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THE EFFECT OF DENTS IN PIPELINES – GUIDANCE IN THE PIPELINE DEFECT ASSESSMENT MANUAL

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ABSTRACT

The Pipeline Defect Assessment Manual (PDAM) project is a joint industry project sponsored by fifteen international oil and gas companies, to produce a document specifying the best methods for assessing defects in pipelines.

A dent reduces the static and cyclic strength of a pipe. Plain dents, dents on welds and dents containing defects are considered here; small scale and full scale tests, theoretical analyses and assessment methods are discussed, and the 'best' methods included in PDAM are described.

INTRODUCTION

Oil and gas transmission pipelines have a good safety record. This is due to a combination of good design, materials and operating practices; however, like any engineering structure, pipelines do occasionally fail. The most common causes of damage and failures in onshore and offshore, oil and gas transmission pipelines in Western Europe and North America are external interference (mechanical damage) and corrosion. Assessment methods are needed to determine the severity of such defects when they are detected in pipelines.

Defects occurring during the fabrication of a pipeline are usually assessed against recognised and proven quality control (workmanship) limits. However, a pipeline will invariably contain larger defects at some stage during its life, and these will require a 'fitness-for-purpose' assessment to determine whether or not to repair the pipeline. Consequently, the past 40 years has seen the development of a number of methods for assessing the significance of defects. Some of these methods have been incorporated into industry guidance, others are to be found in the published literature. However, there is no definitive guidance that draws together all of the assessment techniques, or assesses each method against the published test data, or recommends best practice in their application.

To address this industry need, a Joint Industry Project has been sponsored by fifteen international oil and gas companies[1] to develop a Pipeline Defect Assessment Manual (PDAM). PDAM presents a considered view of the 'best' currently available methods for the assessment of pipeline defects (such as corrosion, dents, gouges, weld defects, etc.), in a simple and easy-to-use manual, and gives guidance in their use. PDAM is intended to be another tool that will assist pipeline engineers in maintaining pipeline integrity. The PDAM project was completed in 2002. PDAM will be made available to the pipeline industry.

THE PIPELINE DEFECT ASSESSMENT MANUAL

PDAM is based upon a comprehensive, critical and authoritative review of available pipeline defect assessment methods. This critical review includes a compilation of all of the published full-scale test data used in the development and validation of existing pipeline defect assessment methods. The full-scale test data is used to assess the inherent accuracy of the defect assessment methods, and to identify the 'best' methods (considering relevance, accuracy and ease of use) and their range of applicability. PDAM describes the 'best' method for assessing a particular type of defect, defines the necessary input data, gives the limitations of the method, and defines an appropriate factor to account for the model uncertainty. The model uncertainty for each assessment method has been derived from a statistical comparison of the predictions of the method with the published test data, based on the prediction interval of the classical linear regression model.

PDAM provides the written text, the methods, recipes for application, acceptance charts and simple examples. Simple electronic workbooks have been developed to permit easy implementation of the 'best' methods.

PDAM has been closely scrutinised throughout its development by the sponsors, and all literature reviews and chapters of the manual have been independently reviewed by international experts in the field of pipeline defect assessment.

PDAM does not present new defect assessment methods; it presents the current state of the art in fitness-for-purpose assessment of defective pipelines. Limitations of the methods recommended in PDAM represent limitations of the available methods, and of the current state of knowledge.

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[1] Advantica Technologies, BP, CSM, DNV, EMC, Gaz de France, Health and Safety Executive, MOL, Petrobras, PII, SNAM Rete Gas, Shell Global Solutions, Statoil, Toho Gas and TotalFinaElf.

TYPES OF DEFECT CONSIDERED IN THE PIPELINE DEFECT ASSESSMENT MANUAL

PDAM contains guidance for the assessment of the following types of defect:

- defect-free pipe
- corrosion
- gouges
- plain dents
- kinked dents
- smooth dents on welds
- smooth dents containing gouges
- smooth dents containing other types of defects
- manufacturing defects in the pipe body
- girth weld defects
- seam weld defects
- cracking
- environmental cracking

In addition, guidance is given on the treatment of the interaction between defects, and the assessment of defects in pipe fittings (pipe work, fittings, elbows, etc.). Guidance is also given on predicting the behaviour of defects upon penetrating the pipe wall (i.e. leak or rupture, and fracture propagation).

