THE PIPELINE DEFECT ASSESSMENT MANUAL

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ABSTRACT

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 major causes of pipeline failures around the world are external interference and corrosion; therefore, 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. These workmanship limits are somewhat arbitrary, but they have been proven over time. However, a pipeline will inevitably 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 a large number of full scale tests of defects in pipelines, and these have led to the development of a number of methods for assessing the significance of defects. Some of these methods have been incorporated in 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 published test data. It is intended to be another tool to help pipeline engineers maintain the high level of pipeline safety.

In addition to identifying the best methods, PDAM has served to identify a number of limitations in the current understanding of the behaviour of defects in pipelines, and the empirical limits in the application of existing methods. This paper discusses the PDAM project, in the context of both the current best practice available for defect assessment and the limitations of current knowledge.

1. INTRODUCTION

The most common causes of damage and failures in onshore and offshore, oil and gas transmission pipelines in Western Europe and the North America are external interference (mechanical damage) and corrosion. Accordingly, the behaviour of defects in pipelines has been the subject of considerable study over the past 40 years, with a large number of full scale tests, analyses and other work having been undertaken. Many different fitness-for-purpose methods have been developed.

Fitness-for-Purpose. Fitness-for-purpose, as discussed here, means that a particular structure is considered to be adequate for its purpose, provided the conditions to reach failure are not reached[1]. Note that fitness-for-purpose may also have a legal and contractual meaning in different countries. Fitness-for-purpose is based on a detailed technical assessment of the significance of the defect. Local and national legislation and regulations may not permit certain types of defects to be assessed by fitness-for-purpose methods or may mandate specific limits. Such issues should always be considered prior to an assessment.

Safety must always be paramount consideration in any fitness-for-purpose assessment. It is always necessary to appreciate the consequences of a failure. These will influence the necessary safety margin to be applied to the calculations.
**Pipeline Integrity Management.** Pipelines are usually related to a breakdown in a ‘system’, e.g. the corrosion protection ‘system’ has become faulty, and a combination of ageing coating, a aggressive environment, and rapid corrosion growth may lead to a corrosion failure. This type of failure is not simply a ‘corrosion’ failure, but a ‘corrosion control system’ failure. Similar observations can be made for failures due to external interference, stress corrosion cracking, etc..

These considerations lead to the conclusion that a ‘holistic’ approach to pipeline defect assessment is necessary; understanding the equation that quantifies the failure load is only one aspect.

Pipeline integrity management is the general term given to all efforts (design, construction, operation, maintenance, etc.) directed to wards ensuring continuing pipeline integrity. The American Petroleum Institute (API) has developed an industry consensus standard that gives guidance on developing integrity management programmes (API 1160)[2]. The American Society of Mechanical Engineers (ASME) is also developing an integrity management appendix for ASME B31.3[3].

**The Pipeline Defect Assessment Manual.** The Pipeline Defect Assessment Manual (PDAM) presents a considered view of the ‘best’ currently available methods for assessing the fitness-for-purpose of defects in pipelines. It is based on a critical review of the published fitness-for-purpose methods and test data. PDAM intended to be a document that will assist in maintaining pipeline integrity. The PDAM project is due for completion in August 2002. PDAM will be made available to the pipeline industry.

This paper summarises the methodology and gives an outline of the content of PDAM. The PDAM document is a consultation document that will assist in maintaining pipeline integrity. The PDAM project is due for completion in August 2002. PDAM will be made available to the pipeline industry.

**NOMENCLATURE**

- $2c$: length of part-wall metal loss defect (mm)
- $d$: depth of part-wall metal loss defect (mm)
- $t$: pipe wall thickness (mm)
- $A$: fracture area of a 2/3 Charpy specimen ($53.55 \text{ mm}^2$ for a 2/3 Charpy specimen) ($\text{mm}^2$)
- $C_V$: CV: 2/3 thickness specimen per $\text{mm}$ Charpy V-notch impact energy (J)
- $D$: outside diameter of pipe (mm)
- $E$: Young’s modulus ($207,000 \text{ Nmm}^{-2}$)
- $H$: dent depth (mm)
- $H_o$: dent depth measured at zero pressure (mm)
- $H_r$: dent depth measured at pressure (mm)
- $K_1$: non-linear regression parameter
- $K_2$: non-linear regression parameter
- $R$: outside radius of pipe (mm)
- $\sigma$: flow stress ($\text{Nmm}^{-2}$)
- $\sigma_0$: hoop stress at failure ($\text{Nmm}^{-2}$)
- $\sigma_Y$: yield strength ($\text{Nmm}^{-2}$)
- $\sigma_U$: ultimate tensile strength ($\text{Nmm}^{-2}$)

**2. FITNESS FOR PURPOSE, ENGINEERING CRITICAL ASSESSMENTS (ECAs) AND PIPELINES**

The fitness-for-purpose of a defect in a pipeline may be determined by a variety of methods ranging from prev ious relevant experience (including workmanship acceptance levels), to model testing, to ‘engineering critical assessment’ (ECA), where a defect is appraised analytically.

**2.1 GENERIC**

Various technical procedures are available for assessing the significance of defects in a range of structures. These methods use a combination of fracture mechanics and limit state (plastic collapse) methods. Both BS 7910: 1999[11] and API RP 579[4] contain detailed engineering critical assessment methods which can be applied to defects in pipelines (although in practice documents are biased towards defects in process plant).

