GL Noble Denton

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Feasibility Study: Fatigue Assessment of Plain Dent Damage

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Executive Summary

The UKOPA dent management strategy recommends the EPRG formulae for estimating the fatigue life of a plain dent. An example of a pipeline dent fatigue curve is provided which shows the reduction in fatigue life associated with increasing dent depth; a constant amplitude hoop stress range of 125 N/mm² is used to construct the loci. A simplified table is also provided, which gives the reduction in fatigue life with increasing dent depth, for dent depth increments of 2.5% of the pipe outer diameter (D). However, this guidance is based on the simplified method in IGEM/TD/1, which uses an S-N curve that was derived for application to pipelines which have been subject to a high level hydrotest (the design fatigue life of the pipeline is not less than 15,000 cycles of 125 N/mm² hoop stress range). The tabulated fatigue life is considered overly conservative; for example, the lower bound fatigue life of a 2.5%D deep dent is specified as 10% of the design fatigue life of the pipeline. In contrast, full scale fatigue tests have demonstrated that regardless of dent shape, a 2.5%D deep dent will have a fatigue life in excess of 15,000 cycles of 125N/mm² (which includes a safety factor of 10 on life).

There are other 'established' methods that have been developed for estimating the fatigue life of pipeline dent damage, the most notable of these being PRCI and API 1156, which are based on S-N curves.

More recently GL Noble Denton developed an S-N curve based plain dent fatigue assessment method. Finite Element Analysis (FEA) methods are used to obtain a realistic estimate of the local dent stress range based on the minimum and maximum pipeline pressures. The fatigue curves in BS 7608 are then used to estimate the plain dent fatigue life based on the local dent stress range. The approach was verified by full-scale fatigue tests on dented line pipe. The results of the analyses were found to be less conservative than, for example, EPRG, and to reflect the effect of dent shape (e.g., spherical or elongated), unlike other methods, which can have a significant effect on fatigue life.

UKOPA would like to assess the feasibility of using stress concentration factors (SCFs) at dents in a generic dent fatigue life estimation procedure and has requested GL Noble Denton to undertake the following:

1. Undertake a literature review and assess the applicability of existing dent SCF equations,

2. To compile dent SCFs generated by GL Noble Denton with those from FEA undertaken by UKOPA members and compare approaches,

3. Undertake S-N curve fatigue life calculations, consistent with the approach outlined in the UKOPA dent management strategy, and compare the resulting fatigue lives,

4. Undertake a gap analysis to identify where further development work would be required.

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

Conclusions

1. The published SCF values for dents in PRCI and API models were obtained from a limited range of linear and non-linear FE analyses.

2. The definition of dent SCFs varies depending on which model is used.

3. For the example dent assessed in this report, the predicted fatigue life based on the methods reviewed in this work ranged from 2,586 cycles to 451,615 cycles; the test was terminated after 151,929 cycles without failure.

4. The EPRG model, which is recommended by PDAM and the UKOPA dent management strategy, is shown to predict relatively short fatigue lives in comparison to other methods reviewed in this report.

The EPRG model may be overly conservative for assessing the fatigue life of a dented pipeline subject to cyclic internal pressure loading.

5. The SCF equations presented in this report are based on a large number of FE analyses undertaken by GL Noble Denton on a wide range of pipe sizes and dent shapes (depth, length and width).

Recommendations

1. Using the existing FE results; undertake additional example calculations of fatigue life using the models reviewed in this report.

2. Undertake additional FE analyses to further validate and improve the fit of the SCF equations (3) and (4); increasing dent depth and a wider range of pipe geometries.

Contents

1 Introduction

The UKOPA dent management strategy[1] recommends the EPRG formulae[2] for estimating the fatigue life of a plain dent. An example of a pipeline dent fatigue curve is provided which shows the reduction in fatigue life associated with increasing dent depth; a constant amplitude hoop stress range of 125 N/mm² is used to construct the loci. A simplified table is also provided, which gives the reduction in fatigue life with increasing dent depth, for dent depth increments of 2.5% of the pipe outer diameter (D). However, this guidance is based on the simplified method in IGEM/TD/1[3], which uses an S-N curve that was derived for application to pipelines which have been subject to a high level hydrotest (the design fatigue life of the pipeline is not less than 15,000 cycles of 125 N/mm² hoop stress range). The tabulated fatigue life is considered overly conservative; for example, the lower bound fatigue life of a 2.5%D deep dent is specified as 10% of the design fatigue life of the pipeline. In contrast, full scale fatigue tests have demonstrated that regardless of dent shape, a 2.5%D deep dent will have a fatigue life in excess of 15,000 cycles of 125N/mm² (which includes a safety factor of 10 on life).

There are other 'established' methods that have been developed for estimating the fatigue life of pipeline dent damage, the most notable of these being PRCI[4],[5] and API 1156[6], which are based on S-N curves.

More recently GL Noble Denton developed an S-N curve based plain dent fatigue assessment method[7],[8]. Finite Element Analysis (FEA) methods are used to obtain a realistic estimate of the local dent stress range based on the minimum and maximum pipeline pressures. The fatigue curves in BS 7608[9] are then used to estimate the plain dent fatigue life based on the local dent stress range. The approach was verified by full-scale fatigue tests on dented line pipe. The results of the analyses were found to be less conservative than, for example, EPRG, and to reflect the effect of dent shape (e.g., spherical or elongated), unlike other methods, which can have a significant effect on fatigue life.

UKOPA would like to assess the feasibility of using stress concentration factors (SCFs) at dents in a generic dent fatigue life estimation procedure and has requested GL Noble Denton to undertake the following:

1. Undertake a literature review and assess the applicability of existing dent SCF equations,

2. To compile dent SCFs generated by GL Noble Denton with those from FEA undertaken by UKOPA members and compare approaches,

3. Undertake S-N curve fatigue life calculations, consistent with the approach outlined in the UKOPA dent management strategy, and compare the resulting fatigue lives,

4. Undertake a gap analysis to identify where further development work would be required.

2 Literature Review of SCF on Fatigue Life Assessment of Dents

Pushing an indenter (e.g., a rock or tooth of excavating machine) into a pipe causes a localised deformation. If the pushing force is small such that deformation of the pipe is within the elastic range, the elastic energy will be recovered when the pushing force is relieved or the indenter is retrieved. As a result there will be no permanent deformation of the pipe geometry. However, if the pushing force is sufficiently large to cause local plastic deformation of the pipe geometry when the indenter is removed and the elastic energy is recovered, a dent will be formed in the pipe due to the plastic deformation. The plastic deformation will increase as the dent depth increases[10]a. A dent in a pipeline causes a local stress and strain

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a There is a typographical error in equation (16); $f_2 \frac{1}{2}\sqrt{\frac{h}{R}}$ should be $f_2 \frac{l}{R}\sqrt{\frac{h}{R}}$, where l is the indenter length.

concentration. Therefore, the fatigue life of the dented pipeline under cyclic internal pressure loading is expected to be reduced.

A dent on a pipeline can be characterised as being constrained or unconstrained. A constrained dent is not free to rebound[b] or re-round[c], because the 'indenter' remains in-situ; a rock dent is an example of a constrained dent. A constrained dent is more likely to be located on the bottom third of the pipeline (between the 4 to 6 to 8 o'clock positions), caused by a hard rock during pipeline laying. On the other hand, an unconstrained dent is considered free to re-round under internal pressure load. An unconstrained dent is more likely to be located on the top two-thirds of the pipeline (between the 8 to 12 to 4 o'clock positions) and be the result of third party interference.

In-line inspection (ILI) records have shown that over 90% of reported dents are plain dents[11]. A plain dent has a smooth change in curvature of the pipe wall and is not associated with other features such as metal loss, welds and cracks.

Experimental tests and FEA [2], [4]-[8],[11]-[15] have shown that the SCF is a function of the dent depth (H) and shape (length L and width W), internal pressure, the pipe diameter to wall thickness (D/t) ratio and whether the dent is constrained or unconstrained. The definition of an SCF is discussed in Section 2.1 and some of the parameters used to describe the SCF are reviewed in Sections 2.2 to 2.6. A summary of SCF definitions is presented in Table 1.

2.1   SCF Definition

The SCF, used when undertaking a fatigue assessment of a dented pipe under cyclic internal pressure loading, is defined as a ratio of the stress range (or stress) at the dent over the stress range (or stress) in the pipe, remote from the dented region. Some of definitions used to describe a dent SCF are:

1. The Tresca stress range at the dent over the pressure range is used in the PRCI model[5] and the API model[6],

2. The equivalent stress range at the dent over the hoop stress range in the pipe is used in EPRG model[2],

3. The maximum principal stress range[d] at the dent over the hoop stress range in the pipe is used in the GL Noble Denton dent fatigue assessment method,

4. The peak hoop stress at the dent over the pipe hoop stress is proposed by Rinehart and Keating[12],

5. The von Mises equivalent stress at the dent over the pipe normal stress is proposed by de Carvalho Pinheiro *et al*[13].

Hence, for the same dent the SCF may be defined by one of the above 5 methods.