The following types of loading have been considered in the development of the guidance: internal pressure, external pressure, axial force and bending moment.

Methods are given in PDAM for assessing the burst strength of a defect subject to static loading and for assessing the fatigue strength of a defect subject to cyclic loading. There are some combinations of defect type, orientation and loading for which there are no clearly defined assessment methods. The assessment of pipeline defects subject to static or cyclic internal pressure loading is well understood, but, in general, other loads and combined loading are not.

THE LAYOUT OF THE PIPELINE DEFECT ASSESSMENT MANUAL

The Pipeline Defect Assessment Manual follows the following format for each defect type and assessment method:

1. A definition of the type of defect.
2. A figure illustrating the dimensions and orientation of the defect relative to the axis of the pipe, and a nomenclature.
3. Notes that highlight particular problems associated with the defect.
4. A flow chart summarising the assessment of the defect.
5. The minimum required information to assess the defect.
6. The assessment method.
7. The range of applicability of the method, its background, and any specific limitations.
8. An appropriate model uncertainty factor to be applied to the assessment method.
9. An example of the application of the assessment method.
10. Reference to alternative sources of information available in national or international guidance, codes or standards.

The flow charts included for each defect type consist of a number of yes-no type questions designed to identify whether or not the methods contained in that chapter are appropriate to the given case, and to indicate the appropriate method to use.

ASSESSMENT METHODS IN THE PIPELINE DEFECT ASSESSMENT MANUAL

A summary of the methods recommended in the Pipeline Defect Assessment Manual for predicting the burst strength of a dent subject to internal pressure is given in Table 1. The 'primary' methods (indicated in normal font) are plastic collapse (flow stress dependent or limit state) failure criteria, and are only appropriate if a minimum toughness is attained (see below). The secondary methods (indicated in *italic font*) are the alternative methods recommended when a minimum toughness is not attained. Upper shelf behaviour is assumed throughout.

General procedures for assessing flaws in structures, based on fracture mechanics, given in BS 7910 [1] (and API 579 [2]) can be applied in general (irrespective of upper or lower shelf behaviour), but will generally be conservative compared to pipeline specific methods. The pipeline industry has developed its own fitness-for-purpose methods over the past 40 years (and, indeed, documents such as BS 7910 recommend that such methods be used). These pipeline specific methods are usually based on experiments, sometimes with limited theoretical validation; they are semi-empirical methods. Consequently, the methods may become invalid if they are applied outside their empirical limits.

Having given an overview of the contents of PDAM, the remainder of this paper (1) summarises the toughness limits derived from full scale test data, and (2) describes in more detail the background to the recommendations for the assessment of dents.

DEFINITIONS

A dent in a pipeline is a permanent plastic deformation of the circular cross section of the pipe. A dent is a gross distortion of the pipe cross-section. Dent depth is defined as the maximum reduction in the diameter of the pipe compared to the original diameter (i.e. the nominal diameter less the minimum diameter) (see Figure 1). This definition of dent depth includes both the local indentation and any divergence from the nominal circular cross-section (i.e. out-of-roundness or ovality).

The following terminology is used here:

smooth dent	a dent which causes a smooth change in the curvature of the pipe wall.
kinked dent	a dent which causes an abrupt change in the curvature of the pipe wall (radius of curvature (in any direction) of the sharpest part of the dent is less than five times the wall thickness)[2].
plain dent	a smooth dent that contains no wall thickness reductions (such as a gouge or a crack) or other defects or

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[2] This is an approximate definition of a kinked dent.

	imperfections (such as a girth or seam weld).
unconstrained dent	a dent that is free to rebound elastically (spring back) when the indenter is removed, and is free to reround as the internal pressure changes.
constrained dent	a dent that is not free to rebound or reround, because the indenter is not removed (a rock dent is an example of a constrained dent).