**2.2 PIPELINE-SPECIFIC**

Documents such as the above are generic; they can be conservative when applied to specific structures such as pipelines. Therefore, the pipeline industry has developed its own fitness-for-purpose methods over the past 40 years (and, indeed, documents such as BS 7910 recom mend that such methods be used). These pipeline specific methods are usually based on experience, so meta mes with limited theoretical validation; they are semi-empirical methods. Consequently, the methods may become invalid if they are applied outside their empirical limits. Accordingly, PDAM has considered the limits of the ex pertimental validation of common methods for specific purposes.

Methods and guidelines developed by the pipeline industry range from the NG-18 equations[3] (which formed the basis of methods such as ASME B31G[6] and API STRENG[7]) and the Ductile Flaw Growth Model (DFGM) (implemented as PAFFC (Pipe Axial Flaw Failure Criteria)[8,9] developed by the Battelle Memorial Institute in the USA) to the guidelines for the assessment of girth weld defects[10], mechanical damage[11] and ductile fracture propagation[12] produced by the European Pipeline Research Group (EPRG).

The conservatism of generic methods compared to pipeline specific methods can largely be attributed to issues of constraint and ductile tearing. Coconstraint is the restriction of plastic flow in the vicinity of the crack tip due to stress triaxiality. Stress triaxiality is induced by load and geometry. The standard test methods use a combination of fracture toughness tests. Design guidelines are often applied at the crack tip to ensure conservative results. Pipelines have low constraint because they are in walled (geometry) and are predominately subject to membrane tensile loading (loading mode). Conventional
Steel was widely used by the end of the 19th century to containing a defect. Notched bar impact testing of iron and long wires (due to the lower probability of the shorter wire on strength and observing that short wires were stronger than long wires (due to the lower probability of the shorter wire containing a defect). Notched bar impact testing of iron and steel was widely used today.

2.3 A BRIEF HISTORY OF PIPELINE DEFECT ASSESSMENT

i. The Early Days….

Fracture mechanics is the science of why things fail. The effect of defects on structures was studied qualitatively as long ago as the 15th century by Leonardo da Vinci; he measured the strength of lengths of iron wire, illustrating the effect of flaws between the fracture stress and the size of a flaw, derived in terms of a simple energy balance from a stress analysis of an elliptical hole by Inglis and the First Law of Thermodynamics. However, the work of Griffith was only applicable to perfectly elastic materials (brittle materials) and efforts to apply the theory to metals were initially not successful.

ii. The Start….

Prior to circa 1950, failure reports of engineering structures did not usually consider the presence of cracks. Cracks were considered unacceptable in terms of safety, and the size of a flaw, derived in terms of a simple energy balance from a stress analysis of an elliptical hole by Inglis and the First Law of Thermodynamics. However, the work of Griffith was only applicable to perfectly elastic materials (brittle materials) and efforts to apply the theory to metals were initially not successful.

iii. The Pipeline Pioneers….

Workers at the Battelle Memorial Institute in Columbus, Ohio extensively studied the failure of defects in line pipe steel, and developed full scale testing, under the auspices of the Pipeline Research Committee of the American Gas Association. The principle objective of this research was to provide a sound and quantitative technical understanding of the relationship between the mechanical properties of the material and the number and size of defects removed. The concept of the flow stress was introduced and a correction for plasticity at the crack tip, required when applying linear elastic fracture mechanics theory to elastic-plastic materials, was proposed.

The researchers noted that defects in line pipe tended to fail in a ductile manner, but at two basic distinctions could be made:

1. ‘Toughness dependent’ failures – to predict the failure stress of these tests only a measure of the fracture toughness was required (where the critical stress intensity factor, \( K_c \), or an empirical correlation with the upper shelf Charpy V-notch impact energy).

2. ‘Flow stress dependent’ (‘plastic collapse’) failures – to predict the failure stress of these tests only a measure of the strength of the material was required.

The work at Battelle led to the development of a flow stress dependent and the toughness dependent, through-wall and part-wall NG-18 equations. A summary of the test data and the transition from toughness to flow stress dependent failure is given in Fig. 1. The underlying expressions and concepts are still widely used today.

The original work on defects of line pipe, in developing bulging of the pipe wall, was more applicable to many newer pipeline applications, but they have been little fundamental work reported, and this is a major, serious and somewhat puzzling omission. There has been a focus on developing ‘patches’ to existing methods, and of proving that these old methods are either (1) highly conservative, or (2) applicable to newer materials or applications via simple testing or numerical analysis.

These are ultimately short-sighted approaches to solving problems; rather, efforts should be directed towards understanding the fundamental reasons why the older methods do not work (or are conservative) and to developing new methods. This is unreasonable to expect that 30 year old methods developed for thin wall, moderate toughness line pipe steels will be applicable to newer steels of higher strength (grade X100 or above) and toughness, larger diameters, thicker wall and deeper water pipelines.
are approaching 50 mm in thickness), higher strains (deep water and arctic conditions (frost heave)) will give rise to greater than 1 percent plastic strains (forces). The original flow stress dependent methods were not conservative (see Fig. 1), an d the methods th at were based on the empirical the p pipeline industry. Whether this can be said of the industry at the start of the 21st century is another matter. Such a failure will impede the development of new design and integrity solutions (high pressure, high stress, high strain, etc.).