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[b] Rebound – also referred to as spring back; the reduction in dent depth due to the elastic unloading that occurs when the indenter is removed from the pipe

[c] Re-round – the change in dent depth under internal pressure

[d] When undertaking a fatigue analysis based on an S-N curve in standards such as BS 7608 [9], it is the principal stress that is used.

2.2 Dent Depth

The dent SCF will increase as the dent depth increases; as a result deep dents will have a shorter fatigue life when compared with a shallow dent. However, the depth of a dent varies at different stages and depends on when the dent was created, i.e. with or without the pipe subjected to internal pressure loading. The depth of a dent can be classified according to the following:

For dents created in the pipe at zero internal pressure and subsequently pressurised, the depth is:

1): Indented depth, H_i – the maximum dent depth prior to removal of the indenter,

2): Dent depth at zero pressure, H_o – the dent depth measured after removal of the indenter and after 'spring back'. After the indenter has been removed, the elastic energy stored in the pipe during the indentation tends to be released as the dent depth reduces. A dent is formed with local permanent plastic strains. Residual stresses are generated in the dent[16].

3): Dent depth measured while the pipe is pressurised, H – the dent depth is further reduced by the internal pressure 'pushing out the dent'. The dent depth decreases as the internal pressure increases.

4): Residual depth, H_r – the dent depth measured at zero internal pressure after spring back, rerounding and shakedown under cyclic pressure loading.

For dents created in a pressurised pipe, the depth is:

1): Indented depth, H_i – the maximum dent depth, prior to removal of the indenter,

2): Dent depth measured while the pipe is pressurised, H – the dent depth measured after the indenter is removed. The dent depth is reduced following 'spring back' and 'rounding'.

3): Residual depth, H_r – the dent depth measured at zero internal pressure after spring back, rerounding and shakedown.

The internal pressure may 'stiff' the pipe for the indenting. Therefore, higher external force is required to indent to the same depth on a highly pressurised pipe[10].

Most of the SCFs correspond to the dent being created at zero internal pressure[e]. The dent depth used in the SCF calculations is as follows:

1) The residual dent depth, H_r, used in the PRCI model[5] and API model[6],

2) The depth at zero pressure after 'spring back', H_o, used in EPRG model[2]. For dents created in pressurised pipe, a correlation between H_o and the dent depth measured at pressure, H, has been developed empirically.

3) The dent depth, H_o, H or H_r, used in GL Noble Denton dent fatigue assessment method,

4) The dent depth, H, used in Rinehart and Keating fatigue assessment method[11],

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[e] Internal pressure has the dual effect of stiffening the pipe (i.e., a greater force is required to produce a dent of a given depth) and causing the dent to spring back further when the indenter is removed (spring back is greater when denting a pressurised pipe because more of the deformation is elastic). Given the same maximum instantaneous dent depth during indentation, the remaining dent depth in a pipeline dented at zero pressure will be greater than the remaining dent depth in a pipeline dented at pressure. Dent damage caused during transportation or construction will be introduced at zero pressure, but generally, damage in the field will be produced at pressure and measured at pressure. Most of the experiments on dented pipe have involved introducing (and measuring) the dent at zero pressure (tests have been done on pipe with dents introduced at pressure, but they are not directly comparable to those where the dent was introduced at zero pressure), which is the condition that all of the models are based on too. A spring back factor is applied to relate the depth of a dent introduced and measured at pressure to a dent introduced and measured at zero pressure.

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5) The indented depth, H_i, used by de Carvalho Pinheiro et al[13].

2.3 Dent Length and Width

An investigation of dent length effect on the fatigue behaviour [11] of a pipeline shows that a long dent has a shorter fatigue life than a short dent of the same depth. The fatigue life of dents proposed by Rinehart and Keating [11], is given as:

$$N \propto \frac{1}{\dfrac{LWH}{D^2 t}} \tag{1}$$

where N is the number of pressure cycles to failure (or fatigue life), L, W and H are the dent length, width and depth measured in an un-pressurised pipe.

The SCF equation which is proposed by Carvalho Pinheiro et al[13], shows that the SCF value is directly proportional to the dent length L, but is inversely proportional to the dent width, W;

$$SCF = 1 + 1.423 \left(\frac{D}{t} \right)^{0.67} \left(\frac{H_i}{D} \right)^{0.62} \left(\frac{L}{W} \right) \tag{2}$$

Two types of dent, i.e., a dome dent created by a spherical shaped indenter and a long dent created by a long bar indenter, were analysed to determine SCFs for use in the API fatigue assessment model[6]. This model shows that, for the unconstrained dent, the long bar dent has a larger SCF value than the dome dent for the dent depth ratio, $H_r/D \geq 3\%$, but for $H_r/D \leq 2\%$ there is no clear trend of SCF value to the dent length. For constrained dents, the long bar dent has a larger SCF value for deep dents ($H_r/D \geq 12\%$), but has a lower SCF value for a shallow dent ($H_r/D < 12\%$).

The effect of dent shape (length and width) is not directly considered in the PRCI[5] and EPRG[2] models.

2.4 Pipe Geometry

Pipe diameter to wall thickness ratio, D/t, has an effect on fatigue life. The value of SCF increases as the D/t ratio increases; for the same dent shape and depth in a high D/t ratio pipe the fatigue life[5],[6],[13] will be less than an equivalent dent shape and depth in a lower D/t ratio pipe, or the fatigue life increases with an increase of the pipe wall thickness. However the opposite is seen for shallow dents ($H_r/D \leq 1\%$) in pipes with a small D/t (≤ 25)[5].

The fatigue strength of welded joints is to some extent dependent on the material thickness, with the fatigue strength decreasing as the thickness increases. For line pipe material thicknesses above 16mm, the allowable stress range has to be reduced by a factor $(t/16)^{1/4}$, where t is the wall thickness. For pipelines laid to IGEM/TD/1 the maximum thickness is unlikely to exceed 19mm, and the correction on stress in this case is a reduction of only 4%. Even at 25mm thickness the reduction in allowable stress range is only 10%, which is comparable with typical tolerances on wall thickness (and hence on actual hoop stress). Hence it is concluded that it is not necessary to apply a thickness correction when assessing the fatigue life of gas transmission pipelines using an S-N approach.

2.5 Pressure

The 'rerounding' or 'push back' by internal pressure will reduce the residual dent depth, H_r. If the pipe is subjected to a higher internal pressure, the residual dent depth will be smaller, and hence the dent SCF will be smaller.

Most of the SCF equations were derived empirically from dents created in pipe at zero pressure; hence a dent on a pressurised pipe, or a dent on an in-service pipeline may have a different profile and hence a different SCF[e]. Figure 1 shows three deformation profiles[16] of the dented pipe along the longitudinal direction. The dent depths, H_i, are all 29.5mm in these three cases. The pipes were subjected to the internal pressure levels of 0 bar (Case 1), 30 bar (Case 2) and 70 bar (Case 3) respectively. In Case 1 (unpressurised pipes), the deformed region appears more widely spread whilst the deformation in the pressurised pipes is more localised. This suggests higher stress concentrations in and around dents in pressurised pipes. The maximum hoop stresses obtained from the FE analyses for Case 2 and Case 3 models are 13.7% and 21% higher than that for the Case 1 model. It should be noted that although the dent depth, H_i, is the same for the three loading cases, the value of H_o, H and H_r may be different. However, experience of dent assessments shows that for pipelines with a design factor up to 0.72[f] and with dent depths H_o up to 7%D, the 'rerounding' under operating pressure after 'shakedown' is relatively small compared with the elastic 'spring back' after the indenter is removed.

2.6   Unconstrained and Constrained Dents

Experimental tests and FE analyses show that, although stress levels within a dent might be similar, the stress range in a constrained dent will be smaller than the stress range in an unconstrained dent under cyclic internal pressure loading[6] since the pipe wall is restricted from moving as the internal pressure fluctuates. Therefore, the fatigue life of a constrained dent is an order of magnitude higher than an unconstrained dent of equivalent shape and depth[14].

3   Review of SCF Values at Dents from FEA

There are no closed form formulae available for calculating the cyclic pressure stress range associated with a dent. To obtain a more realistic estimate of the local dent stress range within a dent when a pipeline is subject to pressure cycling, FEA methods have been used to obtain stress profiles at the minimum and maximum pipeline pressures.

A review of FEA work undertaken to quantify dent SCF's in a dented pipeline subject to cyclic internal pressure is summarised below.

3.1   Work Undertaken on Behalf of PRCI

Three dimensional (3D) linear elastic FEA was undertaken to simulate denting in a 323.9mm diameter pipe [4],[5]. Two wall thicknesses giving a D/t ratio of 18 and 50, and three dent shapes (a long bar dent orientated transverse to the pipe or in the pipe axial direction, and a flat dent to give both a long and wide dent) were chosen for the analyses. The FE mesh was constructed using shell elements. The dent shape was incorporated in a pipe model then an internal pressure load was applied.

Two dimensional (2D) elastic-plastic FEA was also undertaken of rings with dents[4],[5]. The pipe D/t ratio ranged from 18 to 110 and three pipe materials were chosen for the analyses. The analysis steps were as follows:

Step 1:   push a rigid surface indenter into the ring,

Step 2:   remove the indenter,

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[f] The dent assessments conducted by GL Noble Denton are for pipelines with the ratio of hoop stress/SMYS up to 0.72.

