength (units: N/mm<sup>2</sup>)

$2\sigma_A$  = equivalent cyclic stress at R=0 (units: N/mm<sup>2</sup>) see Equation [2]

R = ratio of the minimum to maximum stress,  $\sigma_{min}/\sigma_{max}$  in the stress cycle

$K_s$  = dent stress concentration factor see Equation [5]

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

$$B = \frac{\frac{\sigma_a}{\sigma_U}}{\sqrt{1 - \left( \frac{\sigma_{max} - \sigma_a}{\sigma_U} \right)}} = \frac{\frac{\sigma_a}{\sigma_U}}{\sqrt{1 - \frac{\sigma_a}{\sigma_U} \left( \frac{1+R}{1-R} \right)}} \quad [3]$$

Where,  $2\sigma_a$  = the nominal cyclic hoop stress range (units: N/mm<sup>2</sup>)

$$K_s = 2.871\sqrt{K_d} \quad [4]$$

$K_d$  is given by;

$$K_d = H_o \frac{t}{D} \quad [5]$$

Where,  $H_o$  = dent depth at zero pressure (units: mm) see Equation [6]

t = pipe wall thickness (units: mm)

D = pipe outside diameter (units: mm)

$$H_o = 1.43H_r \quad [6]$$

Where,  $H_r$  = dent depth at pressure (units: mm)

UKOPA recommend that a safety factor of 13.3 is applied to the predicted fatigue life, which corresponds to a 95% one-tail confidence interval (i.e., a 5% probability of a non-conservative prediction).

This is consistent with the recommendations in the Pipeline Defect Assessment Manual (PDAM) [3] which also recommends use of the EPRG method for predicting the fatigue life of a plain dent.

Furthermore, PDAM proposes that the method can be used to estimate the fatigue life of a dent associated with a weld. Providing the weld is defect-free, PDAM proposes that the fatigue life of the dent can be estimated by reducing the predicted fatigue life of a

plain dent (see Equation [1]) of the same depth by a factor of 10. However, this recommendation is limited to a maximum dent depth of 3.9%OD, as measured at zero pressure after spring-back (this corresponds to a dent depth of approximately 2.7%OD when measured at pressure). It is recommended that UKOPA gives consideration to including this guidance within the dent management strategy, which currently does not consider the fatigue life of dents on welds.

### 3 Review

A review is presented below of the acceptance criteria for dent damage with associated metal loss/corrosion. The review primarily considers limits specified in the American and Canadian pipeline codes; ASME B31.8 [4] and CSA Z662 [5], with reference to background reports, as appropriate. The British codes, PD 8010-1 [6] and IGEM/TD/1 Edition 5 [7] are excluded from this review as neither specify acceptance limits for dent plus corrosion damage.

#### 3.1 Pipeline Codes

##### 3.1.1 ASME B31.8:2010

ASME B31.8 states that provided the depth of the dent is not greater than 6%OD and the depth of any associated corrosion is not greater than 10%t a reduction in the maximum allowable operating pressure (MAOP) need not be considered. Corrosion up to 40%t is permitted, although for depths greater than 10%t there is a corresponding reduction in the allowable length of the corrosion, in the pipe longitudinal direction.

The maximum allowable length of corrosion is given by the following equation:

$$L = 1.12 \sqrt{Dt \left( \left( \frac{\frac{d}{t}}{1.1 \left( \frac{d}{t} \right) - 0.11} \right)^2 - 1 \right)} \quad [7]$$

Where, D = pipe outside diameter (units: mm)  
t = pipe nominal wall thickness (units: mm)  
d = maximum depth of corrosion (units: mm)

Equation [7] is similar to the equation specified in ASME B31G:1991 [8] for maximum allowable longitudinal extent of corrosion that is greater than 10%t in depth<sup>2</sup>. The only difference is the factor 0.11 in the denominator; ASME B31G:1991 specifies a factor of 0.15, which gives a slightly less conservative result.

<sup>2</sup> ASME B31G:1991 was superseded in 2009 and again in 2012 [11]. In these latter editions of ASME B31G the equation referenced is no longer given.

### 3.1.2 CSA Z662:2007<sup>3</sup>

The recommended limits in CSA Z662 for dent damage with associated corrosion are similar to the recommendations in ASME B31.8. The maximum allowable dent depth is 6%OD and the depth of any associated corrosion is limited to 10%t. Corrosion up to 40%t is permitted, provided the longitudinal extent of the corrosion is not greater than that specified in ASME B31G:1991, where:

$$L = 1.12 \sqrt{Dt \left( \left( \frac{\frac{d}{t}}{1.1 \left( \frac{d}{t} \right) - 0.15} \right)^2 - 1 \right)} \quad [8]$$

The terms  $D$ ,  $t$  and  $d$  are referenced above, see Section 3.1.1 (Equation [7]).

As noted in Section 10.9.2.5 (and associated commentary) of CSA Z662, in recognition of the conservatism in the ASME B31G:1991 method, use of alternative, 'proven' methods is permitted. Where required by clause 10.9.2.5, CSA Z662 recommends use of either the  $0.85dL$  (where  $d$  and  $L$  are the peak depth and longitudinal length of the corrosion) or effective area methods, which are commonly referred to as 'modified' ASME B31G [9] and RSTRENG [10], respectively. A recommendation when using modified ASME B31G or RSTRENG is that corroded areas of up to 20%t in depth can be safely left in service regardless of length for pipelines operating at stress levels not exceeding 72% SMYS. An overview of the modified ASME B31G and RSTRENG methods is given below.

Modified ASME B31G and RSTRENG were developed in the late 1980's by Battelle, for Pipeline Research Council International, Inc (PRCI), and have been included in ASME B31G:2012 [11]. The original body of burst test data that was used to develop the original ASME B31G assessment method was expanded significantly and used to validate the new methods. Analysis based on these 'new' methods was found to be less conservative than original ASME B31G, but still gave an adequate margin of safety. The main differences between the 'new' methods and original ASME B31G are the definitions of 'flow stress', the format of the stress intensifying effect and idealisation of the corroded area; original ASME B31G assumes a parabolic area equal to  $2/3 dL$ , modified ASME B31G approximates the area to be  $0.85dL$  and RSTRENG uses the effective area of the corrosion calculated iteratively from a river bottom profile.