The pioneering work in the 1960s and 70s made use of ‘leading edge’ knowledge of fracture mechanics, an d th is fundamental research w as act ively supported by the pipeline industry. The original equations and test data, illustrating flow stress and toughness dependent behaviour have been developed to permit easy implementation of the ‘best’ methods. The role of PDAM in the fitness-for-purpose assessment of a defect in a pipeline is summarised in Fig. 9.

PDAM ha s b een closely scrutinised throughout its development by the sponsors, an d al l literature reviews an d 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.

4. TYPES OF DEFECT CONSIDERED IN THE PIPELINE DEFECT ASSESSMENT MANUAL

PDAM contains guidance on 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 therefore as sessment of defects in pipe fittings (pipe work, fittings, elbows, etc.). Guidance is also given on predicting the behaviour of defects on penetration of 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. In summary, the assessment of defects subject to static or cyclic internal pressure loading is understood, but, in general, other loads and combined loading are not.

5. 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 brief 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. Brief notes th at highlight particular problems as 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. An example of the flow chart for the assessment of a smooth dent containing a gouge is given in Fig. 10.

6. ASSESSMENT METHODS IN THE PIPELINE DEFECT ASSESSMENT MANUAL

A summary of all of the methods recommended in the Pipeline Defect Assessment Manual for predicting the burst strength of a defect subject to internal pressure is given in Table 3. Longitudinally and circumferentially oriented defects are considered. The primary methods (indicated in normal font) are plastic collapse (flow stress dependent or limit state) failure criteria, and a more or less appropriate if the 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. Plastic collapse (flow stress dependent or limit state) toughness limits are based on fracture mechanics, given in BS 7910 (and API 579) can be applied in general (irrespective of upper or lower shelf behaviour), but will generally be conservative compared to the pipeline specific methods.

Having given an overview of the contents of P DAM, the remainder of this paper (1) describes the role of toughness and gives empirical toughness limits for the application of flow stress dependent assessment methods, and (2) gives specific guidance on the assessment of gouges and dents and gouges.

7. TOUGHNESS LIMITS

Line pipe steels is generally tough and ductile, and operates on the upper shelf. In initiation and propagation of a partial wall flaw through the wall occurs under ductile fracture mechanism, involving some combination of plastic flow and crack initiation and ductile tearing, involving a process of void nucleation, growth and coalescence. The relative importance of plastic flow and crack initiation and ductile tearing depends on the toughness of the material and the geometry of the defect. Fig. 2 is an illustration of the role of toughness in the failure of a part-wall defect.

![Fig. 2 The effect of material toughness, defect depth, length and acuity on burst strength](image)

As the toughness decreases the burst strength of a defect will decrease. As the toughness increases the burst strength of a defect will increase, but thinning towards an upper limit corresponding to the plastic collapse limit state, where failure occurs due to plastic flow (and can be predicted using limit state methods). Therefore, if the toughness is greater than some minimum value then the failure of a defect will be controlled by plastic collapse and only knowledge of the tensile properties of the material is required to predict the burst strength (as demonstrated in the transition between the toughness dependent and flow stress forms of the NG-18 equations).

The upper bound to the strength of a material is the ultimate tensile strength. If failure is due to plastic collapse then the low strength should be greater than the ultimate tensile strength; failure will occur when the stress in the remaining ligament exceeds . The minimum toughness necessary to ensure that failure is controlled by plastic collapse may be defined empirically as a bove which a given collapse. The DWTT transition temperature is defined as the temperature at which a DWTT specimen exhibits 85 percent shear area. The steel is on the upper shelf if the DWTT transition temperature is less than the current temperature of the steel.

*3* PAFCC incorporates co-relation between fracture toughness and the upper shelf Charpy impact energy; therefore, PAFCC is not applicable to lower shelf (although the theoretical model is applicable if the fracture toughness (K, J or D) is measured).

*4* Brittle (cleavage) fracture can occur in older line pipe steels or under unusual (typically upset) conditions which can cause low temperatures. If the DWTT (Drop Weight Tear Test) transition temperature is less than the minimum design temperature, then initiation will be brittle. A higher upper shelf Charpy V-notch impact energy is also desirable to ensure that failure is controlled by plastic collapse. The 2/3 thickness specimen size equivalent is between 54 J and 68 J.
flow stress dependent" (or pseudo plastic collapse) failure criterion will give reasbaly conservative predictions (taking into account experimental scatter). This is not equivalent to stating that failure is due to plastic collapse. The empirical minimum toughness may be lower than the true minimum toughness because the inherent conservatism in the flow stress dependent failure criteria typicallly leads to plastic collapse because of the inherent experimental scatter. This is not equivalent to "flow stress dependent" (or pseudo plastic collapse) failure criteria.

Wall thickness is also important because of the transition from plane to plane strain behaviour and the increase in constraint with increasing wall thickness. Pipelines are typically thin walled structures (the wall thickness is seldom greater than 1 in. (25.4 mm)). A minimum toughness lower than 1 in. is defined with respect to a minimum wall thickness. Defect acuity is also considered, blunt defects are less sensitive to toughness than sharp defects. Blunt defects record higher burst strengths in low to moderate toughness steels.

**Toughness Limits for the NG-18 Equations** Empirical minimum toughness limits for the applicability of the flow stress dependent though-wall and part-wall NG-18 equations can be defined by reference to the results of relevant full scale burst tests (see section 8.1).

