UKOPA

PENSPEN™

Development of Guidance for the Prioritisation of Dents

Literature Review for Dents Associated with Welds

Document Number:
13131-RPT-001 Rev 0

Penspen Integrity
Units 7 & 8 Terrace Level
St. Peter's Wharf
Newcastle upon Tyne
NE6 1TZ
Tel: +44 (0)191 238 2200
Fax: +44 (0)191 275 9786
www.penspenintegrity.com

REVISION AND AUTHORISATION RECORD

File location: C:\Users\aaron\Documents\Projects\UKOPA\13131 Dent guidance\Work\1 Lit review\13131-RPT-001 Rev0.docx

Rev	Date	Description	By	Checked	PM	Auth
0	03/04/14	Issued for client comments	AL	RPJ	AL	PH

Contents

1. EXECUTIVE SUMMARY

1.1 Background

UKOPA members have identified that modern in-line inspections report large numbers of shallow dents. The existing UKOPA dent management strategy sometimes categorises these dents as requiring repair, particularly when the dent affects a weld and weld toughness data is not available, or pressure cycling is significant. This can lead to an onerous repair schedule.

The use of high resolution geometry tools means that even shallow dents with depths less than 2% of the pipe diameter can now be measured with reasonable accuracy. The methods available to analyse dents, and particularly dents on welds, have not kept pace with the developments in inspection technology. There is research work underway that should enable the industry to better understand the behaviour of dent damage in pipelines.

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

1.2 Objectives

The objective of the present literature review is to review recent international work covering dents on welds, including analytical studies, testing, and failures to identify any developments for the assessment of smooth dents affecting welds, and in particular welds of unknown quality.

1.3 Key Conclusions

1. *Existing guidance is conservative*

   The current assessment methods are provided by pipeline design codes and pipeline specific guidance such as the ERPG fatigue life estimation method. Generally these methods either do not allow dents on welds, or predict that they will fail quickly under significant fatigue loading. However, there are a large number of shallow dents on welds that have been in service under high fatigue loading for many years. There are no known instances of failures of shallow dents on welds, although there have been cases of shallow dents failing due to fatigue loading after removal of the rock that caused the dent. The current assessment methods must therefore be conservative for shallow dents on welds in most cases.

2. *Existing best practice is given in PDAM*

   Generally the pipeline design codes do not allow dents on welds, although some allow dents on good quality welds with depth up to 2% of the pipeline diameter. The codes generally allow detailed engineering analysis. The generic assessment codes such as API 579 and BS 7910 do not generally allow dents on welds. The pipeline specific guidance in PDAM allows assessment of dents on welds if weld quality, particularly toughness and ductility, is sufficient. The best practice method recommended by PDAM is the EPRG dent fatigue life estimation method.

3. *There is no assessment method for dents on welds of poor quality*

   The primary reason for the conservatism in existing guidance is the unknown quality of dented welds. It is critical to determine whether a dented weld may have cracked before any detailed analysis is carried out. If there is a chance of cracking, a dent on a weld should be repaired. If the weld has not been inspected for cracking, the strain applied to the weld should be estimated. A maximum strain limit should be applied. The strain limit should be selected based on the weld quality.

4. *Three weld quality levels are proposed*

   Three weld quality levels with associated strain limits are proposed (described in detail in Section 6.3): ‘known good quality,’ 4% strain limit; ‘probable good quality,’ 2% strain limit; and ‘poor quality,’ no strain limit and no denting allowed.

5. *Future assessment methods are likely to be based on stress analysis*

   It is becoming common practice to use finite element analysis in the assessment of stress concentration and fatigue life of dents. Methods based on finite element analysis can give more accurate estimates of fatigue life than the existing best practice methods such as the EPRG method, primarily because they take full account of the dent shape. Finite element models have not yet been thoroughly validated against full scale tests.

2. INTRODUCTION

2.1 Background

UKOPA members have identified that modern in-line inspections report large numbers of shallow dents. The existing UKOPA dent management strategy [1] sometimes categorises these dents as requiring repair, particularly when the dent affects a weld and weld toughness data is not available, or pressure cycling is significant. This can lead to an onerous repair schedule.

A failure of dent and gouge damage in a pipeline at Bellingham in North America in 1999 resulted in the death of 3 people [2]. Following this failure, increasing emphasis was placed by regulators and the industry generally on the detection, sizing and analysis of mechanical damage in pipelines, and particularly pipelines transporting liquids. Other failures of dents in pipelines since that time have provided added impetus. These failures have been of dents introduced in service (typically third party damage), and of dents introduced at construction (typically rock dents failing after removal of the rock).

Magnetic flux leakage tools and ultrasonic inspection tools can identify the presence of dents, but do not give accurate measurements of dent dimensions. High resolution geometry tools have been developed which can give good data on the dimensions of a dent. The increasing focus on reporting dents from MFL/UT inspections has resulted in pipeline operators being aware of the presence of numerous dents for the first time, even though the dents may have been present for many years. The use of high resolution geometry tools means that with depths less than 2% of the pipe diameter can now be measured with reasonable accuracy. In the current report, ‘shallow dent’ refers to dents with depths less than 2% of the pipe diameter.

The methods available to analyse dents, and particularly dents on welds, have not kept pace with the developments in inspection technology. There is research work underway that should enable the industry to better understand the behaviour of dent damage in pipelines [3,4,5].

The majority of the delayed failures have been of pipelines transporting liquids. This is because pipelines transporting liquids can experience high pressure cycles which result in fatigue cracking at dents. Stresses are locally increased in dents and there may be cyclic through thickness bending as the dent flexes. Gas pipelines generally do not experience similar pressure cycles.

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

The project consists of four phases:

1. Literature review of relevant published work (covered in the present report);
2. Propose modifications to the existing UKOPA dent management strategy;
3. Use the proposed strategy to evaluate test cases of dents where the existing guidance recommends repair;
4. Implement updates to the UKOPA dent management strategy document.

2.2 Objectives

The objective of the present literature review is to review recent international work covering dents on welds, including analytical studies, testing, and failures to identify any developments for the assessment of smooth dents affecting welds, in particular welds of unknown quality.

Future project phases will propose updates to the UKOPA dent management strategy based on the present literature review, then test those updates by application to dents where the existing guidance recommends repair, and finally implement the changes to the strategy document.

3. EXISTING GUIDANCE

Existing guidance on the acceptability of dents is available in three principal forms: standards published by international bodies, generic assessment methods, and pipeline-specific assessment methods. The latter includes documents that are intended to define the 'best practice' in the pipeline industry.

Widely recognised publications that give guidance for dents on welds are reviewed in this section.

3.1 Pipeline Design Codes

Design codes are very general, as they have to cover a wide range of possible pipeline types and scenarios. They are likely to be very conservative for dents on welds in modern linepipe with good quality welds. These codes do not consider static strength and fatigue strength separately. None of the codes differentiate between or give different acceptability limits for 'restrained' or 'unrestrained' dents.

3.1.1 ASME B31.4 – USA Liquid

ASME B31.4 [6] (Section 451.6.2.4) requires all dents affecting the curvature of a seam weld or a girth weld to be removed or repaired.