Step 3: apply the internal pressure.

A mean internal pressure of 34.5, 69 or 103.4 bar was applied to the model, about which the minimum and maximum pressures in the pressure cycle were applied. The SCFs, were determined from the analysis as the ratio of the maximum cyclic hoop stress range in the dent to the cyclic internal pressure range, $\Delta\sigma/\Delta P$.

The SCFs for undertaking a fatigue life assessment[5] were presented in Table B 1 to Table B 7 in Appendix B as a function of pipe D/t ratio, residual dent depth, H_r, mean pressure and yield strength. The results show that the SCF increases with an increase in H_r, and increases with an increase in the D/t ratio except for H/D≤1%, but decreases with an increase in the mean internal pressure. There is no clear relationship between SCF and yield strength. The difference of SCF is up to ±34% between yield stress of 358 N/mm^2 and 483 N/mm^2.

3.2 Work Undertaken on Behalf of API

3D elastic-plastic FEA [6] was undertaken on a 323.9mm diameter pipe with a D/t ratio equal to 34 and 68. The FE mesh was constructed using shell elements. Two different dent shapes were modelled (dome and long bar), and both constrained and unconstrained dents were analysed.

The dents were generated by pushing a 'dome' or 'long bar' shape of indenter into the pipe. The pipe was then subjected to an internal pressure loading with the indenter remaining in position (simulating a constrained dent) or after the indenter had been removed (simulating an unconstrained dent). Although the SCF is defined by $\Delta\sigma/\Delta P$, the definition of $\Delta\sigma$ is different to that of Section 3.1. Here, $\Delta\sigma$ is the 'stress intensity range'. Three different pressure cycling loads were considered to study the effects of mean and maximum pressure, as follows:

1. LRPC - Low range pressure cycle; from 0 to 50% of the maximum operating pressure (taken as 72% of the specified minimum yield strength (SMYS)),

2. HRPC - High range pressure cycle; from 50 to 100% of the maximum operating pressure,

3. FRPC - Full range pressure cycle; from 0 to 100% of the maximum operating pressure.

The residual dent depth, H_r, was taken at zero pressure after the application of one pressure cycle, or taken following 'rerounding' of the dent.

The SCFs are presented in Table C 1 to Table C 4 in Appendix C. It should be noted that each row of the SCF value was computed using a polynomial curve fit of three FEA data, and the data outside the FEA range were extrapolated from the minimum to the maximum FEA dent depth.

It was noted that the SCF increases as the residual dent depth, H_r, increases. The SCF value was found to be higher in an unconstrained dent than in a constrained dent, especially for the long bar dent. For the pipe under LRPC loading, the SCF value is higher for high D/t ratio (D/t=68) than for a low D/t ratio (D/t=34). However, for the pipe under HRPC and FRPC loading, the trend is unclear.

3.3 FEA Undertaken by GL Noble Denton

GL Noble Denton have undertaken a number of FEA and fatigue assessments of smooth dent damage, adjacent dents and dents coincident with welds. The assessed pipe geometries and materials are as follows;

- Diameter ranges from 323.9mm to 1219.2mm

- D/t ratio ranges from 34 to 72

- Cyclic pressure range from 21 bar to 94 bar

- Dent depths up to 7%D

- Pipe material ranging from API 5L grade X42 to grade X80.

Non-linear 3D FE models were constructed using the PATRAN[18] mesh generating software and analysed using the general-purpose FE code ABAQUS[19]. Figure 2 shows an example of an FE mesh and displacement contour plot for a smooth dent, and Figure 3 shows an example of an FE mesh and displacement contour plot for two adjacent dents. The dent(s) was generated by pushing the indenter(s) into the pipe. All of the dents are dome shaped, except for one which was a narrow rectangular shaped dent with a length and width of 100 x 10mm.

The analysis steps were as follows:

Step 1:   Dent the pipe by moving the indenter(s) to the required depth(s),

Step 2:   Remove the indenter(s),

Step 3:   Pressurise the pipe to the minimum operating pressure,

Step 4:   Pressurise the pipe to the maximum operating pressure,

Step 5:   Reduce the pressure in the pipe to the minimum operating pressure.

Step 6:   Reduce the pressure to zero.

In Step 1, the indenter is moved radially towards the pipe surface to a predetermined depth. Contact interference is defined between the indenter and the outer surface of the pipe. Elastic 'spring back' of the dented pipe occurs when the indenter is removed in Step 2. The dent is further 'pushed back' by the pressure load in Steps 3, 4 and 5. The pressure loads of Steps 3 to 5 are repeated until the model shakes down to an elastic response. The final step is to depressurise the pipe to zero.

The analysis shows that high residual stresses exist in the dent after the removal of the indenter. The residual stress may cause reverse yield, when the pipe is subjected to a relatively high internal pressure load, and reduce the permanent dent depth (residual dent depth at zero pressure, H_r). For a dent with the depth H_i or H_o, the residual depth (H_r), will be smaller after it is subjected to a higher internal pressure load or after it 'rerounds' following pressurisation to the maximum operating pressure.

The dent SCF is taken as the difference between the maximum principal stress range (corresponding to the minimum and maximum operating pressure) over the remote hoop stress range in the pipe, away from the dent region. Figure 4 shows a contour plot of maximum principal stress ranges. The highest stress range is located on the outer surface of the pipe as indicated in Figure 2[9]. Figure 5 and Figure 6 show that the SCF increases as the dent depth, H_o or H_r increases.

For a dent depth ratio described by H_o/D (Figure 5), the SCF is given by;

$$SCF = \frac{\Delta\sigma}{\Delta\sigma_{hoop}} = 2.05\ln\left(65\frac{H_o}{D}+1\right)+1 \tag{3}$$

For a dent depth ratio defined by H_r/D (Figure 6), the SCF is given by;

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[9] In the example case presented in this report, the peak of the von Mises equivalent stress range and Tresca stress range is located at the same position as that of the maximum principal stress range. However, the position of the von Mises equivalent, Tresca and maximum principal stress is different at the minimum operating pressure compared with the position at the maximum operating pressure in the pressure cycle.

$$SCF = \frac{\Delta\sigma}{\Delta\sigma_{hoop}} = 1.8\ln\left(88\frac{H_r}{D}+1\right)+1 \tag{4}$$

Both equations give an upper bound SCF for a single smooth dent that was created at zero pressure.

FE analyses show that, for a dented pipeline, the maximum plastic strain occurs on the internal surface of the pipe at the end of Step 1 (dent creation). After the removal of the indenter, the maximum plastic strain remains unchanged to that predicted at the end of Step 1, or equal to the residual plastic strain.

3.4   FEA Conducted by Others

Non-linear FEA undertaken by Rinehart and Keating[12] show that the peak hoop stress is located at the dent periphery, or shoulder, for short dents and at the dent centre for long dents. Fatigue life is related to the parameters given in equation (1), where *L*, *W* and *H* are the dent length, width and depth measured at pressure (after 'spring back' and 'rounding'). As the dent length and/or width increases, the fatigue life decreases for a given dent depth.

An SCF formula for dents was given by de Carvalho Pinheiro *et al*[13] based on their experimental and FEA results on the pipe with a nominal diameter of 73mm. The SCF, calculated as the ratio between the peak von Mises equivalent stress at the dent and the pipe nominal stress away from the dent, is given in equation (2), where *L*, *W* and H_i are the dent length, width and the initial dent depth respectively.

4   Fatigue Life for Dented Pipe

The fatigue life of a plain dent subject to cyclic internal pressure loading can be predicted from empirical or semi-empirical equations. These equations were developed by using published S-N curves with SCFs obtained from full-scale tests and/or FE analyses. The most common methods are presented in Section 4.1 with additional detail in Appendix A.

4.1   Fatigue Life Calculation Models

4.1.1   PRCI Model

The PRCI model is based on the Class B S-N curve from a UK Department of Energy (DOE) guidance document [22] (hereafter referred to as DOE S-N B Curve). SCFs were derived from linear and non-linear FE dent analyses of pipe with a diameter, D = 323.9mm, see Section 3.2. The fatigue life (N) of a plain dent can be predicted from the equations given in Appendix A.1.

The SCFs are given in Table B 1 to Table B 7 in Appendix B.

4.1.2   API 1156 Model

The API 1156 model is based on S-N curves from ASME VIII Division 2 Appendix 5[20]. SCFs were derived from non-linear FE dent analyses of pipe with a diameter, D = 323.9mm. The fatigue life (N) of a plain dent can be predicted from equations given in Appendix A.2.

The SCFs are given in Table C 1 to Table C 4 in Appendix C.

4.1.3 EPRG Model

The EPRG model, which is recommended for use in the PDAM document and the UKOPA dent management strategy, is based on an S-N curve published in DIN 2413[21] with SCFs derived empirically. The fatigue life (N) of a plain dent can be predicted from the equations given in Appendix A.3.

