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ASSESSMENT OF FLAWS IN PIPE GIRTH WELDS[*]

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Abstract

This paper is a review of recent work aimed at assessing the significance of circumferential flaws in pipeline girth welds with respect to avoiding failure due to fracture, including excessive ductile crack extension, and local plastic collapse. One of the objectives of such assessments is to define maximum tolerable flaw sizes and so avoid unnecessary weld repair without compromising the integrity of the pipe. The review focuses on installation and operational conditions that give rise to axial plastic straining in the pipe. It is shown that stress-based assessment methods can be modified to obtain acceptably safe outcomes, but it is also shown that they do have limitations. Strain-based assessment methods are introduced which appear to provide a more robust approach. However, these will require experimental validation before a codified procedure is developed and generally accepted by the industry.

Introduction

Fracture mechanics based assessment procedures are commonly used to define flaw acceptance criteria for girth welds in both onshore and offshore pipelines. These provide an alternative to the so-called ‘workmanship based’ criteria described in pipeline welding codes such as API 1104 [1] and DNV OS F101 [2]. Often, use of workmanship based flaw acceptance criteria can require a higher rate of repair and increased costs, mainly arising from the delay to installation, but without any significant benefit to the integrity of the girth welds. Indeed, there have been instances where an improperly executed repair has initiated failure. The fracture mechanics based procedures such as those described in BS 7910 [3], provide a quantitative means for deciding which welding flaws, identified by non-destructive testing, potentially compromise weld integrity with respect to defined failure criteria and require repair, and those that do not. Although more effort and expenditure are required to carry out the necessary testing and fracture mechanics analyses prior to installation, this is far out-weighed by the benefits in reducing repair costs and delays during pipe-lay operations.

In addition, most workmanship based flaw acceptance criteria are based on the assumption that weld inspection is carried out using radiography, which generally only provides quantitative information about flaw length and lateral position across the weld. It does not provide critical information about flaw height which primarily governs the stability of the flaw. Furthermore, unless favourably orientated with respect to the beam, tight crack-like flaws can be missed. However, ultrasonic based inspection methods are well suited to finding planar or crack-like flaws and techniques such as Automated Ultrasonic Testing (AUT) are increasingly being used to inspect pipeline girth welds and these provide more information about the flaw, especially flaw height and through-wall position; these dimensions have a significantly greater effect on

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integrity than flaw length alone. After making suitable adjustments for flaw sizing uncertainty, fracture mechanics methods are necessary to interpret such data in order to sentence welding flaws for acceptance or repair.

Currently, the fracture mechanics codes that are applied to assessment of pipeline girth welds are essentially stress-based. This means that they are not strictly applicable when the applied longitudinal stress exceeds the actual yield strength of the pipe. For many pipeline installation methods and operating conditions, the applied longitudinal stress is below yield. However, there are a number of installation methods, such as pipe reeling which is used for offshore pipelines, where the welded pipeline is subjected to plastic straining often involving more than one cycle. The strains developed during installation depend on the pipe and reel diameters but are typically in the range of 1-3%. During service, both offshore and onshore pipelines can be subjected to ground movement (e.g. seismic loading, landslip) or temperature changes (lateral buckling) which can also result in longitudinal plastic straining in addition to internal pressure. Under these extreme loading conditions it is essential that any flaws in the girth weld do not extend sufficiently to cause release of pipe contents or initiate unstable fracture.

Strain-based fracture mechanics assessment procedures are significantly more complex than stress-based methods; they require more input data in terms of material properties and loading conditions. Also, codified strain-based methods have yet to be published. Use of 3-D elastic-plastic finite element analysis is sometimes employed for critical projects, but often the timeframe imposed by pipeline projects prevents extensive use of such techniques. Furthermore, there is always the question of validation and whether flaw sizes derived from such analyses are fully supported by full-scale tests. Since it is usual to analyse a large number of pipe conditions and flaw cases, code based, closed-form solutions are desirable in preference to running a large number of finite element analyses. The derivation of such closed-form solutions is not straightforward owing to the large number of variables that need to be considered when plasticity takes place. Progress is being made in this area but a complete solution is not yet available. In the following sections, techniques that are currently being used are outlined.