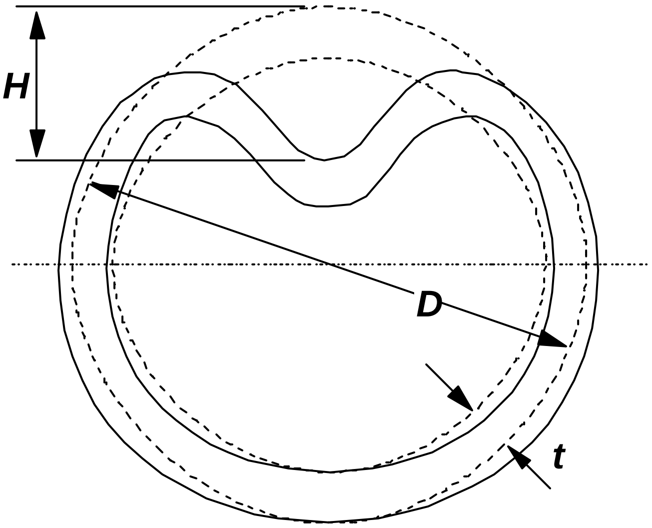

Figure 1 The dimensions of a dent

THE SIGNIFICANCE OF DENTS

A dent causes a local stress and strain concentration and a local reduction in the pipe diameter. The dent depth is the most significant factor affecting the burst strength and the fatigue strength of a plain dent. The profile of the dent does not appear to be a critical parameter, so long as the dent is smooth.

The stress and strain distribution in a dent does depend on the length and width of the dent. The maximum stress and strain in a long dent occurs at the base of the dent, whereas in a short dent it occurs on the flanks of the dent [3-9]. The maximum stress in a long dent is greater than that in a short dent of the same depth [3,4,9]. The different stress and strain distribution is also evident in the results of fatigue tests. In long dents, fatigue cracking is longitudinally orientated and usually occurs in the centre of the dent (but often slightly displaced to one end), whereas in short dents, fatigue cracking usually occurs around the flanks of the dent [6,10,11].

Dents caused by external interference (unconstrained dents) are typically confined to the top half of a pipeline. Rock dents (constrained dents) are found at the bottom of a pipeline. The most likely failure mode of a constrained dent is by puncture, but only if the indenter (e.g. a rock) is sufficiently hard and sharp, and the bearing load is high. Dents may be associated with coating damage, and hence may be sites for the initiation of corrosion or environmental cracking.

A dent should be considered to be on a weld if the dent changes the curvature of an adjacent girth weld or seam weld with respect to the original circular curvature.

The EPRG has published guidelines for the assessment of mechanical damage [12]. The American Petroleum Institute have studied the significance of constrained dents in a pipeline [11]. The Gas Research Institute has conducted a study of research and operating experience of mechanical damage, and has developed guidance for inclusion in the ASME B31.8 code for gas transmission pipelines [13].

The significance of dents in pipelines can be summarised as follows:

i. Plain dents do not significantly reduce the burst strength of the pipe.
ii. The fatigue life of pipe containing a plain dent is less than the fatigue life of plain circular pipe.
iii. Constrained plain dents do not significantly reduce the burst strength of the pipe.
iv. The fatigue life of a constrained plain dent is longer than that of a plain unconstrained dent of the same depth.
v. Kinked dents have very low burst pressures and short fatigue lives.
vi. The burst and fatigue strength of a dented weld, or of a dent containing a defect such as a gouge, can be significantly lower than that of an equivalent plain dent.

Dents in a pipeline can also present operational problems even though they may not be significant in a structural sense. Consequently, any dent remaining in a pipeline should be checked to ensure that it does not significantly reduce flow rates or obstruct the passage of standard, or intelligent, pigs.

TOUGHNESS LIMITS

The minimum toughness (2/3 specimen thickness upper shelf Charpy V-notch impact energy) and maximum wall thickness derived from the published full scale test data for several types of defect are summarised below[3]. These values indicate the potential limits of the various assessment methods. The methods may be applicable outside of these limits, but there is limited experimental evidence. The results of specific studies of the range of validity of specific assessment methods are also indicated. In all cases, it is assumed is that the line pipe steel is on the upper shelf.

Gouges (limit from **burst tests**) The lowest toughness is 14 J (10 ftlbf) and the maximum wall thickness is 21.7 mm (0.854 in.).

Changes to the local microstructure at the base of a gouge, as a consequence of the gouging process, have been studied by CANMET. It is indicated that the effect of such changes were not significant if the upper shelf Charpy V-notch impact energy (2/3 specimen size) exceeded 20 J [14]. The flow stress dependent part-wall NG-18 equation [15] can be used to predict the burst strength of a gouge; the minimum toughness to apply this method is 21 J and the maximum thickness 21.7 mm [16].