The effect of toughness on the accuracy of predictions of the burst strength of an axially orientated, machined, part-wall defect made with the flow stress dependent part-wall NG-18 equations is illustrated in Fig. 3. A flow stress of the average of \(\sigma_t\) and \(\sigma_i\) is used (Eqs. (1) to (3), below). The prediction becomes non-conservative at a lower toughness. The scatter in the range from 20 J to 45 J is also lower than that of a through-wall defect. Failure by plastic collapse, as defined by reference to a minimum wall thickness of 21.9 mm. The maximum wall thickness is 21.9 mm. The difference between part-wall and through-wall defects follows the same trend as tests at 21.9 mm, with the part-wall defect being lower than the through-wall defect. 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 methods are as indicated. In all cases, the basic assumption is that the line pipe steel is on the upper shelf.

**Corrosion** The lowest toughness is 18 J (13 ftlb) and the maximum wall thickness is 22.5 mm (1.0 in.).

**Range of Toughness from Published Data** 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 is summarised below.

![Fig. 3 The effect of toughness on predictions of part-wall burst tests made using the flow stress dependent part-wall NG-18 equation](image)

A similar analysis of tests of axially orientated, machined, through-wall defects in line pipe indicates that a minimum 2/3 specimen thickness upper shelf Charpy V-notch impact energy of 40 J (29.5 ftlb) is necessary for the flow stress dependent through-wall NG-18 failure criterion to be applicable. The maximum wall thickness is 21.9 mm. The difference between part-wall and through-wall defects follows the same trend as tests at 21.9 mm, with the part-wall defect being lower than the through-wall defect.

6 The toughness is not reported in a number of tests; these tests are shown in Fig. 3 as having zero toughness to indicate the range of the test data.

7 Note that the Charpy impact energy is not reported for all of the tests.
assessing corrosion have been validated in line pipe with a wall thickness greater than 25.4 mm.

**Gouges** The lowest toughness is 14 J (10 ft lbf) 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 52 J.

The maximum wall thickness is 19.0 mm (0.75 in.).

**Tests in line pipe** have also been carried out. The tests in line pipe were conducted by a number of different organisations. Tests in line pipe have been conducted by a number of different organisations. Tests in line pipe have been conducted by a number of different organisations.

### 8.1 FULL SCALE BURST TESTS OF ‘GOUGES’

A gouge is surface damage to a pipeline caused by contact with a foreign object that has scrapped (gouged) material out of the pipe, resulting in a metal loss of the effect. The material at the base of the gouge will have reduced ductility and may contain cracking. A gouge may be of any orientation with respect to the pipe axis. A longitudinally orientated gouge is the most severe orientation.

A gouge reduces the burst and fatigue strength of the pipe. A gouge may be of any orientation with respect to the pipe axis. A longitudinally orientated gouge is the most severe orientation.

### 8.2 METHODS FOR PREDICTING THE BURST STRENGTH OF A GOUGE

The assessment of the burst strength of part-wall defects in pipelines derives from work conducted at Battelle in the 1960s and 1970s, culminating in the development of flow stress dependent and toughness dependent forms of both wall and part-wall failure criteria (the NG-18 equations)[5]. The through-wall and part-wall criteria are semi-empirical. The through-wall failure criterion was developed and validated against the results of 92 full scale vessel burst tests containing artificial, longitudinally-orientated, through-wall defects. The part-wall failure criterion was developed and validated against the results of 48 full scale vessel burst tests containing artificial, longitudinally-orientated, machined V-shaped notches.

The flow stress dependent part-wall failure criterion has been widely used as a plastic collapse solution for axial crack-like flaws subject to internal pressure, and appears in documents such as BS 7910 and API 579. Several previously published revews have concluded that the NG-18 equations are the ‘best’ equations for assessing part-wall defects such as gouges[32,33]. The part-wall NG-18 equations are also recommended in the EP RG guidelines for the assessment of mechanical damage[11].

The flow stress dependent part-wall NG-18 equation is as follows:

$$\sigma = \frac{1 - \frac{t}{d}}{1 - \frac{t}{d} \left( \frac{1}{M} \right)}$$

$$\sigma$$ is the flow stress, which is an empirical concept intended to represent the stress at which unconstrained plastic flow occurs in a train h ardening elastic-plastic material via a single parameter. One commonly used definition of the flow stress is

$$\sigma = \frac{\sigma_f + \sigma_U}{2}$$

$$M$$ is the Foliass factor, representing the stress concentration due to the bulging that occurs under internal pressure loading. The

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8 The tests marked with an asterisk have not been included in the statistical comparison of the two methods.

9 Note that there is a large difference between the test temperature and the temperature at which the material properties were measured.
analytical solution for the Folias factor is an infinite series. Three commonly used approximations are given below.

\[ M = \sqrt{1 + 0.26 \left( \frac{2c}{\sqrt{Rt}} \right)^2} \]  
(3)

\[ M = \sqrt{1 + 0.314 \left( \frac{2c}{\sqrt{Rt}} \right)^2 - 0.00084 \left( \frac{2c}{\sqrt{Rt}} \right)^4} \]  
(4)

\[ M = \sqrt{1 + 0.40 \left( \frac{2c}{\sqrt{Rt}} \right)^2} \]  
(5)

Equation (5) is the expression that appears in ASME B31G. It is the most conservative approximation. Equation (4) appears in modified B31G and RSTRENG. Equation (3) is a close approximation to Eq. (4) that is valid for \( 2c/(Rt)^{0.5} \) greater than 8.0.