The ASME B31G:2012 guidance document refers to four assessment levels; Level 0, 1, 2 and 3, described below:

Level 0 : This method relies on tables of allowable defect length and depth which were carried over from ASME B31G:1991. The tables are used if the depth of metal loss is greater than 10% of the pipe nominal wall thickness. Note, the equation to predict the maximum longitudinal extent of the corrosion if the depth of the corrosion is greater than 10%t (Equation [8] above) has been omitted from ASME B31G:2012.

<sup>3</sup> An updated version of CSA Z662 was issued in 2011.

- Level 1 : Both the original ASME B31G and modified ASME B31G methods are classified as Level 1 assessment methods as they require knowledge of the maximum depth and longitudinal extent of the corrosion only.
- Level 2 : RSTRENG is classified as Level 2 because it requires detailed measurements of the corroded surface profile, accounting for the actual profile of metal loss. An RSTRENG assessment is generally undertaken using a spreadsheet or computer program.
- Level 3 : A Level 3 assessment is undertaken using numerical analysis, typically constructed using a finite element (FE) model of the corroded pipeline and then predicting the failure pressure using a validated failure criterion. The analysis should account for all factors that could affect the accuracy of results, including applied loads, boundary conditions and material characteristics.

## 3.2 Test Data

Only a limited number of tests have been undertaken to investigate the effect of plain dent damage with associated metal loss/corrosion on the integrity of a pipeline. The experimental work is summarised below.

### 3.2.1 American Petroleum Institute (API)

A series of full-scale tests were undertaken by Stress Engineering Services and Kiefner and Associates for the American Petroleum Institute (API), which resulted in the publication API 1156 [12]. The work considered the effects of smooth and rock dents on liquid petroleum pipelines. As part of the work program, 3 full-scale burst tests were undertaken of dents with simulated corrosion. A summary of the tests is given in Table 2.

The failure pressure of the first two tests (12%OD dents, 50%t corrosion depth, 230mm corrosion length) was conservatively predicted by RSTRENG, suggesting that there was no effect of the corrosion and the dents. However, the predicted failure pressure of the third test was non-conservative, suggesting that dent depth may have a contributing effect; the dent depth of the third test was 18%OD.

### 3.2.2 Pipeline Research Council International, Inc. (PRCI)

This sub-section provides an overview of a comprehensive program of work undertaken by Kiefner and Associates for PRCI to provide guidelines for the repair of pipeline dents containing 'minor scratches' [13]. Grinding was one of the repair methods investigated for the removal of minor scratches, gouges and associated cracking. In this context, metal removed by grinding is considered comparable to corrosion metal loss as neither affect the micro-structural characteristics of the steel<sup>4</sup>, or introduce any additional stresses in the pipe other than those due to the local geometric change.

The work investigated the effects of dent shape and depth, notch depth and grind out depth. Four different dent shapes and sizes were used. The purpose of the burst tests was to demonstrate that the severity of dent plus 'gouge' damage could be reduced by grinding of the gouge, resulting in failure stresses in excess of 100% SMYS.

A summary of the tests undertaken is given in Table 3. The test procedure was as follows:

1. Machine notch while the pipe is at zero pressure
2. Pressurise to 60% SMYS
3. Indent while at pressure
4. Withdraw indenter
5. Re-pressurise to 60% SMYS (a slight pressure drop was experienced when the indenter was withdrawn), and hold for 1 minute
6. Depressurise and measure residual dent depth/profile
7. Grind away notch (only those specimens identified for repair) and measure remaining wall thickness
8. Re-pressurise to 65% SMYS
9. Depressurise and re-measure residual dent depth/profile
10. Conduct burst test

The results of the full-scale burst tests undertaken are summarised as follows:

- The residual dent depth was measured to be a maximum of 4.1%OD (indenter removed, specimen at zero pressure).
- Ten of the 20 unrepaired specimens exhibited a failure stress less than 100% SMYS, the lowest being 51% SMYS.
- All specimens repaired by dressing exhibited a failure stress greater than 100% SMYS.

The main conclusion from the work undertaken was; provided that the dent depth was not greater than 4%OD, use of a hand-held rotary grinder to remove cracking, gouging or minor scratches was acceptable. There is no restriction on length of grind repair provided the grinding depth is not greater than 20%t. Removal of up to 40%t is permissible, provided the length of the grind out is not greater than that determined from Equation [7].

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<sup>4</sup> Care should be taken when removing defects by grinding to ensure that the hand-held rotary grinding tool is used at an angle not greater than 45° to the pipe surface, and the force applied during grinding is not excessive (i.e., the applied force during grinding should be sufficient to avoid generation of excessive residual stresses, and discolouration of the metal surface due to heat generation which can result in hardened zones and possibly introduce cracking).

The above proposed limits for the repair of stress raising defects in dented pipe are now embodied in the pipeline codes, CSA Z662 and ASME B31.8, although the 20%t limit has been reduced to 10%t, which is consistent with limit specified for corrosion associated with a dent.

### 3.3 Concluding Remarks

The pipeline codes ASME B31.8 and CSA Z662 permit dents up to 6%OD with associated corrosion up to 10%t in depth. Deeper corrosion is permitted, up to 40%t, provided the longitudinal length of the corrosion is within the limits derived by Equation [7] (ASME B31.8) or Equation [8] (CSA Z662).

Both pipeline codes permit the use of alternative corrosion assessment methods, referring to modified ASME B31G and RSTRENG. For pipelines operating at hoop stress levels up to 72% SMYS both methods consider corrosion up to 20%t to be acceptable, regardless of length. For corrosion deeper than 20%t there is a restriction on allowable length.