Plain Dents (limit from **burst tests**) The lowest toughness is 20 J (15 ftlbf) and the maximum wall thickness is 12.7 mm (0.500 in.).

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[3] Note that the Charpy impact energy is not reported for all of the tests.

Plain Dents (limit from **fatigue tests**) The lowest toughness is 14 J (10 ftlbf) and the maximum wall thickness is 17.4 mm (0.685 in.).

Smooth Dents on Welds (limit from **burst tests**) The lowest toughness is 38 J (28 ftlbf) and the maximum wall thickness is 16.8 mm (0.661 in.) (note that there are no measurements of the weld toughness).

Smooth Dents on Welds (limit from **fatigue tests**) The lowest toughness is 19 J (14 ftlbf) and the maximum wall thickness is 16.8 mm (0.661 in.) (note that there are no measurements of the weld toughness).

Kinked Dents No test data.

Dents and Gouges (limit from **burst tests**) The lowest toughness is 16 J (12 ftlbf) and the maximum wall thickness is 20.0 mm (0.787 in.).

SPRING BACK AND REROUNDING

The process of introducing a dent into a pipeline involves both elastic and plastic deformation; when the indenter is removed the dent will 'spring back' to some degree. The depth of a dent in a pipeline changes as the internal pressure changes; a dent rerounds under increasing internal pressure. Rerounding can be elastic (no permanent change in the dent depth), or plastic (a permanent reduction in the dent depth). Under cyclic internal pressure loading a dent can exhibit incremental rerounding behaviour, until it shakes down to an elastic response.

The spring back and rerounding behaviour of a dent depends upon the pipe geometry, the material properties, whether the pipeline is pressurised or unpressurised, and the shape of the dent. The stress concentration in a dent is a function of the dent depth, which is influenced by the spring back and rerounding behaviour of the dent. The response of a dent depends upon its prior loading history.

In most of the full scale tests that have been undertaken to study the effect of plain dents, dents on welds and dents containing other defects, the dent has been introduced into the pipe when the pipe is at zero pressure. In service, most dents will be introduced when the pipe is pressurised (although damage caused during construction will be introduced at zero pressure). Consequently, a spring back and rerounding correction factor is required to relate the results of tests in which the dent has been introduced at zero pressure, to dents introduced in the field.

There have been no full scale tests to directly compare the behaviour of pipes dented at pressure and pipes dented at zero pressure. Quantitative information on the 'spring back' behaviour of dents has been produced in full scale tests by Battelle [17,18], the EPRG [19,20], Det Norske Veritas [21], Gasunie [22,23] and SES (Stress Engineering Services) [10,11]. The only published quantitative information on the rerounding behaviour of dents is that produced in full scale tests by SES [10,11]. Considered as a whole, these tests indicate that:

i. spring back and rerounding is affected by the shape of the dent; long dents spring back and reround more than short dents (and more in the middle than at the ends of the dent), and smooth dents spring back and reround more than dents containing sharp changes in curvature (or kinked dents),
ii. dents introduced into pressurised pipe spring back more than dents (of the same maximum depth) introduced into unpressurised pipe,
iii. a dent is progressively pushed out (rerounded) as the internal pressure increases,
iv. spring back is affected by the nature of the lateral support around the pipe circumference during indentation, and
v. dents in thinner walled pipe spring back and reround more than dents in thicker walled pipe.

Empirical spring back correction factors have been developed by Battelle [18] and the EPRG [19,20], and (for transversly orientated dents) by Gasunie [22]. These empirical correction factors are based only on the depth of the dent, and do not address all of the factors that would be expected to be relevant. Only the Battelle correction factor explicitly includes the internal pressure. A semi-empirical rerounding model has been developed by Rosenfeld [24], but it requires data that is not available in the published test data (although, in principle, it should be more accurate than the empirical correction factors). All of the published correction factors are limited and show considerable scatter when compared to the test data. Relating tests in which dents were introduced at zero pressure to damage in the field remains an area of uncertainty.