The SCF is a function of dent depth and pipe geometry. The dent depth used in the model is based on dents generated at zero pressure and measured after spring back, or H_o. An empirical correlation is given to convert the dent depth, H, measured at pressure, to H_o.

4.1.4 GL Noble Denton Work

For the GL Noble Denton method fatigue life is predicted using the Class B S-N curve from BS 7608[9] where the stress range is modified by an SCF for the dent which is obtained from 3D non-linear FEA.

The SCFs from the dents assessed are plotted in Figure 5 and Figure 6. Upper bound equations for estimating an SCF have been developed in this report which enables the fatigue life (N) of a plain dent to be predicted from the equations given in Appendix A.4.

4.2 Fatigue Life Calculation and Comparison

Full-scale fatigue tests were undertaken by GL Noble Denton on a 323.9x9.5mm pipe with spherical and elongated dents of varying depth[7]. One of the dents was chosen for the fatigue assessment using the models summarised in the previous section. The dent was generated using a spherical indenter with a radius of 75mm and initial dent depth of 27.8mm. The line pipe was manufactured from API 5L Grade X52[23], which has a SMYS of 360 N/mm² and a specified minimum tensile strength (SMTS) of 460 N/mm². Tensile tests of the pipe material show a yield and tensile strength of 440 N/mm² and 549 N/mm² respectively. The pipe was cycled by varying the internal pressure from 10 to 83.5 to 10 barg which resulted in a remote hoop stress range of 125N/mm². The test shows that the fatigue life of this dent is in excess of 151,000 cycles (the test was terminated). The details of the pipe and dent are summarised in Table 2.

A non-linear 3D FE model, shown in Figure 2 was constructed using the PATRAN mesh generating software and analysed using the general-purpose FE code ABAQUS. An initial gap of 2 mm was modelled between the pipe and indenter to prevent overclosure of the contacting surfaces at the beginning of the analysis.

The displacement profile at the end of Step 1 (denting) is shown in Figure 2. The dent depth (H_i) is 27.8mm. After the indenter was removed, elastic 'spring back' of the dent occurred and the dent depth (H_o) reduced to 21.7mm. The dent depth was further reduced by 'push back' or 'rerounding' due to the applied internal pressure. The dent was allowed to shakedown to an elastic response. The resultant dent depth (H) at pressure (83.5 barg) was predicted to be 19.1mm. The residual dent depth (H_r) at zero pressure was 20.4mm. The FE results are summarised in Table 3. As can be seen the dent depth H_i, H_o, and H obtained from the FEA are in good agreement with the test results in Table 2.

The maximum principal stress range for the 73.5 bar pressure cycle (between 10 to 83.5 to 10 barg) is 454 N/mm². The hoop stress range in the pipe away from the dent is 118 N/mm². Therefore, the SCF is 3.85. The SCFs predicted from equation (3) and (4) are 4.44 and 4.38 respectively.

The SCF predicted by the PRCI and API models are based on a pressure range, whilst for the other models it is based on a stress range. Table 4 shows that the predicted SCF values are 89.1 and 62.2 from the PRCI and API model respectively. The SCF can be converted from a pressure range to a hoop stress range by dividing the pressure range by a factor $D/2t$ which for the full-scale test is equal to 17. This gives an SCF of 5.23 and 3.65 for the PRCI and API models respectively. Therefore, the column 6 of Table 4 shows that the

SCF based on stress range is between 2.57 to 8.62. The SCF value from the API method is very close to the FEA result obtained by GL Noble Denton, but the predicted fatigue life cycles from the API model is 17 times higher than GL Noble Denton FEA model.

Table 4 shows that the predicted fatigue life of the dent varies from 2,586 cycles to 451,801 cycles. The EPRG model predicts the lowest fatigue life of 2,586 cycles. The highest fatigue life of 451,801 cycles is predicted using the API model, which is approximately three times higher than the total number of fatigue cycles accumulated (without failure) during the full-scale test of 151,929 cycles.

5 Summary and Discussion

The fatigue life of a plain dent in a pipeline subject to cyclic internal pressure loading can be predicted from empirical or semi-empirical equations. These equations were developed using published S-N curves and stresses obtained local to the dents. These stresses were defined by use of appropriate SCFs.

Different models use different S-N curves, which mostly fit the data from experimental tests and FE analyses. The S-N curves used in the fatigue life prediction of dents are:

1. PRCI: DOE Class B S-N curve,

2. API: S-N curves from ASME VIII Division 2 Appendix 5,

3. EPRG: S-N curves from DIN 2413,

4. GL Noble Denton: BS 7608 Class B curve.

SCFs were obtained from full experimental tests and FEA. Table 1 shows that;

1. The stress, which is used to define the SCF at the dent and subsequently used to predict the fatigue life, is different for the different models reviewed in this report,

2. Values of SCF were obtained from FEA using a shell or solid model, and elastic or elastic plastic analyses. The GL Noble Denton SCFs are derived from a 3D solid model, non-linear FEA,

3. The SCFs used in the different models are related to the dent depth at different stages of deformation, i.e., H_i, H_o, H or H_r,

4. Some of the SCF values used in the fatigue model are based on data from limited pipe geometries, e.g., the PRCI and API model is based on data from FEA undertaken on one pipe diameter (323.9mm).

For a single smooth dent created at zero internal pressure, equation (4) or (5) will give an upper bounded SCF for the dent depth ratio, H_o/D or H_r/D. However, additional FEA covering a wider range of pipe geometries, indenter types and depths (particularly for dent depth H_o/D ratios ranging from 3% to 6%), and loading conditions would be required to verify and improve theses equations.

Dents created on a pressurised pipe, or dents created on in-service pipelines may have a different profile and hence a different SCF. Additional FEA will be required to verify if further modifications to either equation (4) or (5) are required to account for such dents.

An example dent has been assessed using the methods reviewed in this report. The predicted fatigue lives varied from 2,586 to 451,801 cycles, the test being terminated after 151,929 cycles without failure. It was concluded that the EPRG model gave the most conservative estimate of fatigue life for this dent.

Table 4 shows that the SCF value from the API model (SCF = 3.65) is very close to that predicted by GL Noble Denton using FEA (SCF = 3.85). However, the API model predicted a much higher fatigue life than that predicted by the GL Noble Denton method.

6   Conclusions

1. The published SCF values for dents in PRCI and API models were obtained from a limited range of linear and non-linear FE analyses.

2. The definition of dent SCFs varies depending on which model is used.

3. For the example dent assessed in this report, the predicted fatigue life based on the methods reviewed in this work ranged from 2,586 cycles to 451,615 cycles; the test was terminated after 151,929 cycles without failure.

4. The EPRG model, which is recommended by PDAM and the UKOPA dent management strategy, is shown to predict relatively short fatigue lives in comparison to other methods reviewed in this report. The EPRG model may be overly conservative for assessing the fatigue life of a dented pipeline subject to cyclic internal pressure loading.

5. The SCF equations presented in this report are based on a large number of FE analyses undertaken by GL Noble Denton on a wide range of pipe sizes and dent shapes (depth, length and width).

7   Recommendations

1. Using the existing FE results; undertake additional example calculations of fatigue life using the models reviewed in this report.

2. Undertake additional FE analyses to further validate and improve the fit of the SCF equations (3) and (4); increasing dent depth and a wider range of pipe geometries.

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9　　Tables

	SCF Definition	SCF Data	Dent Depth	FE method	FE Model
PRCI[5]	Stress intensity range /pressure cyclic range	Pressed in Table B1-B7	H at mean pressure	Linear and non-linear shell model	D = 323.9mm and various D/t
API[6]	Stress intensity range /pressure cyclic range	Pressed in Table C1 – C4	H_r	Non-linear shell model	D = 323.9mm and D/t = 34 or 68
EPRG[2]	Equivalent stress range/pipe hoop stress range	$2.871\sqrt{(H_o t/D)}$	$H_o = 1.43H$		
GL Noble Denton	Maximum principal stress range/pipe hoop stress range	Obtained from FEA	H_o or H_r	Non-linear solid model	D = 323.9 to 1219.2mm, D/t = 34 to 72
Rinehart and Keating[12]	Peak hoop stress/pipe hoop stress	$\propto D^2 t/(LWH)$	H	Non-linear shell model	
de Carvalho Pinheiro *et al*[13]	Peak von Mises equivalent stress/pipe nominal stress	$1+1.423(D/t)^{0.67}(H_i/D)^{0.62}(L/W)$	H_i	Linear shell mode	

Note:　　H_i – Indented dent depth or initial dent depth.

H_o – Dent depth after the indenter removed or after 'spring back'.

H – Dent depth at pressure after 'spring back' and 'rerounding'.

H_r – Dent depth at zero pressure after 'spring back' and 'rerounding'.

Table 1 – SCFs Used for Dent Fatigue Assessments.

Pipeline								Dent Depth			Fatigue Cycles
D (mm)	T (mm)	D/t	SMYS (N/mm²)	SMTS (N/mm²)	P_{min} (barg)	P_{max} (barg)	ΔP (barg)	H_i (mm)	H_o (mm)	$H_{83.5}$ (mm)	
323.9	9.5	34	360	460	10	83.5	73.5	27.8	21.8	20.8	> 151929

Table 2 – Pipeline and Dent Test Data.

