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EXTENSION OF FULLY-PLASTIC J-SOLUTIONS FOR DEFECT ASSESSMENTS OF CLAD PIPE GIRTH WELDS

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Abstract. *This work addresses the potential effects of an undermatched girth weld on critical flaw sizes for a typical clad pipe employed in subsea flowlines having a girth weld made of UNS N06625 Alloy 625. Attention is given to structural integrity analyses derived from an advanced ECA procedure based on the GE-EPRI framework with fully-plastic solutions for the J-integral incorporating weld strength mismatch effects. These analyses demonstrate that an advanced FAD formulation incorporating the GE-EPRI evaluation methodology reduces significantly the conservatism that would arise from critical crack size estimates derived from a standard FAD formulation.*

Keywords : *J-integral, fully-plastic solution, reference stress, defect assessment, mismatch weld, girth weld, steel catenary riser*

1. INTRODUCTION

Structural integrity assessments of submarine risers and flowlines conducting corrosive and aggressive hydrocarbons represent a key challenge in design and installation of the pipeline infrastructure. Ongoing developments in oil and gas production support the increased use of corrosion resistant alloy (CRA) lined-pipes for the transport of hot and corrosive fluids in flow lines and associated risers in oil and gas subsea systems. The CRA lined-pipes comprises a $2 - 3$ mm thick inner layer made of a very resistant CRA material, such as ASTM UNS N06625 Alloy 625 (American Society for Testing and Materials, 2009, 2011) (which is commercially known as Inconel Alloy 625), either metallurgically bonded (clad layer) or mechanically-lined, and an outer layer made of a more conventional pipeline steel such as, for example, API X65 grade steel. While CRA lined-pipes are more effective against corrosion and much less expensive than solid-CRA pipes, they also require the use CRA filler to produce field girth welds thereby introducing additional complexity in fracture assessments and specifications of critical crack sizes due to the dissimilar nature of the girth weld materials.

Fracture mechanics based approaches enable the introduction of a concise framework in terms of Engineering Critical Assessment (ECA) procedures to explicitly address the potential interaction between stress-controlled cleavage fracture and plastic collapse to predict structural failure by adopting the concept of a failure assessment diagram (FAD) to evaluate the severity of crack-like flaws. Several flaw assessment procedures based upon the FAD concept, such as the R6 methodology (EDF Energy Nuclear Generation Limited, 2013), BS7910 (British Institution, 2013), SINTAP (Programme, 1999) and API 579 (American Petroleum Institute, 2007), among others, are now well established and widely employed to analyze the significance of defects in terms of assessment of structural integrity. However, while applications of FAD-based procedures have proven sufficiently effective in assessing the significance of structural defects in homogeneous materials, they do not necessarily provide reliable and accurate defect acceptance limits for welded components with weld metal strength mismatch. Here, mismatch in the flow properties between the weld metal and the base plate material alters the plastic deformation pattern of crack-like flaws that often occur in the weld metal and heat affected zone (HAZ) region thereby affecting the coupling relationship between remote loading and crack-tip loading (as characterized by J or the crack tip opening displacement - CTOD).

This work addresses the potential effects of an undermatched girth weld on critical flaw sizes for a typical clad pipe employed in subsea flowlines having a girth weld made of UNS N06625 Alloy 625. Attention is given here to structural integrity analyses derived from an advanced ECA procedure based on the GE-EPRI framework with fully-plastic solutions for the J-integral incorporating weld strength mismatch effects. These analyses demonstrate that an advanced FAD formulation incorporating the GE-EPRI evaluation methodology reduces significantly the conservatism that would arise from critical crack size estimates derived from a standard FAD formulation.

2. THE GE-EPRI EVALUATION METHODOLOGY

A convenient methodology to estimate the J Integral for a cracked component such as a circumferentially cracked pipe (the procedure to estimate the CTOD is analogous but it is not addressed here in interest of space - readers are referred to the work of Chiodo and Ruggieri (Chiodo and Ruggieri, 2010) for further details) derives from the fully plastic description of J based upon HRR-controlled crack-tip fields (Hutchinson, 1983) and limit load solutions for a strain hardening material introduced by Shih and Hutchinson (Shih and Hutchinson, 1976) and further validated by Kumar et al. (Kumar *et al.*, 1981) (see also Kanninen and Popelar (Kanninen and Popelar, 1985)). The procedure begins by considering the elastic and plastic contributions to the J-integral as

$$J = \frac{K_I^2}{E'} + J_p \tag{1}$$

in which K_I is the (Mode I) elastic stress intensity factor and $E' = E$ or $E' = E/(1-\nu^2)$ whether plane stress or plane strain conditions are assumed with E representing the (longitudinal) elastic modulus ans ν is the Poisson's ratio. For a circumferential surface crack in a pipe subjected to a (pure) bending moment, an improved expression for parameter K_I is given by API 579 (American Petroleum Institute, 2007).