Otherwise, a dent is considered acceptable if its depth is less than 6% of the pipe diameter, it does not interact with any other anomalies, and an inspection shows that no cracking is present.

Any dent or mitigating action may be accepted if an engineering evaluation according to API 1160 (see Section 3.2.2) shows that the risk is reduced to an acceptable level.

ASME B31.4 (Section 403.3.3) also defines a strain limit of 2% for single non-cyclic events such as fault movement, differential support settlement or subsidence. This limit may be applied to girth and seam welds, and requires the material to be ductile. It is intended to prevent cracking during such single events in the types of welds considered by the code. Though not stated, it would be reasonable to apply this limit to prevent cracking during the denting process.

ASME B31.4 may be applied to older liquid pipelines, with the possibility of high fatigue loading and poor quality welds. It therefore takes a conservative approach.

The requirements of ASME B31.4 are exactly replicated in the USA regulations for liquid pipelines [7].

3.1.2 ASME B31.8 – USA Gas

AMSE B31.8 [8] (Section 851.4.1) considers all dents with depth greater than 2% of the pipe diameter affecting ductile seam or girth welds to be 'injurious'[1], unless an engineering analysis determines otherwise and the maximum strain in the dent is less than 4%. Appendix R of the standard gives a method to calculate strain based on measurements of a

[1] All 'injurious' dents are required to be removed or repaired.

dent. The engineering analysis must consider weld quality, non-destructive examinations, and pipeline operation.

All dents affecting non-ductile seam or girth welds (specifically including acetylene girth welds or seam welds that are prone to brittle fracture) are considered 'injurious'.

Dents containing most other anomalies are considered 'injurious'.

Otherwise, a dent is considered 'injurious' if its depth is greater than 6% of the pipe diameter or the maximum strain in the dent is greater than 6%.

ASME B31.8 takes a less conservative approach to dents on welds compared with ASME B31.4, due to the lower fatigue loading that normally occurs in gas pipelines. The 2% depth limit for dents on welds is conservative compared to the depth limit of 6% in plain pipe, so the performance of the welds under denting and fatigue loading is assumed to be significantly worse than the performance of the plain pipe.

The requirements of ASME B31.8 are exactly replicated in the USA regulations for gas pipelines [9].

3.1.3 CSA Z662 – Canada Liquid and Gas

CSA Z662 [10] (Section 10.10.4.2) considers all dents with depth greater than 2% of the pipe diameter (or 6 mm for pipe diameters 323.8 mm or less) affecting mill or field welds to be defects.

Dents containing most other anomalies are considered defects.

It is stated that it is possible for dents to fail, despite being acceptable to the criteria, particularly if they are caused by very sharp rocks (i.e. they contain high strains), are subjected to large pressure fluctuations over a very long period of time, or are located on a seam weld in low frequency (less than 1 kHz) electric resistance welded (ERW) pipe. It is also stated that dents on the top of pipelines frequently contain gouging, and when reported by ILI, consideration should be given to excavating these features for visual examination.

Any dent considered to be a defect is required to be removed or repaired, unless an engineering analysis demonstrates it is acceptable.

The same depth limit as that specified in ASME B31.8 is applied to dents on welds, despite this standard being applicable to both liquid and gas pipelines. This is likely to be possible because high strains, high fatigue loading and very poor welds are specifically excluded, which is not the case in ASME B31.4 where no dents on welds are considered acceptable.

3.1.4 PD 8010-1 – UK Liquid and Gas

PD 8010-1 [11] (Paragraph 10.12.7) requires any dent found during construction that affects the curvature of a longitudinal or circumferential weld to be removed. No specific guidance is given on dents found during operation.

In line with UK regulations, operators are expected to determine and follow industry best practice. Guidance on best practice is provided by the Pipeline Defect Assessment Manual (PDAM, see Section 3.6.1) and UKOPA (see Section 3.6.2).

3.1.5 DNV-OS-F101 – Norway (Offshore) Liquid and Gas

DNV-OS-F101 [12] (Section 5 D 1300) gives an acceptance limit for dent depth of 3.5% of the pipe diameter for locations where denting is expected to be infrequent. Consideration of fatigue loading is required if the dent will remain in the pipeline for the long term. It is noted (Section 11 D 507) that dents on welds can cause cracks, and removal of the damaged pipe should be considered.

The standard is specifically for offshore pipelines where dents are generally caused during installation or by interaction with anchors or trawling equipment, and pipelines are generally more modern with greater wall thicknesses than onshore.

3.1.6 AS 2885.1 – Australia Liquid and Gas

AS 2885.1 [13] (Section 10.4.4) requires dents found during construction with depth greater than 2% of the pipe diameter (or 6 mm for pipe diameters 323.8 mm or less), or any dents that occur at a weld, to be repaired by replacing the pipeline section containing the dent.

No specific guidance is given for dents found during operation, which is outside the scope of this part of the standard. AS 2885.3 covers operation and maintenance (see Section 3.2.4).

3.1.7 IGEM/TD/1 – UK Gas

IGEM/TD/1 [14] (Section 7.17.3) briefly requires that any dent found during construction must be rectified by cutting out the damaged section of pipe. No guidance is given for dents found during operation, since this is outside the scope of the standard.

3.1.8 NEN 3650-2 – Netherlands Liquid and Gas

NEN 3650-2 [15] (Section 10.2) requires that the pipeline “fitness for purpose” should be maintained when damage occurs. It gives no further guidance, but refers to the revised European Pipeline Research Group (EPRG) assessment method (see Section 4.2.1).

3.2 Pipeline Integrity Management Standards

These standards give general guidance on pipeline integrity management. The guidance generally refers back to the dents allowed by appropriate design codes. Additional information is provided on timescales for action, inspection methods, repair methods, etc.

3.2.1 ASME B31.8S – USA Gas

ASME B31.8S [16] (Section 7.2.3) requires that dents with depth greater than 2% of the pipe diameter affecting ductile seam or girth welds should be examined ‘expeditiously’[2] within a year of determination of the condition.

Dents containing gouges require examination within 5 days of the determination of the condition. Other unacceptable dents as defined in ASME B31.8 (see Section 3.1.2) require examination ‘expeditiously’ within a year of determination of the condition.

[2] The term ‘expeditiously’ is not defined in the standard. It is presumed to mean ‘as soon as practicable’, such that it is not acceptable to delay action within the allowable time limit without good reason.

3.2.2 API 1160 – USA Liquid

API 1160 [17] (Section 9.6) requires dents affecting the curvature of a seam weld or girth weld to be evaluated, repaired or otherwise mitigated within six months of receipt of the final ILI report.

Dents containing metal loss located on the top of the pipeline are required to be reported by the ILI vendor and mitigated by the pipeline operator as soon as possible. Dents with depth greater than 6% of the pipeline diameter, dents containing metal loss located on the bottom of the pipeline, and dents located on the top of the pipeline with depth greater than 2% of the pipeline diameter (or 0.25 in for diameters less than NPS 12), are required to be evaluated, repaired or otherwise mitigated within six months of receipt of the final ILI report.

Reference is made to the applicable limits in ASME B31.4 (see Section 3.1.1).

It is recommended (Section A.2.1.4) that the dents on welds may be assessed for relative risk and repair priority using guidance given in PRCI Report PR-218-9822 “Guidelines for the Assessment of Dents on Welds”.

