NEWCASTLE UNIVERSITY
School of Marine Science and Technology

DRAFT REPORT PREPARED FOR UKOPA

Integrity Assessment of Construction Dents Subject to Fatigue Loading

May 2007

Author: Dr J.M. Race

School of Marine Science & Technology
Newcastle University
Armstrong Building
Newcastle-upon-Tyne
NE1 7RU

EXECUTIVE SUMMARY

NEWCASTLE UNIVERSITY
School of Marine Science and Technology

REPORT PREPARED FOR UKOPA

DRAFT FOR COMMENT

INTEGRITY ASSESSMENT OF CONSTRUCTION DENTS IN PIPELINES SUBJECT TO FATIGUE LOADING

The current requirements for pipeline dent assessment have resulted in large numbers of dents being reported by ILI companies for further consideration by the pipeline operator. However, recent reports of pipeline failures due to fatigue of dents have generated concerns regarding the capability of these acceptance criteria and inspection technologies to identify critical dents before they fail.

This report forms Phase 1 of a proposal made to UKOPA regarding the integrity assessment of construction dents in pipelines subject to fatigue loading. The remit of this report is to consider the integrity assessment of plain dents in relation to static and fatigue loading and to:

i) develop an understanding of the scale of the problem by reviewing pipeline failures and the research being conducted by operators and regulators, particularly in the USA,
ii) critically review current published research findings and discuss the feasibility of these approaches to develop dent management strategies,
iii) advise UKOPA on the benefits of conducting specific additional work.

CONCLUSIONS

As a result of this review, the following conclusions are drawn:

- It can be inferred from the pipeline failure data that failure from plain dents (*i.e.* those not associated with mechanical damage) does not form a significant proportion of the total number of pipeline failures in the US and Europe. However, there is evidence that dents that are acceptable to the current codes and guidance are failing and therefore additional criteria are required to identify these dents before they fail.

- Historically, plain dent acceptance criteria under static loading were based on the depth of the dent, however, recent research has suggested that the strain in the dent may be a better indicator of dent severity for repair. As a result, strain acceptance criteria are now being applied in codes through ASME B31.8. However, a review of the current research in this area has highlighted that no standard method exists for calculating strain and neither is there an industry best practice for interpreting high resolution caliper data for strain assessment.

- For pipelines that are heavily pressure cycled, the fatigue life of the dent should be taken into consideration in the dent severity assessment. This review of the published research has indicated that the fatigue life of a dent is dependent on the dent constraint, the dent geometry (*e.g.* dent length, depth, width, shoulder angle), the pipe geometry (*e.g.* pipe diameter and wall thickness), pipe material and the pressure cycling range experienced by the pipeline. All of these factors should be taken into account in a fatigue life assessment.

- Although pipeline codes recommend a fatigue assessment for dents, there is no codified methodology for calculating the fatigue life of a dent. In this report, two methods for fatigue assessment are reviewed; an approach using design S-N curves accounting for the additional stress concentration due to the dent and an approach using fracture mechanics.

- The S-N method is the most widely used approach for calculating fatigue life, however, the methodology for calculating the stress concentration factors (SCF) in the dents varies in the literature and there is no unified approach. In addition, there is no recommendation for the most appropriate design curve to be used. The fracture mechanics approach is not readily applicable to pipelines with large numbers of dents and requires detailed information regarding crack depth populations in the pipeline.

EXECUTIVE SUMMARY

- The requirements of a robust dent management strategy for plain, rock or construction dents are that it should be easy to use with measurements that can be readily made in the field; not require intensive and expensive Finite Element Analysis (FEA) to be conducted on every dent; recognise the key parameters that contribute to stress and strain concentration in the dent and relate to the pressure cycling regime of the pipe.

- Six dent management strategies employed by pipeline operators and consultants have been reviewed. These strategies are either based on geometry factors, strain calculations or fatigue life calculations to determine dent severity. Based on the criteria for a dent management strategy outlined above, the approaches adopted by DEGT and GE Energy appear to warrant further research and investigation.

RECOMMENDATIONS

On the basis of these conclusions, the following recommendations are made to UKOPA:

- **Benchmarking Study**
  In order to evaluate the benefit and validity of the dent management strategies reviewed in this report, it is recommended that a benchmarking study is conducted which would allow UKOPA members to compare their individual company dent dig and repair criteria against the published dent assessment strategies. This study could also compare dent assessment strategies currently being employed by UKOPA members and develop a best practice approach to dent assessment on the basis of the current literature.

- **SCF Algorithm Development**
  One of the conclusions of this report is that there is no standard method for calculating the stress concentration factors used in fatigue calculations without expensive and extensive Finite Element Analysis (FEA). There is therefore an opportunity to develop algorithms for prediction of dent severity and fatigue lives based on key dent and pipeline parameters that are known to affect the fatigue lives of dents.

  The literature reviewed indicates that this approach is viable, but requires further work to develop a methodology that could be applied to a range of pipelines. This would be an attractive approach for pipeline operators and allow severity factors and fatigue lives to be quickly and easily calculated from ILI data.

  It is therefore recommended that a research project is initiated to develop algorithms to predict SCFs in dents. In this project, UKOPA members would provide the inspection and field data to develop the algorithm and also audit the severity ranking against their own assessments and in-field findings.

Author: **Dr Julia Race**

School of Marine Science & Technology
Newcastle University

Date: **25th May 2007**

CONTENTS

NOMENCLATURE

D	:	Nominal pipe outside diameter
H_0	:	Dent depth at zero pressure
H_r	:	Rerounded dent depth
ID	:	Internal diameter
K_d, K_s	:	Stress concentration factor
L	:	Deformed dent length
L_o	:	Initial dent length
OD	:	Outside diameter
P	:	Internal pressure
N_c	:	Predicted number of cycles to failure
R	:	Minimum stress/maximum stress on fatigue cycle
R_0	:	Radius of curvature of undeformed pipe
R_1	:	External radius of curvature in circumferential direction
R_2	:	External radius of curvature in longitudinal direction
SCF	:	Stress Concentration Factor
SMYS	:	Specified Minimum Yield Stress
t	:	Nominal pipe wall thickness
UTS	:	Ultimate Tensile Stress
W	:	Dent width
ε_{effID}	:	Effective strain on the pipe ID
ε_{effOD}	:	Effective strain on the pipe OD
ε_{cb}	:	Circumferential bending strain
ε_{ci}	:	Net circumferential strain on the pipe ID
ε_{co}	:	Net circumferential strain on the pipe OD
ε_{lb}	:	Longitudinal bending strain
ε_{li}	:	Net longitudinal strain on the pipe ID
ε_{lm}	:	Longitudinal membrane strain
ε_{lo}	:	Net longitudinal strain on the pipe OD
ε_i	:	Biaxial strain on the pipe ID
ε_o	:	Biaxial strain on the pipe OD
κ	:	Curvature
$2\sigma_A$	:	Equivalent cyclic stress at R=0
σ_{CF}	:	Cyclic flow strength
σ_U	:	Ultimate tensile stress
σ_Y	:	Yield stress
$\Delta\sigma$	:	Stress intensity range
Δp	:	Range of applied pressure

1 INTRODUCTION

Dent damage in pipelines may result from either impact damage caused by third parties or construction damage.

Third party damage generally occurs on the upper half of the pipe (between the 8 o'clock and 4 o'clock positions) and has historically contributed to the highest number of pipeline failures. Dents of this type are likely to be significant as they could also contain gouges or cracking and therefore these defects generally require immediate investigation and possible repair. In addition, dents caused by third party damage are unconstrained and therefore able to flex or reround during changes in pressure. Therefore, if failure as a result of mechanical damage is not immediate, it is possible that induced defects can grow in service and cause failure some time after the initial impact.

Dents caused during construction generally occur on the bottom half of the pipe and tend to be constrained by the indenter causing the dent, *i.e.* a stone or rock in the pipeline bed/backfill. Dents on the bottom of the pipeline are generally not considered significant as the dent has survived the pre-service hydrotest and is unable to move or reround due to changes in pressure. A typical pipeline is likely to contain between 1 and 5 dents of this type per km length.

All dents have the potential to cause an increase in stress in the pipeline, and consequently increase the pipeline sensitivity to fatigue damage caused by pressure cycling. Many transmission pipelines are now 20–30 years old and fatigue failures at dent locations are starting to be reported. Such occurrences have raised technical concerns with regulators regarding the perceived conservatism of current dent assessment methods as the dents in question were within the code limits and were reported through standard ILI technologies, however, they were not identified as significant. Operators are also expressing concerns regarding best practice for safe and economic operation of dented pipelines.

In the USA, these concerns have resulted in the initiation of a number of detailed technical studies and research JIPs and regulator requirements for constraints on pipeline operation. In the UK, the response has been for ILI vendors to report all dents in a pipeline and to recommend further investigation. As a result, large numbers of dents on the bottom half of the pipe associated with rocks and backfill loads are being reported to pipeline operators, requiring them to undertake further action to satisfy operator duties and regulator requirements under PSR 96.

In reality, a large number of pipelines contain a large number of dents, the majority of which do not impair integrity or affect operation. Therefore, the current approach potentially involves high cost pigging operations and/or the requirement to excavate, inspect and repair insignificant dents. Guidance is therefore needed in order that operators can identify dents for which excavation and inspection is uneconomic and could potentially be damaging to pipeline safety and dents for which further action is required.

This report forms Phase 1 of a proposal made to UKOPA regarding the integrity assessment of construction dents in pipelines subject to fatigue loading. The aim of this report is to review the work that has been conducted on the response of dents to both static and fatigue loading and to identify the significant parameters contributing to the failure of pipeline dents. The report will investigate how these parameters have been used in dent management strategies and critically evaluate these strategies. Finally, recommendations will be made on additional work that may be required to develop a robust, safe and cost effective dent management strategy.

2 SCOPE OF REPORT

It is important to define the terms and scope of the report at the start. In this report the definition of a dent is taken as "a permanent plastic deformation of the cross section of the pipe caused by external forces[15,56]". A dent that varies smoothly in cross section and contains no potential stress raisers, such as gouges, cracks or welds is defined as a plain dent.

In the literature the terms mechanical damage, external interference or 3rd party damage are often used to describe a particular category of pipeline defect introduced by metal to metal contact caused by excavating or mechanical equipment. Mechanical damage results in changes to the mechanical and metallurgical properties in the vicinity of the contact. Rosenfeld describes typical mechanical damage defects as scrapes, gouges, smeared metal, metal loss not caused by corrosion, cold work, cracking or creasing of the pipe wall[56]. There may also be some residual denting caused by the indentation, however, such a dent is not a plain dent as it contains mechanical damage. Mechanical damage tends to occur on the upper half of the pipeline (between the 4 o'clock and 8 o'clock positions).

It is considered unlikely that a rock dent could contain mechanical damage and, particularly if the coating remains intact, it is 'impossible for the dent to be anything but plain'[56]. Therefore it can be concluded that plain dents are generally caused by rocks in the backfill and therefore are usually located on the bottom half of the pipeline. Rosenfeld[52] does point out, however, that, particularly for small diameter pipelines or those with a shallow depth of cover, it is possible that excavation equipment could cause bottom of line dents.

A dent can be further defined based on its ability to move under the internal pressure, *viz.* unconstrained dents are able to re-round under pressure whereas dents that are constrained are not free to move. In some of the literature, the presence of a restraining feature, usually the indenter, is used to define a constrained dent[15]. Therefore rock dents that have not been excavated are typically described as constrained dents as the rock will remain in place underneath the dent. However, it is not only the presence of a constraining feature that can prevent a dent from re-rounding under internal pressure. It is possible that the local restraint around the dent due to wall thickness or the shape of the dent may prevent it from being able to respond to changes in pressure. These types of dents could also be described as constrained and this definition is used in other parts of the literature[50]. In this report, the broader definition of constrained dent will be used to describe any dent that is not free to move under changes in internal pressure.

The remit of this report is to consider the integrity assessment of plain dents in relation to static and fatigue loading and to:

i) develop an understanding of the scale of the problem by reviewing pipeline failures and the research being conducted by operators and regulators, particularly in the USA,
ii) critically review current published research findings and discuss the feasibility of these approaches to develop dent management strategies,
iii) advise UKOPA on the benefits of conducting specific additional work.

Although a review of non-plain dents, such as dents with cracks, gouges and corrosion and dents on welds is not specifically reviewed, information on these defects will be included where relevant to the assessment of plain dents.

3 REVIEW OF PIPELINE DENT FAILURES

In order to understand the threat posed by plain dents to pipeline integrity, an analysis of the latest published failure data for oil and gas transmission pipelines for the US and Europe has been undertaken as part of this study. As mentioned previously, denting can occur either as a result of external interference or as a result of construction damage, therefore data from both of these failure categories has been studied where information is available. One of the difficulties in conducting analysis of this type is that ‘failure at dents’ is generally not recorded as a discrete category or failure cause in many of the failure databases. In addition, the information is not detailed enough to be able to confirm how many of these failures were construction related, bottom of line dents or even plain dents. In fact CONCAWE[41] is the only source of failure data to publish the number of failures due to construction dents.

3.1 Experience in the US

Data is reported on the failure of natural gas and liquid transmission pipelines in the USA from 1986 on the Department of Transport (DOT) website[48], however, the reporting categories for transmission pipelines changed in 2002 and therefore it is difficult to compare statistics for some failure types. Analysis of the data between 1986 and 2006 indicates that external interference accounts for 31% of failures on natural gas transmission and 27% of failures in hazardous liquid pipelines*. This makes this type of damage the most significant failure cause in US transmission pipelines.

Although the published data is not refined enough to be able to reliably distinguish the number of failures due to material or construction damage, a recent study by the DOT[9] has reviewed the Office of Pipeline Safety (OPS) statistics for gas and hazardous liquid pipelines up to 2003 in an attempt to determine the number of pipeline failures that have occurred as a result of dent damage. The analysis indicated that <0.2% of the incidents on liquid lines and <<0.1% of the incidents on gas pipelines were related to dents. The conclusion of the study was therefore that failures from dents do not form a significant proportion of the total number of pipeline failures.

Kiefner *et al* [36] has also conducted an analysis of the DOT data between 1985 and 2003 to determine the time dependency of mechanical damage failures. This analysis concluded that 83% of the releases in liquid lines and 90% of the releases in gas lines due to mechanical damage occur immediately. Delayed failures could result from an overpressure or from the effects of corrosion, fatigue or stress corrosion cracking (SCC) at the site of the damage. In a more detailed analysis of the 1985 to 1997 data, Kiefner concluded that 19% of the delayed failures in both gas and liquid pipelines were associated with rock dents.

One incident of particular relevance to the current study has been reported by the Marathon Ashland Pipe Line LLC[32,45]. The failure occurred in January 2000 as a result of cracking that had initiated in an unconstrained bottom of line dent. The dent was measured to be 1.67%OD in depth and, although it had been detected on previous ILI surveys, it had not been excavated as it was below the repair criteria of 2%OD. It is highlighted that Enbridge Pipelines have also reported incidents where dents that are acceptable to the code criteria have been known to fail[31,44].

The Marathon pipeline had ruptured three years after the in-line inspection resulting in the loss of 489,000 gallons of crude oil and approximately $12.6M of damage. The pipeline accident report[45] concluded that the probable cause was fatigue cracking in the dent due to fluctuating pressure. However, a subsequent paper by Johnson and Hrncir[32] stated that the cracking was due to near-neutral SCC which had initiated in the dent, as this was an area of increased stress concentration, and had grown by corrosion fatigue. At the time, Marathon believed that the presence of SCC within dents was a unique event, but other instances of cracking were found in dents with high stress concentrations in sections of the pipeline with the required environment for SCC. Therefore, although the dent in itself was not the cause of the failure, it provided the required stress conditions for the failure to occur.