Assessment of Girth Welds for Stresses Below Yield

Before discussing the assessment of girth weld flaws in pipes subjected to strains above yield, it is worth making some observations about assessments for stress below the specified minimum yield strength of the pipe. A general procedure that has been used extensively is BS 7910 [3]. Although this is a general assessment procedure its versatility enables it to be adapted to pipeline girth welds. The procedure not only enables flaw significance to be assessed with respect to avoidance of failure by fracture or plastic collapse, the effects of stable crack extension by ductile crack growth (tearing) and fatigue crack growth can be incorporated. The procedure incorporates the effects of welding residual stresses in the fracture assessment. Since the precise distribution of residual stresses through the pipe wall thickness are not known, the procedure assumes that the residual stress transverse to the weld is uniform and is of yield strength magnitude. Where the weld metal strength over-matches that of the parent pipe, the yield strength assumed is that of the parent pipe. The assumption of yield residual stress has been criticised as conservative, which it is and is intended to be. However, it is often forgotten that the procedure allows this stress to be relaxed to a lower value depending on the applied stress and flaw size. In addition, the procedure does enable an actual residual stress distribution to be incorporated if this has been measured. Furthermore, if the welding conditions are known, guidance is provided to calculate a conservative distribution. Future revisions of BS 7910 will incorporate more comprehensive guidance for girth welds [4]. Ignoring residual welding stresses is potentially dangerous since their presence will increase the driving force for fracture.

It is of interest to note that the 2007 amendment to the 20th edition of API1104 [1] does not appear to specifically address welding residual stresses. The procedure is CTOD based. It implies that residual stresses are only of concern when materials with very low fracture toughness are being considered and such materials are excluded from the assessment because the minimum CTOD has to exceed 0.05 mm at the assessment temperature [5].

Another feature of BS 7910 which is particularly relevant to girth welds is the misalignment or "hi-lo". This is treated as a bending stress which is derived from equations providing stress concentration factors. Misalignment can have a significant effect on increasing the driving force, as illustrated in Figure 1 which was derived from finite element analyses carried out at TWI. For the case considered, the CTOD requirement is doubled at applied strains close to yield (0.5% strain) when misalignment is increased from zero to 3 mm. For larger strains, the gap increases. Since it is not always obvious how misalignment should be treated in assessment to BS 7910, the bending stress that is generated is often treated as a primary stress. This means that it contributes to both the fracture (K_r) and plastic collapse (L_r) axis of the failure analysis diagram (FAD); this is a conservative approach. Recent work at TWI [6] has shown that for materials with smoothly rising stress-strain curves and for applied strains below yield, misalignment can be treated as a secondary stress; that is, it acts as a local stress concentration and does not contribute to plastic collapse (L_r axis of the FAD) but contributes only to the fracture axis (K_r). For strains above yield strain, misalignment starts to contribute to the primary stress in addition to the secondary stress. Similar conditions apply to materials with a yield discontinuity (Lüders plateau) but the applied strain at which misalignment can be treated as secondary needs to be below 0.3%.

Interestingly, the API 1104 flaw assessment procedure does not specifically consider misalignment. Whether this is allowed for by safety factors included in the procedure is not clear, but it does reduce its flexibility in comparison with BS 7910.

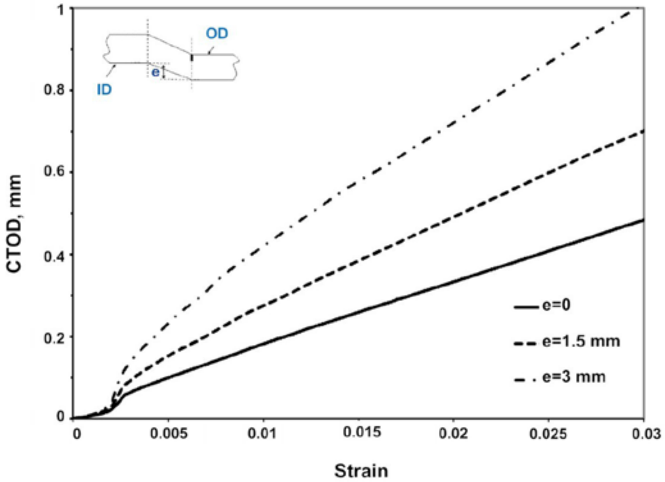

Figure 1. Effect of misalignment (e) in a 400 mm OD x 20 mm WT X65 pipe with a 3x50mm flaw on the OD.