The growth through wall of a sharp, part-wall defect in ductile line pipe occurs through some combination of plastic flow and ductile tearing. The NG-18 equations do not explicitly consider the effects of ductile tearing on the failure of through-wall and part-wall defects. A more sophisticated method for assessing part-wall defects, such as gouges, is PAFFC[9].

![Graph showing comparison of NG-18 equation with test data](image)

**Fig. 4 Failure stress of axially orientated part-wall defects predicted using the part-wall NG-18 equation**

### 8.3 COMPARISON WITH TEST DATA

The flow stress dependent form of the part-wall NG-18 equations is the ‘best’ method in terms of the quality of fit with the published test data for predicting the burst strength of a gouge. However, this equation has been published with different definitions of the flow stress and the Folias factor (\( M \)). Consequently, the various forms of the NG-18 equations have been compared using the published test data. On ly tests of machined notches have been considered. Tests where there is insufficient data and where the upper shelf 2/3 thickness size Charpy impact energy is less than 21 J (see section 7, above) have been excluded. The total number of full scale tests considered in the comparison is 71. The statistics of the ratio of the actual failure stress to the predicted failure stress are given in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>standard deviation</th>
<th>coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) two term Folias (Eq. 5)</td>
<td>1.06</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>three term Folias (Eq. 4)</td>
<td>1.02</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>approximate Folias (Eq. 3)</td>
<td>0.99</td>
<td>0.13</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Note: (1) average of yield strength and tensile strength, (2) yield strength plus 10 ksi, and (3) tensile strength.

### Table 1 Statistical comparison of NG-18 equation with several forms of the Folias factor and flow stress

There is little difference between the three forms of the Folias factor, the approximate two term factor (Eq. (3)) and the three term factor (Eq. (4)) being almost identical; similarly for a flow stress of the average of \( \sigma_Y \) and \( \sigma_U \), and one of \( \sigma_l \) plus 10 ksi (as quoted in Kiefner et al. (1973)). A flow stress equal to \( \sigma_l \) gives, on average, non-conservative predictions, and a slight increase in the scatter. A comparison between the predictions made using the NG-18 equation, with a flow stress of the average of \( \sigma_U \) and \( \sigma_U \) and the two term Folias factor (Eqs. (1) to (3)), and the published full scale test data is shown in Fig. 4.

### 8.4 RECOMMENDATION IN PDAM

PDAM recommends the semi-empirical NG-18 part-wall flow stress dependent failure criterion with the approximate two term Folias factor and a flow stress of the average of yield strength and tensile strength (Eqs. (1) to (3)). The equations should not be applied if the 2/3 thickness specimen size upper shelf Charpy V-notch impact energy is less than 21 J (16 ft lb). The wall thickness must be less than 21.7 mm.

The part-wall NG-18 equation does not give a lower bound estimate; accordingly, a ‘model uncertainty’ has been derived. The effect of applying a confidence interval corresponding to a 95 percent one-tail confidence level is illustrated in Fig. 5; note that all of the tests with a toughness greater than 21 J are conservatively predicted.
When assessing a gouge it is important to consider the possibility of cracking at the base of the gouge and the presence of a dent. An assessment can be non-conservative if these issues are not considered. This may mean that it is necessary to excavate the pipeline to perform a detailed inspection of the damage. It is suggested that the measured depth of a gouge be increased by 0.5 mm to account for the possibility of cracking at the base of the gouge, unless an inspection technique is used to detect and measure cracking.

![Graph](image)

**Fig. 5** Failure stress of axially orientated part-wall defects predicted using a lower bound to the part-wall NG-18 equation

**8.5 RANGE OF APPLICABILITY**

The recommended method for assessing the burst strength of a longitudinally orientated gouge has been compared against the results of 92 full scale burst tests of vessels containing artificial, machined part-wall defects and gouges, including some materials other than line pipe steel. The range of the test data included in the comparison is as follows (in SI units). This gives an indication of the range of applicability of the part-wall NG-18 equation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
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<tbody>
<tr>
<td>Pipe Diameter, mm</td>
<td>114.0 to 1422.4</td>
</tr>
<tr>
<td>Wall Thickness, mm</td>
<td>5.6 to 21.7</td>
</tr>
<tr>
<td>(2R/t) ratio</td>
<td>13.3 to 104.0</td>
</tr>
<tr>
<td>Grade (API 5L)</td>
<td>X52 to X100</td>
</tr>
<tr>
<td>Yield strength, Nmm(^2)</td>
<td>379.2 to 878.0</td>
</tr>
<tr>
<td>Tensile strength, Nmm(^2)</td>
<td>483.3 to 990.0</td>
</tr>
<tr>
<td>Yield to tensile ratio</td>
<td>0.69 to 0.99</td>
</tr>
<tr>
<td>2/3 Charpy Impact Energy, J</td>
<td>13.6 to 261.0</td>
</tr>
<tr>
<td>Notch Depth (d), mm</td>
<td>0.49 to 16.8</td>
</tr>
</tbody>
</table>

\(d/t\) 0.088 to 0.92
Notch Length (2c), mm 14.0 to 609.6
\(2c/(Rt)^{0.3}\) 0.41 to 8.16
Burst Pressure, Nmm\(^2\) 1.84 to 142.0
Burst Stress, Nmm\(^2\) 61.4 to 880.7
Burst Stress (percent SMYS) 13.7 to 132.5

**9. THE ASSESSMENT OF THE BURST STRENGTH OF A DENT AND GOUGE IN PDAM**

A dent is a depression which produces a gross disturbance in the curvature of the pipe, caused by contact with a foreign body resulting in plastic deformation of the pipe. External interference can cause both metal loss defects (gouging) and dents.