A 20%t corrosion limit, irrespective of length, is also supported by the results of full-scale tests reported by Kiefner and Associates [13] and API 1156 [12]. The work by Kiefner and Associates, although focusing on dents with metal loss due to grinding, demonstrated that dents up to 4%OD with associated metal loss up to 20%t will have a failure stress greater than 100% SMYS. The results of the limited number of tests reported in API 1156, demonstrated that dents up to 12%OD with corrosion up to 50%t has a failure stress not less than 89% SMYS.

It is considered likely that the 10%t limit on corrosion depth in ASME B31.8 and CSA Z662 is due to the limitations of the original ASME B31G method, which reduces to 10%t metal loss for 'long' corrosion.

A comparison is given in Figure 1 of the critical length loci as specified in ASME B31.8 and CSA Z662 (Equations [7] and [8] above) and the failure loci predicted using original ASME B31G and modified ASME B31G methods. The loci correspond to a failure stress of 100% SMYS. As can be seen, long defects up to 20%t in depth are considered acceptable to modified ASME B31G which, as stated in Section 3.1.2, gives a conservative but more accurate prediction of critical defect size compared with ASME B31G.

The analyses and full-scale burst test results for dent plus corrosion and dent plus metal loss due to grinding would suggest that dent depths up to 6%OD with corrosion up to 20%t in depth are acceptable for pipelines operating at stress levels up to 72% SMYS.

To further demonstrate the effect a dent with associated corrosion up to 20%t in depth a limited number of FE analyses have been undertaken, details of which are summarised in Section 4.

## 4 Finite Element Analysis

A limited number of FE analysis have been undertaken to support the conclusions from the full-scale tests summarised above towards assessing the significance of plain dent damage with associated metal loss/corrosion.

The analysis undertaken is typical of a 'Level 3' assessment, as recommended in the ASME B31G guidance document.

The models are based on a pipe size and material grade; 914x12.7mm (outside diameter and wall thickness), grade X65 line pipe.

One dent depth (a residual dent depth, following elastic springback, of 6%OD) was studied, but the size and shape of the associated corrosion was varied (the corrosion depth was the same for each model, 20%t), as follows;

Shape	Length (longitudinal)	Length (circumferential)
Pit	2t	2t
Longitudinal groove	32t	2t
Circumferential groove	2t	32t
Patch	32t	32t
Wide-spread	the thickness of the entire model was reduced by 20%, from the external surface	

For these simulations the dents were idealised as being spherical in shape with an indenter radius of 100mm.

A summary of the models generated is given below, followed by a summary of the results obtained.

#### 4.1 Model Generation

Quarter symmetry, three dimensional non-linear FE models were constructed using the mesh generating software, PATRAN 2008r2 [14] and analysed using the general purpose FE code, ABAQUS version 6.9.1 [15]. The FE models were meshed using 8-noded reduced integration solid elements of type 'C3D8R', with four elements through the pipe wall thickness in the dent/metal loss region. Remote from the damage a coarser mesh was used, reducing to two elements through the thickness. The element type and mesh density were considered sufficient based on previous FE studies undertaken by GL on 'corrosion' damage. Furthermore, a mesh sensitivity study was undertaken, as recommended in BS 7910 (Annex G) [16], which confirmed the suitability of the mesh.

Due to the highly non-linear characteristics of the problem, the analysis allowed for both material non-linearity and large localised non-linear deformation to be considered (NLGEOM)

The dent was introduced into the pipe outer surface using a 'spherical' shaped indenter, which was modelled as a rigid surface. The ABAQUS rigid-deform contact key was used; the indenter was the master surface, the pipe outer surface was the slave surface. The indenter was offset from the pipe outer surface by 2mm to prevent over-closure of the contacting surfaces at the beginning of the analysis. The denting step was

displacement controlled, the displacement of the indenter being equivalent to the corresponding percentage of the pipe diameter plus a 2mm offset<sup>5</sup>.

## 4.2 Material Properties

The material stress-strain behaviour used in the analysis was previously generated as part of the Line Pipe Corrosion (LPC) Group Sponsored Project [17]. The grade X65 stress-strain curve was obtained from a round-bar tensile specimen tested at ambient laboratory temperature. The stress-strain data were converted to equivalent true stress-true strain data and input into ABAQUS as a piece-wise linear approximation using the \*PLASTIC option. In addition, an elastic modulus and Poisson's ratio of 210kN/mm<sup>2</sup> and 0.3 respectively, were used.

The true stress-true strain data are presented in Appendix A.

## 4.3 Boundary Conditions

Symmetry boundary conditions were used to reduce the size of the FE models. Two axes of symmetry were applied to the quarter models, in the X=0 and Z=0 planes (see Figure 2). The nodes along the bottom of the pipe were restrained from moving in the Y-direction to prevent rigid body motion. The 'pipe' was extended sufficiently far from the area of damage to ensure that application of the boundary conditions did not influence the deformation behaviour and stresses in the area of interest.

In order to represent the pipe sections being capped off downstream, pressure end loads were applied to the unrestrained end of the model.

## 4.4 Assessment Method

The denting simulation was undertaken in 3 steps;

- Step 1 : The indenter is displaced into the pipe outer surface.
- Step 2 : The indenter is removed, allowing the dent to spring back elastically (target dent depth being 6%OD).
- Step 3 : The internal pressure is then increased monotonically until the conditions for failure have been achieved, and the corresponding incremental increase in pressure was less than 0.0001 (approximately 0.02 bar).

The failure criterion used in this work was validated for corrosion damage only and may not necessarily be the most appropriate criterion for dent plus corrosion. There is no recognised failure criterion for dent plus corrosion damage.

The von Mises equivalent stress was monitored at three points through the remaining ligament as the internal pressure in the pipe was increased. The failure pressure was determined as being equal to the pressure when the mean von Mises equivalent stress

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<sup>5</sup> The target dent depth of each model, after elastic spring back, was 6%OD. The required initial dent depth varied slightly between the different models due to the change in stiffness associated with the area of metal loss modelled, i.e., pit, groove (axial or circumferential), patch and wide-spread corrosion.

in the ligament is equal to the true ultimate tensile strength of the material (675 N/mm<sup>2</sup>). This method is consistent with the approach described in BS 7910 (Annex G) for predicting the failure pressure of corroded pipelines.