Assessment of Girth Welds Involving Plastic Strain During Installation

Assessment Procedure

One assessment method which is commonly applied to define flaw acceptance criteria for girth welds employed in reeled pipeline is an extension of the stress-based method described in BS 7910. It was developed by a team involving DNV, TWI and SINTEF and is now codified in Recommended Practice, DNV RP F108 [7]. The procedure is also referred to in DNV OS F101 [2], which describes offshore pipeline design in general. The novel features of the method are that the stress-strain curve from the parent pipe is used to derive the stress from the maximum reeling strain for each stage in the reeling process (reeling-on, reeling-off and including straightening). The procedure accommodates misalignment at the girth weld, which can locally increase strain, using a combination of the elastic stress concentration factor and the Neuber method to transform stress into strain. The Neuber method enables the strain concentration factors arising from local geometric discontinuities such as misalignment and differences in pipe wall thickness, to be transformed into strains which are additive to the globally applied strain.

The Neuber equation is stated as follows:

$$\sigma_{Neuber}\, \varepsilon_{Neuber} = \sigma_{nominal}\, \varepsilon_{nominal}\, K_t^2 \qquad (1)$$

K_t = theoretical Stress Concentration Factor (SCF) (assumed = K_m)
$\sigma_{nominal}$ = nominal stress (excluding SCF)
$\varepsilon_{nominal}$ = nominal strain (excluding SCF)
σ_{Neuber} = actual stress (including SCF)
ε_{Neuber} = actual strain (including SCF)

The intersection of the Neuber curve (viz the right hand side of the equation) with the stress-strain curve provides the stress (and strain) which includes the effect of the stress concentration and this is the input into the analysis. Such analyses are best conducted using the material true stress-true strain curve but for small applied strains the difference is small.

Based on numerical analyses and experiment, all positive strain increments are considered to contribute to crack extension, even when the pipe is nominally in compression at that stage during installation. In practice this means the maximum strain achieved during reeling on, and the pipe bending over the aligner (including the effect of misalignment), need to be assessed separately for possible crack extension from a hypothetical flaw. The stress derived from the stress-strain curve is used to determine both the fracture (K_r) and plastic collapse (L_r) axes of the failure analysis diagram (FAD). Specifically, the stress is treated as a primary stress which is used to determine the stress intensity factor and reference stress for the K_r and L_r axes, respectively. The reference stress is derived from the Kastner equation in BS 7910 (see P.4.3.2 of the standard) [3]. The Level 3B FAD described in BS 7910 is employed, since it permits stable ductile crack extension to take place but to still avoid failure by unstable fracture and plastic collapse. The amount of stable crack extension allowed by DNV-RP-F108 is limited to 1 mm. The method is based on the assumption that the weld metal (and HAZ) tensile properties are higher than those of the parent pipe (or are said to be overmatching). Specifically, the weld metal stress strain curve is required to be higher than that of the parent pipe up to the maximum strain experienced during installation. This overmatching “protects” flaws contained by the weld metal and HAZ by preventing strains from concentrating at these locations.

The need for weld metal strength overmatching is critical to the successful application of the assessment method, as will be shown later, but it has important implications for the choice of parent pipe tensile properties. Since the pipe in the longitudinal direction can have a range of strengths above the specified minimum, the weld metal must be stronger than the highest pipe strength supplied. Furthermore, since the fracture mechanics analysis uses the stress-strain curve to establish stress from the applied strain, the highest strength pipe must be used to ensure that the stress input for the analysis is not underestimated. For practical purposes, the mean plus two standard deviations stress-strain curve is used in the assessment. Furthermore, DNV OS F101 [2] limits the difference between the maximum and minimum longitudinal parent pipe yield strength to below 100 MPa maximum in order to limit excessive demands on weld metal yield strength.

Although the procedure was validated by full-scale testing of pipe subjected to repeated plastic straining simulating reeling operations, subsequent numerical analyses have shown that it can be potentially non-conservative if all the criteria defined in DNV RP F108 are not adhered to. However work [7] has shown that conservatism is maintained if weld metal yield strength overmatching is achieved and welding residual stresses are not ignored but treated in accordance with BS 7910 recommendations; this is illustrated in Figure 2.