A dent containing a gouge (or other type of metal loss defect) is a very severe form of damage. The burst strength of a smooth dent containing a gouge is lower than the burst strength of an equivalent plain dent, and lower than that of an equivalent gouge in undented pipe. The fatigue strength of a smooth dent containing a gouge is lower than that of an equivalent plain dent.

**9.1 FULL SCALE BURST TESTS OF DENTS AND ‘GOUGES’**

A large number of full scale ring and vessel burst tests of a smooth dent containing a single ‘gouge’ have been conducted by a variety of different organisations, see below. The total number of published tests is 242. However, most of the tests have actually been of machined notches or slots, rather than gouges. A variety of different test methods have been used, as indicated below. All of the machined notches (slots) and gouges have been longitudinally orientated, except for the Gasunie tests in which transverse dents were introduced into pipe.

The tests can be variously described as follows:

1. Damage introduced at zero pressure; introduce the dent and then machine a ‘V-shaped’ notch (artificial gouge) in the base of the dent
   - British Gas (1982, 1989) \([24,34]\) (108 ring tests and 23 vessel tests)
   - Tokyo Gas (1998\*) \([35]\) (vessels) (3 tests)

2. Damage introduced at zero pressure; machine a ‘V-shaped’ notch (artificial gouge) and then introduce the dent
   - Battelle (1979, 1986) \([22,36-38,39]\) (vessels) (30 tests)
   - Nanyang Technical University (1992\*) \([40]\) (vessels) (17 tests)

3. Damage introduced at zero pressure; machine a ‘V-shaped’ notch (artificial gouge) and then introduce the dent (a sharp steel triangular block was inserted in the notch between the cylindrical indenter and the pipe)
   - DNV (2000) \([41]\) (vessels) (1 test)

4. Damage introduced at zero pressure; introduce the dent and then scrape (gouge) the pipe using a tool bit mounted on a pendulum

\(11^*\) The tests marked with an asterisk have not been included in the statistical comparison of the two methods.
5. damage (dent) introduced at pressure; machine a ‘V-shaped’ notch (artificial gouge) at zero pressure and then introduce the dent at pressure
- S ES (1996) (vessels) (14 tests)

6. damage (dent) introduced at pressure; gouge at zero pressure and then introduce the dent at pressure
- EPRG (1991*, 1992*) (vessels) (8 tests)

7. damage introduced at low pressure (150 psi) or zero pressure; damage introduced using an indenter with a machined sharp edge (with a 60 deg. ree in cluded an gle) along its length
- Battelle (1978*) (vessels) (2 tests)

8. damage introduced at pressure; dent and gouge introduced simultaneously using a specially designed test rig
- British Gas (1983*) (vessel) (1 test)
- Battelle (1986*) (vessels) (17 tests)

9. damage (transverse dent) introduced at pressure and gouge introduced at zero pres sure; dent at pressure, depressurise (holding indenter in place) and then scrape (gouge) the pipe using the indenter
- Gasunie (1986*, 1990*) (vessels) (10 tests)

10. damage introduced at pres sure; machine a blunt (rounded) notch at zero pressure and then introduce the dent at pressure

11. damage introduced at zero pressure; machine a 1 in. wide slot (artificial corrosion) and then introduce the dent
- S ES (1997*) (vessels) (3 tests)

Internal pressure s tiffens t he res ponse of t he pipe t o press u re), the gouge length, and the gouge depth.

Internal pressure stiffens the response of the pipe to pressure, the gouge length, and the gouge depth.

The behaviour of a dent containing a gouge is complex. A dent and gouge is a geometrically unstable structure. The base of the gouge may contain crack ing and the properties of the material in the dent are affected adversely. Outward movement of the dent promotes initiation and growth of cracking in the base of the gouge, changing the compliance of the dent and gouge structure. The failure of a dent and gouge defect involves high plastic strains, wall thinning, movement of the dent, crack initiation, ductile tearing and plastic flow. An analysis of the failure mechanism of a dent and gouge defect is described by Leis et al. (2000).

Empirical relationships for predicting the burst strength of a smooth dent containing a gouge have been proposed by British Gas, the EP RG, Battelle, and others. A semi-empirical fracture model was adopted by the EP RG, which includes more sophistication in the failure mechanism of a dent and gouge defect.

The two most quoted models for predicting the burst strength of a smooth dent containing a gouge based on the results of full scale burst tests, in which the damage was introduced at zero pressure by notching and then denting the pipe. The failure stress, normalised by the flow stress, was related to an empirical parameter, denoted $Q$. The model is defined as a function of the upper shelf Charpy impact energy (for a 2/3 size specimen), the dent depth, and the gouge depth.