## 4.5 Results

A set of 6 models were created to investigate the effect of size (longitudinal and circumferential extent) of corrosion that is 20%t deep on the failure characteristics of a dent. The surface dimensions of the corrosion modelled are expressed as multiples of the pipe wall thickness and the depth is given as a percentage of pipe wall thickness (e.g., 2t x 2t x 20%t is axial length x circumferential width x depth);

- Model 1: pipe with 6%OD final dent, no corrosion
- Model 2: pipe with 6%OD final dent, pitting corrosion (2t x 2t x 20%t)
- Model 3: pipe with 6%OD final dent, longitudinal groove (32t x 2t x 20%t)
- Model 4: pipe with 6%OD final dent, circumferential groove (2t x 32t x 20%t)
- Model 5: pipe with 6%OD final dent, patch (32t x 32t x 20%t)
- Model 6: pipe with 6%OD final dent, wide-spread corrosion ( $\infty$ t x  $\pi$ Dt x 20%t)<sup>6</sup>

The variation in von Mises equivalent stress through the ligament was monitored at three locations within the dent, during pressurisation;

- at the dent centre
- the location along the pipe longitudinal direction within the dent where the von Mises equivalent stress was the highest
- the location around the pipe circumference within the dent where the von Mises equivalent stress was the highest

Figure 3 show the variation in von Mises equivalent stress for Model 5; dent plus patch corrosion. As can be seen, before any increase in internal pressure there is a residual stress distribution present which is due to the plastic deformation of the pipe on removal of the indenter.

Failure was deemed to occur at the first attainment of one of these three regions satisfying the failure criterion. The results of the analyses are presented in Table 4. As can be seen;

- The dent-pit and dent-circumferential groove models gave the highest predictions of failure pressure; 182.8 and 182.7 bar, respectively
- The wide-spread corrosion model gave the lowest predicted failure pressure; 147.0 bar
- The failure pressure of the dent only model was similar to the predicted failure pressure of the dent-pit and dent-circumferential groove models

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<sup>6</sup> Wide-spread corrosion extends around the full circumference and entire length of the model.

A duplicate set of models were analysed, excluding the dent, to enable the effect of the dent to be assessed. The results of these analyses are also presented in Table 4 for comparison.

As can be seen, the dent plus corrosion feature has a higher predicted *maximum* pressure than the equivalent model without the dent, suggesting that the geometric constraint introduced by the dent has a beneficial effect on the failure behaviour of the damaged pipe. This effect is not so apparent in Model 1 (difference of 0.7 bar), and the difference is small for Model 3 (4.0 bar) and Model 5 (8.5 bar). The biggest difference is for Model 2 and Model 4 where the failure pressure was seen to increase by approximately 14% for both.

The results for Model 6, which considers wide-spread corrosion on the pipe outer surface, suggests that failure would occur in the pipe body, away from the dent; the maximum pressure for the model excluding the dent was 134 bar, but for the dent plus wide-spread corrosion model the maximum pressure within the dented region was predicted to be 147 bar.

## 5 Fatigue Assessment Method for Dent plus Corrosion Damage

There is no method for predicting the fatigue life of a dent with associated metal loss due to corrosion.

UKOPA recommends use of the EPRG method for predicting the fatigue life of a plain dent (see Section 2).

Until 2009 there was no method for predicting the remaining fatigue life of corrosion in a pipeline subject to pressure cycling. GL developed a method as part of a consolidated program of work funded by the PRCI and the US Department of Transportation (DOT) Pipelines and Hazardous Materials Safety Administration (PHMSA) [18], which was verified by a limited number of full-scale cyclic pressure tests. The method is based on the approach to the fatigue design of welded structures (BS 7608 [19]), where fatigue life is defined by a particular stress-life (S-N) curve applicable to the geometry of the component being assessed. The GL method is based on the BS 7608 Class B fatigue design curve, with a modification to the input stress range to take account of the stress raising effect of the area of metal loss.

The input stress range is modified by a stress concentration factor (SCF), the magnitude of which is dependent on the pipe size and the area of metal loss; depth, and longitudinal and circumferential extent. Closed form equations were developed based on the results of a series of numerical analyses to predict the SCF for an area of corrosion within the following limits;

Pipe:

Pipe diameter (D) : up to 1270mm  
Wall thickness (t) : 9.5mm up to 19.1mm  
D/t : 40 to 100

Corrosion:

Depth : not greater than 60%t  
Longitudinal length : from 25 to 1000mm  
Circumferential length : from 25 to 1000mm

Due to the changing relationship observed between the SCF and defect geometry two separate equations were developed; one based on the pipe hoop stress, the other on the axial stress. When the circumferential length of the corrosion was *greater than* 100mm and the longitudinal length *less than* 40mm the SCF could either be hoop or axial driven, so it was recommended that the highest of the two SCFs should be used in the assessment.

The equations were developed based on SCFs that were mapped out for a series of corrosion depths; 20, 40, 60 and 80%t.