3.2.3 PD 8010-4 – UK Liquid and Gas

PD 8010-4 [18] (Section 9.3) requires that features identified during pipeline inspections should be assessed using recognised design codes or guidelines.

In line with UK regulations, operators are expected to determine and follow industry best practice. Guidance on best practice is provided by PDAM (see Section 3.6.1) and UKOPA (see Section 3.6.2).

3.2.4 AS 2885.3 – Australia Liquid and Gas

AS 2885.3 [19] (Section 9.4.2.4) requires that assessments should be carried out for all dents, taking account of the workmanship limits specified in AS 2885.1 (see Section 3.1.6). All dents on welds are unacceptable to AS 2885.1, thus detailed assessment is required for all dents on welds.

The recommended fitness for purpose assessment methods for dents are API 579 level 1, 2 or 3 (see Section 3.5.1), the workmanship limits in DNV-OS-F101 (see Section 3.1.5), or finite element analysis with fatigue analysis.

All unacceptable dents should be repaired, rerated or remediated.

3.2.5 T/PR/P/11 – UK Gas

T/PR/P/11 [20] (Sections 8.6 and 8.7) classifies all dents affecting a seam weld, girth weld or heat affected zone as ‘severe’ or ‘extreme’ forms of damage. Immediate pressure reduction is required. A timescale for investigation and repair is not given, but it would be expected that such repairs would be prioritised, due to their assigned severity. It is recommended that expert assistance should be sought to determine the reduction in fatigue life caused by a dent.

3.3 Pipe Manufacture Standards

These standards specify the requirements for individual pipe spools supplied by pipe mills. Their guidance is generally more conservative than pipeline design codes, so that good quality pipe can be used in a pipeline designed with any current code.

3.3.1 API 5L

API 5L [21] (Section 9.10.5.2) considers smooth dents with depth greater than 6.4 mm, or length or width exceeding 0.5 times the pipe diameter to be defects which must not be present in finished pipes. No account is taken of whether the dent is located on a weld.

3.4 Workmanship Standards

Workmanship standards provide guidance on minimum standards of welding, and are likely to give the best measurable limits to indicate good weld quality.

3.4.1 API 1104

API 1104 [22] gives detailed guidance on workmanship limits for seam and girth welds. Limits are given for the sizes of various weld defects and methods to measure them, including lack of penetration, porosity, inclusions, etc.

In particular, guidance is given on the allowable mechanical properties of completed welds (Section A.3.2). The key limits relevant to dent assessments are:

- The tensile strength of the weld should be over-matched compared to the strength of the pipe. Preferential straining of the weld should be avoided. In tensile tests including the weld, the specimen should fail in the pipe, not in the weld.

- The full-size Charpy toughness of the weld should exceed 30 J for each test and 40 J on average, for a defined set of test specimens. The shear area should exceed 50%.

Taken together, these requirements ensure that cracking is unlikely to develop in a dented weld when small plastic strains are applied during the introduction of shallow dents.

Historical versions of API 1104, which were current when many operational pipelines were constructed, had less stringent requirements. For example the 1966 version [23] only applied to girth welds, and did not require Charpy testing. It also permitted oxyacetylene welding, which is now considered an indicator of poor weld quality. It required that:

- Welds should be over-matched compared to the pipe material, which should be determined by tensile testing.

- A nick-break test should be performed. This consists of adding a small notch to the centre of a weld sample, breaking the weld by application of an impact, and inspecting the fracture surface. Complete penetration and fusion were required, and limits were placed on the number of gas pockets and slag inclusions visible in the fracture.

Thus whilst some older welds are now considered poor quality, many operational pipelines have welds that would now be considered good quality but for which there are no Charpy test results for comparison with current standards. Charpy test results are the best indicator of weld toughness, but it is not always necessary to consider welds without Charpy results to be poor quality, and other indicators are required to cover these circumstances.

3.4.2 BS 4515

BS 4515 [24] has a similar scope and intention to the current version of API 1104, and gives the same guidance as described in Section 3.4.1.

3.5 General Defect Assessment Standards

These standards are intended for assessment of defects in metallic structures in general, including pipelines. Their scope is large, so their guidance is generally conservative compared to pipeline-specific methods that are only applicable to pipeline materials and construction standards.

3.5.1 API 579

API 579 [25] (Section 12.4.3.1) gives three levels of assessment for dents in cylindrical shells, that are applicable to pipelines.

The Level 1 assessment criterion is essentially a dent depth limit of 7% of the pipeline diameter, measured at zero internal pressure. Dents on welds are not permitted. Significant cyclic pressure loading is not permitted.

The Level 2 assessment is the same as the Level 1 assessment, except that significant cyclic pressure loading is allowed, and a method is provided to calculate a safe fatigue life. The revised EPRG method (see Section 4.2.1) is used to estimate fatigue life, and a safety factor of 10 is applied. Dents on welds are not permitted, although the revised EPRG method is partly based on tests of dents on welds.

The Level 3 assessment allows stress analysis to be used to assess a dent (presumably including dents on welds, though this is not stated explicitly), where sufficient information is available about the ductility and toughness of the dented material. Calculation of the strain in the dent is required, but no limit is given. Methods based on SN curves or fracture mechanics are suggested to calculate fatigue life from the stress cycles predicted by stress analysis.

3.5.2 BS 7910

BS 7910 [26] (Sections C.2.1 and C.3) mentions that dents should be considered when assessing other flaws. Its focus is on assessment of crack-like defects, and dents in this context are seen as a stress concentration that will affect the stress applied to a crack. No guidance is given for the assessment of dents alone, except to refer to PDAM (see Section 3.6.1).

3.6 Pipeline Specific Dent Assessment Guidance

The best practice guidance that has been developed for assessing the acceptability of defects in pipelines is generally less conservative than codes and generic assessment methods. This guidance is only applicable to pipeline materials and construction standards, and requires detailed knowledge of the defect properties and the applied loading.

3.6.1 PDAM

The Pipeline Defect Assessment Manual (PDAM) [27] (Section 24) gives best practice guidance based on an extensive review of evidence published before 2005. It notes that:

- The burst and fatigue strength of a dented weld is difficult to predict and can be significantly lower than that of a plain dent of the same depth, due to the possibility of the weld being damaged (cracked) during the denting process.
- The fatigue strength of a dented weld will be lower than that of a plain dent of the same depth because of the reduced fatigue strength of the weld compared to the parent plate.

PDAM states that there are no published assessment methods for dents located on welds.

PDAM concludes that dents that are located on welds but are otherwise plain should be repaired if any of the following are true:

- The linepipe has low toughness (an upper shelf full size Charpy impact energy of less than 27 J), where indicators of low toughness linepipe include:
    - Old linepipe (manufactured before 1970);
    - Linepipe not manufactured to API5L or equivalent;
    - An operating temperature less than the drop weight tear test transition temperature.
- The dent is subjected to loads other than internal or external pressure;
- The dented weld cannot be inspected;
- The weld is under-matched (the tensile strength of the weld is less than the linepipe, or the yield strength of the weld is less than the linepipe);
- The weld is likely to contain cracks or defects;
- The weld is suspected of having a low toughness (a full size Charpy impact energy of less than 30 J minimum and 40 J on average from three specimens), where indicators of low toughness welds include:
    - Old linepipe (manufactured before 1970);
    - Linepipe not manufactured to API5L or equivalent;

- Welds not fabricated to a recognised pipeline welding standard or fabricated before the existence of such standards;
- Low frequency electric resistance welds, induction welds, flash welds or oxyacetylene welds;
- An operating temperature less than the drop weight tear test transition temperature.