* In this analysis ‘external interference’ includes the figures from the categories for operator excavation damage, damage by outside forces, vandalism, third party, previously damaged pipe and damage by vehicles.

3.2 Experience in the UK and Europe

The latest failure and incident data from the CONCAWE[16], EGIG[25] and UKOPA[13] databases has also been analysed as part of this study. In the CONCAWE and EGIG databases, the majority of pipeline incidents result from external interference. The UKOPA database presents a slightly different picture in that the data is skewed by historical failures that occurred due to internal cracking when the system was transporting wet town gas. However, the data does show that external interference accounts for the second largest number of failures, more than corrosion. All of the failure data for external interference and construction or material damage are compared in Figure 1.

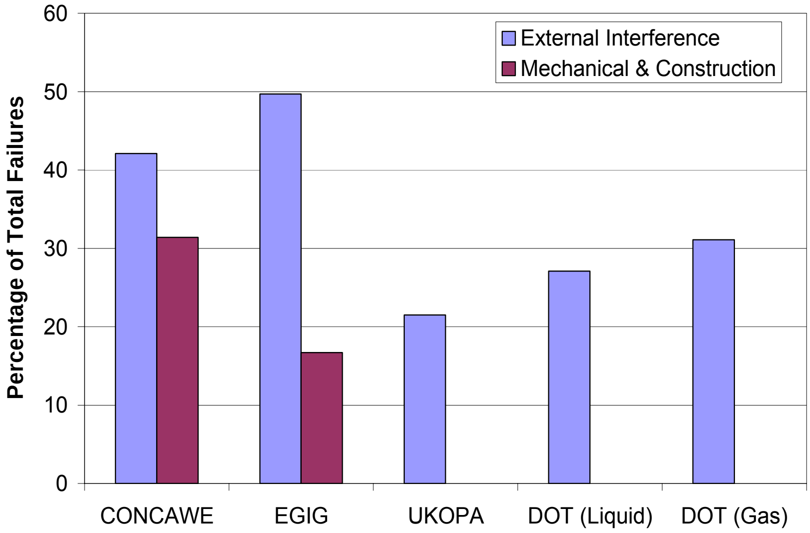


Figure 1 – Percentage of Failures Due to External Interference and Construction/Material Damage

Only the CONCAWE and EGIG data allows the number of failures due to mechanical and construction damage to be analysed, and in both cases, this category is the second highest cause of failure. The CONCAWE data also records the number of failures due to construction dents. Over the 30 years between 1971 and 2004 there were six failures due to this type of dent, which represents 1.6% of the total number of spillages from oil pipelines in this period.

One of the further conclusions that CONCAWE drew from the analysis of failures over 30 years was that there was no evidence that the number of age-related mechanical failures, for example due to metal fatigue, were increasing[41]. This would be of concern for pipelines that were heavily pressure cycled and could start to exhibit repeat fatigue related failures, either at weld defects or dents, as they reached the end of their fatigue lives.

However, since that report, one dent fatigue failure has been reported to CONCAWE[16]. The pipeline was an oil pipeline laid in 1973. During the construction the pipeline had been dented on a section under a rural road. Subsequent fatigue cycling had resulted in the initiation and propagation of a fatigue crack which had eventually caused the failure of the pipeline and an estimated €810,000 in clean up costs.

3.3 Failure Statistics Analysis Conclusion

Although it is recognised that the failure data is too coarse to draw any firm conclusions about the exact role of plain dents in pipeline failures, it is evident that failures from dents alone do not form a significant proportion of incidents.

If denting is caused as a result of mechanical damage, it is likely that these dents will contain additional damage, such as gouges or scratches, and over 80% will result in immediate failure.

The issue is therefore to be able to detect and evaluate the dents, particularly plain dents on rocks or dents resulting from construction, which evidence suggests, can cause delayed failure as a result of additional problems such as stress corrosion cracking or fatigue.

The next stage of this report will review the research base for the assessment of plain dents under static and fatigue loading.

4 STATIC DENT RESEARCH

Much of the research into the failure of plain dents under pressure loading has indicated that plain smooth dents do not significantly reduce the burst strength of pipelines and therefore do not require repair[2,26,56], unless they are very deep[15]. There is currently no analytical method available for calculating the failure pressure of a plain dent and therefore the traditional and codified acceptability limits for plain dents have been empirically derived on the basis of dent depth from full-scale test results. Recently, however, it has been suggested that dent depth alone is not sufficient to define the severity of a plain dent and that the strain in the dent may be a more robust indicator of dent severity. The background and theory to both these dent criteria (depth and strain) are reviewed in this section.

4.1 Depth Based Assessment

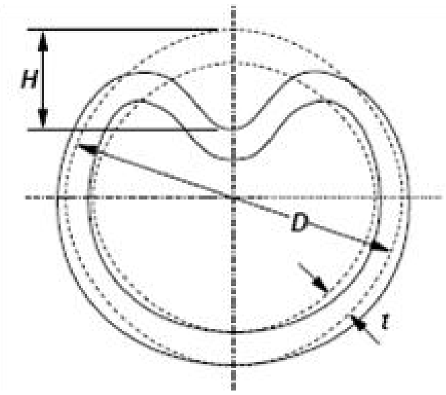


Figure 2 – Definition of Dent Depth[15]

When using a depth based assessment criteria it is firstly important to understand how the depth of the dent is measured. In B31.8[5], the dent depth is defined as "the gap between the lowest point of the dent and the prolongation of the original contour of the pipe in any direction". Cosham and Hopkins[15] define the dent depth as "the maximum reduction in the diameter of the pipe compared to the original diameter".

One of the problems with measuring dent depth is that the original contour is hard to define as there will always be some ovality associated with the dent. Rosenfeld[52,55] concludes that, as the ovality cannot be separated from the dent, the assessment criteria will necessarily include associated ovality. This concept is illustrated in Figure 2[15]. The dent depth (**H**) is therefore usually expressed as a percentage of the original nominal outside diameter (**D**).

Another issue with dent depth measurement is that the depth of the dent will change when the indenter is removed and will also change under the influence of variations in internal pressure due to the phenomena of spring back and rerounding.

4.1.1 Spring Back and Rerounding

The process of denting a pipeline produces both elastic and plastic responses in the material. When the indenter is removed, the elastic component of the deformation is recovered and the dent will move outwards *i.e.* the dent depth will decrease. This recovery is termed 'spring back'.

Rerounding occurs under the influence of the internal pressure if the dent is unconstrained and therefore free to move. As the internal pressure increases, the dent is pushed out and the dent depth decreases. Rosenfeld[53] has postulated that the process of rerounding includes initial plastic recovery of the dent depth to a depth that is dependent on the internal pressure and the pipe properties. Whether further rerounding is plastic or elastic is determined by the magnitude of the stress cycles. The dent will eventually shake down to stable elastic behaviour when the dent depth cycles about a mean depth, which is a function of the dent geometry and the amplitude of the pressure fluctuations.

Most of the full scale tests that have determined the dent acceptance criteria have been conducted by introducing the dent at zero pressure and then pressuring the test pipes. Although this set-up is applicable for construction dents, in practice, many dents are introduced when the pipe is pressurised. In addition, ILI or field measurements of dents are also made when the pipe is pressurised. In these cases, the effects of spring back and rerounding have to be taken into account when determining dent acceptability. In practice, this is achieved by the use of a spring back correction factor.

As part of the Pipeline Defect Assessment Manual (PDAM) JIP, Cosham and Hopkins[15] have reviewed the published spring back correction factors. They conclude that most of the factors are empirically derived and do not take into account all of the aspects that would be expected to contribute to the extent of spring back and rerounding; such as dent shape, internal pressure and wall thickness. In addition, there is a lot of scatter in the test data in relation to rerounding which increases the uncertainty in prediction[15,53]. Rosenfeld[52,53] has derived a semi-empirical factor based on a parametric study of the test data which takes into account the dent depth and width, the pipe D/t ratio, the internal pressure and the elastic modulus. However, the recommended spring back correction factor in PDAM is the revised EPRG (European Pipeline Research Group) factor:

$$H_o = 1.43H_r \qquad \textit{Equation 1}$$

where H_o is the dent depth at zero pressure and H_r is the rerounded dent depth.

It is recognised that, although it is easy to use with the available data, one of the limitations of this factor is that it does not include the influence of the internal pressure. Therefore, Gaz de France have recently revisited this correction factor using Finite Element Analysis (FEA) and further experimental tests[38]. The expression that they have developed takes into account the length of the dent and the internal pressure at the time of denting:

$$H_o = \pi.H_r.\left(\frac{1}{\pi - 2.\alpha.\arctan\left(\frac{L}{H_r}\right).\arctan\left(0.1\frac{D}{t}\frac{P}{\sigma_Y}\right)}\right) \qquad \textit{Equation 2}$$

In this equation, α is a correction factor to ensure that the prediction is always conservative. Unfortunately, Gaz de France have not published the values of the constants used in the correction factor so the results cannot be compared with other published data. However, they do conclude that this relationship yields less conservative results than those of Equation 1.

4.1.2 Summary of Plain Dent Burst Tests

As mentioned previously, the understanding of the effects of dents on pipelines has been developed primarily through testing. Experience has shown that scale models do not correlate to actual pipe behaviour and therefore most of the testing has been conducted on full-scale specimens or ring samples. A comprehensive review of over 75 burst test of unconstrained dents has been made by Cosham and Hopkins[15] and the results are summarised in Figure 3. The majority of these tests have been conducted by introducing the dent at zero pressure, removing the indenter and then pressurising the pipe to failure. It is also important to highlight that the dent depths in these tests were measured under zero pressure after any spring back had occurred.

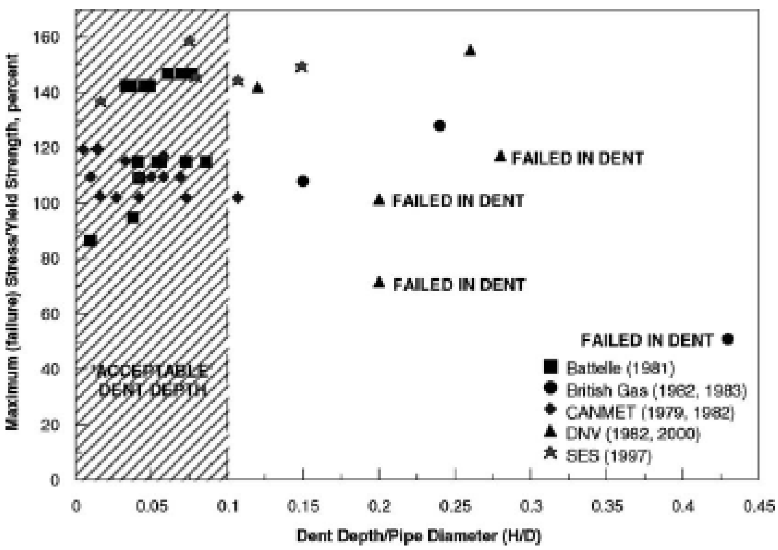


Figure 3 – Maximum Failure Stress of Plain Dents[15]

Only four of the failures in the published test data set occurred in the dent (highlighted in Figure 3), the remainder either failed at a weaker location in the pipe material or the test was terminated.

There is little published information available on the effect of dent constraint on failure pressure. However, a limited number of tests have been conducted by Alexander and Kiefner[1] to simulate rock dents. In three of these tests, a pyramid shaped indenter was used to puncture a pressurised test pipe. In another experiment, the pipe was indented to a depth of 12%OD under zero pressure and the indenter was held in place as the pipe was pressurised. The pipe started to leak when the stress in the pipeline had reached 72%SMYS.

4.1.3 Depth Acceptance Criteria

From the analysis of the test results, it has been concluded by many researchers[1, 2,15,55] that, under static loading, plain dents, which contain no stress raisers and are able to reround, do not adversely effect the integrity of the pipeline. However, on the basis of the test data, criteria have been set regarding acceptable limits for plain dents based on the depth of the dent. British Gas[30] concluded that plain dents less than 8%OD could safely remain in the pipeline, although they recognised that even dents upto 24%OD may not compromise the integrity of the pipeline. EPRG state that repair of plain dents is only required if the depth **measured at pressure** is greater than 7%OD[51]. This is also the criteria adopted in PDAM, which recommends a limit of 10%OD for unconstrained plain dents measured at zero pressure or 7%OD if measured at pressure (incorporating the spring back factor of Equation 1). On this basis, if the dent is constrained, a dent limit of 10%OD could be applied.

A discussion of code requirements on dent depth acceptability levels is provided in Section 6, however, it is worth highlighting here that the ASME B31.8 and B31.4 codes, impose a limit of 6%OD on plain dents under static loading. Although this limit has been set on the basis of the test results, it is understood that it also takes into account the dent depth limit required to ensure the safe passage of in-line inspection tools[55]. However, it is recognised that ILI tools are now available which are able to negotiate larger deformations and there is potential to relax this limit.

An exception to the statement that plain dents do not affect pipeline integrity occurs if the dents are located on rocks that have damaged the coating and subsequently shield the pipeline from the effects of CP[55].

4.1.4 Effect of Re-rounding

As most of the dents in the database were introduced under zero pressure, the test data allows the effects of rerounding to be studied. As the pressure is increased the dents will try to reround plastically to regain the original cross sectional profile of the pipe. The research by Alexander and Kiefner[1] found that even deep smooth dents of initial depth of upto 18%OD reround to less than 4%OD if the stress in the pipeline is raised to 72%SMYS. Indeed above 65%SMYS, experimentation indicated that smooth plain dents that are unconstrained will reround by 60 to 90% of the total initial dent depth.

On this basis, it was concluded that, if dents greater than 5%OD were detected in a pipeline that had been pressurised to at least 72%SMYS since the introduction of the dent, it was highly likely that these dents were constrained rock dents. In addition, under static loading, the guidance in API 1156[1] indicates that constrained dents only pose a threat to pipeline integrity of the indenter has the potential to puncture the pipe wall.

Rosenfeld considers similar guidelines for gas pipelines and concludes that, for pipelines operating at ‘moderate hoop stress levels’, dents less than 2%OD are either unconstrained, rerounded from an initially greater depth or simply very shallow constrained dents[55,56].

4.1.5 Stresses and Strains in Dents

There has been some published theoretical and small scale experimental work which has looked at the effects of dent shape, particularly dent length, in relation to the location of peak stresses and strains in plain dents[11,37,47]. It can be concluded from this work that the location of the point of maximum stress and strain concentration changes as the length of the changes. For a short dent (defined as a dent that whose axial length is less than twice the width[37]) the location of maximum stress and strain is at the rim of the dent. As the length of the dent is extended in relation to the width (*i.e.* as the dent is elongated), the maximum stress concentration moves to the root of the dent.

The work conducted by Lancaster and Palmer[37] was conducted on aluminium pipe in which the dent was introduced into the pipe before it was strain gauged. The strain measurements reported are therefore not the absolute strains in the pipe, but the changes in strain on subsequent pressurisation from the residual level. This work is therefore not able to define a maximum strain limit for pipeline dents in terms of absolute strain but is useful in identifying where the regions of high stress and strain occur in dents. This becomes important in respect to location of fatigue cracking, as will be discussed in more detail in Section 5.3.2.

It is highlighted that as the dent rerounds, the stress and strain distribution in the dent will change due to the changing shape.

4.2 Strain Based Assessment

All of the criteria reviewed above are based on dent depth, however, as dent damage is related to strain, it has been suggested that the dent profile may be a better measure of plain dent severity than dent depth[9,52]. The latest version of ASME B31.8[5] has therefore introduced a strain based acceptance criterion, as well as a method for estimating the strain in dents in Appendix R.