The empirical relationship is given by the following equations (in imperial units)

$$\frac{\sigma_f}{\sigma} = \frac{(Q - 300)^{0.6}}{90} \quad (6)$$

$$Q = C_1 \left( \frac{H}{2R} \right) \left( \frac{d}{t} \right) \quad (7)$$

$$\sigma = \sigma_f + 100000 \text{ psi} \quad (8)$$

Fig. 6 shows a comparison between the predictions made using the empirical $Q$ factor model and the published full scale test data.

The Dent-Gouge Fracture Model The dent-gouge defect is modelled as an axially oriented, continuous dent (of constant width) with a single, infinitely long, axially oriented, sharp notch located at the base of the dent. The length of the dent or the gouge is not considered. The elevated membrane and bending stresses at the base of the dent are considered, through an approximate solution based on thin shell theory and Castigliano’s second theorem. The underlying fracture model,
considering the reaction between fracture (toughness) and plasticity, is a collapse modified strip-yield model. The model was calibrated using the results of 111 ring and 21 vessel burst tests of smooth dents containing machined notches (notch then was calibrated using the results of 111 ring and 21 vessel burst plasticity, is a collapse modified strip-yield model. The model considering the reaction between fracture (toughness) and vessel test data, therefore, the correlation between Charpy and fracture toughness is not generally applicable).

The dent-gouge fracture model is defined as follows (in SI units)

\[
\sigma = 2\pi \cos^{-1} \left[ \exp \left( \frac{1.5\pi E}{\sigma^2 A_d} \left[ Y_1 \left( 1 - 1.8 \frac{H_o}{D} \right) + Y_2 \left( 10.2 \frac{R H_o}{t D} \right) \right] \right)^2 \right]^{1/2}
\]

\[
Y_1 = 1.12 - 0.23 \left( \frac{d}{t} \right) + 10.6 \left( \frac{d}{t} \right)^2 - 21.7 \left( \frac{d}{t} \right)^3 + 30.4 \left( \frac{d}{t} \right)^4
\]

\[
Y_2 = 1.12 - 1.39 \left( \frac{d}{t} \right) + 7.32 \left( \frac{d}{t} \right)^2 - 13.1 \left( \frac{d}{t} \right)^3 + 14.0 \left( \frac{d}{t} \right)^4
\]

\[
K_1 = 1.9
\]

\[
K_2 = 0.57
\]

\[
H_o = 1.43 H_f
\]

The flow stress assumed in the dent-gouge fracture model is not appropriate for higher grade steels (greater than X65), due to the increasing yield to tensile ratio with line pipe grade.

The dent-gouge fracture model is based on tests in which the damage was introduced at zero pressure, and the dent depth is the atfer spring back and measured at zero pressure. Therefore, a correction must be made for dents introduced at pressure and measured at pressure. A semi-empirical rerouting correction factor developed by the EPRG is proposed (Eq. (11)). This correction factor relates the dent depth (after the removal of the indenter) measured at pressure to that measured at zero pressure, for dents introduced at zero pressure. It is worth noting that in the empirical correction is based on limited test data, and that alternative methods have been developed which should be more robust (e.g., Rosenfeld (1998) [57]), although there is limited test data available to validate such methods and they require more in formation than is given in the relevant published tests. There have been no burst tests which have directly compared the effect of denting at pressure and denting at zero pressure on the failure behavior of a smooth dent containing a gouge. Consequently, correcting for denting at pressure remains an area of considerable uncertainty.

\[
\sigma_0 = \frac{2}{\pi} \cos^{-1} \left[ \exp \left( \frac{113}{\sigma^2 A_d} \left[ Y_1 \left( 1 - 1.8 \frac{H_o}{D} \right) + Y_2 \left( 10.2 \frac{R H_o}{t D} \right) \right] \right)^2 \right]^{1/2}
\]

\[
Y_1 = 1.12 - 0.23 \left( \frac{d}{t} \right) + 10.6 \left( \frac{d}{t} \right)^2 - 21.7 \left( \frac{d}{t} \right)^3 + 30.4 \left( \frac{d}{t} \right)^4
\]

\[
Y_2 = 1.12 - 1.39 \left( \frac{d}{t} \right) + 7.32 \left( \frac{d}{t} \right)^2 - 13.1 \left( \frac{d}{t} \right)^3 + 14.0 \left( \frac{d}{t} \right)^4
\]

\[
K_1 = 1.9
\]

\[
K_2 = 0.57
\]

\[
H_o = 1.43 H_f
\]

Fig. 7 shows a comparison between the predictions made using the semi-empirical dent-gouge fracture model and the published full scale test data.

### 9.3 COMPARISON WITH TEST DATA

The empirical Q factor model and the dent-gouge fracture model are compared against the published test data in order to determine the ‘best’ method in terms of the quality of fit with the test data. A number of the tests can not be considered because of the absence of toughness, actual material properties or dent depth after spring back measured at zero pressure. Tests involving transverse dents or tests in which the ‘gouge’ length has been ground smooth have also been excluded.

The total number of full scale tests considered is 162, including 93 ring tests and 69 vessel tests. The formulation of the Q factor model is such that if Q is less than 300 ft.lbf.in⁻², then the failure stress cannot be defined. Therefore, although the ‘gouge’ length is given for all of the 69 vessel tests, the Q factor model can only be applied to 55 of these tests.