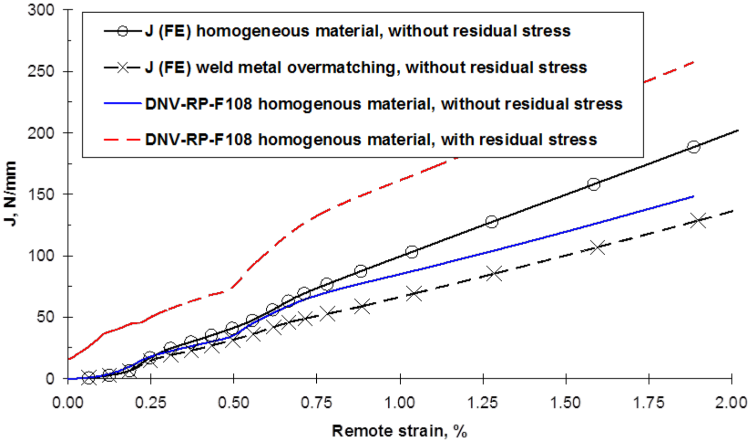

Figure 2. Remote Strain (%) depending on J (N/mm) for a 3 x 50 mm surface flaw at the weld root fusion boundary in a X65 pipe with OD = 324 x 20.6 mm WT. Homogeneous material (parent pipe) was employed in the reeling procedure (DNV-RP-F108) and both homogeneous and 20% weld strength overmatched materials employed in the numerical (FE) analyses [8].

Recent work has also indicated that there are limitations in the use of the Kastner equation to determine the reference stress in the FAD. The Kastner solution can be considered to provide a combination of local and global collapse conditions for surface flaws. Since the elastic-plastic driving force estimated by the assessment line in the FAD is critically dependent upon the reference strain at high L_r values, a local collapse reference strain may be more appropriate. Use of a flat plate reference stress solution has been suggested [9] as a simple expedient. Its effect on the driving force compared with what are considered to be accurate 3D - finite element analyses predicting J driving force (based on work carried out at TWI) is illustrated in Figure 3.

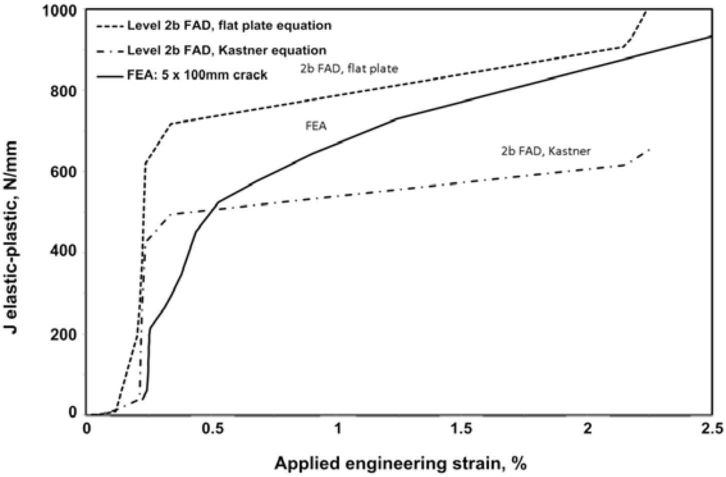

Figure 3. Comparison of the effect of using the Kastner and flat plate equations for reference stress on J driving force estimated using the Level 2b FAD in BS 7910 relative to finite element analyses for a 3 x 100 mm surface crack in a 273 x 20 mm X65 pipe.

One of the features of the DNV-RP-F108 [7] assessment method is that it is primarily concerned with analysis of surface flaws; there are no specific solutions given for embedded flaws. Although embedded flaws can be analysed according to BS 7910, it is considered that the solutions given are not appropriate for embedded flaws in pipes subject to plastic strains and are considered to be over pessimistic. Indeed, the solutions given in BS 7910 have limitations since they refer the user to flat solutions to determine both K and reference stress and more appropriate solutions would be desirable. The simple expedient adopted in DNV-RP-F108 is to treat the allowable height of the surface flaw as being the same as the allowable total height of the embedded flaw provided that it is not closer to the nearest surface than the allowable surface height; otherwise it is considered to be surface breaking.

Work conducted at TWI confirms that the existing flat plate solutions for embedded flaws in BS 7910 are indeed pessimistic [10]. Initially it was thought that they could be improved by applying a correction to the reference stress solution. Unfortunately, the correction factor depends on flaw height and length so a single correction is not possible. Instead, a method using a J-based reference stress solution has been proposed [10] but simple closed equations for use in routine assessments are yet to be developed.