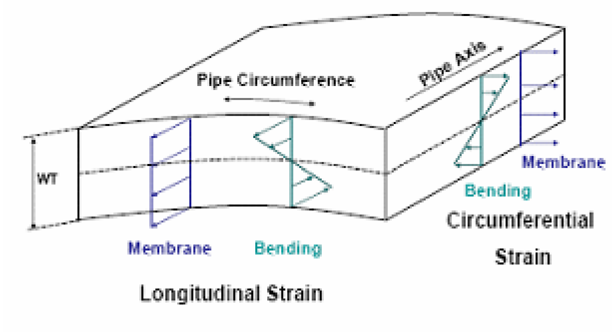


Figure 4 – Strain Components in the Pipe Wall[42]

There are two components of strain acting in the pipe wall in the circumferential and longitudinal directions. Within each of these directions, the strain can be further separated into membrane and bending components. As shown in Figure 4, the membrane strain is constant through the pipe wall but the circumferential strain varies linearly though the pipe wall about the neutral axis at t/2. The through thickness strain is assumed to be zero although this assumption is open to debate[42].

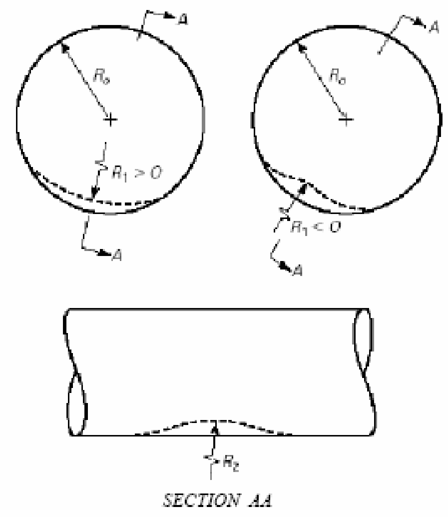
	**Circumferential Bending Strain** R_o = Radius of curvature of undeformed pipe surface R_1 = External surface radius of curvature in circumferential direction *R_1 is positive when the dent partially flattens the pipe and R_1 is negative for a re-entrant dent* **Longitudinal Bending Strain** R_2 = External radius of curvature in the longitudinal direction *R_2 is generally always negative*

Figure 5 – Dent Geometry as Defined in ASME B31.8 and reference in Noronha et al[46]

4.2.1 Calculation of Bending Strain

The bending strain in the dent can be calculated directly from the measurement of the dent shape in the longitudinal and circumferential directions (Figure 5).

The formulae that are presented in the literature for the calculation of the longitudinal bending strain (ε_{lb}) in a dent assume that when a pipeline is dented, it acts as an elastically stressed, straight plate (ASME B31.8[5], Rosenfeld[54]. The strain in the dent is then calculated using thin plate theory:

$$\varepsilon_{lb} = -\frac{t}{2R_2} \qquad \textit{Equation 3}$$

The circumferential bending strain is the strain that is set up around the circumference of the pipe and the approach that is used in this case is to consider the bending of a thin shell (ASME B31.8[5], Rosenfeld[54]). In this case, the initial curvature of the pipe κ_o has to be taken into account. The circumferential bending strain ε_{cb} is then equal to the change in curvature which occurs when the pipe is dented[59]. Again, for a pipeline, the maximum strain will occur at the surface and therefore:

$$\varepsilon_{cb} = \frac{t}{2}\left(\frac{1}{R_o} - \frac{1}{R_1}\right) \qquad \textit{Equation 4}$$

The bending strains are therefore proportional the wall thickness and the dent curvature and can be calculated from the measured dent shape. It is well documented[17,42,46,54,61] that the equations in Appendix R of ASME B31.8 for longitudinal and circumferential bending strains are incorrect in that the factor of ½ (shown in Equations 3 and 4) is missing from the ASME B31.8 code. Calculations made using the code equations would therefore be overly conservative by a factor of 2.

4.2.2 Calculation of Membrane Strain

In the longitudinal direction the deformation must involve some extension of the pipe wall. Rosenfeld *et al*[54] present an equation for calculating the longitudinal membrane strain as:

$$\varepsilon_{lm} = \frac{(L - L_o)}{L_o} \qquad \textit{Equation 5}$$

where, L_o is the initial length of the dent and **L** is the length after deformation. As this is hard to calculate from field or experimental data an empirical approximation to the longitudinal membrane strain is used which has been validated using finite element analysis[9].

$$\varepsilon_{lm} = \frac{1}{2}\left(\frac{D}{L}\right)^2 \qquad \textit{Equation 6}$$

In the ASME B31.8 strain methodology, the circumferential membrane strain is assumed to be negligible as the pipe is assumed to accommodate the deformation without significant deformation in this direction.

The above approach to the calculation of the membrane strains has recently been described by Lukasiewicz[42] as being simplistic and inaccurate and he argues that the assumption that the circumferential strains are negligible is not supported by FEA. Instead he presents a methodology for calculating the membrane strains using a specialised and simplified finite element model.

4.2.3 Combined Strain

Rosenfeld *et al*[54] have combined the three strain components discussed to determine net strains on the internal and external surfaces of the dent. The net circumferential strains on the OD and ID surfaces are:

$$\varepsilon_{co} = \varepsilon_{cb} \text{ and } \varepsilon_{ci} = -\varepsilon_{cb} \qquad \textit{Equation 7}$$

The net longitudinal strains at the OD and ID surfaces are:

$$\varepsilon_{lo} = \varepsilon_{lm} + \varepsilon_{lb} \text{ and } \varepsilon_{li} = \varepsilon_{lm} - \varepsilon_{lb} \qquad \textit{Equation 8}$$

The biaxial strains are then combined as follows to obtain the net strain at the OD and ID surfaces:

$$\varepsilon_o = \sqrt{\varepsilon_{co}^2 - \varepsilon_{co}\varepsilon_{lo} + \varepsilon_{lo}^2} \text{ and } \varepsilon_i = \sqrt{\varepsilon_{ci}^2 - \varepsilon_{ci}\varepsilon_{li} + \varepsilon_{li}^2} \qquad \textit{Equation 9}$$

In these equations it is assumed that the strains combined at the dent apex and therefore that this is the location of maximum strain. As indicated in Section 4.1.5, this assumption may not be valid for short dents.

The literature contains alternative methods for combining the strain components in a dent to those quoted in ASME B31.8 (Equation 7). Baker[9] develops an approach based on effective strain[19] which reduces to the following equations for the OD and ID surfaces when applied to the dented pipeline situation:

$$\varepsilon_{effOD} = \frac{2}{3}\sqrt{\varepsilon_{co}^2 - \varepsilon_{co}\varepsilon_{lo}^2 + \varepsilon_{lo}^2} \text{ and } \varepsilon_{effID} = \frac{2}{3}\sqrt{\varepsilon_{ci}^2 - \varepsilon_{ci}\varepsilon_{li}^2 + \varepsilon_{li}^2} \qquad \textit{Equation 10}$$

Lukasiewicz[42] presents the following equation for combining the longitudinal and membrane strains:

$$\varepsilon_{effOD} = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_{co}^2 + \varepsilon_{co}\varepsilon_{lo} + \varepsilon_{lo}^2} \qquad \textit{Equation 11}$$

4.2.4 Calculation of Strain & Acceptance Criteria

Using the criterion in ASME B31.8 to determine the strain in the dent, the problem reduces to one of determining the radius of curvature of the dent in both the longitudinal and circumferential directions (Equation 3 and 4). The ASME code does not provide guidance on how to calculate the radius of curvature.

Rosenfeld *et al*[54] have developed a technique using high resolution caliper tool data to derive the local cold strain associated with the indentation. This method derives a 2-D profile of the pipe surface using a piece-wise Bessel cubic interpolation then calculates the total strain using an osculating circle approach to calculate the curvature.

Another approach by Noronha *et al*[46] uses a B-spline method to calculate the radius of curvature but found the results obtained using this method to be comparable with those of the osculating circle method. Dawson *et al*[17] determine the radius of curvature by fitting a series of quadratic equations to the profile of the dent and then use the following relationship for the curvature of a line to determine the radius of curvature:

$$R = \frac{1}{\kappa} = \frac{\left(1 + \left(\frac{dy}{dx}\right)^2\right)^{\frac{3}{2}}}{\left(\frac{d^2y}{dx^2}\right)} \qquad \textit{Equation 12}$$

Once strains are measured they must be compared to a strain criterion. Rosenfeld[55] suggested that a suitable strain criteria may be between 3 and 12%. This is based on the ASME B31.8 code that permits field bends that produce a cold strain of 3% in the pipe wall and the observation that the likelihood of puncture in dents increases where the material strain exceeds 12%. Therefore a recommendation was made that a value of 6% strain be adopted. This has now been codified in ASME B31.8[5] and is also specified in the US Federal Regulations[63]. For dents on ductile seam or girth welds the strain limit is reduced to 4%.

4.3 Summary

A review of the published research on the analysis of plain dents confirms that they do not present a significant threat to the integrity of the pipe. Although, historically, dent acceptance criteria were based on the depth of the dent, recent research has suggested that the strain in the dent may be a better indicator of dent severity for repair. However, based on this review, it is concluded that the methodology is not yet robust enough to accurately predict dent strains based on dent profile. In addition, the strain acceptance criteria have not been adequately verified to determine whether the current limit of 6% is realistic.

5 DENT FATIGUE RESEARCH

Whilst the previous section has concluded that a plain dent will not pose a problem to the integrity of the pipeline under static loading, the fatigue life of a dented pipeline has been shown, through extensive testing, to be less than the fatigue life of plain pipe[15]. As described in Section 4.1.1, if a dent is unconstrained and free to reround, changes in internal pressure will result in changes in the depth and shape of the dent, and therefore the stress and strain distributions within the dent. Under the action of continued internal pressure cycling and incremental rounding and re-rounding of the dent, cracks will initiate and propagate at the locations of highest stress concentration and a fatigue failure will result. It is therefore important to be able to predict the fatigue life of a dented pipeline on the basis of the number of pressure cycles to failure. Two particular approaches for fatigue life prediction are presented here; empirical or semi-empirical models using S-N curves and fracture mechanics models.

5.1 Prediction of Dent Fatigue Life Using the S-N Approach

A number of semi-empirical and empirical models for predicting the fatigue life of plain dents have been developed using design fatigue curves. These models have recently been reviewed by Cosham and Hopkins[15] and compared against the published experimental dent fatigue data. The basic methodology involves using published fatigue (S-N) curves from an appropriate design code and accounting for the stress concentration in the dent by the use of a stress concentration factor (SCF). The SCF is applied to the cyclic stress range and the number of cycles to failure can then be calculated from the design curve to determine the fatigue life (e.g. Figure 6). It is highlighted that this approach assumes that no initial crack is present in the dent and therefore the fatigue life includes the time to initiate and propagate a crack.

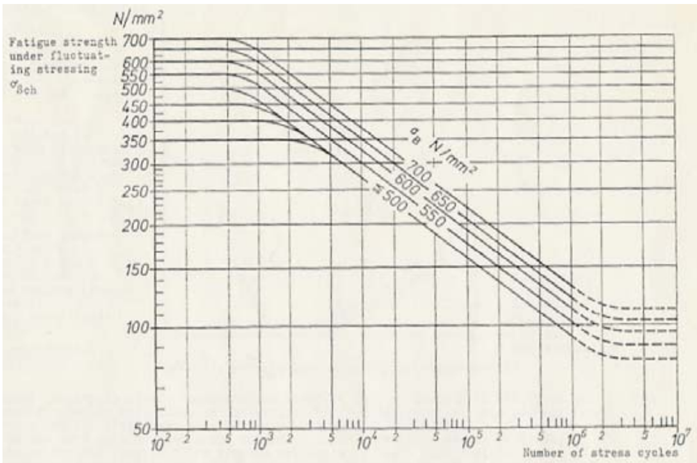


Figure 6 – Typical fatigue curve from DIN 2413[24]

To illustrate the approach, four methodologies are reviewed here; those due to PRCI[28,52], EPRG[51] and API 1156[1].

5.1.1 EPRG Model

The EPRG approach is based on S-N curves for longitudinal submerged arc welded pipe published in DIN 2413[24] (Figure 6)). The DIN code gives a series of S-N curves which are dependent on both the mean stress and ultimate tensile strength. Based on these curves, the equation proposed by EPRG is:

$$\mathbf{N_C = \exp\{4.292[\ln(UTS - 50) - \ln(2\sigma_A \times K_S) + \ln 100\}} \qquad \textit{Equation 13}$$

where

$\mathbf{N_C}$ = predicted number of cycles to failure
UTS = ultimate tensile strength, N/mm^2
$\mathbf{2\sigma_A}$ = equivalent cyclic stress at R = 0, N/mm^2
R = minimum stress / maximum stress on fatigue cycle.
t = wall thickness
$\mathbf{H_o}$ = dent depth measured as zero pressure
$\mathbf{H_r}$ = dent depth measured at pressure
$\mathbf{K_s}$ = stress concentration factor = $2.871\sqrt{\mathbf{K_d}}$ where $\mathbf{K_d = H_o \frac{t}{D}}$

The SCF (**K_s**) used in the EPRG method has been derived empirically and is a function of the dent depth and the pipe geometry. The dent depth used in the model is the dent depth at zero pressure and therefore, if using dent depths measured at pressure (*i.e.* from a caliper inspection tool) the dent depth needs to be corrected for spring back. The recommended spring back correction factor proposed by EPRG is given by Equation 1.

These recommendations were updated by Roovers *et al*[51] in 2000 with new equations to cover the assessment of smooth dents (defined as dent radius > 5 x wall thickness) and sharp dents (defined as dent radius < 5 x wall thickness).

Both the original EPRG method and the updated EPRG method have been evaluated by statistical correlation against the test data[15]. The recommendation of this research is to use the original EPRG method as this provides the best fit to the published full-scale test data (Equation 13). In addition, a safety factor of 13.3 is recommended for a 95% probability of conservative prediction of the test data.

Industry experience suggests that the EPRG model gives very conservative estimates of dent fatigue life and predicts fatigue lives much lower than the service life of the dent even though no failure of the dent has been observed[17].

5.1.2 PRCI – Cyclic Pressure Fatigue Life of Plain Dents

In 1992, PRCI initiated a research project to predict the fatigue life of plain dents, predominantly for offshore pipelines although the findings can also be applied to onshore pipelines[26,28]. The fatigue life is predicted using the DOE-B S-N curve[60], which was shown to give a better fit to the experimental data than Curve X' in API-RP2A[6]. The equation used to predict fatigue life is given by:

$$\mathbf{N_c} = \left(\mathbf{4.424x10^{23}}\left(\left[\frac{\Delta\sigma}{\Delta \mathbf{p}}\right]\Delta \mathbf{p}\right)\right)^{-4} \qquad \textit{Equation 14}$$

In this equation, the stress concentration factor (SCF) is given by the parameter $\frac{\Delta\sigma}{\Delta p}$ and is defined as the 'peak cyclic stress to change in internal pressure ratio'. The SCF values were determined using finite element modelling for discrete combinations of mean pressure, material strength, D/t ratio and d/D ratio and are provided as a set of look up tables in the report. To use the model, the SCF is read from the tables and then applied in Equation 14. This approach avoids the requirement to conduct FEA on every dent, but does mean that intermediate values of the input data have to be estimated.

5.1.3 API 1156 Model

One of the remits of the API 1156[1] work was to provide a methodology that pipeline operators could use to predict the number of cycles to failure for constrained† or unconstrained dents from the dent depth and the pressure level. The API 1156[1] model adopts a similar approach to the PRCI model described in Section 5.1.2, except that, instead of the DOE-B curve, a modified ASME Section VIII Division 2 Appendix 5[3] design curve is used which is given by the equation:

$$\mathbf{N_c} = \exp\left(\mathbf{43.944} - \mathbf{2.971}\ln\left(\frac{\mathbf{1}}{\mathbf{2}}\left[\frac{\Delta\sigma}{\Delta \mathbf{p}}\right]\Delta \mathbf{p}\right)\right) \qquad \textit{Equation 15}$$

The API 1156 model also considers a wider range of input parameters for the calculation of the SCF values and SCFs were developed using finite element analysis for a range of pipe diameters, residual dent depths, dent shapes, constraint and pressure cycling conditions. These are provided in the text as a series of look-up tables. The approach in API 1156 was validated against two experimental results and, although the results appear promising, it is recognised by the authors that more work is required to permit this approach to be used with confidence. However, it is suggested that this model could be used as a dent-ranking methodology in the future.