H_i (mm)	H_i/D (%)	H_o (mm)	H_o/D (%)	H_{Pmin} (mm)	H_{Pmin}/D (%)	H_{Pmax} (mm)	H_{Pmax}/D (%)	H_r (mm)	H_r/D (%)	$\Delta\sigma$ (N/mm²)
27.8	8.6	21.8	6.7	20.2	6.2	19.1	5.9	20.4	6.3	444

Table 3 – Dent Depth and Maximum Principal Stress Range from FEA.

Model	Dent Depth	Pressure Range, ΔP	Stress Range, $\Delta\sigma$	SCF $\dfrac{\Delta\sigma}{\Delta P}$	SCF $\dfrac{\Delta\sigma}{\Delta\sigma_{hoop}}$	Fatigue Life, Cycles	Fatigue Safety
PRCI[5]	$H_r/D = 6.3\%$	1066 psi		89.14*	5.23	5425	
API[6]	$H_r/D = 6.3\%$	1066 psi		62.2	3.65	451801	
EPRG[2]	$H = 19.1$mm $H_o = 1.43H = 27.3$mm	7.35 N/mm²			2.57+	2586	
GL Noble Denton with FEA	n/a	7.35 N/mm²	444 N/mm²		3.76	25989‼	
GL Noble Denton with equation (3)	$H_o/D = 6.7\%$	7.35 N/mm²	444 N/mm²		4.44	13338‼	
GL Noble Denton with equation (4)	$H_r/D = 6.3\%$	7.35 N/mm²	444 N/mm²		3.86	23469‼	
de Carvalho Pinheiro et al[13]	$H_i = 27.8$mm				8.62&		

Note: * with $H_r/D = 6.3\%$ mean pressure = 823 psi and D/t = 34.

   + K_s.

   ‼ with BS 7608 class B curve.

   & with dent length x width was taken approximately as 300mm x 130mm, which estimated from FEA model.

Table 4 – Predicted SCFs and Fatigue Lives.