If the above criteria are met, it is proposed that dents on welds should be repaired if any of the following are true:

- The dent depth exceeds 3.9% of the pipeline diameter when measured at zero pressure, or 2.7% measured when internal pressure is applied;
- The predicted dent fatigue life has been exceeded.

It is recommended that the EPRG method (see Section 4.2.1) can be used to estimate the fatigue life of a dent on a good quality weld. A model uncertainty factor of 13.3 should be applied to account for the scatter in the test data used to develop the method. A further safety factor of 10 should be applied to account for the reduced fatigue life of the weld compared to the parent plate. This often leads to the prediction of a negligible fatigue life, even for dents that have been present for many years, and is one of the reasons UKOPA is carrying out the current study.

3.6.2 UKOPA Dent Management Strategy

The existing UKOPA dent management strategy [1], which the present study will revise, gives a higher repair priority to dents located on welds. It recommends that the methods in PDAM should be used to estimate dent fatigue life.

For dents on welds, a repair is always required if the dent depth is greater than 2% of the pipe diameter, the strain is greater than 4%, or the weld toughness is less than 27J. This is more conservative than the PDAM depth limit of 3.9% at zero pressure or 2.7% when internal pressure is applied.

The model uncertainty factor of 13.3 should be used as recommended in PDAM. The fatigue life reduction factor of 10 for dents on welds recommended by PDAM is not mentioned explicitly, but should be used.

Different sets of investigation priorities are recommended depending on whether: only MFL / UT inspection data is available; or, geometry inspection data is also available. The differences between the sets of investigation priorities are not logical in some cases:

1. A dent may increase in priority after geometry data becomes available. For example, a plain top of line dent with no coating damage would be assigned priority 11 using MFL / UT data. If geometry data became available and showed that the dent depth was greater than 7%, the dent would be assigned a higher priority of 5. The MFL / UT priority order is consistent with the relative severity of the categories.
2. The priority levels from each set are not directly comparable. For example, a bottom of line dent associated with metal loss and a weld is assigned category 6 in the

MFL / UT set, and category 7 in the geometry set. This would be relevant to an operator defining a repair schedule for multiple pipelines, of which only some have geometry inspections.

Some of the MFL / UT priority categories allow a geometry inspection where geometry data would not be beneficial. For example, a top of line dent associated with metal loss and a weld (category 1) would require repair regardless of the results of a geometry inspection.

4. PUBLICATIONS SUPPORTING EXISTING GUIDANCE

The existing guidance for the acceptability of dents on welds is based on a range of testing and assessment methods. The published documents that support the existing guidance are reviewed in this section.

4.1 Testing

Full scale testing of dents on welds has been carried out by a number of institutions using a wide range of linepipe types. These test results have been used to validate the best practice methods for assessing dent acceptability, for example in PDAM [27,28].

4.1.1 Battelle (1981)

Eiber et al [29] report that burst tests were carried out in the early 1960s on three sections of linepipe where unrestrained dents had been artificially introduced into the seam weld.

Two tests used ERW pipe (assumed to be low-frequency ERW, based on the date), and one test used SAW pipe. Upper shelf 2/3 scale Charpy impact energies of 20 to 25 ft-lb were recorded in the pipe body, equivalent to full-size results of 40 to 50 J. However, at the test temperature of 63 to 67°F, 2/3 scale Charpy impact energies of 12 to 17 ft-lb were measured, equivalent to full-size results of 24 to 30 J. Brittle fracture area was 55% to 60% at this temperature. This pipe does not meet API5L requirements, which are an average Charpy impact energy of 27 J at 0°C (32°F), and 85% shear area. It is likely that the weld toughness and ductility were low.

One test caused cracking of the ERW seam during indentation, resulting in a very low failure pressure equal to 7% of the nominal pipe burst strength. The dent depth was 7.8% of the pipe diameter. Whilst this test shows that deep dents can cause immediate cracking of poor quality welds, it is not relevant to the discussion of shallow dents in the current study.

The other two tests introduced dents with depths of 5.8% and 4.5% of the pipe diameter. Bursting occurred at 82% and 100% of the nominal pipe burst strength. These tests show that relatively large dents can sometimes be tolerated even in, by modern standards, low quality pipe and seam welds.

No fatigue tests were performed on dents located on welds.

It was concluded that dents on welds may have very low burst strengths, and should be repaired.

4.1.2 British Gas (1989)

British Gas carried out seven burst tests and eight fatigue tests of unrestrained dented seam welds [30]. These tests used 75 mm pipe rings, effectively simulating infinitely long dents. Ring tests should be conservative, because the restraint provided by the surrounding pipe is not present. The type of weld is not indicated, but it is believed to have been a submerged arc weld [28].

The failure stress was as low as 24% of the linepipe SMYS, for a dent with a depth of 4.9% of the pipe diameter, and a linepipe full size Charpy impact toughness of 31 J. Three dents

on the seam weld with depths up to 4.5% of the pipeline diameter survived to greater than the linepipe SMYS.

The fatigue life was as low as 67 cycles of a hoop stress equal to 28% of SMYS, for a dent with a depth of 4.0% of the pipe diameter. The highest recorded fatigue life was 9529 cycles of a hoop stress equal to 30% of the yield strength, for a dent with a depth of 3.9% of the pipe diameter.

The key differences between the dents that burst at low pressure or failed after a small number of cycles and those that did not is not clear. This apparently random nature is probably caused by undetected cracking in the weld.

It was concluded that dents on welds may have low burst strengths and fatigue lives, and should be repaired.

4.1.3 Stress Engineering Services (1994)

Stress Engineering Services carried out six fatigue tests of unconstrained dents located on welds [31].

Three tests were located on ERW seam welds and three tests were located on girth welds. These tests formed part of a large study at SES, sponsored by the PRCI, of the fatigue strength of plain dents, dents on welds and dents with gouges.

No toughness data is given for the ERW welds, but as they are modern, it can be assumed that they were good quality.

All of the tests on dented girth welds resulted in failures in the dented area, and two of the tests on dented seam welds failed in the dented area (the third test was terminated prior to failure). For one of the tests it is indicated that the failure occurred in the girth weld, but no details are given for whether failure occurred in the weld in the other tests.

It was concluded that the dents on seam welds did not have significantly lower fatigue lives than equivalent plain dents, but that the dents on girth welds had a fatigue life as low as 9.4% of the life of an equivalent plain dent. It was reported that the circumferential position of the dent relative to the seam weld did not significantly affect the fatigue life of dents located on seam welds.

4.1.4 Stress Engineering Services (1997)

Stress Engineering Services carried out four burst tests, four proof tests and 14 fatigue tests of unconstrained dents located on welds. This work was reported in API 1156 [32].