† It is highlighted that this is the only method that allows the fatigue life of constrained dents to be predicted.

5.1.4 PRCI – Model for Fatigue Rating Shallow Unrestrained Dents

PRCI commissioned a project conducted by Kiefner and Associates with the remit to "develop guidelines that enable pipeline operators to assess the severity of dents on the basis of their fatigue life in service[52]". The approach that was adopted was to develop a mathematical model to estimate the local bending stresses in a dent. Once the local bending stresses are known, it is possible to analyse how they change with variation in pressure and therefore to estimate the fatigue life of the dent using an S-N approach. The mathematical procedure was simplified into a set of design curves that can be used to give a pipeline a basic fatigue life rating based on the pipe and dent geometry (principally D/t, d/D and d/W), material properties and the frequency of full operating pressure cycles.

The mathematical model that was developed by Rosenfeld is comprehensive and takes into account the effect of the initial rerounding of the dent after formation and the subsequent effects of rerounding on dent depth and dent width to estimate the cyclic stress range for any pressure cycle operating on the dent. This calculation requires detailed pressure cycling information. The number of cycles to failure is then determined from the modified form of the ASME B31 Code for Pressure Piping. The modification replaces the yield stress in the equation for the design curve by the cyclic flow stress, σ_{CF}, defined as:

$$\sigma_{CF} = \frac{1}{2}\left(\frac{2}{3}\sigma_Y + \sigma_U\right) \qquad \textit{Equation 16}$$

To use the model in its most complicated form is, by the reports own admission, cumbersome and therefore the predictions of the model have been regressed to provide a shortcut to calculating the cyclic stress, however, even this simplified algorithm requires multiple iterations to converge on a predicted fatigue life. Therefore, the models have been summarised in a series of basic fatigue rating curves that are published in the report. For any given D/t, d/D, d/W, material grade and pressure cycling range the fatigue life for the dent can be calculated, provided that the input data is within the range for which the model has been developed.

The disadvantage of this approach is that the design curves are only published for discrete values of the pipe and dent geometry and interpolation of the curves is required for intermediate values, which makes the process very manual and time consuming for a large number of dents. The other drawback is that the curves are based on initial dent geometries. However, most ILI or field measurements are taken when the dent is fully rerounded. In this case, it is recommended in the report that, as it is difficult to achieve dents greater than 10%OD[26], this should be taken as the initial value for d/D with the same d/W ratio.

It is further highlighted that no operator experience with the use of the PRCI model could be found in the published literature. However, it is felt that it would be possible to codify the methodology to enable it to be used with SCADA pressure data and ILI dent geometry measurements, thereby making it more accessible.

5.1.5 Summary

There is no agreement in the literature regarding the most appropriate S-N curve to use for application to dent fatigue and much of the work has been based on validation against experimental data.

As mentioned previously, the curves available in DIN 2413[24] are used in the EPRG model and have also been adopted in other S-N modelling work[17]. Fowler[26,27,28] has concluded that Curve X' in API-RP2A[6] is too conservative for this application and that the DOE-B[60] S-N curve is more accurate. However, Rosenfeld[52,53] has concluded that the curve that gave the best correlation to the dent fatigue data was a modified form of the ASME B31 Code for Pressure Piping.

The ASME Section VIII Division 2 Appendix 5[3] design curve is used in API 1156[1]. Stevick *et al*[58] also used a fatigue curve that is based on the ASME Section VIII Division 2 Appendix 5 curve, with modifications for the medium and low cycle stress ranges, combined with the American Welding Society (AWS) A-curve[7]. These curves were used to assess a portion of the TransAlaska Pipeline System[29].

In addition, there is no standard for determining stress concentration or stress intensification factors, some of which are determined experimentally[51] and some by FEA[1,11,17,18,26,27,28,49,]. The limitation of using FEA to determine stress concentration factors is that detailed analysis has to be performed on every dent to be analysed which is an expensive and time consuming process. De Carvalho *et al*[18] have therefore attempted to develop an analytical equation, based on FEA results, to relate the SCF to the critical geometry variables of the dent.

$$SCF = 1 + 1.423\left(\frac{D}{t}\right)^{0.67}\left(\frac{d}{D}\right)^{0.62}\left(\frac{L}{W}\right) \qquad \textit{Equation 17}$$

This equation can be used to determine the stress concentration factor under static loading and work is continuing to extend the model to account for cyclic stress cycles.

5.2 Determining Fatigue Lives Using Fracture Mechanics

Fleet Technology first published details of their dent assessment model in 1999 and have been developing the model since through a JIP in the USA and Canada[20,21,22,23]. The model combines FEA with fracture mechanics crack growth theory to predict dent fatigue lives. The input data into the model includes details about the pipe characteristics (*e.g.* the pipe dimensions and mechanical properties), 3-D dent geometry data (which can be obtained from ILI data), details of any defects or stress raisers in the dent (such as pre-existing cracks, welds *etc.*), information about the pipeline pressure cycling history and a determination of whether the dent is constrained or unconstrained. It is recognised that often this data will not be available and, in these cases, representative data is used in the model based on engineering judgement.

The finite element model is used to reproduce the dent shape measured in the field and then a cyclic pressure loading is applied using a fatigue crack growth model that assumes a small pre-existing flaw. Therefore, unlike the S-N approach, which considers both the initiation and propagation phases of fatigue crack growth, in the Fleet Technology model only the propagation of the crack is modelled. Although the correlation between experimentally observed and calculated fatigue lives was very good, it was considered that this might have been due to the fortuitous selection of an initial defect size[20]. In addition, the stress-strain characteristics for the pipe material are required and this makes this model difficult to apply in the field as this information is very rarely available.

5.3 Factors Affecting Dent Fatigue Life

5.3.1 Dent Constraint

Based on previous discussion, it would be expected that if a dent was prevented from responding to changes in internal pressure, the fatigue life of this dent would be longer than an equivalent unconstrained dent. This conclusion is confirmed by tests on constrained dents conducted by Kiefner and Alexander[34] and Keating and Hoffmann[33]. Baker[9] suggests that the difference in fatigue life could be at least an order of magnitude based on work conducted by the Texas Transportation Institute (Figure 7).

In the work by Kiefner and Alexander[34], it was also shown that the mode of failure in a constrained dent is significantly different from that in an unconstrained dent. They conducted fatigue tests on six constrained dents, four of which failed during the duration of the tests and found that the cracking was orientated in the circumferential direction just beyond the edge of the indenter and propagated from the ID to the OD of the pipe. However, in similar testing on unconstrained dents, the cracking was axially orientated, located within the dented region and propagated from the OD to the ID. In tests quoted by Rinehart and Keating[49], it was found that almost all constrained dents exhibited cracking around the periphery of the dent‡. For unconstrained dents, the location of the cracking was dependent on the geometry, long dents cracked in the dent centre whilst short dents cracked at the dent periphery.

‡ In this study the dent was restrained by mechanically preventing the indentors from moving out of the dent. Therefore this study is particularly relevant for application to rock dents.

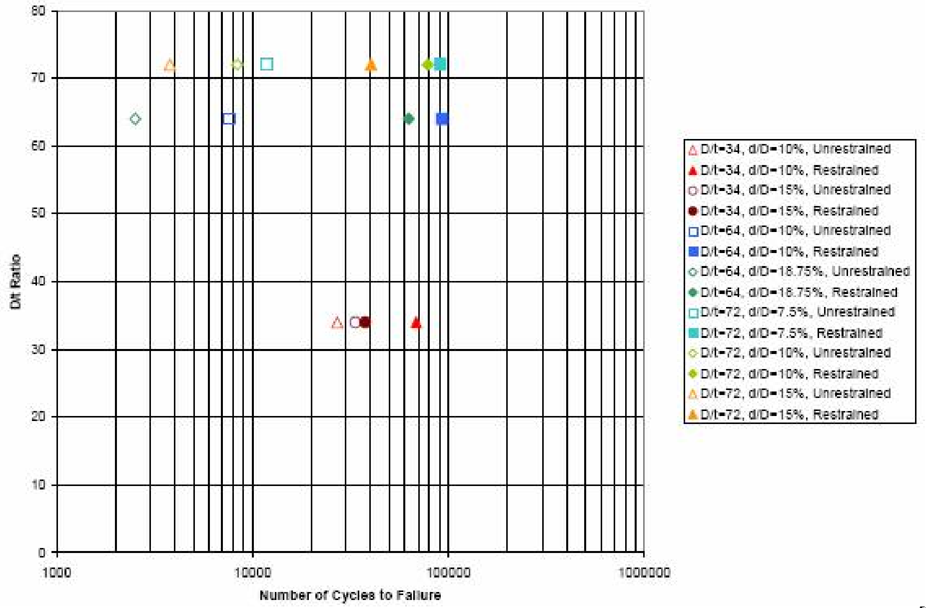


Figure 7 – Comparison of Fatigue Lives for Constrained and Unconstrained Dents[9]

5.3.2 Dent Geometry Factors

Fatigue theory indicates that crack initiation and propagation are most likely to occur at locations of high stress concentration. Therefore research into the parameters that affect dent fatigue behaviour has concentrated on determining the geometry factors that increase the stress concentration in the dent. These studies have been both experimental and using FEA.

As described in Section 5.1.1, the EPRG model principally considers the **depth** of the dent to estimate the fatigue life and predicts that fatigue life will decrease with increasing dent depth. This prediction has been shown to be consistent with experimental observation[1,2,26, 27,34,50,52].

However, the dent geometry, dent restraint (*i.e.* the ability of the dent to move under cyclic pressure), and the rerounding stiffness (*i.e.* the relative amount of rerounding) are also considered to be important and inter-related factors in determining the dent fatigue life.

It was mentioned previously (Section 4.1.5) that, using FEA analysis, Beller *et al*[11] found that the point of maximum stress concentration for a semi-spherical dent was at the rim of the dent. As the length of the dent was extended in relation to the width (*i.e.* as the dent was elongated), the maximum stress concentration moved to the root of the dent. In relation to fatigue, this observation indicates that there is a critical ratio of length to width where the location of fatigue cracking would move from the rim to the centre of the dent. Unfortunately the critical ratio was not defined in this work. It was also shown by Rinehart and Keating[49] that the fatigue lives of dents with centre cracking were, on average, an order of magnitude shorter than dents with peripheral cracking. It was therefore concluded that long dents are more fatigue critical than short dents and that dent length was also an important geometrical factor. Importantly, the definition of a long and a short dent is also not presented in this work.

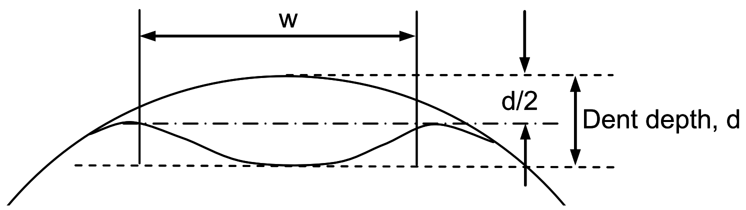


Figure 8 – Dent shoulder angle measurement

Rosenfeld[52] concluded that the ability of a dent to reround is related to the aspect ratio of the dent (*i.e.* the dent to width ratio) and that fatigue lives increase with increasing d/W ratio *i.e.* deep but narrow dents have a longer fatigue life than shallow, wider dents as they are less flexible. It was recognised that the width of the dent is difficult to measure due to bulging around the shoulders of the dent and therefore the dent width is defined as the distance between the points on the dent where the depth is half the maximum depth (Figure 8). It is interesting to note that, in a study of 436 mechanical damage features (dents and dent/gouge features), Rosenfeld *et al*[57] found that any dent with an aspect ratio greater than 0.06 was likely to contain a crack, indicating that this parameter could also be related to bending stresses and strains.

By combining the parameters, dent depth (d/D), dent length (L/D) and rerounding stiffness, Rinehart and Keating[50] developed an geometric expression which is inversely proportional to fatigue life. In this model the parameter W/t was used as a measure of the rerounding stiffness. Therefore the following expression is obtained:

$$\textbf{Fatigue Life} \propto \frac{1}{\frac{LdW}{D^2 t}} \qquad \textit{Equation 18}$$

This equation is consistent with the experimental observation that the fatigue life decreases with increasing dent depth and dent length and can be shown to be directly related to the stress concentration factor[18], which should be expected as the stress concentration factor is inversely related to fatigue life[17].

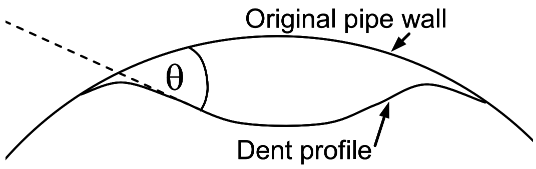


Figure 9 – Dent shoulder angle measurement

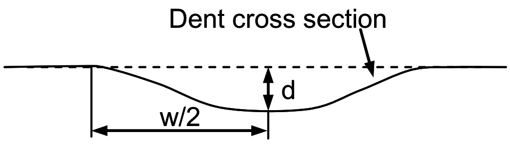


Figure 10 – Dent acuity measurement

Other geometric parameters cited in the literature as affecting the fatigue life are the dent shoulder slope and the dent acuity[22]. These parameters are illustrated in Figure 9 and Figure 10. Although there is a lot of scatter in the published data, the relationship indicates that the greater the dent shoulder angle (*i.e.* the higher the degree of ovalisation) the shorter the fatigue life. Similarly, it can be shown that the greater the dent acuity (*i.e.* the sharper the dent) the shorter the fatigue life[22].

5.3.3 Pipe Geometry Factors

Research has also indicated that the ratio of the pipe diameter to the wall thickness is a critical parameter in determining dent fatigue life and that the fatigue life of the dent decreases with increasing D/t ratio[26,52]. Indeed Carvalho *et al*[18] show that the D/t ratio is directly related to SCF values and therefore also inversely related to fatigue life. In static tests, Kiefner and Alexander have shown that pipes with lower D/t ratios exhibit less rerounding[34]. The D/t ratio may therefore be considered to be a better measure of the rerounding stiffness than the W/t parameter used by Keating in Equation 18[50]. It is highlighted that this result is in contradiction to the modelling work of Dinovitzer *et al* who show that the fatigue life increases with increasing D/t ratio using a FEA model[22].

The observation that fatigue life decreases with increasing D/t ratio could be attributed to the fact that pipes with smaller D/t ratios are stiffer and more resistant to denting as a greater amount of plasticity is required to form a dent of a given depth. Indeed, in a study of 9,851 dents in 63 pipelines, Dawson *et al*[17] found that the number of dents in the pipeline and the depth of those dents increased with increasing D/t ratio.

5.3.4 Material Factors

Fowler[26] conducted experimental work in which dents of different depths, in pipe material ranging from Grade X46 to Grade X80, were subjected to fatigue testing. The results indicated that, for a given dent depth, the fatigue life decreased with increasing SMYS. This result was confirmed by FEA work conducted by Dinovitzer *et al*[22], who calculated the fatigue lives of dents in X52, X60 and X70 pipe, and mathematical modelling work by Rosenfeld[52]. This effect can be attributed to the ability of the dent to reround due to the decreasing plasticity of the material, thereby increasing the remaining dent depth undergoing cyclic deformation.