10 Figures
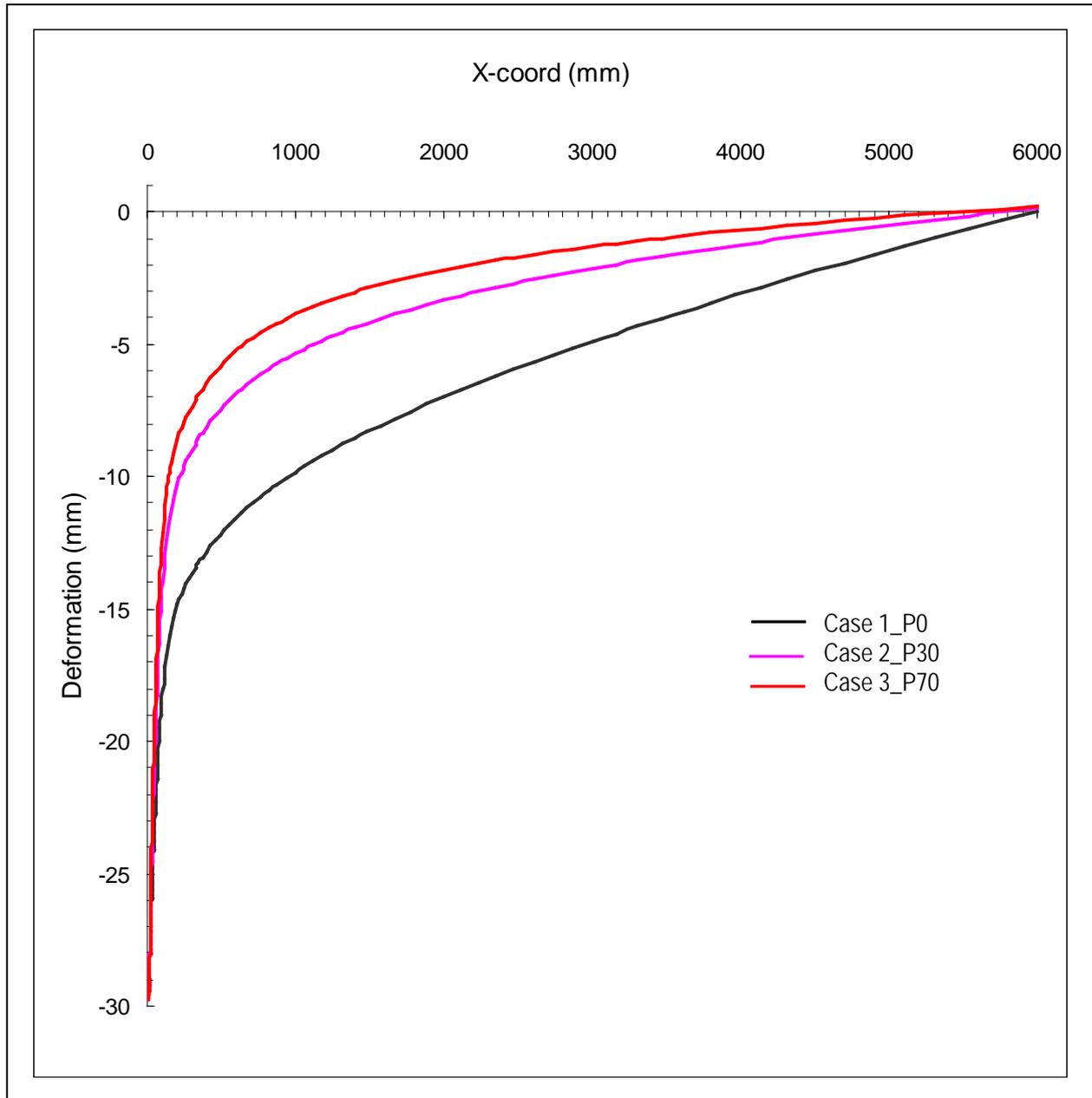
Figure 1 – Profiles (Half) of the Dents in the 914.4mm x 12.5mm Pipes, Indented under 0, 30 and 70 barg Internal Pressure.
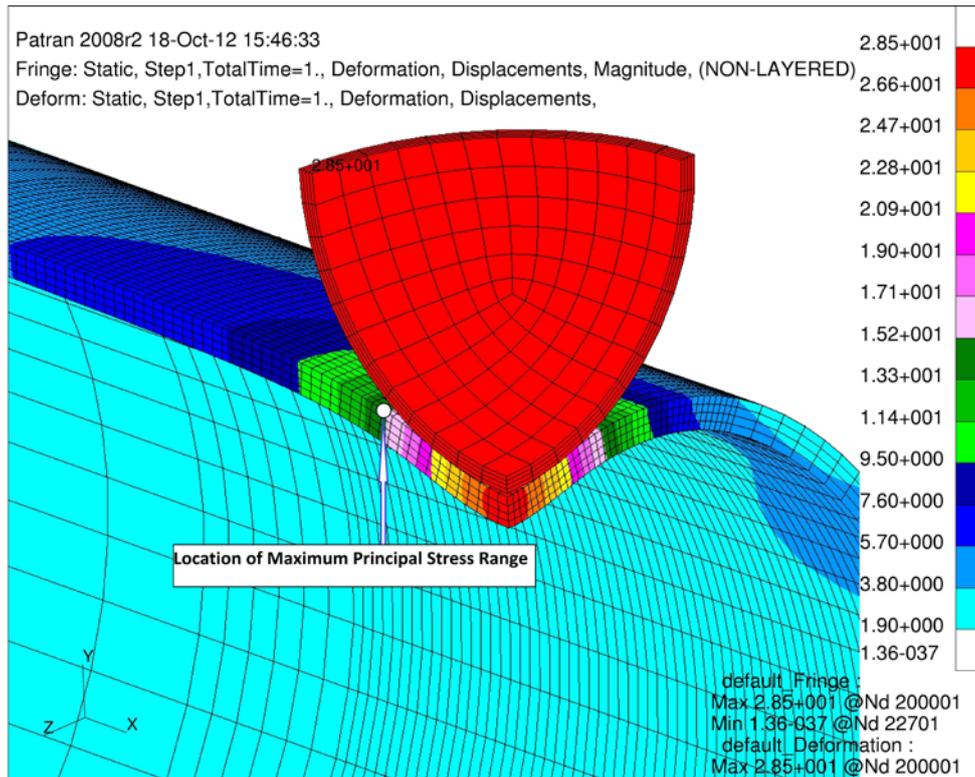
Figure 2 – Displacement Contour Plot from Single Smooth Dent FE Analysis on 323.9x 9.5mm Pipeline (from GL Noble Denton).
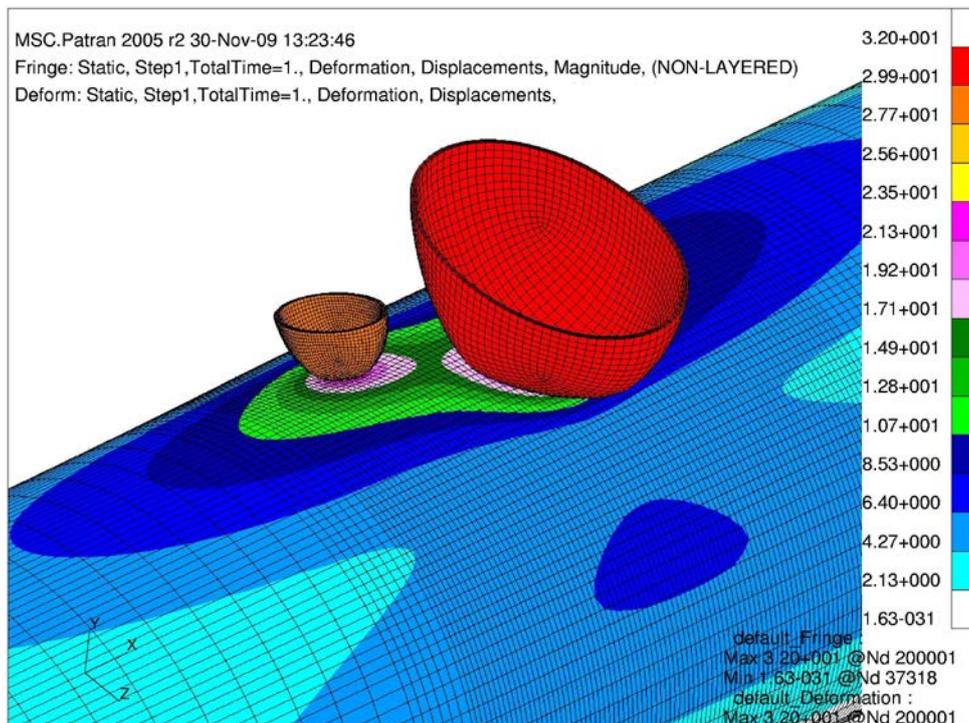
Figure 3 – Displacement Contour Plot from Adjacent Dents (Two Dents) FE Analysis on 609.6 x 11.9mm Pipeline (from GL Noble Denton).
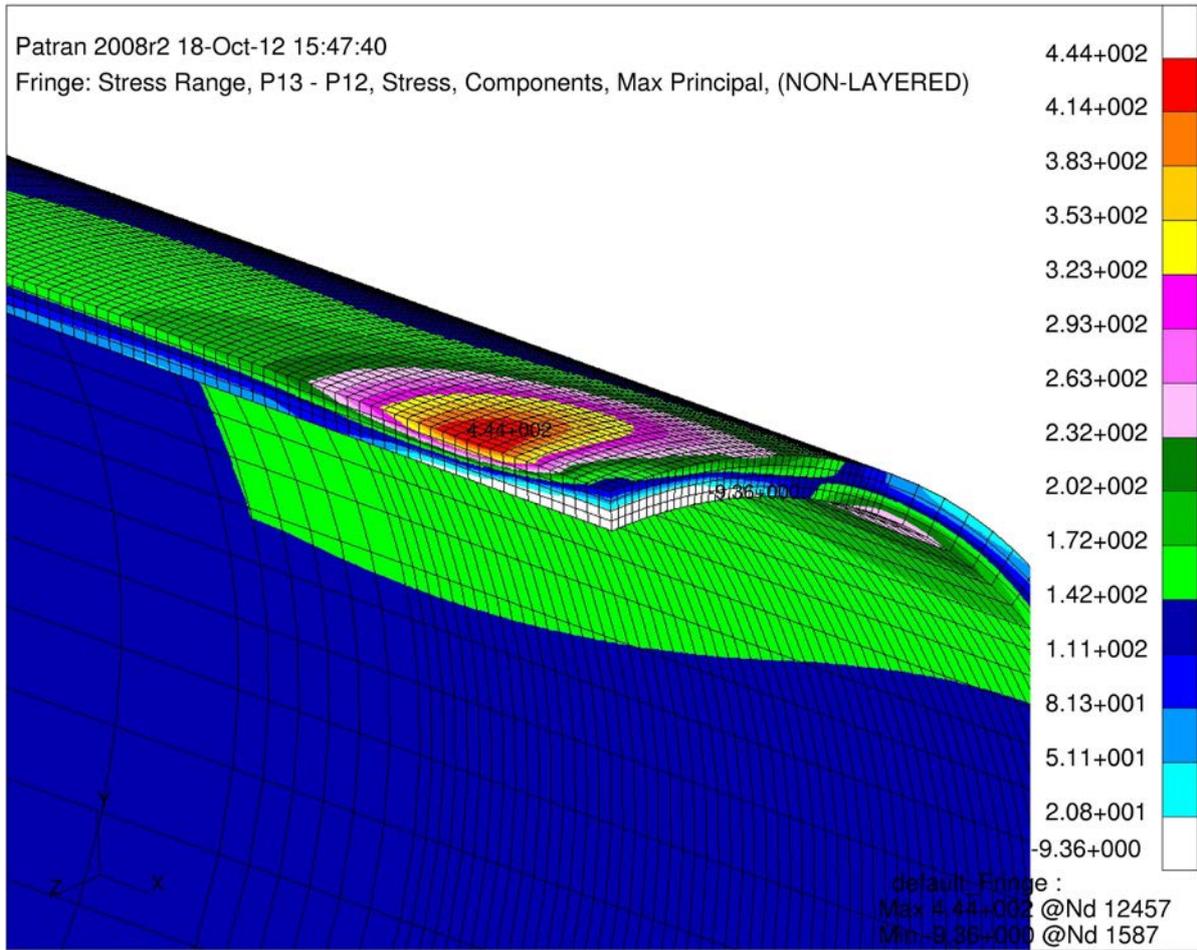
Figure 4 – Maximum Principal Stress Range Contour Plot from Dent FE Analysis on 323.9x 9.5mm Pipeline (from GL Noble Denton).
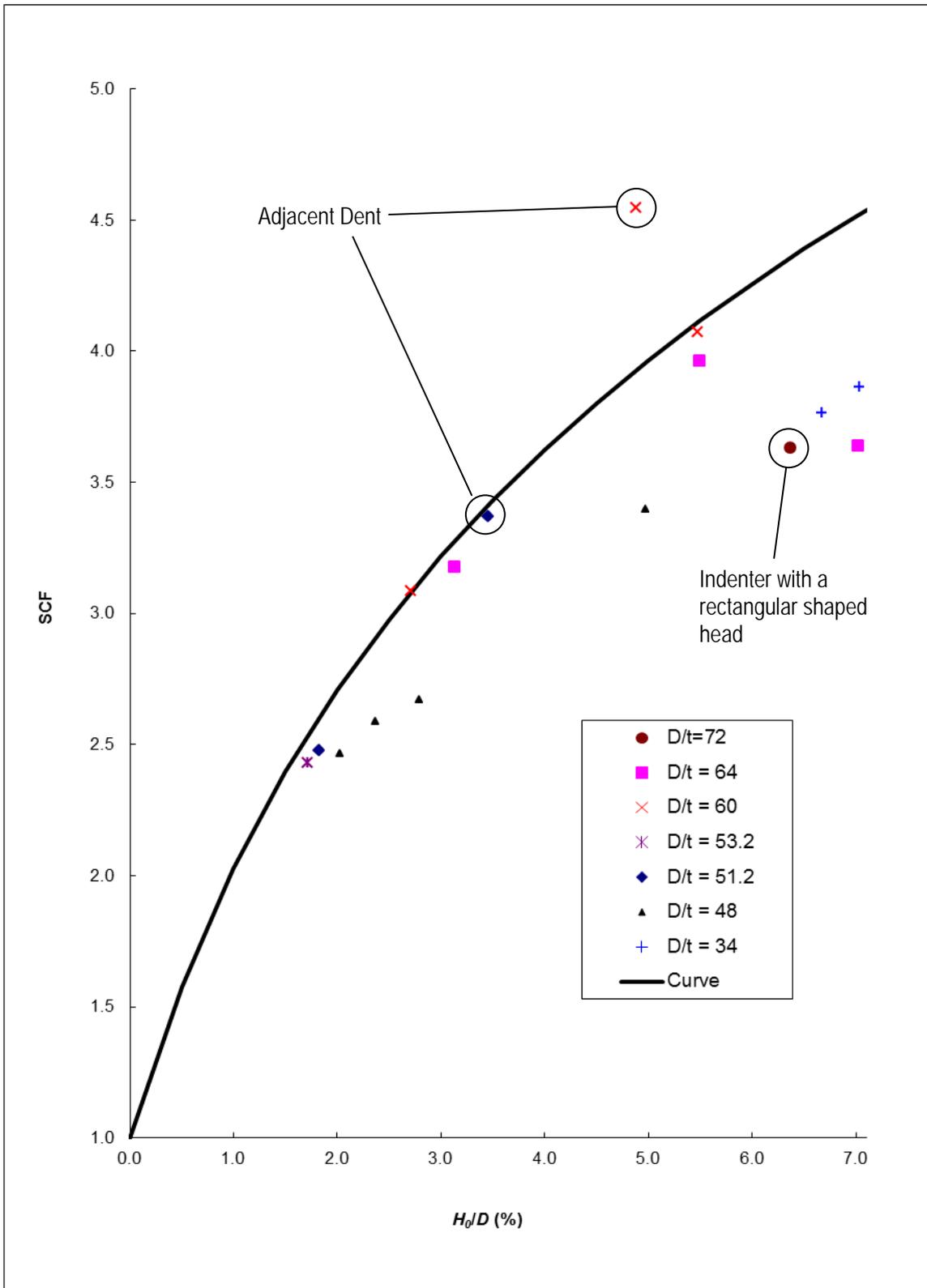
Note: The dent depth, H_o, was taken at zero pressure after the indenter was removed, or after 'spring back'.