All of the burst tests were located on an ERW seam weld. Two of the proof tests were located on an ERW seam weld, and two were located on a girth weld. The dent depths varied between 2.6% and 9.0% of the pipeline diameter, after re-rounding. All the burst tests failed outside the dent, at stresses significantly above the yield strength. All the proof tests survived the maximum applied hoop stresses of 90% to 101.5% SMYS.

No toughness data is given for the ERW welds, but as they are modern, it can be assumed that they were good quality.

It was concluded that dents (up to the depths tested) on good quality ERW seam welds do not affect the static strength of the pipe.

Eight of the fatigue tests were located on an ERW seam weld, one was located on a SAW seam weld, and five were located on girth welds. The dent depths varied from 1.1% to 4.2% of the pipe diameter. The applied hoop stress range varied from 68% to 73% of SMYS. Fatigue failures occurred in ten of the fourteen tests, including all of the tests on girth welds. The lowest fatigue life was 71 cycles.

It was concluded that the presence of minor stress concentrations (such as the toe of a weld and ripples in girth welds) appeared to reduce the fatigue life. It was suggested that the effect was not as great as that of dent depth. It was concluded that it would be prudent to repair a dented weld if the depth of the dent exceeded 2% of the pipe diameter.

4.2 Assessment Methods

The existing guidance for the acceptability of dents on welds makes use of several assessment methods. These methods have been developed based on the results of full scale testing programmes.

4.2.1 EPRG

The original empirical model developed by the European Pipeline Research Group (EPRG) was described by Corder and Chatain in 1995 [33]. It is based on the S-N curve for the fatigue strength of (longitudinal) submerged arc welded pipe given in DIN 2413, combined with a calculation of the stress concentration due to the dent.

This method is recommended by PDAM [27] for the assessment of plain dents (not containing welds) because it gives the best fit with published full scale test data. PDAM recommends that a model uncertainty factor of 13.3 should be applied to the predicted fatigue lives to account for the scatter in the test data. PDAM also recommends that a further safety factor of 10 should be applied to account for the reduced fatigue life of the weld compared to the parent plate. The existing UKOPA dent management strategy [1] makes the same recommendations as PDAM, but does not mention the further safety factor of 10 for dents on welds.

A revised model was published by EPRG in 2000 [34,35,36]. This was evaluated for inclusion in PDAM, but was not found to give as good a fit to published test data compared to the original EPRG model.

4.2.2 SES

Stress Engineering Services (SES) produced a semi-empirical model in 1994 (reported by Fowler et al [31]) and a modified version in 1997 (reported by Alexander and Kiefner [32]), based on full scale testing (Sections 4.1.3 and 4.1.4 respectively).

These methods apply to plain dents only, and not to dents on welds.

5. RECENT PUBLICATIONS

This section reviews publications that have been made since the best practice guidance in PDAM [27] and the UKOPA dent management strategy [1] was published.

5.1 Testing

5.1.1 SES / PRCI

Stress Engineering Services (SES) carried out 34 full scale fatigue tests of restrained and unrestrained dents, reported by Bolton et al [3]. The work was sponsored by the Pipeline Research Council International (PRCI) and the US DoT, and also included the development of finite element models validated using the test data.

Two tests included dents centred 2 inches from longitudinal seam welds, three tests included dents centred on girth welds, and 11 tests included dents centred 2 inches from girth welds. No reason is stated for the 2 inch offsets between the dent centre and the welds, however it is stated that the peak strain range occurred 2 inches from the centre of the dent. Thus it is likely that the intention was to place the weld in the location of highest strain. The seam weld type is not reported, but modern grade X52 and X70 linepipe was used, so it is likely that the welds were of good quality.

It was concluded that for a given number of pressure cycles, the dent depth expected to fail is smaller for dents on welds than for dents in plain pipe. The aim of the work was to produce test data to support later work and validated finite element models; no general quantification was given for the relationships between fatigue life, dent dimensions and the presence of a weld.

5.2 Failures

Penspen is not aware of any published data relating specifically to in-service failures of dents on welds where the presence of the weld is considered to be a significant contributor to the failure.

5.3 Assessment Methods

5.3.1 PRCI / PHMSA / BMT Fleet: Weld Interaction

BMT Fleet carried out finite element analysis to determine the criteria for interaction between a restrained rock dent and a weld [4]. This work was carried out for the Pipeline Research Council International (PRCI) and the US DoT Pipeline & Hazardous Materials Safety Administration (PHMSA). The work explicitly did not include prediction of the burst or fatigue strength of dents on welds.

It was determined that the presence of a seam weld causes no reduction in the fatigue life of a dent if the seam weld is located outside the region where the pipe radius is reduced by the dent. This is subject to the following criteria:

- The dent is a restrained rock dent that is acceptable to strain criteria such as those given in ASME B31.8 (see Section 3.1.2);

- Fatigue failure is caused by internal pressure fluctuations;
- The dent is symmetrical.

The work was carried out using X52 and X65 materials, and diameter to thickness ratios of between 37 and 96. However, the report notes that the results are so consistent that the conclusion for seam welds would also apply to other materials and pipe geometries.

No simple rule was produced for interaction between dents and girth welds. A series of regression relationships were produced based on the finite element analysis results.

5.3.2 PRCI / BMT Fleet: Dent Fatigue Life Assessment

BMT Fleet is currently carrying out work to produce accurate methods to evaluate the fatigue life of dents based on finite element analysis, validated using full scale tests [5]. This is being carried out for the Pipeline Research Council International (PRCI). An interim report was produced in 2012, which contains the current results from the project.

A validated 'screening' method is not yet available. It is expected that this method will be based on data available from basic in-line inspection reports, such as dent depth, width and length.

Extensive finite element modelling has been carried out, and validated against full scale test results. This work firstly illustrates that validated finite element modelling can be an acceptable and accurate method to replace large numbers of full scale tests. Secondly, the work highlights some of the key modelling considerations that must be made to ensure accuracy, particularly when modelling the indenting process directly. The behaviour of the linepipe material under extensive plastic straining was found to be of particular concern, because this has a significant effect on the formation of cracks and the dent fatigue life.

5.4 Dent Management Strategies

5.4.1 TransCanada

Adams and Zhou describe a dent management strategy implemented at TransCanada Pipeline Limited [37].

Their approach uses high-resolution in-line inspection geometry data for multiple dents in a pipeline. It consists of multiple stages of assessment, becoming more accurate and less conservative at each stage:

1. Process the 3D dent geometry data and extract the geometric characteristic parameters – rank these to assess their relative significance to pipeline integrity;
2. Perform detailed finite element analysis to determine the stress concentration for a selected number of dents based on the geometric characteristic parameters – rank the dents based on the stress concentration;
3. Perform fatigue analysis to determine the remaining life for a selected number of dents based on the stress concentration – rank the dents based on the predicted remaining life.

For low-resolution geometry inspection data, correlations with high resolution data are used. This is made possible by the large population of similar dents in this operator's system.

This process focusses primarily on assessing the relative severity of the reported dents. This allows analysis and repair effort to be spent where it is most valuable. The predicted fatigue life of each dent is only a secondary output.

This again demonstrates the finite element analysis can be a valuable part of a multi-level dent analysis strategy.