5.3.5 Pressure Cycle Regime

Liquid pipelines tend to be more heavily pressure cycled, in terms of number and magnitude of pressure cycling than gas pipelines, as illustrated in Figure 11. For example, a gas transmission pipeline in the US may be subjected to 60 cycles per year at a magnitude of 14 bar, whereas a liquid line could experience 1800 such cycles in a year[2]. Therefore, dent fatigue is generally perceived as more of an issue in liquid pipelines.

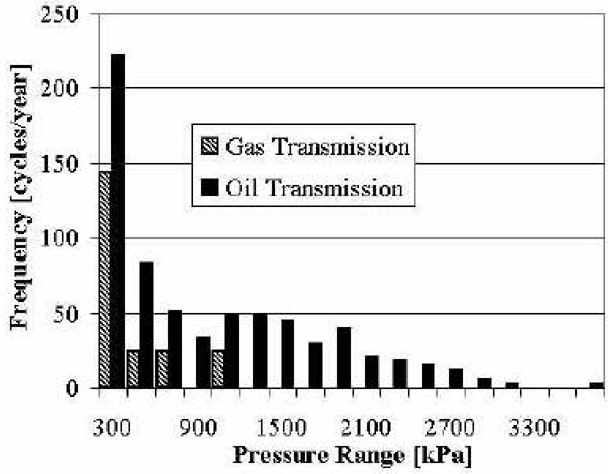


Figure 11 – Pressure Cycling Characteristics for Gas and Oil Pipelines[22]

There has been some published work to try and quantify the magnitude of pressure cycling in a pipeline. In this work, Kiefner[35] has characterised typical pressure cycling regimes for a pipeline based on a benchmarking scheme (Table 1). This scheme is based on actual pressure patterns observed in pipelines that have failed as a result of fatigue§.

The values in the 'Percent SMYS' column indicate a hoop stress cycle, for example, a very aggressively cycled pipeline may experience 20 cycles from 72%SMYS to zero and back to 72%SMYS. In the work conducted for API 1156[1], pressure cycling was divided into three ranges; low range pressure cycle (0-50%MOP), high range pressure cycle (50-100%MOP) and full range pressure cycle (0-100%MOP).

Percent SMYS	Very Aggressive	Aggressive	Moderate	Light
72	20	4	1	0
65	40	8	2	0
55	100	25	10	0
45	500	125	50	25
35	1000	250	100	50
25	2000	500	200	100
Total	**3660**	**912**	**363**	**175**

Table 1- Benchmark Annual Cycle Counts (Kiefner[35])

The pressure cycling range is important in terms of dent fatigue life and the fatigue life has been shown to decrease with increasing pressure cycle range[36]. This is not a surprising result and is indeed the basis for the S-N prediction methods (e.g. Figure 6).

In work conducted for PRCI, Rosenfeld[52] analysed the effects of four pressure cycling regimes, representing different operational characteristics of gas and liquid pipelines, on the fatigue life of unconstrained plain dents. Two of the regimes included no full operating pressure cycles (*i.e.* zero to full maximum operating pressure to zero) and two of the regimes included different frequencies of full operating pressure cycles. On the basis of calculations conducted using a mathematical algorithm to estimate fatigue lives, it was found that, as the number of full operating pressure cycles increased, the calculated fatigue lives decreased. It was therefore concluded that, in terms of the pressure cycling regime, the critical parameter is the number of full operating pressure cycles and that large numbers of smaller pressure cycles had a relatively small influence on fatigue life.

§ It is highlighted that this work was conducted for fatigue cycling of low frequency ERW pipe and not specifically for fatigue of dents.

6 DENT ACCEPTANCE STANDARDS

The code requirements for dent acceptability have grown out of the research and full-scale testing described in Sections 4 and 5. Historically, the acceptability of dents introduced during service has been based on the dent depth, although recent code revisions and guidance documents have recognised that the strain in the dent and the effects of fatigue should be considered. Although ASME B31.8 Appendix R (Section 4.2) does provide a procedure for assessing the strain in dents, there is no codified methodology for conducting fatigue assessments.

	Plain Dents	
	Constrained	**Unconstrained**
ASME B31.8[5]	Upto 6%OD or strain level upto 6%	
ASME B31.4[4]	Upto 6% OD in pipe diameters > NPS 4 Upto 6mm in pipe diameters < NPS 4	
API 1156[1,34]	Upto 6%OD, >2% OD requires a fatigue assessment	
EPRG[51]	≤7%OD at a hoop stress of 72%SMYS	
PDAM[15]	Upto 10%OD	Upto 7%OD
Z662[62]	Upto 6mm for ≤ 101.6mm OD or <6%OD for >101.6mm	

	Dents at welds	Dents with cracks or gouges	Dents with corrosion
ASME B31.8[5]	Upto 2%OD or 4% strain on ductile welds Not allowed on brittle welds	Not allowed	Assess individually
ASME B31.4[4]	Not allowed	Not allowed	Not allowed
API 1156[1,34]	Upto 2%OD on ductile welds Not allowed on brittle welds	Not allowed	Not considered
EPRG[51]	Not allowed	Not allowed	Not allowed
Z662[62]	Not allowed	Not allowed	Not allowed

Table 2 - Summary of Static Dent Assessment Methods

A summary of the code and best practice guidance for the assessment of dents in pipelines is provided in Table 2.

As well as providing guidance on acceptable dent depths, there is also information provided in the literature on the effects of re-rounding on dent depth. In gas pipelines operating at ‘moderate hoop stress levels[55]’, unconstrained dents can re-round under the applied internal pressure. Rosenfeld[55] states that any dent indicated by ILI to be deeper than 2%OD is almost certainly constrained by soil or rocks. Therefore, dents less than 2%OD may be unconstrained, re-rounded from an initially greater depth or very shallow constrained dents.

Similar limits for constrained dents in liquid pipelines are presented in API 1156[1,34]. Due to re-rounding effects in areas of the pipeline which have been pressurised to greater then 72% SMYS, unconstrained plain dents with depths greater than 5% are extremely unlikely in liquid pipelines. The report concludes that the current limit of 6%OD in B31.4 is sound, however, the acceptability of unconstrained dents greater than 2% should be based on a dynamic rather than a static assessment.

One of the key findings of the work conducted as part of API 1156 was that, for rock dents, the primary mode of failure if the rock remained in place was a puncture if the rock was sharp enough. In addition, from a fatigue point of view, it would be preferable to leave the rock in place, although it is recognised that this could increase the risk of corrosion.

Dents associated with welds are susceptible to cracks at the internal weld toe during denting, particularly in low toughness material. Historically therefore, dents on welds were not allowed to the pipeline codes, however, Rosenfeld[55] and API 1156[1,34] suggest that smooth dents upto 2%OD on ductile (*i.e.* moderate to high toughness) welds can safely remain in the gas and liquid pipelines and this has been incorporated into the latest codes.

Mechanical damage is viewed as one of the most severe forms of pipeline damage as it is often accompanied by cracking and gouging. This combination of a loss of wall thickness (*i.e.* a gouge or a crack) and a dent is the severest form of pipeline defect and can record very low burst pressures and fatigue lives. It is highlighted that for dents containing corrosion, the two defects can be assessed separately *i.e.* the corrosion is assessed to the corrosion assessment codes and the dent is assessed to the appropriate code limits.

In the United States, operators of oil and gas pipelines have to comply with the Federal Regulations 49 CFR 192[63] and 49 CFR 195[64] for pipelines operating in High Consequence Areas (HCAs). These recommendations specify response times for different dents depending on location and depth and are summarised in Table 3.

Anomaly	49 CFR 192	49 CFR 195
A dent that has any indication of metal loss, cracking or a stress raiser	Immediate	Upper ⅔ of the pipe – immediate Lower ⅓ of the pipe – 60 day
A dent with depth greater than 6%OD	Upper ⅔ of the pipe – one year* Lower ⅓ of the pipe – monitored	Upper ⅔ of the pipe – immediate Lower ⅓ of the pipe – 180 day
A dent with depth greater than 3%OD on the upper ⅔ of the pipe	Not defined	60 day
A dent with depth greater than 2%OD on the upper ⅔ of the pipe	Not defined	180 day
A dent with depth greater than 2%OD that affects pipe curvature at a weld	One year*	180 day
* can be downgraded to a monitored condition providing engineering analyses of the dent demonstrate that critical strain levels are not exceeded. In the case of a dent affecting a weld, the weld properties must also be considered		

Table 3 – Comparison of Dent Assessment Requirements in 49 CFR 192 and 49 CFR 195[9]

One of the assumptions of these requirements is that dents on the top of the pipeline are more likely to have been caused by third party damage, whilst those on the bottom of the pipeline are more likely to be rock or construction dents. Consequently, the remediation actions for rock dents are less immediate than for potential mechanical damage.

7 DENT MEASUREMENT AND DETECTION

The previous section has demonstrated that in order to make an assessment of a dent to the current codes, information about the depth or shape of the dent is required, the orientation of the dent and the association of the dent with welds, cracks, gouges or corrosion. Unfortunately there is not one in-line inspection (ILI) tool that can determine all of the required information and therefore dent assessment has to be carried out using a combination of ILI data. In API 1156[34], a useful table is provided which summarises the capabilities of ILI tools for providing the required dent information (Table 4).

Dent Attribute	Geometry Tool	High Resolution Geometry Tool	Metal Loss Tool	Crack Detection Tool
Location along pipeline	✓	✓	✓	✓
Orientation	✓	✓	✓	✓
Size (%OD)	✓	✓		
Size and shape of dent		✓		
Detects dents on welds	✓	✓	✓	✓
Detects metal loss in dent			✓	
Detects cracks in dents				✓
Detects rock dents				

Table 4 – Capabilities of In Line Inspection Tools for Dent Information – adapted from API 1156

7.1 Geometry Tools

Geometry or caliper tools measure changes in the internal diameter of the pipeline and fall into two categories; single channel and multi-channel, high resolution tools. Single channel tools are basic tools that are generally used for line-proving on new-build projects as they only provide information on distance and minimum pipe diameter. The main drawback of these types of tools for conducting dent assessment is that they do not provide any information on dent orientation and the resolution of the tool is not sufficient to be able to accurately determine the shape and extent of the dent. Therefore, for dent assessment, a multi-channel caliper tool should be used which, not only provides dent depth and location data, but also provides additional information on the dents such as dent orientation. The increased resolution of multi-channel tools also means that detailed geometry information can be obtained which can be used in strain based assessments and can allow 3-D representations of the dents to be built up.

There are different technologies available for measuring the pipe bore (*e.g.* ultrasonic sensors, electromagnetic sensors, laser optical imaging) but most caliper tools are based on a mechanical arm design as this design tends to be more robust and less sensitive to dirt and debris in the pipeline. In this design, a number of sensor arms are located around the diameter of the tool which make physical contact with the pipe wall. As the caliper passes over a dent, the mechanical movement of the sensor arm is measured and recorded.

There are limitations with the mechanical arm caliper design in that the probability of detection of a dent is determined by the percentage of the pipe circumference that is covered by the sensor arms at any one time. For example a simple caliper tool with 12 caliper arms has a typical coverage of about 55%[12]. It is therefore possible for small deformations to pass between adjacent fingers. It is also possible that as the sensor arms ride over the dent they can splay out and therefore miss the deepest part of the dent.

In the longitudinal direction the resolution is determined by how many measurements are made in terms of either lapsed time or distance. Where the sampling rate is determined by lapsed time then the resolution of the tools can be affected by changes in velocity of the tool. For lapsed distance measurements which are determined by an odometer, any slippage in the odometer reading due to rapid acceleration or deceleration of the tool can affect the resolution of the readings. Industry practice indicates that linear sampling every 6.4mm would be classified as high resolution data and sampling at distances of 25mm or greater would be low resolution[9].

In the circumferential direction the resolution is determined by the number of sensors on the tool, which, in general is fixed by the diameter of the pipe. For example, for a 20" caliper tool with 18 sensors, the distance between sensors is approximately 86mm *i.e.* the distance between readings in the circumferential direction could be 10-12 times greater than that in the longitudinal direction.

7.2 Metal Loss Detection Tools

Although caliper tools can locate dents, determine their size and shape and identify whether they are associated with welds, they cannot detect whether there is any associated metal loss. For this, a metal loss detection tool is required, which can size a metal loss defect within a dent but cannot size the dent. Therefore, in order to make a full dent assessment the results of the caliper and metal loss inspections have to be aligned.

7.2.1 Magnetic Flux Leakage (MFL)

Magnetic flux leakage tools detect defects by the application of a magnetic field in either the longitudinal or circumferential direction. As the tool travels through the pipeline, powerful permanent magnets magnetise the surrounding metal via wire brushes that contact the pipe wall. Sensors surrounding the circumference of the tool record the change in the magnetic field. The change in the magnetic field can then be related to metal loss defect dimensions using algorithms developed from test runs in pipes with machined defects of known dimensions.

As the inspection tool moves over a dent, the physical movement of the sensors detects the presence of the deformation. The MFL tools are therefore able to locate plain dents, dents associated with metal loss and dents associated with welds with details of the circumferential orientation of the dent and the dimensions of any metal loss. The MFL tools are not designed to measure the depth or the profile of the dent, nor can they distinguish between metal loss caused by corrosion and metal loss caused by gouging. However, it is possible to obtain information from the size and shape of the magnetic signals that has been used to determine the severity of dents on a pipeline[61].

The current MFL tools apply a high strength field to the pipe wall to be able to analyse metal loss effectively. However, at lower magnetic field strengths, it is possible to detect changes in the magnetic properties of the steel that result from the stresses, strains and microstructural damage induced by the denting process. There is work being conducted at a number of institutions[40,14] to identify whether low strength magnetic signal characteristics can be correlated to such dent parameters as re-rounding characteristics and stress and strain gradients. This would enable a prototype tool to be developed to evaluate mechanical damage severity from the magnetic signals.

7.2.2 Ultrasonic Wall Thickness Measurement (USWM)

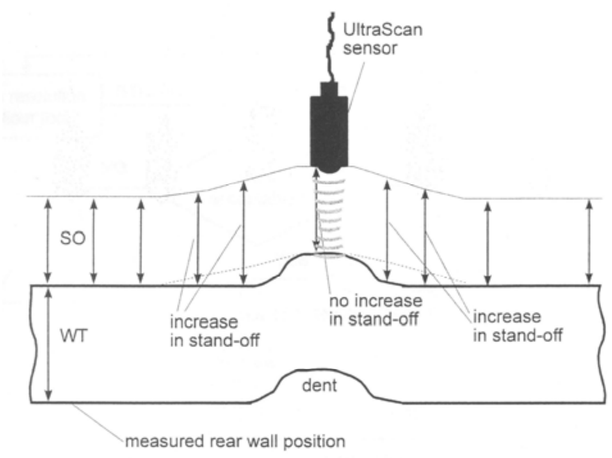


Figure 12 - Variation in Stand-Off Values at a Dent

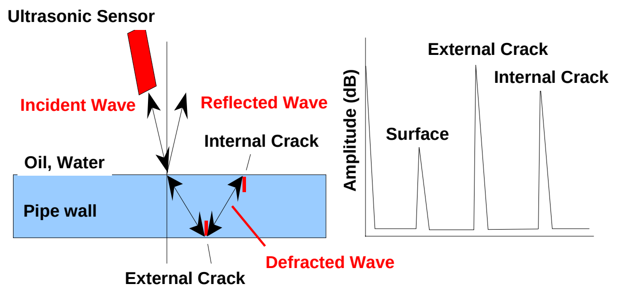
Ultrasonic Wall Thickness Measurement (USWM) tools are based on an ultrasound system, which uses the ultrasound echo time technique to measure the remaining wall thickness of pipes by sending an ultrasonic beam at 90° through the pipe wall. However, ultrasonic tools are also capable of detecting geometry features that affect the bore of the pipe. In particular, the tool is very sensitive to small deformations of the pipe that cause movement of the sensor carrier. The separation of the carrier from the internal wall leads to variations in the sound path of the ultrasonic beam which is translated into measurable changes in the values of the recorded stand-off distances as illustrated in Figure 12.