Figure 5 – SCF's with H_o/D for Unconstrained Dents (from GL Noble Denton).
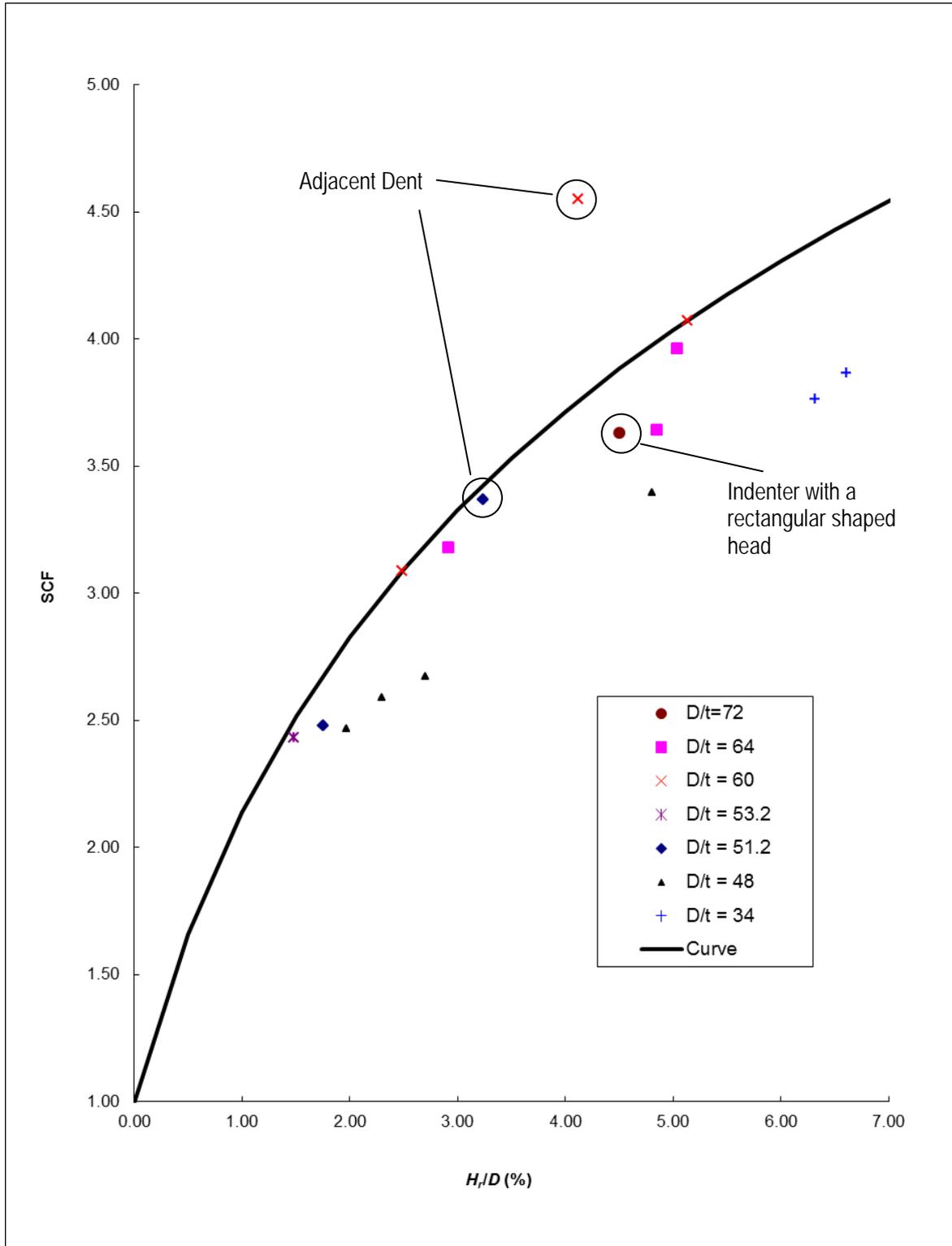
Note: The residual dent depth, H_r, was taken at zero pressure after the indenter was removed, or after 'spring back' and 'shakedown'.

Figure 6 – SCF's with H_r/D for Unconstrained Dents (from GL Noble Denton).

Appendix A   Fatigue Life Prediction Models

A.1   PRCI Model

The PRCI model[5] is based on an S-N curve; the DOE B curve. The S-N curve is design based, corresponding to a mean minus two standard deviation (a 2.3% probability of failure). SCFs were derived from linear and nonlinear FE dent analyses on pipes with a diameter, D=323.9mm. The fatigue life (N) of a plain dent is given by;

$$N = 4.424 \times 10^{23} \left(SCF \times \Delta P \right)^{-4}$$ (A.1.1)

where $SCF = \dfrac{\Delta \sigma}{\Delta P}$ (A1.2)

$\Delta \sigma$ = hoop stress range (units: psig)

and ΔP = cyclic pressure range (units: psig).

Values of SCF with the dent depth at mean pressure, *H*, are listed in Table D.1 to Table D.7 of Reference [5].

A.2   API Model

The API model[6] is based on a modified S-N curve in ASME VIII Division 2 Appendix 5 (Figure 5-110.1 for low carbon steels with a tensile strength less than 80ksi (555 N/mm²)). The ASME fatigue curves are design based and are conservative by a factor of 2 on stress and 20 on the number of cycles. To convert the 'design' curve to a 'fatigue' curve, the S-N curve was modified to remove the factor of safety on the predicted number of cycles. SCFs were derived from nonlinear FE dent analyses on pipes with a diameter, D=323.9mm. The fatigue life (N) of a plain dent is given by;

$$N = e^{43.944} \left(\frac{1}{2} SCF \cdot \Delta P \right)^{-2.971}$$ (A.2.1)

where $SCF = \dfrac{\Delta \sigma}{\Delta P}$ (A.2.2)

$\Delta \sigma$ = stress intensity range (units: psig)

and ΔP = cyclic pressure range (units: psig).

Values of SCF with the dent residual depth at zero pressure after rerounding, H_r, are listed in Table 6.2 to Table 6.5 of Reference [6].

A.3   EPRG Model

The EPRG model [2], which is recommended in the UKOPA dent management strategy, is based on an S-N curve for a submerged arc welded pipe given in DIN 2413, modified by a dent SCF which has been derived empirically and is a function of dent depth and pipe geometry . The fatigue life (N) of a plain dent is given by (no factors of safety are included);

$$N = 1000 \left(\frac{\sigma_U - 50}{2 \sigma_A K_s} \right)^{4.292}$$ (A.3.1)

where

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

(A.3.2)

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

(A.3.3)

$$K_s = 2.871\sqrt{K_d} = SCF$$

(A.3.4)

$$K_d = H_o \frac{t}{D}$$

(A.3.5)

σ_{min} = hoop stress under minimum pressure loading (units: N/mm²)

σ_{max} = hoop stress under maximum pressure loading (units: N/mm²)

σ_a = 0.5(σ_{max} - σ_{min}) (units: N/mm²)

σ_U = tensile strength (units: N/mm²)

$2\sigma_A$ = equivalent cyclic stress at R = 0 (units: N/mm²)

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

K_s = dent stress concentration factor

H_o = dent depth at zero pressure before rerounding (units: mm)

t = pipe wall thickness (units: mm)

D = pipe outside diameter (units: mm).

The EPRG model

$$H_o = 1.43H$$

(A.3.6)

H = dent depth at pressure (units: mm).

The S-N curve used in this method is based on a lower bound fit to full-scale experimental fatigue data on different pipe types; seamless and welded (approximately 95% confidence limit). Although there is no factor of safety on predicted life, following the recommendations in the PDAM document, the UKOPA dent management strategy recommends 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).

A.4 GL Noble Denton Model

The GL Noble Denton model is based on the Class B S-N curve in BS7608[h]. The S-N curve is design based, corresponding to a mean minus two standard deviation (a 2.3% probability of failure). The fatigue life (N) of a plain dent is given by;

$$N = 1.01 \times 10^{15} (SCF \times \Delta\sigma)^{-4}$$

(A.4.1)

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[h] It should be noted that there is a typographical error in Equation (1) from Section 4.2.1 of BS 7608.

$$SCF = \frac{\Delta\sigma}{\Delta\sigma_{hoop}} \qquad\qquad\qquad\qquad (A.4.2)$$

$\Delta\sigma$ = maximum principal stress range (units: N/mm²)

and $\qquad\qquad$ $\Delta\sigma_{hoop}$ = hoop stress range in the pipe away from stress concentrations (units: N/mm²).