Since this work is interested in corrosion up to 20%t in depth, the SCFs will always be dominated by the hoop component of stress. To reduce the errors associated with the fit of the equation to the numerical data, the constants for the hoop equation were re-assessed. The SCFs are calculated using the following expression, which gives a mean fit to the data (error of +5.8%, -9.5%);

$$SCF_{HOOP} = A_1 + \left[ A_2 (CD)^2 \left( \frac{\ln(ACL)}{\ln(CCL)} \right)^2 \right] + \left[ A_3 \frac{CD^2}{\left( \frac{CCL}{\sqrt{Dt}} \right)} \right] + \left[ A_4 \frac{(CD)^2 ACL}{CCL} \right] + \left[ A_5 (CD)^2 \ln \left( \frac{CCL}{ACL(CD)} \right) \right] \quad [9]$$

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<sub>1</sub> to A<sub>6</sub> are equation fitting constants, which for corrosion up to 20%t in depth are as follows;

A<sub>1</sub> : 1.47  
A<sub>2</sub> : 8.91  
A<sub>3</sub> : -0.23  
A<sub>4</sub> : -0.72  
A<sub>5</sub> : 0.67

The EPRG dent fatigue life model (see Equation [1]) requires calculation of an 'equivalent cyclic stress', which is determined from the nominal cyclic hoop stress range (see Equation [3]). It is recommended that the nominal cyclic hoop stress range in Equation [3] is first multiplied by the above SCF, to enable calculation of the equivalent cyclic stress (Equation [2]). A 'mean fit' SCF is recommended as the predicted fatigue life from Equation [1] is then divided by 13.3 to give a lower bound estimate.

To date there is no published experimental data to support the above proposed modification to the EPRG dent fatigue life model to enable consideration of the effect of associated corrosion. It is recommended that UKOPA undertake a limited number of full-scale pressure cycle tests to support this recommendation.

## 6 Discussion

The aim of this work was to undertake a feasibility study to investigate whether corrosion up to 20% of the pipe wall thickness in depth had a detrimental effect on the behaviour of a dent in a pipeline.

An initial study was undertaken to identify the limits on dent plus corrosion depth specified in pipeline codes and to then review the background to these limits. As discussed in Section 3.3, ASME B31.8 and CSA Z662 permit dents up to 6%OD in depth with associated corrosion up to 10%t in depth. Deeper corrosion, up to 40%t is permitted, although there are restrictions on the length of the corrosion in the pipe longitudinal direction. Both pipeline codes permit the use of alternative corrosion assessment methods, recommending the use of modified ASME B31G and RSTRENG. Both of these 'alternative' methods consider corrosion up to 20%t in depth to be acceptable, regardless of length. A 20%t corrosion limit is also supported by full-scale tests. The review suggests that the UKOPA limits of a 6%OD dent with associated corrosion up to 20%t are acceptable for pipelines operating at hoop stress levels up to 72% SMYS.

It should be noted that for pipelines with dent only damage the empirical limits on dent depth proposed by EPRG and PDAM are based on tests undertaken on line pipe up to and including grade X65. GL is aware of research by EPRG to investigate the burst strength of dent damage in pipelines constructed from grade X80 line pipe. Until the results of this work are published and reviewed by UKOPA it is recommended that the UKOPA dent plus corrosion limits of 6%OD (dent) and 20%t (corrosion) are specified for pipelines constructed from line pipe up to and including grade X65.

A limited number of FE models were constructed to investigate the effect of 20%t corrosion associated with a dent. The corrosion shape was varied; pit, patch, longitudinal groove and circumferential groove to determine what affect corrosion size had on the remaining strength of a dent. These were bounded by a dent only model and a dent plus wide-spread corrosion model.

The results of the FE study suggested that the dent may provide a beneficial effect as the failure pressure of a dent plus corrosion feature was found to be higher than the corresponding failure pressures for just the corrosion features (i.e., without the dent) predicted using FE.

The failure pressure for each model, excluding the presence of the dent, was also predicted using the standard Level 1 assessment methods; ASME B31G and modified ASME B31G. The results of the assessment are presented in Table 5. The assessment methods do not consider the circumferential extent of the corrosion. The predictions are based on depth and axial length (i.e., length in the pipe longitudinal direction) only. Hence, the predicted failure pressure of the pit and circumferential groove, both having an axial length of  $2t$ , is identical. Similarly, the longitudinal groove and patch had an axial

length of  $32t$ , so the predicted failure pressure is again identical, although less than the previous cases due to the increase in length.

It is interesting to see from a comparison of Table 4 and Table 5 that the predicted failure pressures for the dent plus corrosion features are higher than the predicted failure pressures of the corrosion features only.

Although there may be scope for further investigations to look at the effect of dent shape (e.g., elongated dents, either longitudinal or transverse), it would appear based on the evidence in the public domain and the supporting FE study undertaken in this work that corrosion up to  $20\%t$  in depth will not have a significant effect on the behaviour of a dent up to  $6\%OD$  in depth. It is judged that the UKOPA limits of  $6\%OD$  dent with corrosion up to  $20\%t$  in depth are acceptable for pipelines operating at hoop stress levels up to  $72\%$  SMYS.

Although there are methods available for determining the fatigue life of plain dent damage (UKOPA recommends the use of the EPRG model, see Section 2), there is no recommended method for predicting the impact of additional corrosion damage on the predicted fatigue life of the dent.

A modification to the EPRG model is suggested based on the results of work undertaken by GL to develop a fatigue life assessment method for corrosion damage in a pipeline that is pressure cycled. The proposed modification is to multiply the input nominal cyclic stress range by an SCF to take account of the local geometric stress concentration due to the area of metal loss. A closed form equation is presented to enable a prediction of the SCF for corrosion up to  $20\%t$  in depth.

There is no experimental data in the public domain to support this proposed modification, hence it is recommended that UKOPA consider undertaking some limited full-scale pressure cycle tests to support this modification.

## 7 Conclusions

1. The pipeline codes ASME B31.8 and CSA Z662 permit dents up to  $6\%OD$  in depth with corrosion up to  $10\%t$  in depth in the body of the pipe (not associated with a seam or girth weld). Corrosion up to  $40\%t$  is permitted, although any corrosion greater than  $10\%t$  in depth will be restricted by length.
2. A limited number of full-scale tests have been found in the public domain which considers dents plus machined metal loss defects and dents plus areas of metal loss due to grinding (simulation of defect removal by grinding). Those tests support the UKOPA limits of  $6\%OD$  dents with corrosion up to  $20\%t$  in depth in pipelines operating at hoop stress levels up to  $72\%$  SMYS.
3. A limited number of FE models were created of dents with corrosion up to  $20\%t$  in depth to investigate whether the general size and shape of the corrosion had a detrimental effect on the dented pipeline. The predicted failure pressures were found to differ, depending on shape, although the predictions were higher than the failure pressures predicted for the dent only model, and the corrosion only models. The results suggested that the geometrical constraint introduced by the dent had a beneficial effect on the failure behaviour of the damaged pipe.