Ultrasonic tools are able to detect the presence and orientation of plain dents and dents associated with welds and metal loss, but again, are not designed to determine the depths of the dents. One of the problems with the ultrasonic tools is that if the dent has a sharp angle, the sensor carrier can be lifted too far from pipe wall resulting in signal loss which in turn affects the measurement of any associated metal loss. It is also claimed that the detailed analysis of the dent signals from a USWM tool can allow a qualitative assessment of dent severity[9,17] and dent depth[57] as the change in the stand-off distance can be related to dent depth. However, it is considered that this is not an accurate or reliable method for determining dent depth.

7.3 Crack Detection Tools

Although an alignment of caliper and metal loss inspection run data will identify the locations of plain dents, dents on welds and dents associated with metal loss, it is not possible to determine whether fatigue cracking is present in the dents. In order to identify cracking, a separate crack detection inspection must be undertaken.

For liquid pipelines, Ultrasonic Crack Detection (USCD) is the most appropriate tool. The principle of the inspection is similar to USWM except that the pulses of ultrasound emitted by the tool are directed circumferentially into the pipe wall at an angle that generates 45° shear-waves within the metal (Figure 13). The angle of incidence means that the beam is reflected and diffracted from axial aligned cracking.



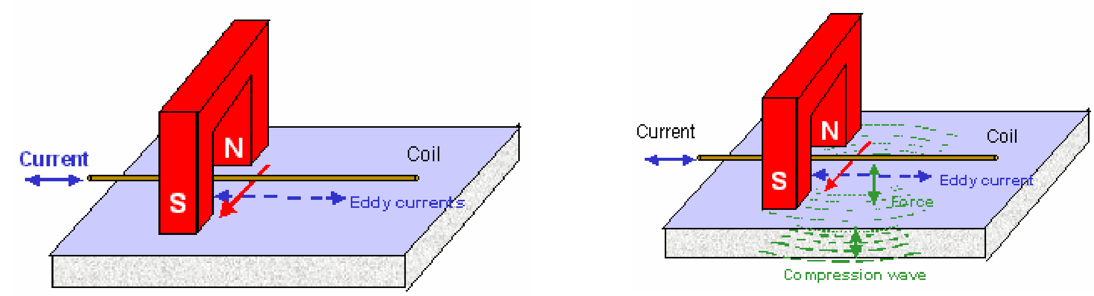
Propagation of ultrasonic shear waves through the pipe wall

Resulting A-scan, transducer signal vs time

Figure 13- Principles of Operation for USCD

For gas pipelines, using the USCD tool would require the inspection tool to be run in a liquid slug. Therefore the most appropriate inspection tool for gas pipeline uses Electro Magnetic Acoustic Technology (EMAT). EMAT allows ultrasound to be generated in a steel pipe wall without the requirement for a liquid couplant to transfer the ultrasound into the steel.

The basic principle of EMAT to generate a compression wave of ultrasound is shown in Figure 14. A magnetic field is established in the pipe wall using magnets. A coil carrying AC current at 90° to the magnetic field produces eddy currents in the pipe wall. A force normal to the pipe wall is exerted on the eddy currents, which generates ultrasound travelling through the pipe wall.



Eddy currents induced into the pipe ***Compression waves travelling though pipe wall***

Figure 14 - Principles of Electro Magnetic Acoustic Technology (EMAT)

Both of these tools (USCD and EMAT) will also detect dents in the pipeline and dents on welds and dents with associated cracking, but will not detect dents with metal loss. In addition, it is highlighted that research has shown that the orientation and location of cracking in a dent is dependent on the dent shape (Section 5.3.2) and whether the dent is constrained or unconstrained (Section 5.3.1). Therefore, before running a crack detection tool it should be established whether cracking in the expected location and orientation will be detected.

7.4 Detecting Rock Dents

As highlighted in Table 4, there is no inspection tool that is able to detect the presence of rock dents. However, if the orientation of the dent is known then, based on the requirements of 49 CFR 192[63] and 49 CFR 195[64], it can be assumed that dents located in the bottom third of the pipeline are rock dents. In addition, the guidance in API 1156[1,34] and the recommendations of Rosenfeld[55], indicate that the depth of the dent, linked to the location information, will also indicate whether it is likely that a dent is constrained by a rock.

7.5 Using ILI Data to Determine Dent Strains

One of the requirements for being able to conduct a dent strain analysis is the ability to accurately define the profile of the dent. However, care has to be taken to ensure that the high resolution caliper data is correctly interpreted to avoid the introduction of errors.

The raw caliper data obtained from the ILI tool is unfiltered and contains a large amount of background noise due to the inherent vibration of the tool and the pipe wall surface irregularities. The data has therefore to be filtered to produce a realistic dent shape. However, the algorithm that is used to smooth the data may not be sensitive enough to detect the peak profile in the dent and this will affect the calculated radius of curvature and therefore the calculated strains.

It was also mentioned previously that the resolution of caliper inspection tools in the circumferential direction is much poorer than in the longitudinal direction (Section 7.1) due to the number of readings that are being taken and the number of sensors. Noronha *et al*[46] have investigated the effect of the resolution in the circumferential direction on the calculated strain results and concluded that in order to achieve an accurate estimate of strain in a 12” diameter pipe, 64 sensors were required. Unfortunately, this level of resolution is not yet available for this diameter of pipe. Dawson *et al*[17] recognised this limitation for calculating strains in the circumferential direction and, based on symmetry results from field dents, assume that the shape of the dent is symmetrical and that the longitudinal profile (*i.e.* the profile with the better resolution) can be used to represent the dent profile in both directions.

8 DENT MANAGEMENT STRATEGIES

One of the issues that face pipeline operators is that the current requirements for pipeline dent assessment have resulted in large numbers of dents being reported by ILI companies for further consideration by the pipeline operator. Many of the dents can be readily prioritised for repair on the basis of their association with other features, such as welds or metal loss and their position on the pipeline (*i.e.* in the top or bottom of the pipe). However, this may still leave a significant number dents on the pipeline which fall within the dent criteria, but may still pose a threat, particularly from fatigue.

Based on the research and best practices reviewed in this report, pipeline operators and consultants have developed strategies for screening the ILI results and determining appropriate and manageable dig and repair strategies for plain dents. The strategies that are available in the open literature are reviewed and evaluated in the following sections.

8.1 Fleet Technology (BMT) Dent Assessment Model

Fleet Technology developed their dent assessment model using FEA as described in Section 5.2. Although the model has been validated against the full-scale dent fatigue data in API 1156[1,34], it was recognised that the computational time required to assess each dent did not make it a suitable tool for screening ILI results. Therefore, Fleet Technology began developing a methodology, based on the dent assessment model, to rank dents based on factors that could be readily quantified and were considered to affect the service life of the dented pipe. The results of this work were published in two stages.

8.1.1 Initial Model

The initial or first stage of the model proposed a characterisation based on the relative risk of dent failure[22]. At the time of publishing this model, the details were not completely developed and therefore no conclusions could be drawn, however, the parameters that were considered by Fleet Technology in 2002 were:

- the pipe characteristics: diameter, wall thickness and material
- dent geometry: shape, curvature, depth, shoulder radius (Figure 9), acuity (Figure 10)
- operational characteristics: line pressure history, indentor contact
- interacting localised effects: metal loss and welds

It was then envisaged that the dent relative risk would be calculated using an equation of the form:

$$\textbf{Dent relative risk} = \mathbf{P x \Sigma A_i} \qquad \textit{Equation 19}$$

where **P** is the effect of the operational pressure spectrum and $\mathbf{A_i}$ is the effect of each of the dent parameters such as shape *etc.*. Each of the risk factors would be weighted for its relative importance using a series of factors or empirical equations.

The effect of the pressure spectrum factor was to determine the accumulated damage for different dents along the pipeline using a scale factor that could be calculated using:

$$\textbf{Scale Factor} = \frac{\textbf{Dent Service Duration}}{\textbf{Reference Service Duration}} \qquad \textit{Equation 20}$$

In this formula, the reference service duration could either be taken as the pipeline design life, the service life of the pipeline or the service life of the oldest dent. The difficulty with the application of this approach is determining the dent service duration. In most cases it is not possible to determine at what point the damage occurred in the pipeline.

8.1.2 Updated Model

In 2003 Fleet Technology[23] published the next stage of the dent characterisation project, which extended the previous work to produce a dent relative ranking parameter given by:

$$\text{Dent Factor} = \text{Pressure Factor} \times \text{Dent Geometry Factor} \qquad \textit{Equation 21}$$

$$\text{Dent Factor} = \frac{\Sigma\ \text{Geometric Parameter Contributions}}{\text{Equivalent Annual Number of Cycles}} \qquad \textit{Equation 22}$$

The calculation of the geometry factors and pressure factors are described in the following sections, although, as much of the work is proprietary, it is not possible to determine the exact methodology used in the model from the published data. However, using this methodology, a dent factor, which has the "units" of years, is determined for each dent and the most severe dents excavated.

- ***Dent Geometry Factor***

  In this research the geometric description of the dent was updated and the dent described as a series of longitudinal and transverse sections through the dent peak (Figure 15). This removed the requirement to measure dent angles.

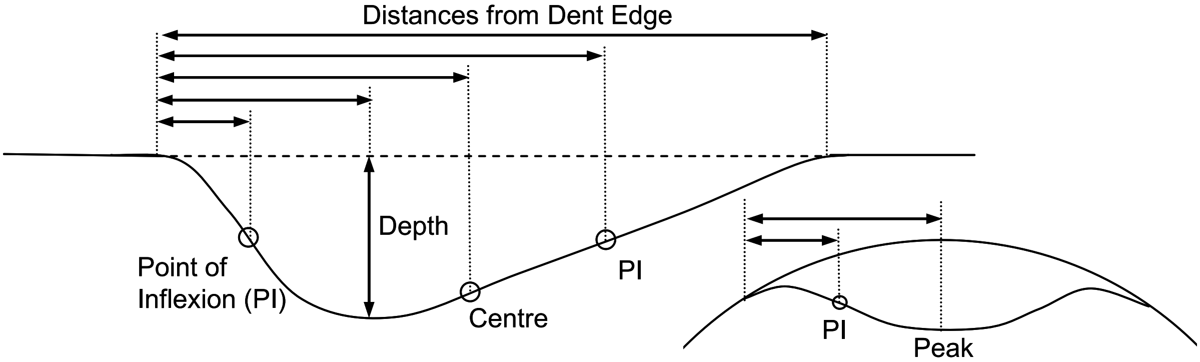


Figure 15 – Measurement of Dent in the Transverse and Axial Directions

The dent geometry was then characterised by using non-dimensional parameters such as the dent depth (as a %OD), the D/t ratio and parameters relating to the transverse and axial shoulder sharpness given by the ratio of the distance to the point of inflexion over the distance to the dent peak. The combination of each of the geometric parameters gives the dent geometry factor.

- ***Pressure Factor***

  The pressure factor allows the severity of the pressure cycling that each dent experiences to be taken into account in the model. Therefore dents that are in sections of the pipeline that are more heavily pressure cycled have higher calculated dent factors. The methodology takes the SCADA pressure cycling data and uses a Rainflow counting method[8] to convert the complex pressure cycling pattern into a series of pressure range frequencies. Using Miner's rule, the number of cycles at a stress range equivalent to a quarter of the yield stress of the material are calculated that would produce the same amount of fatigue damage as the observed pressure spectrum[43]. This allows the data to be normalised for each pipeline section and the equivalent annual number of cycles to be calculated for each dent.

The strength of this model is that it is attempting to rank the dent shape factors that affect stress concentrations and dent re-rounding (*i.e.* dent depth, length and width) and combine them with a pressure factor to indicate the likelihood of fatigue cracking. In addition, removing the necessity to measure dent angles increases the model's repeatability in the field. Unfortunately the published details are not sufficient to allow the model to be applied and therefore the results can not be verified for any pipeline system.

8.2 Enbridge Pipelines/Fleet Technology – Rapid Characterisation Process

8.2.1 Initial Model

Enbridge Pipelines had been working with BMT Fleet Technology as part of the JIP described in Section 8.1. However, whilst this work was continuing, Enbridge used some of the early results to develop a 'rapid characterisation' process that could be used with ILI results to identify dents for excavation and repair without the need to conduct FEA on each dent[31]. The methodology is based on the premise outlined in Section 5.3.2 that the shape characteristics of the dent are important in determining whether a dent will fail. Enbridge used three shape factors to determine an 'estimated severity factor' by which they could prioritise the dents for repair; the dent depth (as a percentage of OD), the dent shoulder angle, (θ) as shown in Figure 9 and the ratio of dent width to the width of the deformed area. The measurement of this parameter is illustrated in Figure 16. Each of these factors is given a grade according to the grading scheme shown in Table 5.

d/D (%)	Factor A	Theta (degrees)	Factor B	w/W	Factor C
≥ 4	4	90-100	5	0 - 0.25	4
3.5 - 4	3	100-110	4	0.25 - 0.5	3
2.5 - 3.5	2	110-130	3	0.5 – 0.75	2
≤2.5	1	130-150	2	>0.75	1
		>150	1		

Table 5** – **Enbridge Dent Severity Factor Scores

The overall grading for each dent is then taken as the average of each of the shape factors (*i.e.* (A + B + C)/3) to group the dents based on severity. The most severe grouping has a factor average of ≥3.5 and below this a further seven groups are defined with each group having a band width of 0.5. The paper does not indicate which groups are considered severe enough for excavation.

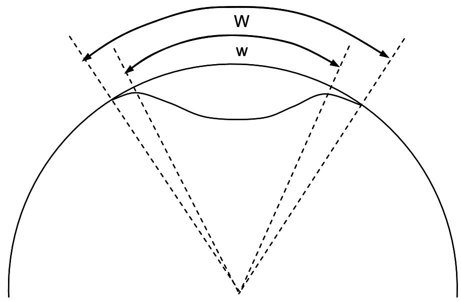


Figure 16 – Dent width measurement (w/W)

Although the published model is sufficient to apply to other pipelines, the parameters that are used (*e.g.* the angle (θ) and the w/W measurement) are not adequately defined to the extent that accurate and repeatable field data can be measured.

8.2.2 Updated Model

In 2004, Enbridge published an update to this approach using the latest results from the Fleet Technology model[44]. In this work they calculate the dent factor outlined in Section 8.1.2 using both the geometry factors and the pressure factor. Each dent is given a ranking and the excavation program is developed based on this ranking. As the excavations continue, the information is fed back into the program to inform future decisions, *e.g.* dents in sections where cracking have been found are grouped separately in the methodology.

8.3 API 1156 – Field Guide for Assessing Dents and Buckles

In the second phase of API 1156, Kiefner and Alexander[34] developed an approach for determining the severity of dents and provided a methodology for determining whether a dent requires repair or can safely remain in the pipeline.

The model is based on a risk-ranking methodology that takes into account the material properties and operational characteristics of the pipeline, the location of the dent around the pipe circumference, whether it is associated with metal loss or stress raisers and the depth of the dent.

The basic equation is given as:

$$\mathbf{P} = (\mathbf{P_m} + \mathbf{P_i})\frac{\mathbf{d}}{\mathbf{D}} = (\mathbf{A} + \mathbf{B} + \mathbf{C} + \mathbf{W} + \mathbf{M} + \mathbf{R})\frac{\mathbf{d}}{\mathbf{D}} \qquad \textit{Equation 23}$$

Where $\mathbf{P_m}$ is the material ranking parameter and $\mathbf{P_i}$ is the inspection information ranking parameter. The more information that is available, the more parameters can be included in the ranking as detailed in the following sections.