Fracture Mechanics SENT Testing

The other novel feature associated with strain based analysis concerns the type of specimen used in fracture mechanics testing. Fracture toughness is determined using surface notched, single edge notch tension (SENT) specimens. These have been found to be more representative of pipe fracture behaviour than the more conventional and standardised, deeply notched, single edge bend specimens (SENB). This is because the crack-tip stress-strain field in the specimen (or crack-tip constraint) better replicates that of a circumferential crack in a pipe than does a standard, deeply notched SENB specimen which provides significantly higher crack tip constraint [11]. A consequence is that higher fracture toughness is determined using SENT compared with SENB specimens. Fracture toughness is defined by a J-integral resistance curve, since it is assumed that, for the materials and temperatures involved during installation, upper shelf performance will be achieved and unstable fracture by cleavage (in ferritic steels) will not take place. The geometry of the SENT specimen is shown in Figure 4. Rectangular or square section specimens are permitted and these can be either pin-loaded or clamped using wedge or hydraulic grips, as illustrated. The day-light between the clamps is defined as ten times the specimen width. (The specimen width is similar to the pipe wall thickness). If pin loading is employed, the only practical method of achieving this with the notch orientation employed is to clamp the specimen and then pin load the clamp. The specimen is surface notched and fatigue cracked to a depth ranging between 20 and 50% of the specimen width. Specimens are notched and fatigue precracked to test the weld metal (either from the weld cap or root side) and HAZ as illustrated in Figure 5. A notch from the weld cap side is often used to test the HAZ to minimise problems with missing the target HAZ if the fatigue crack tip is longer than expected. A comparison of the J resistance curve obtained from bend (SENB) and tension (SENT) is shown in Figure 6 indicating the differences that are typically observed.

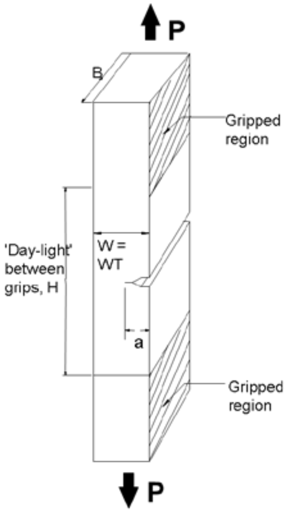

Figure 4. SENT specimen to DNV-RP-F108, B = W or 2W, H = 10W.

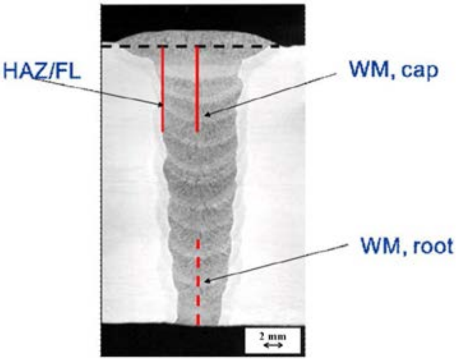

Figure 5. Girth weld showing notch locations for SENT specimens.

The procedure is intended to be applicable to ductile materials (it is not generally applicable to situations when the SENT specimen fails by cleavage), and to girth welds which have a higher yield strength than the parent pipe (i.e. overmatch). There is no fundamental reason why results from SENT specimens which fracture by cleavage should not be used in an assessment. However, fracture toughness values obtained from such tests would be expected to result in impractically small allowable flaw sizes for high strain applications. Furthermore, there is concern that since cleavage is sensitive to changes in crack-tip constraint, increases in crack-tip constraint in the pipe girth weld due to variations in geometry and/or material could trigger cleavage at lower fracture toughness than that determined in the SENT tests. Results from standard, deeply notched bend specimens (such tests to BS 7448: Part1) are not subjected to such concerns since these are designed to provide high crack-tip constraint which provides lower bound fracture toughness.

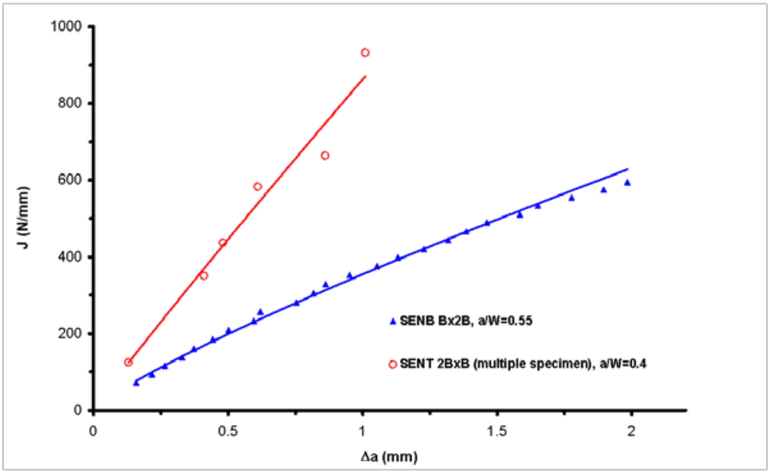

Figure 6. Comparison of J resistance data obtained from weld metal using through thickness notched SENB and surface notched SENT specimens.