The revised EPRG correction factor (as described by Corder and Chatain (1995) [25]) is the only one that can be easily used, and its effect easily assessed against the published test data. However, it (like the other empirical methods) is not a robust correction factor. The revised EPRG correction factor is recommended in PDAM.

$$\frac{H_o}{D} = 1.43\frac{H_r}{D}$$

H_o	equivalent dent depth at zero pressure
H_r	dent depth remaining after damage (after spring back)
D	outside diameter of pipe

PLAIN DENTS

Burst Strength of Plain Dents

Plain dents do not significantly reduce the burst strength of the pipe, unless they are very deep. This observation is based on several studies of the significance of plain dents; the results of the full scale burst tests confirm the high static strength of plain dents (see Figure 2) [9,11,20,21,26-30]. The results of over 75 burst tests of unconstrained plain dents have been published (dating from 1958 to 2000), but failure in the dented area only occurred in four tests (the remainder of the tests were terminated prior to failure). Note that in all of the full scale tests on plain dents, the dent depths were measured at zero pressure after spring back.

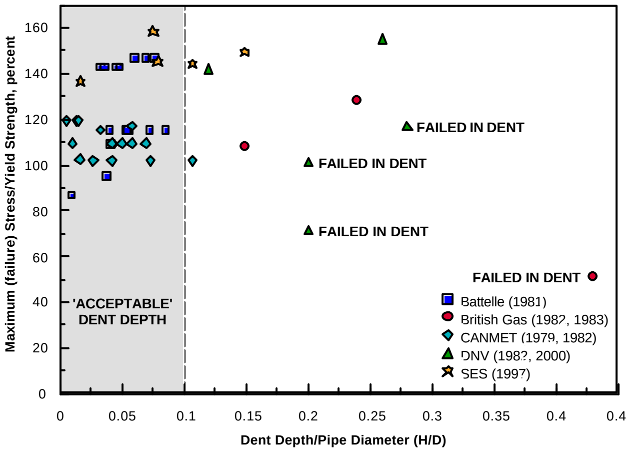


Figure 2 Maximum (failure) stress of plain dents

On pressurisation the dent attempts to move outward, allowing the pipe to regain its original circular shape. Provided that nothing restricts the movement or acts as a stress concentration (e.g. a gouge, a kink, or a weld), then the dent will not significantly reduce the static burst strength of the pipe. The large stresses and strains introduced by the dent are accommodated by the ductility of the pipe. Deep dents tend to fail either because they are unable to reround or because of wall thinning in the dented area (in tests, outward bulging has been observed in dented areas that have rerounded [21]).

The limited number of burst tests on constrained dents indicates that they have a burst strength at least that of an equivalent unconstrained dent, unless the indenter is sharp [11].

There are no published analytical methods for assessing the burst strength of a plain dent; rather, the results of full scale tests have been used to derive empirical limits for the acceptability of plain dents. Based on a review of available burst test data, British Gas stated that a plain dent of less than 8 percent of the pipe diameter (and possibly up to 24 percent) has little effect on the burst strength of pipe [20,29]. The EPRG recommendations for the assessment of mechanical damage state that plain dents of less than 7.0 percent of the pipe diameter, measured under pressure, are acceptable provided they are not subjected to internal pressure fluctuations [12]. Analysis of more recent test data suggests 10 percent (including a factor of safety on the dent depth). There are currently research efforts to develop limits for plain dents based on strain [13].

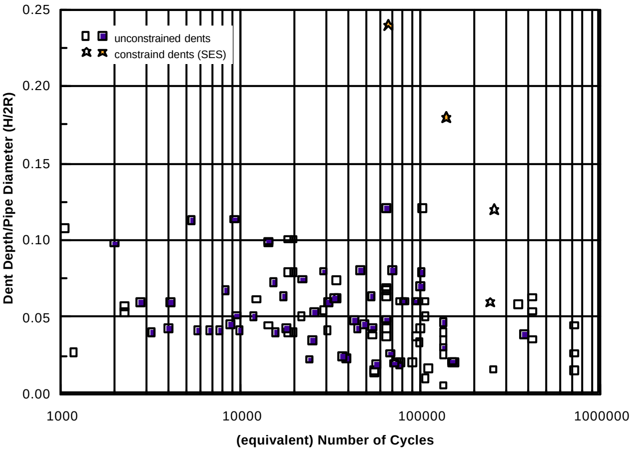
A limit of 10.0 percent of the pipe diameter (irrespective of whether the dent is measured at pressure or at zero pressure) is recommended in PDAM for an unconstrained plain dent, or a constrained plain dent, subject to static internal pressure loading. This compares with a limit of 6.0 percent of the pipe diameter in the proposed ASME B31.8 guidance (although this limit also includes operational considerations).