8.3.1 Pipe Properties and Operational Characteristics (P_m)

In Equation 23, **A** is the geometry relative risk factor, which is related to the D/t ratio for the pipe. As mentioned in Section 5.3.3, pipe with larger D/t ratio is more susceptible to denting than small D/t pipe and therefore scores more highly in this factor. The factor **B** denotes the relative risk for brittle fracture propagation after denting. The best information on this factor comes from fracture toughness testing, however, it is recognised that this information is rarely available and therefore a scoring system is presented based on the age and type of pipe. The pressure cycling regime of the pipe is included in factor **C**, the relative operational risk. This factor is based on the pressure cycling range, the number of pressure cycles per year and the operating stress of the pipeline.

8.3.2 In-Line Inspection Information (P_i)

The parameter $\mathbf{P_i}$ expresses the likelihood of failure based on in-line inspection information and, for dents, is characterised by three parameters. **W** takes into account the presence of welds in the dent and also ranks the severity based on the type of weld *i.e.* whether the dent is located on an ERW weld. The parameter **M** in Equation 23 accounts for the presence of corrosion-caused metal loss within the dent. The problem with this parameter is that an in-line inspection tool is unable to distinguish between metal loss caused by mechanical damage and metal loss resulting from corrosion. The final parameter **R** characterises the location of the dent. A dent located on the top of the pipe, and therefore more likely to have resulted from mechanical damage, is weighted more heavily in this parameter than a dent on the bottom of the pipe. Depending on the type and resolution of the inspection tool that has been run, some of the information required for these parameters may not be available, in which case they are omitted from Equation 23.

8.3.3 Strategy Evaluation

This field guide is attractive in that it is easy to use and the data that is required is, in general, readily available from ILI tools or can be easily measured in the field. However, in essence, the ranking parameters are simply applying code guidance and, apart from the multiplier of the dent depth, are not taking into account dent shape to determine severity. It is therefore considered that this method does not allow plain dents to be ranked in terms of relative risk, other than on depth and location.

8.4 Duke Energy Gas Transmission (DEGT) Dent Strategy

DEGT have developed a dent management strategy using dent depth and dent strain as the governing criteria[61]. The process has been developed for a natural gas pipeline for which it was known from an analysis of the pressure cycling data that fatigue was not a concern.

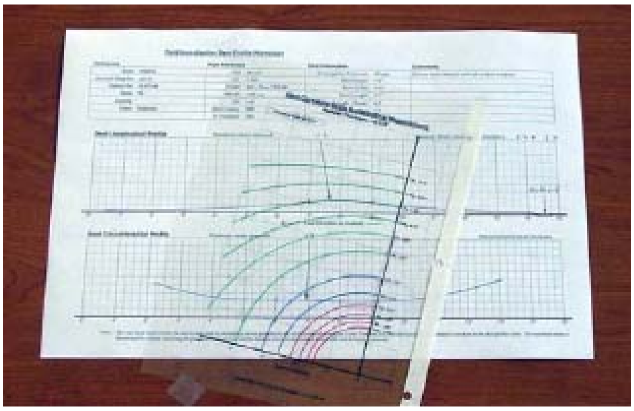


Figure 17 – Matching of strain curves to dent profile measured using a profile gauge[61]

The first stage of the plan is an analysis of HR-MFL data to identify dents with metal loss, dents on welds, dents with particularly significant signal response, particularly if they are located on the top of the pipe and dents that contain multiple sharp peaks. These dents are then prioritised based on the risk that they pose to the pipeline. If there are a significant number of high risk dents then DEGT will run a high resolution caliper inspection tool to measure the dent geometry and calculate dent strain. DEGT have adapted this approach to be used in the field by producing a series of radius of curvature plots at given strain levels for each wall thickness. When a profile measurement of the dent is taken in the field the radius plots can be matched to the profile and the strain read directly from the charts (Figure 17).

In the strain analysis, using either ILI or field measurements, only the longitudinal bending strain is calculated (Equation 1) and compared to the 6% criterion. Therefore no account is taken of the circumferential strain or the bending strains. In theory this will yield an unconservative strain result[9] and could lead to critical dents remaining in the pipeline if the 6% strain criterion is adopted. However, based on their analysis, Dawson *et al*[17] have proposed that the total strain in the dent could be approximated to the longitudinal bending strain for the purpose of ranking dents for excavation.

DEGT have also developed a series of flow charts which they use to develop strategies for their response to dents reported in ILI and in the field[61]. In this approach, strain assessments are only conducted on dents with depths greater than the code depth criteria (2%OD for dents on welds and 6%OD for plain dents). However, it has been shown that dents that are below the 6%OD depth criteria can have strains greater than 6%[54]. Baker[9], who adopts a similar approach in the dent evaluation process recommended in the OPS Dent Study, recognises that the strain criteria could be exceeded for shallow dents and therefore suggests that a strain criteria should be considered for all pipeline dents.

The DEGT approach is attractive in that the templates enable strain measurements to effectively be taken in the field. However, the limitations described above, in terms of the neglect of other strain components in the assessment and the restriction of the strain assessment to dents with depth>6%OD, should be addressed to determine whether critical dents are being missed in the analysis.

8.5 GE Energy Dent Strategy

The dent management strategy developed by GE applies a dent strain criterion to pipelines that are not heavily pressure cycled and a fatigue risk assessment for pipelines that are heavily pressure cycled[17].

The dent strain assessment is similar to that applied by DEGT and uses ILI profile results to determine the strain in the dent using the equations in ASME B31.8, but recognising the missing factor of 2. As mentioned previously, the resolution of the ILI caliper data is higher in the longitudinal direction than in the circumferential direction. However, for the dents analysed, GE found that the longitudinal and circumferential profiles were similar when plotted on the same co-ordinate system (*i.e.* the dents were essentially symmetrical) and therefore they used the profile with the best resolution (the longitudinal profile) to represent the data. In turn, this approach yields similar results for longitudinal, circumferential and total strain and therefore, essentially only the longitudinal bending strain is used to rank the severity of dents on the pipeline.

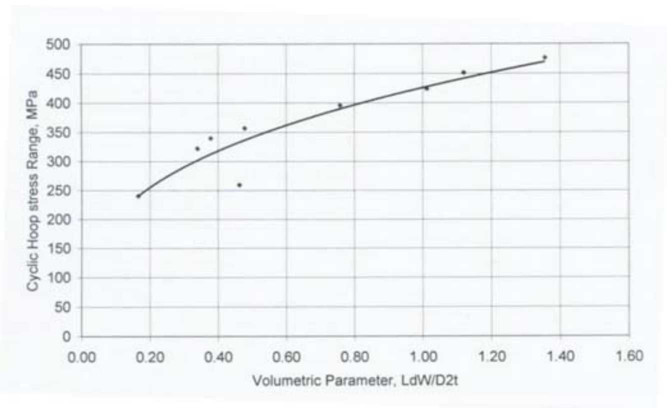


Figure 18 – Correlation between volume parameter and cyclic hoop stress range from FEA[17]

For pipelines that are heavily pressure cycled the methodology uses an S-N approach with FEA to determine the appropriate SCF to be applied to the DIN 2413 S-N curves[24]. The fatigue lives can then be calculated for each dent on the pipeline. As mentioned previously, however, performing FEA on every dent on a pipeline may not be practical and GE have found a positive correlation between the dent volume parameter proposed by Rinehart and Keating[50] in Equation 18 and the hoop stress range and hence fatigue life (Figure 18). This finding could be used to predict fatigue lives for dents without extensive FEA analysis, although further work is required to confirm that the relationship holds across pipe geometries and properties.

The methodologies for strain and fatigue assessment employed by GE are using the latest research in terms of both static and dynamic dent assessment. The relationship between the dent volume parameter and the cyclic hoop stress has been recognised in the literature (Section 5.3.2) although has not been applied to a dent assessment strategy. The use of this relationship could be investigated further by adopting the SCF equation proposed by de Carvalho[18] (Equation 17) and alternative S-N curves (Section 5.1.5).

8.6 Trans Alaska Pipeline System - Rosenfeld *et al*

Alyeska inspected the Trans Alaska Pipeline System (TAPS) using a UT metal loss inspection and a high resolution caliper inspection tool. In these inspections, 77 locations of 'minor' mechanical damage were detected (plain dents and dents with metal loss). Alyeska investigated 42 sites that were considered to be the most severe sites and found evidence of denting, superficial gouging and/or cracking. Based on the results of these inspections, Alyeska wanted to determine whether the remaining 35 features required investigation. Consequently, Rosenfeld *et al*[57] developed a mechanistic fatigue model for the assessment of these minor mechanical damage features. The method is similar to the fracture mechanics fatigue crack growth methodology described in Section 5.2. A stress concentration factor was calculated for each dent and then the fatigue life of the dent was calculated for a number of assumed crack depths using a fracture mechanics approach. On this basis, it was concluded that the 33 of the 35 features were extremely minor with calculated fatigue lives much greater than the expected pipeline life.

It was mentioned in Section 5.2 that one of the weaknesses of the fracture mechanics approach was the assumption that had to be made on initial crack size. However, in this work, Rosenfeld *et al* were able to use the data from the previous 436 investigations that had been carried out on the TAPS to estimate realistic initial crack sizes. One caution that the authors make is that, although the model has proved effective on the TAPS, the model cannot be directly applied to other pipelines as many of the parameters used (such as material properties, field data, pressure cycling information *etc.*) are specific to TAPS.

8.7 Summary

The requirements of a robust dent management strategy for plain, rock or construction dents are that it should:

- be easy to use with measurements that can be readily made in the field,
- not require intensive and expensive FEA to be conducted on every dent,
- recognise the key parameters that contribute to stress and strain concentration in the dent,
- relate to the pressure cycling regime of the pipe.

In the dent strategies reviewed here, that are being used by operators and integrity consultants, the more robust methods will consider all of these parameters. In this respect, the approaches adopted by DEGT and GE Energy appear to warrant further research and investigation to establish the limitations and validity of the methods over a range of pipeline and dent geometries, material properties and operating conditions.

Although the approaches outlined for dent fatigue assessment in API 1156 (Section 5.1.2) and PRCI (Section 5.1.4) have not been adopted by an operator in the published literature, these are both approaches which could fulfil the dent management criteria and should be investigated to determine whether they could be applied to a case study pipeline. In particular, one of the benefits of the API 1156 approach over the GE Energy approach is that it does explicitly consider constrained rock dents.

9 CURRENT DENT RESEARCH AND RECOMMENDATIONS FOR FURTHER WORK

This review has indicated that there is a significant, historical body of research in the area of plain dent integrity and the response to fatigue. More recently, the pipeline research organisations have specifically investigated the current acceptance standards for plain dents and, in particular, the assessment of rock dents[1,9,34,55]. Most significantly, this has led to the recent change to the assessment of dents in terms of strain criteria rather than depth criteria. However, current research into dent strain and fatigue of plain dents is not being conducted by pipeline research organisations, but by universities, integrity organisations and operators. This is evidenced by a review of the relevant papers presented at the recent International Pipeline Conference (IPC, 2006)[14,17,18,38,42,46,57,61].

The research organisations (PRCI, EPRG and PHMSA) are primarily concentrating on the assessment of mechanical damage rather than purely plain dents or dent fatigue. A review of the current research portfolios of these organisations in this area is presented in the following sections:

9.1 Current PRCI Research on Mechanical Damage

PRCI have prioritised the current needs in mechanical damage research into three main areas; damage detection sizing and characterisation, severity assessment and repair and damage management strategies[10].

- ***Detection Sizing and Characterisation:***
  It is recognised that, although existing ILI technology will detect mechanical damage, the reliability of the tools for accurate discrimination is an area that requires addressing. Therefore, initial work has concentrated on detection characterisation through project PRCI-MD-1, which includes; the development of a new inspection tool to discriminate between critical and benign mechanical damage using a combination of MFL and Non-Linear Harmonics (NLH)[**]; a review of the performance characteristics of current ILI tools; and the generation of an understanding of the MFL signals associated with mechanical damage.

- ***Severity Assessment:***
  Although there have been many full-scale tests to investigate the effects of dents and gouges, many of these tend to over simplify the actual conditions on the pipeline and therefore research is now being directed at trying to establish a fundamental understanding of the failure of mechanical damage. In this area (PRCI-MD-4), projects are concentrating on developing and validating mechanics-based models for mechanical damage.

- ***Repair and Damage Management Strategies:***
  Mechanical damage repair and management strategies are being investigated through projects PRCI MD-2 and MD-5. Initial studies are gathering an inventory of types of mechanical damage experienced by oil and gas operators as a basis for the development of predictive severity models and risk ranking and screening models. In terms of repair, research is concentrating on in-field inspection procedures for mechanical damage including the definition of safe pressure reductions and grinding limits.

PRCI have committed to spending $3M per year over the next five years on this mechanical damage program and see it as one of their key research areas.

9.2 Current EPRG Research on Mechanical Damage

The EPRG has always been active in research into the effects of mechanical damage on pipelines and the most recent research was published in 2000[51]. As well as generating an extensive test database, this research has also summarised methods for the assessment and prevention of external damage. However, there is no indication of planned future work in this area in the public domain.

[**] NLH is a technique for measuring the changes in magnetic properties of a material under the influence of imposed external stresses and strains.

9.3 Current PHSMA Research on Mechanical Damage

The research and development of the Pipeline and Hazardous Materials Safety Administration (PHMSA) mainly concentrates on near-term projects to increase the safety of the US pipeline system. In this respect they are conducting specific projects related to the detection of mechanical damage and damage prevention. Current and recent research includes:

- ***Nonlinear Harmonic-Based Mechanical Damage Severity Criteria for Delayed Failures in Pipelines***

  The objective of this research is to develop criteria to assess the severity of gouged dents based on fatigue life predictions but also using NLH sensors to detect surface strains left in the pipeline after gouging. This work is being co-funded by PRCI (see Section 9.1) and the inspection tool development is being conducted by Tuboscope.

- ***Effectiveness for Prevention Methods for Excavation Damage***

  The aim of this project, which was completed at the end of 2006, was to develop a fault-tree model to estimate the frequency of third party strikes on a pipeline based on pipeline condition and prevention practices. Using this model, the most effective prevention methods can be selected for particular pipelines.

- ***Mechanical Damage at Welds***

  This project has been conducted by Fleet Technology and is investigating the current requirements in the pipeline design standards for the repair of dents on welds in gas pipelines. The premise is that if the current code requirements can be relaxed then this will release maintenance budget for pipeline operators to address more significant integrity issues.

9.4 Further Research Requirements

Although the current research being conducted by the pipeline research institutes is concentrating on mechanical damage, this review has highlighted that there are still some key issues that need to be resolved in the implementation of dent management strategies for plain, rock and construction dents.

9.4.1 Strain Based Assessment

From a fundamental point of view, further research is required to effectively apply strain based criteria to dent assessment. This review has highlighted that, although there is a methodology for calculating strains in dents in ASME B31.8, there appears to be little confidence in this method in the recent literature[42,46] and no standard method for calculating radius of curvature. For example, in the literature reviewed, three different methods were utilised for calculating radius of curvature. Therefore, the development of a standard best practice methodology for calculating radius of curvature that is easy to use and apply to inspection data is recommended.

As the strain results calculated are critically dependent on the radius of curvature, small changes in the radius can have a large effect on the strain. The radius is dependent on the dent geometry measurements, which, in turn, are dependent on the accuracy and analysis of the caliper tool. Therefore, further research into the analysis, filtering and required resolution of caliper data to minimise the error in strain calculation would be beneficial.

Finally, the current strain level of 6% appears be arbitrary and it is considered that the industry would benefit from further work to understand whether this limit is realistic or whether it should be increased or decreased.