4. There is no method available for predicting the fatigue life of a dent plus corrosion feature. There are methods available for determining the fatigue life of a dent (UKOPA recommend use of a model developed by EPRG) or corrosion damage (a model developed by GL Noble Denton for PRCI and the US DOT). A model is proposed 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 GL Noble Denton corrosion model. There is no experimental data to support this modification; hence further work will be required.

## 8 Recommendations

1. The UKOPA limits for dent plus corrosion damage should be limited to pipelines constructed from line pipe up to and including grade X65. Dent only limits for pipelines constructed from grade X80 line pipe are currently being investigated by EPRG. Once the EPRG work is in the public domain it should be reviewed by UKOPA, and the limits extended if appropriate.
2. Consideration should be given to undertaking additional FE studies to further investigate the effects of pipe geometry, material grade and dent depth.
3. Consideration should be given to investigating the effect of dent shape on the behaviour of combined dent plus corrosion damage as the limited numerical studies undertaken in this work considered only spherical shaped dents.
4. To further support the proposed modification to the EPRG dent fatigue model it is recommended that UKOPA give consideration to undertaking a limited number of full-scale pressure cycle tests on combined dent plus corrosion damage.
5. Consideration should be given to including the method recommended in PDAM for estimating the fatigue life of a dented weld.

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Criterion		Reference Source
Plain dent – maximum depth <sup>1</sup>	7% OD	EPRG, PDAM
Plain dent – maximum strain <sup>1</sup>	6%	ASME B31.8 <sup>2</sup>
Plain dent on ductile weld <sup>3</sup> – maximum depth <sup>1</sup>	2% OD	ASME B31.8 <sup>2</sup>
Plain dent on ductile weld <sup>3</sup> – maximum strain <sup>1</sup>	4%	ASME B31.8 <sup>2</sup>
Plain dent with associated metal loss due to corrosion	Treat as plain dent if corrosion depth is not greater than 20% of the pipe wall thickness	UKOPA Members <sup>4</sup>

- Notes:**
1. where both dent depth and dent strain are available, dent depth should be used to prioritise dents
  2. ASME B31.8 addresses gas pipelines; the assessment criteria are assumed to apply to onshore gas and liquid pipelines
  3. Charpy impact energy of the weldment is not less than 27J in a full-size Charpy specimen
  4. Corrosion limit is based on that applied by a number of UKOPA member companies. The accepted code limit is 10%t

Table 1 UKOPA dent assessment criteria

Pipe OD	Dent type	Damage		Prediction	Test result	
		Dent depth (% OD)	Length of corrosion (mm)	Failure pressure (Bar)	Failure pressure (Bar)	Failure stress (%SMYS)
323.9	Dome	12	230	82.0	94.1	89
323.9	Long bar	12	230	82.0	93.6	89
323.9	Long bar	18	255	73.8	60.7	58

- Notes:** The depth of the corrosion was 50%t for each test.

Table 2 Dent plus corrosion test results from API 1156 [12]

Damage type	Initial dent depth (%OD)	Notch size		Grindout depth <sup>§</sup> (%t)
		Depth (%t)	Length (mm)	
Dent*	5, 10, 15, 20			
Notch**		5, 10, 15	300	
Grindout		5, 10, 15	300	Up to 17.5
Dent plus notch	5 to 15	5 to 18	50 to 300	
Dent plus grindout	5 to 20	5 to 18	50 to 300	Up to 61

- Notes:** \* The purpose of the dent only tests was to determine the residual dent depth on removal of the indenter.
- \*\* The purpose of the notch only tests was to determine the extent of any associated cracking in the base of the notch due to pressurisation of the test specimen to 65% SMYS
- § Sufficient material was removed by grinding to remove the machined notch and any associated cracking from its base. The length of the grind repair was just sufficient to remove the notch.

Table 3 Summary of tests undertaken towards investigating the repair of pipeline dents containing minor scratches [13]

Model		Initial dent depth (%OD)	Residual dent depth (%OD)	Predicted failure pressure (Bar)	Maximum pressure	
ID	Corrosion				Dent plus corrosion (Bar)	Corrosion only (Bar)
1	No corrosion	10.54	6.02		182.7	182.0
2	Pitting	10.66	5.99	181.3	182.8	160.0
3	Long groove	10.50	5.99	145.2	164.0	160.0
4	Circ groove	10.60	5.99	182.4	182.7	160.0
5	Patch	10.46	6.01		168.5	160.0
6	Wide-spread	11.45	6.00		147.0	134.0