Fatigue Life of Plain Dents

Full scale tests of rings and vessels containing plain dents have demonstrated that the fatigue life of a plain dent is less than that of an equivalent circular section of pipe [9-11,20,28,29]. A total of 99 full scale fatigue tests of rings and vessels containing unconstrained plain dents have been published, of which 45 tests resulted in a failure in the dented area. The fatigue life decreases as the dent depth increases (the larger the dent depth, the larger is the stress and strain concentration in the dent), although the test data shows considerable scatter (see Figure 3).

Dents have been observed to incrementally reround under cyclic internal pressure loading [10,24,28], implying that the stress concentration reduces over time. In some of the tests in which the maximum stress was high (to simulate a hydrotest), the dent was permanently pushed out (rerounded) during the first cycle, and the pipe regained its circular shape, reducing the stress concentration [20,28,29]. Consequently, no fatigue failure occurred. The fatigue life of a dent will be affected by the mean stress level because higher mean stresses promote rerounding (the higher the mean stress for a given cyclic stress range, the longer the fatigue life).

SES have conducted four fatigue tests of constrained smooth dome shaped dents [11]. The limited test data suggests that a constrained plain dent will have a fatigue life that is at least that of an unconstrained plain dent of the same depth (see Figure 3).



Note: In this figure, open symbols (e.g. ○) denote tests that did not fail during the test (the test was terminated prior to failure) and closed symbols (e.g. ●) denote tests that did fail during the test.

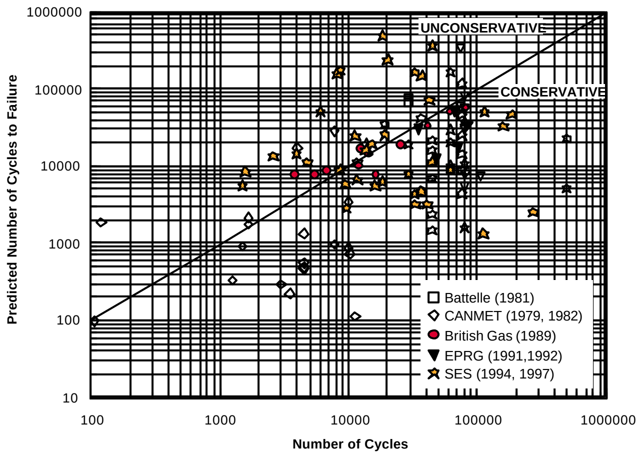
Figure 3 Fatigue life of unconstrained and constrained plain dents

A number of semi-empirical or empirical methods for predicting the fatigue life of a plain dent subject to cyclic pressure loading have been developed, including models by the European Pipeline Research Group (EPRG) [12,25], SES [11,10], Rosenfeld [24] and Shell [31].

The empirical model proposed by the EPRG is based on the S-N curve for the fatigue strength of (longitudinal) submerged arc welded pipe given in DIN 2413 [32], and an empirical stress concentration factor which is a function of the dent depth and the pipeline geometry (derived from 26 fatigue tests of plain dents conducted by British Gas [29] and the EPRG [19,20]) [12]. The dent depth used in the EPRG model is the dent depth measured at zero pressure. The SES model is also based on an S-N curve and a stress concentration to account for the presence of the dent [10,11].

The stress concentration factor was developed from elastic-plastic finite element analyses of dented pipe and is expressed in tabular form in terms of the yield strength, diameter to wall thickness ratio (*D*/*t*), the ratio of the rerounded dent depth to nominal diameter, and the average pressure.

A comparison of the EPRG and SES models based on all of the published plain dent fatigue test data indicates that the EPRG model (as proposed by Corder and Chatain (1995) [25]) is the more accurate model, although the scatter between the predictions and the experimental results is large in both cases (as illustrated for the EPRG model in Figure 4). The Shell and Rosenfeld models both require data that is not given in the published test data. PDAM recommends the use of the original EPRG plain dent fatigue model.