5.5 Reviews of Current Assessment Methods

5.5.1 Kiefner and Leewis

Kiefner and Leewis have compiled a comprehensive review of current pipeline defect assessment methods [38]. This work was completed for the Pipeline Research Council International (PRCI).

After reviewing the methods described in Section 4.2 of the present report, the authors succinctly summarise the current state of the use of numerical analysis in dent assessment:

> "It should be apparent that no single equation or expression is currently available that is capable of predicting the safe operating pressure or time to failure of a dent or mechanical damage and which is (a) simple to use, and (b) accurate. Moreover, different models often give different answers for the same example problem. It is unlikely that a "B31G"[3] for dents that is simple, accurate, and reliable will ever be developed. Moreover, if such an equation were proposed, it would almost certainly be highly inaccurate or very conservative. It is more likely that rather complex procedural approaches that combine elements of stress analysis and fracture mechanics will continue to evolve, and that more than one such approach will be practiced within the industry."

The authors are referring to the kind of finite element work described in Sections 5.3 and 5.4 of the present report. They continue:

> "Very simple models will tend to be inaccurate as a result of excessive simplification of a complex problem. For that reason they may well give results a pipeline operator cannot utilize because the conservatism required to compensate for a lack of accuracy requires such models to be highly restrictive. More accurate models are likely to involve rather complex procedures which require some technical understanding in depth about the nature of the damage and evaluating the fitness for service of damaged pipe. Such models are likely to be proprietary, and may be beyond the ability of a typical pipeline operator to perform on a routine basis."

It will be necessary to consider the complexities of dents individually, in order to progress beyond the simplified and conservative methods currently in common use.

[3] This refers to the widely used and very successful ASME B31.G method for assessing corrosion defects.

5.5.2 Dawson et al

Dawson et al describe the results of analysis of two example dents detected by in-line inspection. The results of the methods recommended by PDAM [27] are compared with the results of finite element modelling [39]. This work did not specifically consider dents on welds.

It was shown that the PDAM methods, which predicted fatigue lives of less than one year for the example dents, are significantly conservative, since both dents had been in service without failure for 15 years. Such results are commonly found when the PDAM methods (including the recommendations for dents on welds) are applied to the dents reported by in-line inspections, although little published data is available.

The finite element analysis predicted fatigue lives of 20 to 55 years. It is noted that the finite element analysis was not validated against tests, and incorrectly used stresses directly from an elastic-plastic analysis in an elastic stress S-N fatigue curve based assessment. However, the demonstration of the conservatism in the PDAM methods remains relevant and valid.

6. DISCUSSION

6.1 History of Failures

Current dent assessment methods generally predict that dents on welds will fail quickly under significant fatigue loading, including the EPRG method recommended as best practice by PDAM and the existing UKOPA guidance. However, there are a large number of shallow dents on welds that have been in service under high fatigue loading for many years. There are no known instances of failures of shallow dents on welds. The current guidance must therefore be conservative in most cases.

Dents with depth less than 2% of the pipe diameter have only recently begun to be detected accurately and reported by in-line inspection tools and vendors. There is no history of failure in these previously undetected shallow dents on welds. There have been a few cases reported of shallow dents failing due to fatigue after the removal of the rock that caused the dent. The current assessment methods were developed for, and based on testing of, deeper dents. Development of the assessment methodologies has not kept pace with the developments in inspection technologies.

6.2 Existing Guidance

Generally the pipeline design codes do not allow dents on welds. One exception is ASME B31.8, which allows dents with depth up to 2% of the pipe diameter, but this code is only applicable to gas pipelines, which are likely to have low fatigue loading. The pipeline design codes generally allow a detailed engineering analysis of dents, including dents on welds.

The generic assessment codes such as BS 7910 and API 579 do not generally allow dents on welds, although API 579 allows assessment if weld ductility and toughness is sufficient, without giving specific guidance.

The pipeline specific guidance allows assessment of dents on welds if weld quality, particularly toughness and ductility, is sufficient. The best practice method recommended by PDAM is the EPRG dent fatigue life estimation method. A combined safety factor of 133 is recommended. This is very conservative for most shallow dents on welds where fatigue loading is significant, as shown by the large number of dents of this type which are currently in service, but are predicted to have failed many years ago.

6.3 Weld Quality

The primary reason for the conservatism in existing guidance is the unknown quality of dented welds. Small cracks can form in poor quality welds when they are strained during the introduction of a dent. These cracks can grow by fatigue and cause the pipeline to fail. However, good quality welds can be tolerant of the plastic strains applied during denting, and may have no deleterious effect on the fatigue life of a dent.

It is critical to determine whether a dented weld may have cracked before any detailed analysis is carried out. If there is a chance of cracking, a dent on a weld should be repaired. If possible, a dented weld should be inspected for cracking. Otherwise, weld toughness and ductility criteria should be applied. If possible, this should be based on test results, but if these are not available, other indicators of low toughness and ductility, such as those given in PDAM (see Section 3.6.1), may be used.

The results of full scale testing show that cracked welds generally fail immediately or have extremely short fatigue lives. If a dent has been in an operational pipeline for many years without failure while subject to fatigue loading, it is therefore probable that cracking did not occur when the dent was introduced. This can give an indication of weld quality. It is noted that fatigue loading can cause cracks to initiate in poor quality welds some time after the initial introduction of a dent, particularly if the cyclic stress is high.

If the weld has not been inspected for cracking, the strain applied to the weld should be estimated, for example using the method specified in ASME B31.8 Appendix R with high resolution geometry inspection data. A maximum strain limit should be applied. The strain limit should be selected based on the weld quality.

Three quality levels of welds and associated strain limits are proposed for both girth welds and seam welds:

1. *Known good quality welds*

   Known good quality welds meet the criteria for probable good quality welds (below) and have test data to demonstrate a sufficient Charpy toughness (greater than 30 J minimum and 40 J on average from three specimens).

   An assessment of the strain in the dent should be conducted if high resolution geometry inspection data is available (see Section 6.5). A strain limit of 4% should be used as recommended in ASME B31.8 [8]: this is intended for gas pipelines with acceptable welds, but the formation of cracking in the weld during denting is independent of the pipeline product or fatigue loading.

   If the strain in the dent is acceptable, an assessment of dent fatigue life should be conducted (see Section 6.6).

2. *Probable good quality welds*

   Probable good quality welds are likely to have a sufficient Charpy toughness (greater than 30 J minimum and 40 J on average from three specimens), but do not have Charpy test data available. The following are indicators of sufficient toughness – several of these are recommended by the Pipeline Defect Assessment Manual (PDAM) [27], but note that none of these indicators are sufficient evidence alone:

   - Pipe manufactured after approximately 1970;
   - Pipe manufactured to API 5L or equivalent;
   - The weld was fabricated to a recognised pipeline welding standard such as API 1104 or equivalent;
   - The pipe manufacturer is known to have been producing good quality welds at the date of manufacture;
   - Visual and magnetic particle (or similar) inspection of a sample of welds (at least 0.1% of the pipes in the pipeline) shows a good quality weld with a clean cap, no spatter, no surface-breaking planar flaws, and no undercut;

- Non-destructive testing of a sample of welds (at least 0.1% of the pipes in the pipeline) using manual shear wave ultrasonic technology (UT), time of flight diffraction (TOFD), or other suitable method shows no anomalies outside the workmanship limits in a current welding standard.