9.4.2 Fatigue Assessment

One of the issues regarding the fatigue assessment of dents using the S-N approach is that, in order to ensure that the methodology is not too conservative, detailed FEA is required on individual dents to determine the appropriate stress concentration factors. This is time consuming, expensive and unrealistic for pipelines that may have hundreds of dents. The approach adopted in API 1156[1] to produce look-up tables for SCFs based on FEA is promising, but limited by the number of simulations that were run in this project. However, further work to develop algorithms that could be developed for SCFs based either on FEA or the dent parameters of Rinehart and Keating[50] or de Caravalho[18] could yield a useful methodology for ranking dents based on their fatigue life predictions.

The literature review has also indicated that there is no standard recommendation regarding the most appropriate S-N curves to use for dent fatigue assessment. Investigation into this problem would require a detailed review of the dent fatigue data using an FEA based SCF approach and then comparing the test data fatigue life against the different S-N curves available in design codes to define the most appropriate curves.

Finally, there is the opportunity for developing a fracture mechanics dent fatigue model (*e.g.* Section 5.2) that could be used for critical dents. However, as has been indicated previously, these approaches rely critically on the assumption made on initial crack size.

10 RECOMMENDATIONS TO UKOPA

One of the specific remits of this report was to advise UKOPA on the benefits of conducting specific additional work to develop a dent management strategy. As a result of this review two recommendations for further work that could be conducted collaboratively by member companies of UKOPA are proposed.

10.1 Benchmarking Study

A number of dent strategies were reviewed in Section 8 and although the methodology for some of these strategies was not complete enough to allow a comparison, it is considered that the DEGT, GE Energy method, API 1156 field guide, PRCI model and the Enbridge initial rapid characterisation approach could be applied to dent data on the basis of the published information.

A benchmarking study is therefore proposed that could be conducted relatively easily and would allow UKOPA members to compare their individual company current dent dig and repair criteria against the published dent assessment strategies. In addition, this study could also benchmark the different dent assessment strategies currently being employed by UKOPA members and develop a best practice approach to dent assessment on the basis of the current literature.

It is a proposed that a series of case study pipelines would be assessed on the basis of the different strategies and a ranking list of critical dents developed. This list would be compared against the operators own dig and repair criteria and the results of field excavations to determine whether these dent assessment strategies would be more or less cost effective to employ than current procedure. The case study pipelines should be selected such that enough field data and caliper data is available to allow the critical dimensions to be determined and for which pressure cycling data has been measured.

10.2 SCF Algorithm Development

As mentioned in Section 9.4.2, there is an opportunity to develop algorithms for prediction of dent severity and fatigue lives based on key dent and pipeline parameters that are known to affect the strain and fatigue lives of dents. The work of Dawson *et al*[17] and Alexander and Kiefner[1] indicates that this approach is viable, but requires more FEA modelling to develop a methodology that could be applied to a range of pipelines.

In this work, it is proposed that neural networks are used to develop the algorithms. The networks will be trained to recognise patterns between the key input parameters and the calculated SCF from FEA. Based on this training, an algorithm will be produced which will be able to calculate the SCF for a dent without the requirement for further FEA. The algorithm will be designed such that the input values are parameters that can quickly and easily be determined from inspection and pipeline data. As the SCF is an indicator of fatigue life, then this parameter could be used to rank dents in terms of their severity.

In this project, UKOPA members would provide the inspection and field data to train the neural network and also audit the severity ranking against their own assessments and in-field findings. The benefit of such an approach is that, although FEA will be used to train the network, it will not be required to assess the individual dents on a pipeline.

10.3 Conclusion

If there is interest in pursuing either of these projects, either as individual companies or as a JIP, then please contact:

Dr Julia Race
School of Marine Science & Technology

Tel: 0191 222 6964
E-mail: j.m.race@ncl.ac.uk

11 REFERENCES

1. Alexander, C.R. and J.F. Kiefner, *Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines,* American Petroleum Institute, API 1156, November 1997

2. Alexander, C.R. *Review of Experimental and Analytical Investigations of Dented Pipelines*. in *American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP*. 1999.

3. American Society of Mechanical Engineers, *Boiler and Pressure Vessel Code,* Section VIII, Division 2, 1995

4. American Society of Mechanical Engineers, ASME B31.4, *Liquid Transportation System for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia and Alcohols*, 1992 Edition

5. American Society of Mechanical Engineers, ASME B31.8, *Gas Transmission and Distribution Piping Systems*, 2004 Edition

6. American Petroleum Institute (API) Recommended Practice 2A, *Planning, Designing and Constructing Fixed Offshore Platforms,* May 16, 2003

7. American Welding Society, D1.1-1996, *Structural Welding Code - Steel*

8. ASTM E 1049-85, *Standard Practices for Cycle Counting in Fatigue Analysis*, ASTM International, 2005

9. Baker, M., *Dent Study*, Final Report, TTO Number 10, Integrity Management Program, Delivery Order DTRS56-02-D-70036, DOT Research and Special Programs Administration, Office of Pipeline Safety, November 2004

10. Batte, D. *Technology Research – Issues and Opportunities*, Presentation to the PRCI Detection and Characterisation Panel, Mechanical Damage Technical Workshop, Houston, 28 Feb – 1 March 2006

11. Beller, M., C. Mattheck, and J. Zimmermann. *Stress Concentrations in Pipelines due to the Presence of Dents*. in *Proceedings of the First International Offshore and Polar Engineering Conference*. 1991. Edinburgh, Scotl: Publ by Int Soc of Offshore and Polar Engineers (ISOPE), Golden, CO, USA.

12. Beuker, T. and F. Rahe, *High-quality, Smart Pig Dent Inspection Complies with Rules for Gas, Liquid Lines.* Pipeline and Gas Journal, 2005. **232**(3): p. 40.

13. Browne, D. and R. Hicks, *UKOPA Pipeline Fault Database - Pipeline Product Loss Incidents (1962-2004),* UKOPA Fault Database Management Group, 2005.

14. Clapham, L., V. Babbar, and A. Rubinshteyn. *Understanding Magnetic Flux Leakage Signals from Dents*. in *6th International Pipeline Conference*. 2006. Calgary, Alberta, Canada: ASME.

15. Cosham, A. and P. Hopkins, *The Effect of Dents in Pipelines - Guidance in the Pipeline Defect Assessment Manual.* International Journal of Pressure Vessels and Piping, 2004. **81**(2): p. 127.

16. Davis, P. M., J. Dubois, A. Olcese, F. Uhlig, J-F. Larivé, D.E. Martin, *Performance of European Cross-Country Oil Pipelines: Statistical summary of reported spillages - 2004*, CONCAWE, 2006.

17. Dawson, S.J., A. Russell and A. Patterson, *Emerging Techniques for Enhanced Assessment and Analysis of Dents* in Proceedings of the International Pipeline Conference, IPC 2006

18. De Carvalho, B., I.P. Pasqualino and S. Barros da Cunha, *Stress Concentration Factors of Dented Pipelines* in *Proceedings of the International Pipeline Conference*, IPC 2006

19. Dieter, G.E., *Mechanical Metallurgy,* 2nd edition, pub. McGraw and Hill, 1984

20. Dinovitzer, A., et al. *A Dent Assessment Model*. in *Offshore Mechanics and Arctic Engineering*. 1999. St. Johns, Newfoundland: ASME.

21. Dinovitzer, A., et al. *A Pipeline Dent Assessment Model Considering Localised Effects* in *Proceedings of the 3rd International Pipeline Conference*. 2000. Calgary, Alberta: ASME.

22. Dinovitzer, A., et al. *Geometric Dent Characterization* in *Proceedings of the International Pipeline Conference*, IPC 2002

23. Dinovitzer, A., *Dent Integrity Assessment* in *Proceedings of the API 54th Annual Pipeline Conference*, April 2003

24. DIN 2413 Part 1, 'Design of Steel Pressure Pipes', Deutshe Norm, October 1993

25. EGIG *Gas Pipeline Incidents: 6th Report of the European Gas Incident Data Group*, 2005.

26. Fowler, J.R., A.T. Katsounas, R. Boubendier, *Criteria for Dent Acceptability of Offshore Pipelines,* PRCI Report PR-201-927, Pipeline Research Council International Catalog No. L51671, July 1992

27. Fowler, J.R. *Criteria for Dent Acceptability in Offshore Pipeline* in *Proceedings of the Annual Offshore Technology Conference*. 1993.

28. Fowler, J.R., C.R. Alexander, P.J. Kovach, L.M. Connellly, *Cyclic Pressure Fatigue Life of Pipelines with Plain Dents, Dents with Gouges and Dents with Welds,* PRCI Report PR-201-927/201-9324, Pipeline Research Council International Catalog No. L51705e, June 1994

29. Hart, J.D., et al. *Fatigue damage calculations for a dented and ovalled section of the TransAlaska Pipeline System at Thompson Pass*. 1998. Calgary, Can: ASME, Fairfield, NJ, USA.

30. Hopkins, P., D.G. Jones, and A.C. Clyne. *The Significance of Dents and Defects in Transmission Pipelines*. in *International Conference on Pipework, Engineering and Operation*. 1989. London: Institure of Mechanical Engineers.

31. Ironside, S.D. and L.B. Carroll, *Pipeline Dent Management Program* in Proceedings of the International Pipeline Conference, IPC 2002

32. Johnston, D.C. and T.G. Hrncir. *Using In-line Inspection to Address Deformations Containing Near-neutral pH Stress Corrosion Cracking*. 2002. Calgary, Alta., Canada: American Society of Mechanical Engineers.

33. Keating, P.B & R.L. Hoffmann, *Fatigue Behaviour of Dented Petroleum Pipelines*, A Report of the Texas Transportation Institute for the Office of Pipeline Safety, U.S. Department of Transportation, Contract No. DTRS 56-95-C-0003, May 1997

34. Kiefner, J.F. & C.R. Alexander, *Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines (Phase II),* American Petroleum Institute, Addendum to API 1156, October 1999

35. Kiefner, J.F. *'Dealing with Low Frequency Welded ERW Pipe and Flash Welded Pipe with Respect to HCA Related Integrity Assessments'*, Proceedings of Engineering Technology Conference on Energy, Houston, Texas, February 2002

36. Kiefner, J.F., C. Kolovich, and K. Kolovich. *Pipeline Incidents Caused by Mechanical Damage*. Presentation to the PRCI Detection and Characterisation Panel, Mechanical Damage Technical Workshop, Houston, 28 Feb – 1 March 2006

37. Lancaster, E.R. and S.C. Palmer, *Strain Concentrations in Pressurized Dented Pipes.* Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 1996. **210**(1): p. 29.

38. Le Bastard, A. *Influence of Internal Pressure for Depth Measurement on a Dent* in *Proceedings of the Biennial International Pipeline Conference, IPC* 2006. Calgary, Alta.

39. Leis, B.N., T.P. Forte, and X. Zhu. *Integrity analysis for dents in pipelines*. in *Proceedings of the Biennial International Pipeline Conference, IPC*. 2004. Calgary, Alta.

40. Leis, B.N., et al. *Recent Developments in Avoiding, Detecting and Assessing Severity of Mechanical Damage*. in ETCE/OMAE2000 Joint Conference, Energy for the New Millenium. 2000. New Orleans, LA.

41. Lyons, D. *Western European Cross Country Oil Pipelines 30 Year Performance Statistics,* CONCAWE, Report No. 01/02, 2002.

42. Lukasiewicz, S.A., J.A. Czyz, C. Sun, and S. Adeeb, *Calculation of Strains in Dents Based on High Resolution In-Line Caliper Survey*, IPC2006 Paper 10101, Presented at 6th International Pipeline Conference, Calgary, 2006

43. Maddox, S.J., *Fatigue Strength of Welded Joints*, 2nd edition, 1991, Published by Abingdon

44. McCoy, J. and S. Ironside, *Dent Management Program* in *Proceedings of the Biennial International Pipeline Conference*, IPC 2004

45. National Transport Safety Board Report PAB-01/02, Pipeline Accident Brief DCA-00-MP-004 Regarding Pipeline Failure and Leak of the Marathon Ashland Pipe Line LLC Crude Oil Pipeline at Winchester, Kentucky, November 2004

46. Noronha, D.B., R.R. Martins, B.P. Jacob and E. Souza, '*The Use of B-Splines in the Assessment of Strain Levels Associated with Plain Dents*', Paper No.IBP1245-05, Rio Pipeline 2005 Conference and Exposition

47. Ong, L.S., A.K. Soh, and J.H. Ong, *Experimental and Finite Element Investigation of a Local Dent on a Pressurized Pipe.* Journal of Strain Analysis for Engineering Design, 1992. **27**(3): p. 177.

48. PHMSA Pipeline Safety Program *Pipeline Safety Incident Reports,* Pipeline and Hazard Materials Safety Administration, 2007, Available from http://www.phmsa.dot.gov/

49. Rinehart, A.J. and P.B. Keating. *Predicting the Fatigue Life of Long Dents in Petroleum Pipelines* in Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - *OMAE*. 2002.

50. Rinehart, A.J. and P.B. Keating. *Length Effects on Fatigue Behaviour of Longitudinal Pipeline Dents* in Proceedings of the International Pipeline Conference, IPC. 2002.

51. Roovers, P., R. Bood, M. Galli, U. Maerewski, M. Steiner, M. and M. Zarea, *EPRG Methods for Assessing the Tolerance and Resistance of Pipelines to External Damag*e, Pipeline Technology, Volume **II**, Brugge 29/09/00

52. Rosenfeld, M.J. *Development of a Model for Fatigue Rating Shallow Unrestrained Dents,* PRCI Report PR-218-9405, Pipeline Research Council International Catalog No. L51741, 19th September 1997

53. Rosenfeld, M.J. *Investigations of Dent Rerounding Behaviour*. in *Proceedings of the International Pipeline Conference, IPC*. 1998. Calgary, Can: ASME.

54. Rosenfeld, M.J., P.C. Porter, and J.A. Cox. *Strain Estimation using Vetco Deformation Tool Data*. in *Proceedings of the International Pipeline Conference, IPC*. 1998. Calgary, Can: ASME.

55. Rosenfeld, M.J., *Proposed New Guidelines for ASME B31.8 on Assessment of Dents and Mechanical Damage*. 2001, Topical Report GRI-01/0084, Gas Technology Institute.

56. Rosenfeld, M.J., J.W. Pepper, and K. Leewis, *Basis of the New Criteria in ASME B31.8 for Prioritization and Repair of Mechanical Damage* in Proceedings of the International Pipeline Conference, IPC 2002, Calgary, Alberta

57. Rosenfeld, M.J., et al. *Deterministic Assessment of Minor Mechanical Damage on Pipelines*. in *6th International Pipeline Conference*. 2006. Calgary, Alberta, Canada: ASME.

58. Stevick, G.R., J.D. Hart, and B. Flanders. *Fatigue Curves for Damage Calculations for a Dented and Ovalled Section of the TransAlaska Pipeline System*. 1998. Calgary, Can: ASME, Fairfield, NJ, USA.

59. Timoshenko, S. & S. Woinowsky-Krieger, *'Theory of Plates and Shells'*, Second Edition, 1970, Published by McGraw Hill

60. UK Department of Energy (DOE), *'Offshore Installation: Guidance on Design and Construction'*, April 1984

61. Warman, D.J., D. Johnston, J.D. Mackenzie, S. Rapp, B. Travers , *Management of Pipeline Dents and Mechanical Damage in Gas Pipelines* in Proceedings of the International Pipeline Conference, IPC 2006

62. Z662:1999, *Oil and Gas Pipeline Systems*, Canadian Standards Association

63. 49CFR192, 'Pipeline Safety: *Pipeline Integrity Management in High Consequence Areas (Gas Transmission Pipeline)'*; Final Rule, Department of Transportation, 15 December 2003

64. 49CFR195 Pipeline Safety: *Pipeline Integrity Management in High Consequence Areas (Hazardous Liquid Operators With 500 or More Miles of Pipeline)*; Final Rule, Department of Transportation, 1 December 2000