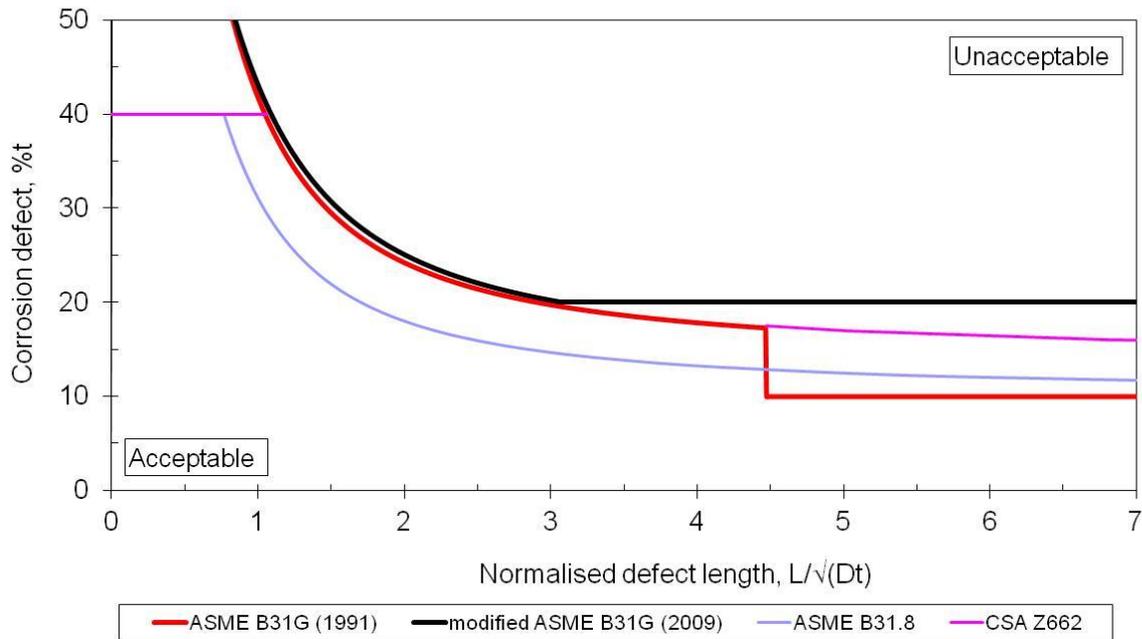
- Notes:** 1. Residual dent depth is the dent depth after removal of the indenter (zero internal pipe pressure)
2. Predicted failure pressure is the pressure at the first attainment of a through wall ligament von Mises equivalent stress equal to the material true ultimate strength
3. Maximum pressure is the final pressure increment from the FE analysis, when subsequent increments were less than 0.0001 (0.02 bar)

Table 4 FE results

Model		ASME B31G	Modified B31G
ID	Corrosion	(Bar)	(Bar)
2 4	Pit Circ groove	136.4	149.3
3 5	Long groove Patch	123.3	130.9
6	Wide-spread	109.5	120.0

- Notes:**
1. The pit and circumferential groove had the same predicted failure pressure as the axial length of each was  $2t$ . The longitudinal groove and patch also had the same failure pressure as the axial length of each was  $32t$
  2. The predicted failure pressure for wide-spread corrosion assumed an axial length of  $12m$

Table 5 Failure pressure predictions: Corrosion only



- Notes:**
1. D and t is pipe outside diameter and wall thickness, and d and L is depth and length (in the pipe longitudinal direction) of the metal loss/corrosion
  2. The modified ASME B31G (2012) locus is based on the specified minimum yield strength for grade X80 steel, and provides a lower bound critical defect size locus for pipelines constructed from lesser material grades.
  3. The ASME B31.8 and CSA Z662 loci are capped at a depth of 40%t, consistent with the maximum depth permitted in the design codes.

Figure 1 Loci of critical defect size for metal loss/corrosion

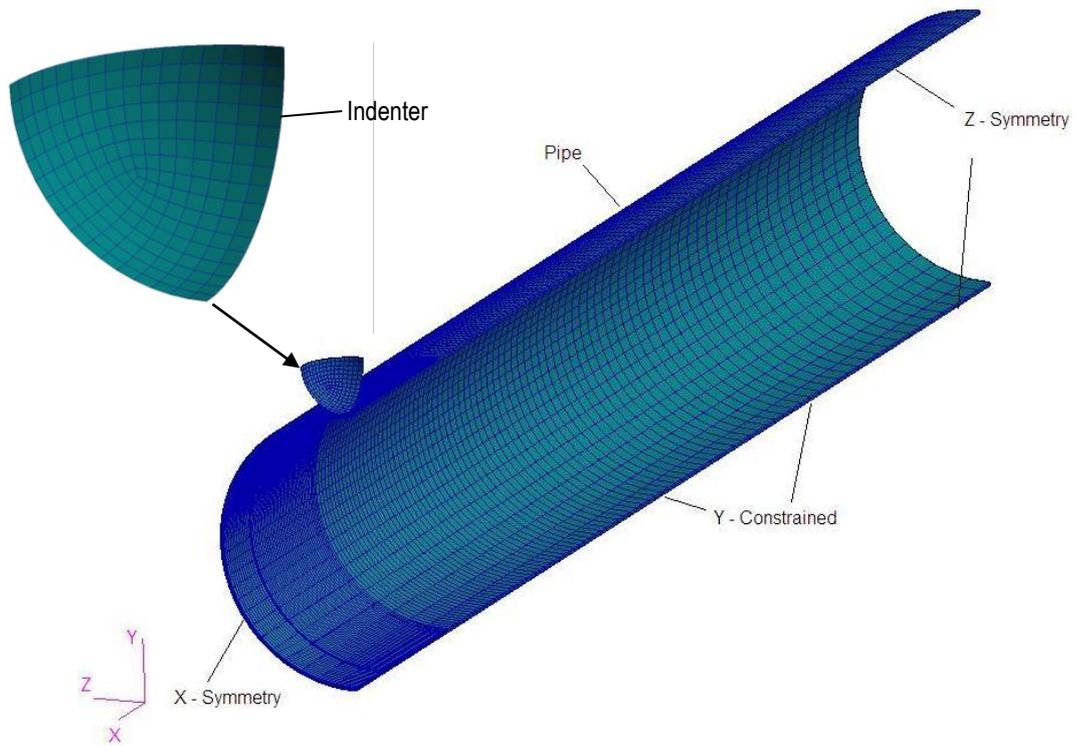
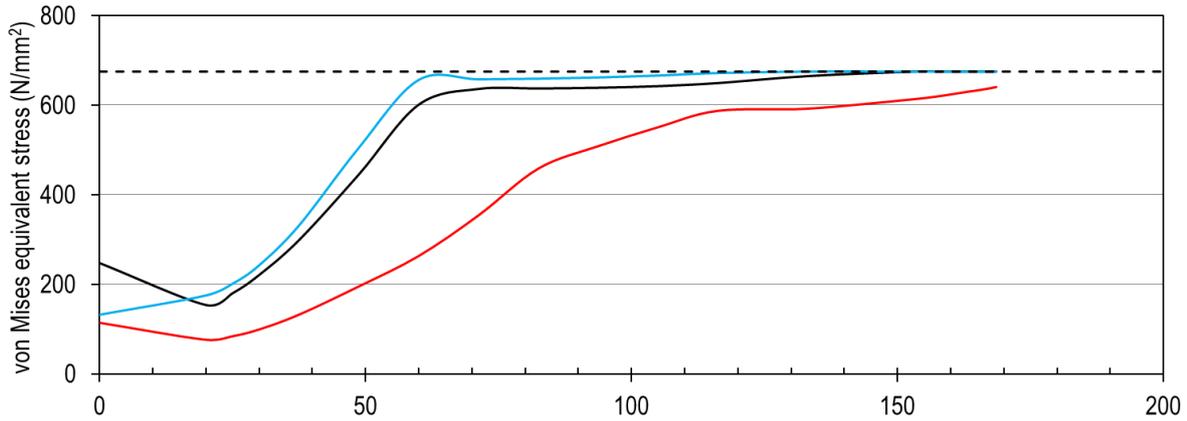
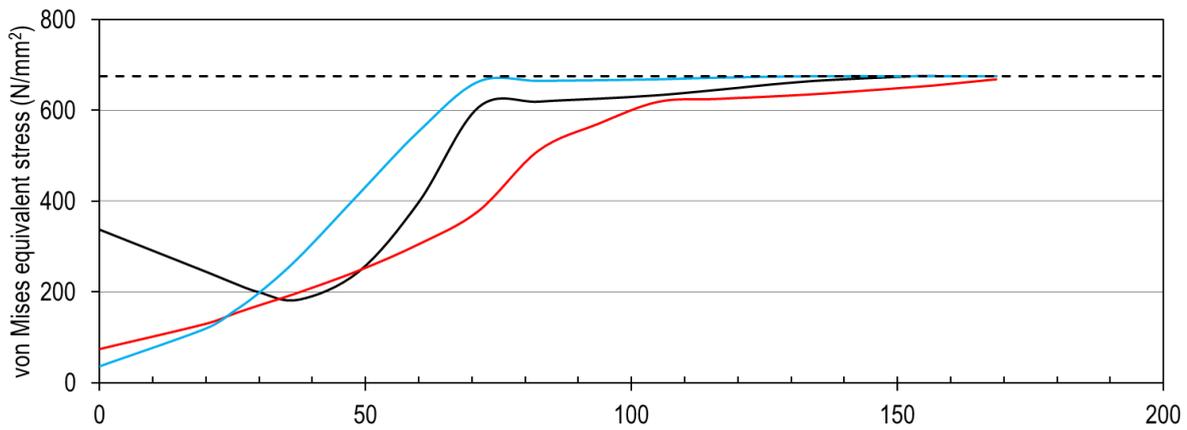