Occasionally, pop-ins have been experienced when testing SENT specimens; although usually these have not been in the context of pipe reeling applications but in other cases where the benefits of higher fracture toughness are desired. These are observed as sudden decreases in force and increases in crack mouth opening displacement on the test record which go on to rise significantly above the values at pop-in. Often the pop-in can be related to an arrested brittle fracture on the specimen fracture face. This is an indication of the presence of a localised region of low fracture toughness or LBZ (local brittle zone). However, they could also be a result of a local shear fracture arising from crack path deviation. The structural significance is an open question. The concern is whether the arrested brittle fracture in the specimen can be replicated in a pipe under high loading (and possibly carrying hazardous fluids). Clearly, further work in this area is needed if SENT specimens are to be employed on materials or testing conditions where fully ductile behaviour cannot be achieved.

Finally, it needs to be pointed out that currently there is no national standard that addresses SENT testing. Although guidance is provided in DNV-RP-F101 this is insufficient to cover all the requirements of testing, analysis and qualification. A start on this has been made in the UK and a BSI committee (ISE_101_4_2) is in the process of drafting a SENT testing standard with a view to publishing a Draft for Public Comment in 2012.

Segment Testing

The DNV-RP-F108 [7] procedure requires segment specimens (taken from the girth weld and containing an artificial sharp notch, usually introduced by electro-discharge machining) to be tested in order to validate the assessment procedure. The notch depth employed is representative of that which would be permitted to remain in the girth weld. Because the width of the segment specimen is 50 mm, a representative flaw length cannot be employed and typically this is limited to 25 mm maximum. There are a number of requirements specified in DNV-RP-F108 for the segment test, but one of the most important features is that the specimens undergo a straining cycle which replicates the strains experienced during installation. After completing the straining cycles, the specimen is broken open and the amount of stable ductile crack extension or tearing measured. The assessment that was conducted on the pipe is repeated specifically for the segment specimen with the objective of estimating the amount of stable crack extension. If the estimate is equal or greater than that measured from the test, the assessment procedure is considered to be validated. If not, the material fracture toughness (or its resistance curve) is adjusted downwards so that a conservative prediction is made. Once validated for one flaw size, a range of flaw sizes can be determined which will not compromise the integrity of the girth weld during installation.

Strain-Based Assessment

Effects of Internal Pressure and Pipe Straining

When the applied strain increases beyond yield strain, codified stress based assessment procedures have limitations since they are unable to predict the increase in the driving force (CTOD or J) for fracture. As discussed above, various methods are employed to correct for this. Before discussing strain based assessments, it is worth briefly reviewing some important aspects of the behaviour of circumferential cracks in pipe subjected to plastic straining.

The addition of an axial strain to a pipe already under internal pressure produces a significant increase in driving force compared with the un-pressurised pipe at strains above yield strain, as illustrated in Figure 7 which was derived from finite element analysis conducted at TWI. In the case shown, the pipe is strained in bending but the effect is the same when the pipe is loaded in tension. At one time it was thought that the biaxial loading condition caused by the combination of internal pressure and external pipe straining would result in an increase in crack-tip constraint and that the use of the low crack-tip constraint SENT specimen would provide an non-conservative (underestimate) of fracture toughness. Indeed, this is thought to be one of the reasons why DNV-OS-F101, Appendix A recommends that although SENT specimens are acceptable to define fracture toughness for installation, for the operational condition (which will involve internal pressure), fracture toughness has to be determined using high constraint SENB specimens [2].

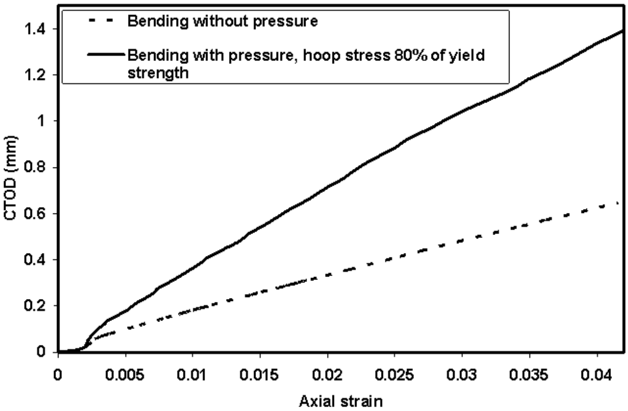

Figure 7. Finite element analysis prediction of CTOD driving force versus axial strain in a 400 mm OD x 20 mm WT X65 pipe with and without internal pressure in the presence of a surface crack 3 mm high and 50 mm long.