Values of SCF can be estimated from an upper bound curve fit to the results of a number of FEA results, The equation to use depends on whether the dent depth is defined by H_r or H_o, as follows:

$$SCF = \frac{\Delta\sigma}{\Delta\sigma_{hoop}} = 2.05\ln\left(65\frac{H_o}{D} + 1\right) + 1 \qquad\qquad (A.4.3)$$

or $\qquad\qquad$ $SCF = \frac{\Delta\sigma}{\Delta\sigma_{hoop}} = 1.8\ln\left(88\frac{H_r}{D} + 1\right) + 1.$ $\qquad\qquad$ (A.4.4)

Appendix B   PRCI SCF Values

H_r/D (%)	D/t							
	18	20	25	30	35	40	45	50
1	14.21	13.55	12.53	23.98	35.44	46.90	58.35	69.81
2	20.16	22.09	27.20	37.54	47.88	58.23	68.57	78.91
3	26.10	30.63	41.87	51.10	60.33	69.56	78.78	88.01
4	32.04	39.18	56.55	64.66	72.77	80.88	89.00	97.11
5	37.98	47.72	71.22	78.22	85.21	92.21	99.21	106.2
6	43.93	56.26	85.89	91.77	97.66	103.5	109.4	115.3
7	49.87	64.80	100.6					
8	55.81	73.34	115.2					
9	61.76	81.88	129.9					
10	67.70	90.42	144.6					
11	73.64	98.96	159.3					

Table B 1 – PRCI SCFs for Dent under Average Operating Pressure of 34.5 bar.

H_r/D (%)	D/t							
	18	20	25	30	35	40	45	50
1	13.94	13.25	15.00	20.93	29.80	38.68	47.55	56.43
2	19.64	21.18	25.20	32.53	39.87	47.20	54.53	61.87
3	25.35	29.11	38.34	44.14	49.93	55.72	61.51	67.31
4	31.05	37.04	51.49	55.74	59.99	64.24	68.50	72.75
5	36.76	44.97	64.63	67.34	70.05	72.77	75.48	78.19
6	42.46	52.89	77.78	78.95	80.12	81.29	82.46	83.63
7	48.17	60.82	90.92					
8	53.87	68.75	104.1					
9	59.58	76.68	117.2					
10	65.28	84.61	130.4					
11	70.99	92.53	143.5					

Table B 2 – PRCI SCFs for Dent under Average Operating Pressure of 69 bar.

H_r/D (%)	D/t							
	18	20	25	30	35	40	45	50
1	13.65	13.06	15.00	19.61	27.20	34.79	42.38	49.96
2	19.14	20.39	23.66	39.65	35.63	41.62	47.60	53.58
3	24.63	27.73	35.31	39.69	44.06	48.44	52.82	57.20
4	30.12	35.06	46.95	49.72	52.50	55.27	58.05	60.82
5	35.61	42.39	58.59	59.76	60.93	62.1	63.27	64.44
6	41.11	49.73	70.23	69.79	69.36	68.93	68.50	68.06
7	46.60	57.06	81.87					
8	52.09	64.39	93.51					
9	57.58	71.73	105.1					
10	63.07	79.06	116.8					
11	68.56	86.39	128.4					

Table B 3 – PRCI SCFs for Dent under Average Operating Pressure of 103.4 bar.

H_r/D (%)	D/t					
	50	60	75	90	100	110
1	42.06	48.54	58.30	68.06	94.54	81.04
2	54.93	59.85	67.25	74.65	79.57	84.5
3	67.83	71.17	76.21	81.25	84.59	87.95
4	80.70	82.48	85.16	87.84	89.62	91.41
5	93.59	93.80	94.12	94.44	94.65	94.86
6	102.47	102.70	103.07			

Table B 4 – PRCI SCFs for Dent under Average Operating Pressure of 34.5 bar and with Yield Strength of 358 N/mm².

H_r/D (%)	D/t					
	50	60	75	90	100	110
1	54.21	54.43	54.75	55.07	55.29	55.5
2	51.47	53.57	56.73	59.89	62.0	61.1
3	48.72	52.71	58.71			
4	45.97	51.84	60.69			

Table B 5 – PRCI SCFs for Dent under Average Operating Pressure of 62 bar and with Yield Strength of 358N/mm².

H$_r$/D (%)	D/t					
	50	60	75	90	100	110
1	43.35	47.25	53.12	58.99	62.89	66.81
2	57.82	60.65	64.92	69.19	72.02	74.87
3	72.26	74.04	76.71	79.38	81.16	82.94
4	85.73	87.44	88.51	89.58	90.29	91.0
5	101.23	100.81	100.3	99.83	99.42	99.07
6	115.67	114.18	112.10	110.08	108.55	107.13
7	120.14	127.55	123.89			

Table B 6 – PRCI SCFs for Dent under Average Operating Pressure of 34.5 bar and with Yield Strength of 483 N/mm^2.

H$_r$/D (%)	D/t					
	50	60	75	90	100	110
1	41.15	44.09	48.53	52.97	55.91	58.87
2	48.12	50.65	54.46	59.27	60.80	63.34
3	54.88	57.08	60.39	63.70	65.90	68.11
4	61.64	63.51	66.32	69.63	71.0	72.88
5	67.15	69.18	72.25			

Table B 7 – PRCI SCFs for Dent under Average Operating Pressure of 62 bar and with Yield Strength of 483 N/mm^2.

Appendix C   API 1156 SCF Values

Pipe D/t	Residual Dent Depth (percent H_r/D)									
	1	2	3	4	5	6	7	8	9	10
Low Range Pressure Cycle (0 - 50% MOP)										
34	38.5	42.7	47.1	51.5	56.0	60.7	65.6	70.4	75.4	80.5
68	81.1	103.5	128.9	145.1	164.3	182.5	199.5	215.5	230.4	244.3
High Range Pressure Cycle (50 - 100% MOP)										
34	34.8	38.7	42.5	46.2	49.8	53.2	56.6	59.8	62.9	65.9
68	70.7	87.1	101.4	113.6	123.7	131.7	137.7	141.5	143.3	
Full Range Pressure Cycle (0 - 100% MOP)										
34	32.9	38.0	42.8	47.4	51.7	55.8	59.7	63.4	66.8	70.0
68	71.0	90.8	107.1	119.8	128.9	134.4	136.3			

Table C 1 – SCFs for Unconstrained Dome Dents.

Pipe D/t	Residual Dent Depth (percent H_r/D)									
	1	2	3	4	5	6	7	8	9	10
Low Range Pressure Cycle (0 - 50% MOP)										
34	20.9	41.6	59.8	75.6	89.0	100.0	108.6	114.7	118.4	
68	70.8	123.3	167.5	203.3	230.9	250.1	261.0	263.6		
High Range Pressure Cycle (50 - 100% MOP)										
34	27.0	41.6	54.2	64.8	73.4	80.0	84.7	87.4	88.0	
68	63.7	86.8	105.3	119.4	129.0	134.2	134.9			
Full Range Pressure Cycle (0 - 100% MOP)										
34	28.6	44.8	58.1	68.3	75.6	79.8	81.1			
68	70.9	102.0	123.8	136.1	139.0					

Table C 2 – SCFs for Unconstrained Long Bar Dents.

Pipe D/t	Dent Depth (percent d/D)								
	2	4	6	8	10	12	14	16	18
Low Range Pressure Cycle (0 - 50% MOP)									
34	33.6	42.6	50.4	57.1	62.7	67.2	70.6	72.8	73.9
68	128.5	138.7	148.8	159.0	169.1	179.3	189.4	199.6	209.7
High Range Pressure Cycle (50 - 100% MOP)									
34	33.7	37.5	40.8	43.8	46.3	48.5	50.3	51.7	52.7
68	73.1	77.2	81.3	85.5	89.6	93.7	97.8	101.9	106.0
Full Range Pressure Cycle (0 - 100% MOP)									
34	37.6	40.5	43.3	45.8	48.2	50.3	52.2	53.9	55.4
68	84.4	88.2	92.1	95.9	99.7	103.6	107.4	111.2	115.1

Table C 3 – SCFs for Constrained Dome Dents.

Pipe	Dent Depth (percent d/D)								
D/t	2	4	6	8	10	12	14	16	18
Low Range Pressure Cycle (0 - 50% MOP)									
34	37.9	41.5	46.6	53.2	61.2	70.7	81.7	94.1	108.0
68	78.2	117.5	152.4	182.9	209.0	230.7	248.0	260.9	269.4
High Range Pressure Cycle (50 - 100% MOP)									
34	21.4	27.9	34.5	41.1	47.8	54.6	61.4	68.3	75.2
68	38.8	59.4	78.7	96.7	113.5	129.0	143.2	156.1	167.8
Full Range Pressure Cycle (0 - 100% MOP)									
34	23.6	30.5	37.5	44.4	51.3	58.2	65.1	72.0	78.9
68	70.5	83.7	97.1	110.6	124.3	138.1	152.1	166.2	180.4

Table C 4 – SCFs for Constrained Long Bar Dents.