- Records show, or it is considered likely that, a high level hydrotest has been completed, giving a hoop stress of at least 90% of specified minimum yield stress (SMYS), and there is no evidence that hydrotest failures were caused by welds.

An assessment of the strain in the dent should be conducted if high resolution geometry inspection data is available (see Section 6.5). A strain limit of 2% should be applied as recommended in ASME B31.4 [40] to prevent cracking in welds (including in older pipelines) during single non-cyclic events. The 2% strain limit is likely to be conservative for this weld category, however test data specifically for this weld category is very scarce.

If the strain in the dent is acceptable, an assessment of dent fatigue life should be conducted (see Section 6.6).

3. *Poor quality welds*

Poor quality welds are welds where cracking is credible during the denting process. This includes any of the following indicators, several of which are recommended by PDAM:

- Welds of known low toughness (Charpy toughness less than 30 J minimum and 40 J on average from three specimens);

- Pipe not manufactured to API 5L or equivalent;

- An operating temperature less than the drop weight tear test transition temperature;

- The weld is under-matched (the tensile strength of the weld is less than the linepipe, or the yield strength of the weld is less than the linepipe);

- The weld is likely to contain cracks or defects;

- Welds not fabricated to a recognised pipeline welding standard such as API 1104 or equivalent, or fabricated before the existence of such standards;

- Low frequency electric resistance welds, induction welds, flash welds or oxyacetylene welds;

- Welds with a history of causing hydrotest failures;

- Welds with evidence of significant anomalies when samples are inspected.

Strain and fatigue life assessments should not be carried out, because cracking is credible during the denting process. All dents on these poor quality welds should be repaired.

6.4 Dent Depth Limit

In line with the guidance in PDAM [27] and ASME B31.8 [8], plain dents greater than 7% depth and dents on welds greater than 2% depth generally should not be allowed. Exceptions may be made if detailed analysis, confirmation of weld quality, and ideally inspection for cracking, are completed, and it can be shown that the passage of pigs will not be impeded.

6.5 Dent Strain Assessment

High resolution geometry in-line inspection data can be used with the method described in ASME B31.8 Appendix R [8] to calculate the peak strain in a dent. Most geometry inspection data contains irregularities, for example due to sensor lift-off or debris in the pipeline, which cause large over-estimates in the calculated strain values. Some smoothing of the geometry data is usually required, but this must be done carefully to preserve the essential features of the dent shape. No particular smoothing method has been widely accepted by the industry, but methods using B-splines and local polynomial regression have been used.

6.6 Mandatory Fatigue Analysis for Dents on Known / Probable Good Quality Welds

If the dent strain is less than the allowable strain, a fatigue analysis should be carried out to predict the remaining fatigue life of the dent, either using the methods recommended by PDAM, or a method based on finite element analysis (see Section 6.7).

6.7 Detailed Assessment Using Finite Element Analysis and SN Curves

It is becoming common practice to use finite element analysis in the assessment of stress concentration and fatigue life of dents. Finite element models have been developed which agree with a limited number of full scale tests [5], however they have not yet been thoroughly validated. There are several pitfalls that the analyst must be aware of, and no particular method has yet become accepted by the industry.

A primary input to such analysis may be the detailed dent geometry as measured by a high resolution in-line inspection geometry tool. Alternatively, the full dent formation process may be modelled, although accurate results from this approach depend on detailed knowledge of the linepipe material properties [5], which may not be available.

The fatigue loading should be determined based on historical internal pressure data at the dent location or an anticipated future internal pressure cycling regime. The rainflow method may be used to count the pressure cycles in recorded pressure data.

Finite element analysis is generally used to calculate the stress concentration in a dent. A lower bound SN curve is selected that is appropriate for the weld, or the base material in the dent is not on a weld. PD 5500 [41] provides SN curves that may be used for good quality welds. It is important to only use elastic stresses with an SN curve. The dent fatigue life can be estimated by combining the stress concentration, pressure history and SN curve.

7. CONCLUSIONS

1. *Existing guidance is conservative*

   The current assessment methods are provided by pipeline design codes and pipeline specific guidance such as the ERPG fatigue life estimation method. Generally these methods either do not allow dents on welds, or predict that they will fail quickly under significant fatigue loading. However, there are a large number of shallow dents on welds that have been in service under high fatigue loading for many years. There are no known instances of failures of shallow dents on welds, although there have been cases of shallow dents failing due to fatigue loading after removal of the rock that caused the dent. The current assessment methods must therefore be conservative for shallow dents on welds in most cases.

2. *Existing best practice is given in PDAM*

   Generally the pipeline design codes do not allow dents on welds, although some allow dents on good quality welds with depth up to 2% of the pipeline diameter. The codes generally allow detailed engineering analysis. The generic assessment codes such as API 579 and BS 7910 do not generally allow dents on welds. The pipeline specific guidance in PDAM allows assessment of dents on welds if weld quality, particularly toughness and ductility, is sufficient. The best practice method recommended by PDAM is the EPRG dent fatigue life estimation method.

3. *There is no assessment method for dents on welds of poor quality*

   The primary reason for the conservatism in existing guidance is the unknown quality of dented welds. It is critical to determine whether a dented weld may have cracked before any detailed analysis is carried out. If there is a chance of cracking, a dent on a weld should be repaired. If the weld has not been inspected for cracking, the strain applied to the weld should be estimated. A maximum strain limit should be applied. The strain limit should be selected based on the weld quality.

4. *Three weld quality levels are proposed*

   Three weld categories with associated strain limits are proposed (described in detail in Section 6.3): ‘known good quality,’ 4% strain limit; ‘probable good quality,’ 2% strain limit; and ‘poor quality,’ no strain limit and no denting allowed.

5. *Future assessment methods are likely to be based on stress analysis*

   It is becoming common practice to use finite element analysis in the assessment of stress concentration and fatigue life of dents. Methods based on finite element analysis can give more accurate estimates of fatigue life than the existing best practice methods such as the EPRG method, primarily because they take full account of the dent shape. Finite element models have not yet been thoroughly validated against full scale tests.

8. REFERENCES

[1] Anon; *UKOPA Dent Management Strategy*; UKOPA/10/0051 Version 10; 2010.

[2] Anon; *Pipeline Rupture and Subsequent Fire in Bellingham, Washington, June 10 1999*; National Transportation Safety Board; NTSB/PAR-02/02; 2002.

[3] Bolton B., Semigo V., Tiku S., Dinovitzer A., Zhou J.; *Full Scale Cyclic Fatigue Testing of Dented Pipelines and Development of a Validated Dented Pipe Finite Element Model*; Proceedings of the 8th International Pipeline Conference; IPC2010-31579; Calgary, Canada; 2010.

[4] Anon; *Evaluation of the Interaction of Mechanical Damage and Welds*; BMT Fleet report to Materials Committee Pipleine Research Council International and Pipeline & Hazardous Materials Safety Administration U.S. Department of Transportation; Report number 5827C.FR; July 2006.

[5] Anon; *Dent Fatigue Life Assessment*; MD 4-9 BMT Fleet Interim Report to the Pipeline Research Council International; 6837IR2 Revision 00; July 2012.