Note: In this figure, open symbols (e.g. ○) denote tests that did not fail during the test (the test was terminated prior to failure) and closed symbols (e.g. ●) denote tests that did fail during the test.

Figure 4 Predictions of the fatigue life of a plain dent using the EPRG model

SMOOTH DENTS ON WELDS

Burst Strength of Dented Welds

Full scale tests have demonstrated that dents containing welds can exhibit very low burst pressures [9,11,20,29] (see Figure 5); the minimum burst pressure in one test was 7 percent of the SMYS (specified minimum yield strength). There are a total of 18 published burst tests of rings or vessels containing smooth dents on the seam weld (four on old (low frequency) ERW (electric resistance welding) seam welds, six on modern ERW seam welds, seven on longitudinal double SAW (submerged arc welding) seam welds) and 2 published burst tests of vessels containing smooth dents on the girth weld.

The low burst strength (and fatigue strength, see below) of a dented weld can probably be attributed to the weld cracking during indentation, spring back or rerounding, and the presence of welding defects. The large variability in the burst strength of dented welds of similar depths is probably due to whether or not the weld cracked during denting. Mention is made of indications of cracking in some of the welds in the tests conducted by Battelle and British Gas, but the test information is not reported in sufficient detail to clearly identify the reasons for the low stress failures [9,20,29]. The six tests on modern ERW seam welds and the two tests on girth welds (all conducted by SES) did not fail. There is no information in the published literature on the toughness of the welds or whether the dented welds contained welding defects.

Dented welds are usually repaired or removed if found in a pipeline. The morphology of the damage often means that it is very difficult to completely inspect the dent and, more importantly, the weld for cracking or other damage. Girth welds may be more susceptible to damage during denting because they typically contain more welding defects than seam welds. There are no methods for reliably predicting the burst strength (or fatigue strength) of a smooth dent on a weld[4].

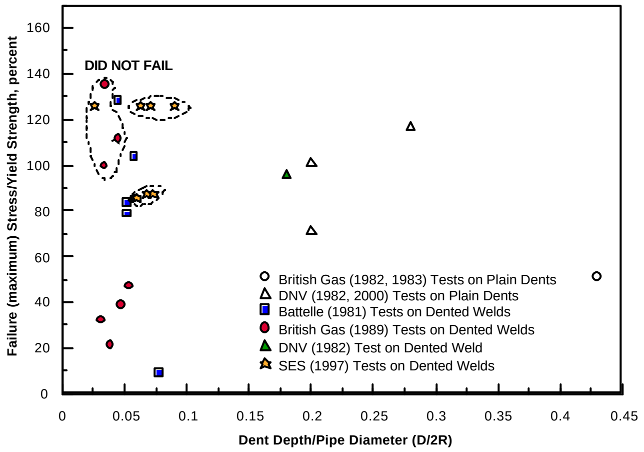


Figure 5 Maximum (failure) stress of smooth dents on welds and plain dents

Fatigue Life of Dented Welds

Fatigue tests on pipe rings containing dented seam welds [29], and fatigue tests on vessels containing dented seam welds and dented girth welds [10,30] have demonstrated that the fatigue life of a dent containing a weld can be considerably lower than the fatigue life of an equivalent plain dent (see Figure 6) or of a weld in undented pipe. There are 22 published full scale fatigue tests of vessels containing smooth dents on the seam weld (eleven on modern ERW seam welds, two on low frequency ERW seam welds, and nine on longitudinal double SAW seam welds) and 8 published tests of smooth dents on the girth weld.

Compared to a plain dent, the fatigue life of a dented weld can be reduced by a factor of the order of at least ten; in some tests very short fatigue lives have been recorded (see Figure 6). The dented welds exhibiting longer fatigue lives are those tests on modern ERW seam welds and on girth welds (all conducted by SES). Considering the SES tests only, it is apparent that dented girth welds may have lower fatigue lives than dented seam welds.