<table>
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<td>0.48</td>
<td>0.44</td>
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<td>1.80</td>
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<td>Q factor</td>
<td>1.45</td>
<td>0.88</td>
<td>0.61</td>
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Note: (1) all tests, (2) limited number of tests (refer to text).

### Table 2 Statistical analysis of predictions made using the semi-empirical dent-gouge fracture model (EPRG) and the empirical Q factor model (PRCI)

The statistics of the ratio of the actual failure stress to the predicted failure stress for the two models are given in Table 2. Two subsets of the test data are considered: in (1) all of the tests applicable to each model are considered, whilst in (2) the tests are limited to those to which the Q factor model can be applied, and therefore, a comparison is 162, including 93 ring tests and 69 vessel tests. The formulation of the Q factor model is such that if Q is less than 300 ft.lbf.in⁻², then the failure stress cannot be defined. Therefore, although the ‘gouge’ length is given for all of the 69 vessel tests, the Q factor model can only be applied to 55 of these tests.

| (1) fracture model | 1.09 | 0.48 | 0.44 |
| Q factor | 1.80 | 2.02 | 1.12 |
| (2) fracture model | 1.23 | 0.64 | 0.52 |
| Q factor | 1.45 | 0.88 | 0.61 |

Note: (1) all tests, (2) limited number of tests (refer to text).
the predictions of dent-gouge tests compared to the predictions of gouges and notches in undented pipe using the part-wall NG-18 equation (see above).

Fig. 6 Failure stress of dent and gouge defects predicted using the empirical Q factor model

Fig. 7 Failure stress of dent and gouge defects predicted using the semi-empirical dent-gouge fracture model

9.4 RECOMMENDATION IN PDAM

PDAM recommends the dent-gouge fracture model for assessing the burst strength of a smooth dent containing a single, axially orientated gouge.

The dent-gouge fracture model does not give a lower bound estimate of the burst strength of a combined dent and gouge, accordingly a model uncertainty has been derived. The effect of applying a confidence interval corresponding to a 95 percent one-tail confidence level is illustrated in Fig. 8.

The assessment of a dent and gouge defect is difficult. The morphology of the damage is such that ultrasonic inspection techniques may not be reliable. In this case the measured depth of the gouge be increased by 0.5 mm, as discussed above.

Fig. 8 Failure stress of dent and gouge defects predicted using a lower bound to the semi-empirical dent-gouge fracture model

9.5 RANGE OF APPLICABILITY

The dent-gouge fracture model has been compared against the results of 162 full scale burst tests of rings and vessels containing dent-gouge defects or dent-notch defects. The range of the test data included in the comparison is given below (in SI units). This gives an indication of the range of applicability of the dent-gouge fracture model.

Pipe Diameter, mm 216.3 to 1066.8
Wall Thickness, mm 4.8 to 20.0
2R/t ratio 33.6 to 107.7
Grade (API 5L) X42 to X65
Yield strength, Nmm⁻² 279.2 to 543.3
Tensile strength, Nmm⁻² 475.0 to 701.2
yield to tensile ratio 0.61 to 0.87
2/3 Charpy Impact Energy, J 16.3 to 130.7
Dent Depth, mm 1.5 to 146.5
H/2R 0.42 to 18.0
Notch Depth (d), mm 0.18 to 6.1
d/t 0.014 to 0.51
Notch Length (2c), mm 50.8 to 810.0
2c/(Rt)² 0.84 to 8.98
Burst Pressure, Nmm⁻² 0.972 to 25.24
Burst Stress, Nmm⁻² 29.2 to 626.8
Burst Stress (percent SMYS) 7.05 to 151.5
ACKNOWLEDGMENTS

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REFERENCES


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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 term ‘manufacturing defect’ covers a wide range of pipe body defect (laminations, inclusions, seams, cold shuts, gouges, plug scores, pits, rolled-in slugs, etc.). Consequently, it may not be possible to characterise a manufacturing defect in the pipe body as a metal-loss or crack-like defect, it is then generally necessary to rely on workmanship limits and industry experience.
3. Environmental cracking (stress corrosion cracking, hydrogen blisters, hydrogen stress cracking, etc.) can be very difficult to assess and cannot necessarily be simply characterised as a crack-like defect.

Table 3 Recommended methods the Pipeline Defect Assessment Manual for assessing the burst strength of defects subject to static internal pressure loading
1. Identify defect dimensions.
2. Identify appropriate section of the pipeline defect assessment manual.
3. Consult 'defect specific' flow chart.
4. Consult background information as necessary.
5. Identify defect assessment method.
6. Conduct fitness-for-purpose assessment:
   1. Static loads
   2. Cyclic loads
7. Consider consequences of a failure.
8. Acceptance criterion (safety factor).
10. Refine fitness-for-purpose assessment, seek specialist assistance, or take appropriate remedial action.
11. Review the defect as acceptable?
12. Yes, no further assessment required.
14. Consult description of method as necessary.
15. Consult applicable method.
16. Minimum information required to undertake the assessment.
17. Regulations and design codes and standards.

Fig. 9 The role of the Pipeline Defect Assessment Manual in the fitness-for-purpose assessment of a pipeline defect.
Indications of low toughness include: old linepipe, linepipe not manufactured to API 5L, or an operating temperature less than the DWTT transition temperature.

Fig. 10 The assessment of a smooth dent containing a gouge