However, finite element analyses conducted to quantify crack-tip constraint in strained pipes, with and without internal pressure, show that the crack-tip constraint is not significantly affected by the inclusion of internal pressure. This was investigated by TWI and the results are illustrated in Figure 8. Here crack tip constraint, in terms of the elastic-plastic Q stress is shown as a function of the applied driving force in terms of J-integral. Less negative values of Q-stress signify higher crack tip constraint. It is clear from the figure that as the applied J is increased, crack-tip constraint decreases. In addition, when crack-tip constraint is determined in an SENT specimen with the same ratio of crack depth to pipe wall thickness (a/W) as the pipe, similar levels of crack-tip constraint are obtained. If a more deeply notched SENT specimen is employed (in this case a/W = 0.4), crack-tip constraint is increased. This indicates that SENT specimens can be used to assess fracture toughness for operational conditions where there is a combination of internal pressure and axial strain. The results also indicate that if SENT specimens are employed for flaw assessment for this purpose, the notch depth in the specimen should not be less than the flaw depth in the pipe.

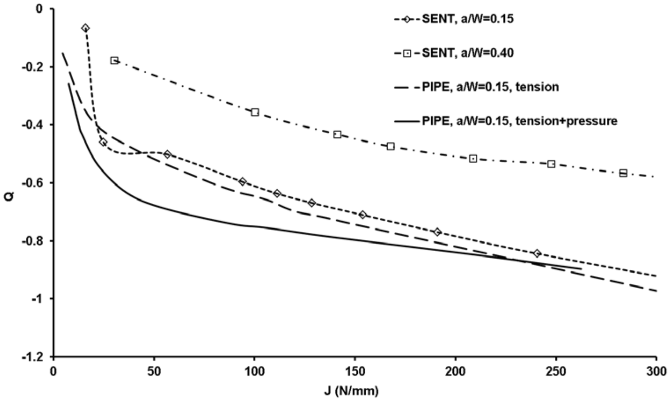

Figure 8. Crack-tip constraint in terms of Q stress versus applied J for SENT specimens and pipes with and without internal pressure (hoop stress = 80% SMYS). The pipe is 400 mm OD x 20 mm WT and to X65.

The conclusions drawn from finite element analyses on the similarity of crack-tip constraint in SENT specimens and strained pipe with internal pressure appears to be supported by experimental data reported by Kibey et al [12]. Figure 9 shows CTOD resistance curves (CTOD versus ductile crack extension) for pipes with and without internal pressure and SENT specimens with similar a/W values. All the results fall within the same scatter band and confirm that it is appropriate to use SENT specimens (the concept of transferability of fracture toughness between specimen and component is confirmed).

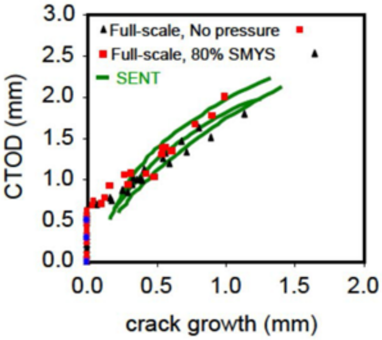

Figure 9. CTOD versus ductile crack extension for X70 pipe subjected to axial straining with and without internal pressure compared with CTOD resistance curve from a SENT specimen with the same notch depth (from Kibey et al [12]).

Strain Based Assessment Methods

A number of research workers in the UK, Norway [13] and North America have been developing specific strain-based assessment methods for pipeline girth welds. In the case of North American developments, the emphasis has been on predicting strain capacity of the pipeline when the girth weld contains welding flaws. In Europe, the emphasis has been more on defining flaw acceptance criteria which are used to define inspection regimes. In North America there are two programmes examining strain-based design of pipelines; a PRCI (Pipeline Research Council International) sponsored project [14] and [15] which is on-going, and another run by ExxonMobil which has published initial recommendations. ExxonMobil [16] and [17], have carried out extensive numerical analysis and full-scale pipe tests to derive parametric equations to define strain-capacity. The procedure is CTOD (crack tip opening displacement) based and three levels of assessment are proposed, with each higher level requiring more sophisticated information about material properties. Their work has shown that strain capacity is dependent on the following factors: crack size (height and length), misalignment at the girth weld, weld metal strength overmatch, pipe wall thickness, strain hardening (defined in terms of yield to tensile ratio), uniform elongation of the pipe material, fracture toughness (in terms of a CTOD resistance curve) and internal pressure.