[6] Anon; ASME B31.4-2012; *Pipeline Transportation Systems for Liquids and Slurries*; American Society of Mechanical Engineers; 2012.

[7] Anon; 49 CFR Part 195.452; *Transportation of Hazardous Liquids by Pipeline: Operation and Maintenance*; PHMSA; October 2011.

[8] Anon; ASME B31.8-2012; *Gas Transmission and Distribution Piping Systems*; American Society of Mechanical Engineers; 2012.

[9] Anon; 49 CFR Part 192.933; *Transportation of Natural and Other Gas By Pipeline: Minimum Federal Safety Standards: Gas Transmission Pipeline Integrity Management*; PHMSA; October 2011.

[10] Anon; CSA Z662-11 Update Number 1; *Oil and Gas Pipeline Systems*; Canadian Standards Association; 2012.

[11] Anon; PD 8010-1:2004; *Code of practice for pipelines – Part 1: Steel pipelines on land*; British Standards Institution; 2004.

[12] Anon; DNV-OS-F101 2012; *Submarine Pipeline Systems*; Det Norske Veritas; 2012.

[13] Anon; AS 2885.1-2012; *Pipelines – Gas and liquid petroleum – Part 1: Design and construction*; Standards Australia; 2012.

[14] Anon; IGEM/TD/1 Edition 5; *Steel pipelines and associated installations for high pressure gas transmission*; The Institution of Gas Engineers and Managers; UK.

[15] Anon; NEN 3650-2:2003; *Eisen voor buisleidingsystemen - Deel 2: Aanvullende eisen voor leidingen van staal*; Nederlands Normalisatie-instituut; 2003 [Unofficial translation; Requirements for Pipeline Systems – Part 2: Steel; Universe Technical Translation; USA; 2003].

[16] Anon; ASME B31.8S-2012; *Managing System Integrity of Gas Pipelines*; American Society of Mechanical Engineers; 2012.

[17] Anon; API STD 1160-2001 First Edition; *Managing System Integrity for Hazardous Liquid Pipelines*; American Petroleum Institute; 2001.

[18] Anon; PD 8010-4:2012; *Pipeline systems – Part 4: Steel pipelines on land and subsea pipelines – Code of practice for integrity management*; British Standards Institution; 2012.

[19] Anon; AS 2885.3-2012; *Pipelines – Gas and liquid petroleum – Part 3: Operation and maintenance*; Standards Australia; 2012.

[20] Anon; T/PR/P/11; *Work Procedure for Inspection and Repair of Damaged Steel Pipelines Designed to Operate at Pressures Greater Than 2 bar*; Transco, UK; 2004.

[21] Anon; API 5L-2012; *Specification for Line Pipe*; Forty-fifth edition; The American Petroleum Institute; 2013.

[22] Anon; API STD 1104-2005 Twentieth Edition; *Welding of Pipelines and Related Facilities*; American Petroleum Institute; 2010.

[23] Anon; API STD 1104 10th Edition; *Standard for Welding Pipe Lines and Related Facilities*; American Petroleum Institute; 1966.

[24] Anon; BS 4515-1:2009; *Pipeline systems – Part 4: Steel pipelines on land and subsea pipelines – Code of practice for integrity management*; British Standards Institution; 2008.

[25] Anon; API 579-1 Second Edition; *Fitness-For-Service*; American Petroleum Institute; 2007.

[26] Anon; BS 7910:2013 Amendment 1; *Guide to methods for assessing the acceptability of flaws in metallic structures*; British Standards Institution; 2013.

[27] Cosham A., Hopkins P.; *The Pipeline Defect Assessment Manual (PDAM) – A Report to The PDAM Joint Industry Project*; Penspen Report Number 9909A-RPT-001 R1.05; June 2006.

[28] Cosham A.; *Assessment Methods for Dents in Pipelines – A Report to the Pipeline Defect Assessment Manual Joint Industry Project*; Report Number NR99014/4238.1.74/R3; February 2001.

[29] Eiber R.J., Maxey W.A., Bert C.W., McClure G.M.; *The Effects of Dents on the Failure Characteristics of Linepipe*; Battelle Columbus Laboratories, NG-18, Report No. 125, AGA Catalogue No. L51403; May 1981.

[30] Hopkins P., Jones D.G., Clyne A.C.; *The Significance of Dents and Defects in Transmission Pipelines*; Paper C376/049, Proceedings International Conference on Pipework, Engineering and Operation; Institution of Mechanical Engineers, London; February 1989.

[31] Fowler J.R., Alexander C.R., Kovach P.J., Connelly L.M.; *Cyclic Pressure Fatigue Life of Pipelines with Plain Dents, Dents with Gouges, and Dents with Welds*; Final Report to the Pipeline Research Committee of the American Gas Association; Report PR-201-927 and PR-201-9324; Stress Engineering Services, Inc.; June 1994.

[32] Alexander C.R., Kiefner J.F.; *Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines*; Final Report to The American Petroleum Institute; Stress Engineering Services, Inc., and Kiefner and Associates, Inc.; API Publication 1156, First Edition; November 1997.

[33] Corder I, Chatain P.; *EPRG Recommendations for the Assessment of the Resistance of Pipelines to External Damage*; Proceedings of the EPRG/PRC 10th Biennial Joint Technical Meeting On Line Pipe Research; Cambridge, UK; April 1995.

[34] Bood R., Galli M., Marewski U., Roovers P., Steiner M., Zaréa M.; *EPRG Methods for Assessing the Tolerance and Resistance of Pipelines to External Damage (Part 1)*; 3R International; 10-11/1999, pp. 739-744.

[35] Bood R., Galli M., Marewski U., Roovers P., Steiner M., Zaréa M.; *EPRG Methods for Assessing the Tolerance and Resistance of Pipelines to External Damage (Part 2)*; 3R International, 12/1999, pp. 806-811.

[36] Roovers P., Bood R., Galli M., Marewski U., Steiner M., Zaréa M.; *EPRG Methods for Assessing the Tolerance and Resistance of Pipelines to External Damage*; Pipeline Technology, Volume II; Proceedings of the Third International Pipeline Technology Conference, Brugge, Belgium; 21-24 May 2000; R. Denys, Ed.; Elsevier Science; 2000; pp. 405-425.

[37] Adams K., Zhou J.; *In-Service Dent Management from an Operator's Perspective*; Proceedings of the 5th International Pipeline Conference; IPC04-0437; Calgary, Canada; 2004.

[38] Kiefner J., Leewis K.; *Pipeline Defect Assessment – A Review of Commonly Used Methods*; Report to the Pipeline Research Council International; PR-218-05404, Catalog number L52314; 2011.

[39] Dawson S.J., Russel A., Patterson A.; *Emerging Techniques for Enhanced Assessessment and Analysis of Dents*; Proceedings of the 6th International Pipeline Conference; IPC2006-10264; Calgary, Canada; 2006.

[40] Anon; ASME B31.4-2012; *Pipeline Transportation Systems for Liquids and Slurries*; American Society of Mechanical Engineers; 2012.

[41] Anon; PD 5500:2012; *Specification for unfired fusion welded pressure vessels*; British Standards Institution; 2012.