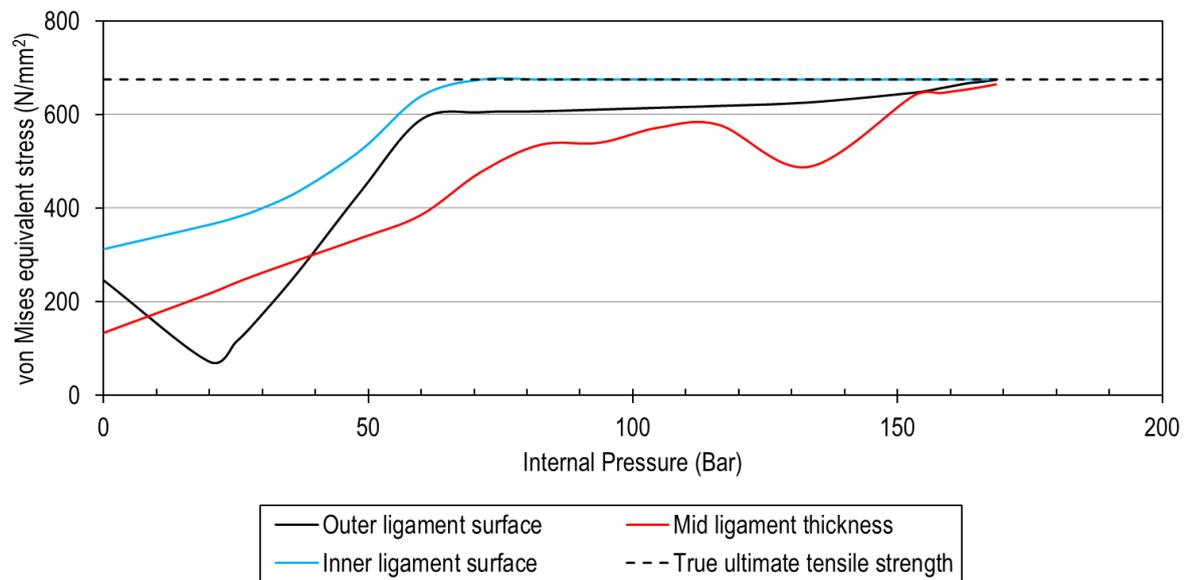
Figure 2 FE model



(a) Dent centre



(b) Pipe longitudinal direction, within the dent



(c) Pipe circumferential direction, within the dent

Figure 3 Model 5: pipe with 6%OD final dent, patch corrosion (32t x 32t x 20%t depth)

## Appendix A True Stress-Strain Curve (grade X65 line pipe)

The true stress-strain data was measured from a round bar tensile specimen that was tested at ambient laboratory temperature, approximately 20°C [17].

True Plastic Stress (N/mm <sup>2</sup> )	True Plastic Strain
445.0	0.000
475.0	0.003
499.4	0.006
522.0	0.011
534.0	0.014
547.2	0.017
560.0	0.022
573.9	0.028
586.3	0.035
596.1	0.038
607.0	0.045
618.6	0.054
626.9	0.059
636.6	0.068
643.5	0.073
658.3	0.086
670.5	0.098
675.0	0.103
675.0	0.500