To date, Level 1, the most basic or screening level, and Level 2, an intermediate level, have been published [17]. Here, strain capacity is defined as a function of crack size, pipe wall thickness and weld strength overmatch (in terms of tensile strength). Internal pressure is included and set to be equivalent to a hoop stress of 80% specified minimum yield strength. At Level 1, fracture toughness is not required since a lower bound resistance curve is assumed which is based on experimental data. A fixed value of misalignment of 3 mm is assumed and the uniform elongation up to tensile strength in the standard tensile test is set at 6%. At Level 2, fracture toughness in the form of a CTOD resistance-curve is determined but the results are not directly used in the assessment. Instead, the experimental resistance curve is compared with three reference resistance curves and the one which is just exceeded is used in the assessment. In addition to the variables considered at Level 1, misalignment can be varied, as can the uniform elongation. The procedure is applicable to steels with strength levels from X65 to X80. The comparison between predicted and experimentally measured strain capacity is conservative (for the range of pipeline girth welds tested), as illustrated in Figure 10. As currently formulated, the ExxonMobil approach is limited to certain materials and loading conditions.

The SENT specimen design is similar to the one described in DNV-RP-F108, Figure 4, except that the specimen has a square cross-section, is side grooved to a depth 5% of thickness on each side after fatigue precracking and is loaded by clamping the sides of the specimen. A CTOD resistance curve is obtained from the material. CTOD is derived by simple extrapolation of the opening displacement of a pair of clip gauges mounted above the notch mouth, to the fatigue crack tip.

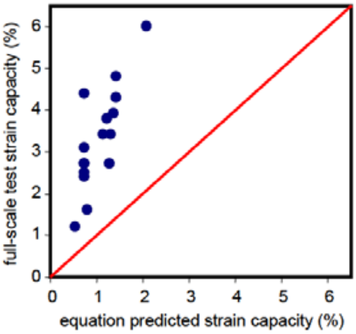

Figure 10. Comparison of full-scale test capacity with predicted strain capacity using Level 1 strain capacity equation (from Kibey et al [16]).

A more general strain-based assessment framework has been proposed by others [18] and [19]. This is set within the failure analysis diagram (FAD) approach described in the R6 integrity assessment procedure, which is extensively used in the electricity generating industry. Although R6 is stress-based, a new section is being prepared which essentially replaces the stress-based plastic collapse axis (L_r) of the FAD with the ratio of the reference strain to the yield strain of the material (D_r). The K_r axis is relatively unchanged and fracture toughness is defined in terms of J-integral. The procedure has been found to be applicable to thick section components, but can be potentially non-conservative for thin walled components such as pipes where the flaw height is a significant proportion of the wall thickness. This is thought to arise from the assumption that the reference strain is equal to the applied strain. TWI [20] has been developing a strain-based procedure, similar to the one proposed by Budden, but significantly, is developing specific reference strain solutions for flaws in pipeline girth welds. However, in order to derive appropriate reference strain solutions it is necessary to employ finite element analyses. In these analyses, the reference strain is defined such that the FAD assessment line implied is consistent with the failure assessment line obtained from the material stress-strain curve. In order to do this, a large number of analyses is required to create a library of reference strains, since the reference strain will depend on flaw dimensions. The approach is promising and is able to deal with misalignment, axial straining plus internal pressure. The strength of the proposed approach is that it is set within the flaw assessment framework of BS 7910. The procedure uses the existing elastic solutions for stress intensity factor to generate the K_r axis on the FAD and fracture toughness is defined in terms of J-integral. Furthermore, it is not restricted by material type or loading condition. So within the limits of the reference strain solutions, the approach will be applicable to a wide range of pipeline loading conditions. Validation of these procedures is ongoing at TWI through full-scale pipe girth welds subjected to a combination of internal pressure and axial straining.

Conclusions

In conclusion, codified stress-based methods used for assessing the significance of circumferential flaws in pipe girth welds have limitations when applied to pipe subjected to plastic straining. Various corrections can be applied to the assessment method to ensure that the conditions for failure from flaws are not underestimated. Currently, these corrections appear to provide acceptable results in terms of providing safe and workable acceptable flaw sizes, thus minimising the need for unnecessary repair. The procedures work for small strains, but the way forward appears to be strain-based assessment methods. At present, a number of strain-based approaches are being developed. A universally accepted and codified approach is not yet here. It is generally agreed that extensive experimental validation is necessary, especially when the methods are applied to large pipeline projects, where a failure or even a leak could have significant consequences to the environment, loss of production and adversely affect the reputation of the owner/operator.

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