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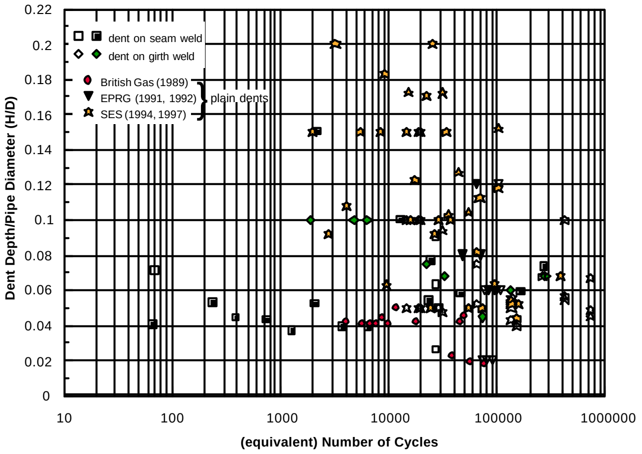
[4] A dent on a weld is similar to a dent in the parent plate containing a gouge or a crack. The methods for predicting the burst strength of a dent and gouge demonstrate considerable scatter when compared to the burst test data.

There are no methods for reliably predicting the fatigue life of a dented weld.



Note: In this figure, open symbols (e.g. ○) denote tests that did not fail during the test (the test was terminated prior to failure) and closed symbols (e.g. ●) denote tests that did fail during the test.

Figure 6 Fatigue life of smooth dents on welds

KINKED DENTS

There is no research reported in the literature that describes experimental studies of the behaviour of kinked dents, or methods for the assessment of kinked dents. It is to be expected that kinked dents will have a lower burst and fatigue strength than equivalent plain dents.

Kinked dents may be susceptible to longitudinal (axial) cyclic stresses arising from secondary (external) loads, in addition to cyclic internal pressure. This will depend upon the shape of the kinked dent, and whether it can reround under increasing internal pressure without inducing large stress concentrations. Tests of wrinkled bends (which have some of the characteristics of a circumferentially orientated kink, but are not as severe) have shown no significant reduction in the burst strength, but a significant sensitivity to cyclic axial loads [33,34].

There are no published methods for predicting the behaviour of kinked dents. Therefore, a kinked dent should be repaired, or specialist advice sought.

SMOOTH DENTS AND GOUGES

A smooth dent containing a gouge (or other part-wall metal loss defect) is a very severe form of mechanical damage. The background to the PDAM recommendations for the assessment of the burst strength of a smooth dent containing a gouge have been described elsewhere (see Cosham and Hopkins (2002) [16]).

In summary, PDAM recommends a semi-empirical dent-gouge fracture model developed by British Gas [35] for predicting the burst strength of a dent and gouge defect, (and subsequently included in the EPRG recommendations for the assessment of mechanical damage [12]). Since the dent-gouge fracture model does not give a lower bound estimate of the burst strength of a dent and gouge, an appropriate 'model uncertainty' must be applied [16].

DENTS AND OTHER DEFECTS

A dent could be associated with other defects that are typically found in pipelines, including pipe body (manufacturing) defects, corrosion and environmental cracking. There is no research reported in the literature that describes experimental studies of the behaviour of a smooth dent containing a defect other than a gouge (such as corrosion, a weld defect or another gouge). The only exception is a small number of tests of dents containing blunt grooves or slots, or dents containing notches that have subsequently been ground smooth [11,21,29,30,36].

There are no methods for assessing defects which cannot be readily classified as part-wall defects. It may be reasonable to assume that a defect in a smooth dent which can be characterised as a part-wall defect can be assessed as though that defect was a gouge, but there is limited experimental validation of such an approach.

ACKNOWLEDGMENTS

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Table 1 Recommended methods in the Pipeline Defect Assessment Manual for assessing the burst strength of mechanical damage defects (dents and gouges) subject to static internal pressure loading

	internal pressure (static) longitudinally orientated	**internal pressure (static) circumferentially orientated**
gouges	NG-18 equations [15] *PAFFC* [37,38] *BS 7910* [1] *(or API 579* [2]*)*	Kastner local collapse solution [39] *BS 7910 (or API 579)*
plain dents	dent depth less than 10 percent of pipe diameter (empirical limit)[2]	
kinked dents	no method[1]	
smooth dents on welds	no method	
smooth dents and gouges	dent-gouge fracture model [12,35]	no method
smooth dents and other types of defect	dent-gouge fracture model	no method

Note:

1. ‘No method’ represents both limitations in existing knowledge and circumstances where the available methods are too complex for inclusion in a document such as PDAM.
2. The acceptable dent depth may be significantly smaller if the dent is subject to cyclic loading.