For an elastic-plastic material obeying a Ramberg-Osgood model (Anderson, 2005; Dowling, 1999) to describe the uniaxial true stress ($\bar{\sigma}$) vs. logarithmic strain ($\bar{\epsilon}$) response given by

$$\frac{\bar{\epsilon}}{\epsilon_{ys}} = \frac{\bar{\sigma}}{\sigma_{ys}} + \alpha \left(\frac{\bar{\sigma}}{\sigma_{ys}} \right)^n \tag{2}$$

where α is a dimensionless constant, n defines the strain hardening exponent, σ_{ys} and $\epsilon_{ys} = \sigma_{ys}/E$ define the yield stress and strain, the plastic component, J_p, is expressed as

$$J_p = \alpha \epsilon_{ys} \sigma_{ys} b \left[h_1(a/W,\ \ell,\ n) \right] \left(\frac{P}{P_0} \right)^{n+1} \tag{3}$$

where a is the crack size, W denotes the cracked component width, $b = W - a$ defines the uncracked ligament, ℓ represents a characteristic length for the cracked component, P is a generalized load and P_0 denotes the corresponding (generalized) limit load. In the above expression, h_1 is a dimensionless factor dependent upon crack size, component geometry and strain hardening properties. The previous solution for J_p became widely known as the GE-EPRI methodology (Kumar *et al.*, 1981; Zahoor, 1989). Recent work of Chiodo and Ruggieri (Chiodo and Ruggieri, 2010) has expanded these J solutions to include a wide range of circumferentially cracked pipes subjected to bending with varying crack geometries and strain hardening properties applicable to homogeneous materials.

To introduce an estimation procedure for J_p in a cylinder or pipe having a circumferential surface crack located at the girth weld centerline based upon the previous fully-plastic solution, consider the crack configuration subjected to bend loading illustrated in Fig. 1, in which $2h$ represents the weld groove width. Moreover, to facilitate development of the fully plastic solution for J_p incorporating effects of weld strength mismatch, it proves convenient to first define the mismatch ratio, M_y, as

$$M_y = \frac{\sigma_{ys}^{wm}}{\sigma_{ys}^{bm}} \tag{4}$$

where σ_{ys}^{bm} and σ_{ys}^{wm} denote the yield stress for the base metal and weld metal. The above methodology can then be extended in straightforward manner to define J_p for this crack geometry by the following expression

$$J_p = \alpha_{wm} \epsilon_{ys}^{wm} \sigma_{ys}^{wm} b \left[h_1 \left(\frac{a}{t},\ \frac{D_e}{t},\ \theta,\ \frac{2h}{t},\ M_y,\ n_{wm} \right) \right] \left(\frac{M_b}{M_0^{wm}} \right)^{n_{wm}+1} \tag{5}$$

in which the subscript (superscript) wm indicates that the corresponding quantities are related to the weld metal properties. In the above expression, D_e is the pipe (cylinder) outer diameter, t is the wall thickness, $b = t - a$ now defines the uncracked ligament, h is the weld groove half width, M_b denotes the applied bending moment and the surface crack length is described by the angle θ (see Fig. 1) as (American Petroleum Institute, 2007; Zahoor, 1989)

$$\theta = \frac{\pi c}{2 D_e} \tag{6}$$

where c is the circumferential crack half-length.

In the above Eq. (5), the limit bending moment, M_0^{wm}, is defined in terms of the weld material (rather than the base plate material) and conventionally given by (American Petroleum Institute, 2007; Zahoor, 1989)

$$M_0^{wm} = 2 \sigma_{ys}^{wm} R_m^2 t \left(2 sin\beta - \frac{a}{t} sin\theta \right) \tag{7}$$

in which R_m denotes the mean radius ($R_m = (R_e + R_i)/2$ where R_e and R_i are the external and internal radius) and parameter β is defined as

$$\beta = \frac{\pi}{2}\left[1 - \left(\frac{\theta}{\pi}\right)\left(\frac{a}{t}\right)\right] \quad . \tag{8}$$

The limit load solution for the bending moment given by Eq. (7) is applicable in the range $(\theta + \beta) \leq \pi$ (American Petroleum Institute, 2007; Zahoor, 1989). Here, it is also understood that the previous Eq. (7) has a clear interpretation as corresponding to a limit load solution applicable to a circumferentially surface cracked pipe made of a homogeneous material having the weld metal flow properties (yield stress, σ_{ys}^{wm}, and the associated strain hardening exponent, n_{wm}); a condition often referred to as "all weld metal" (AWM).

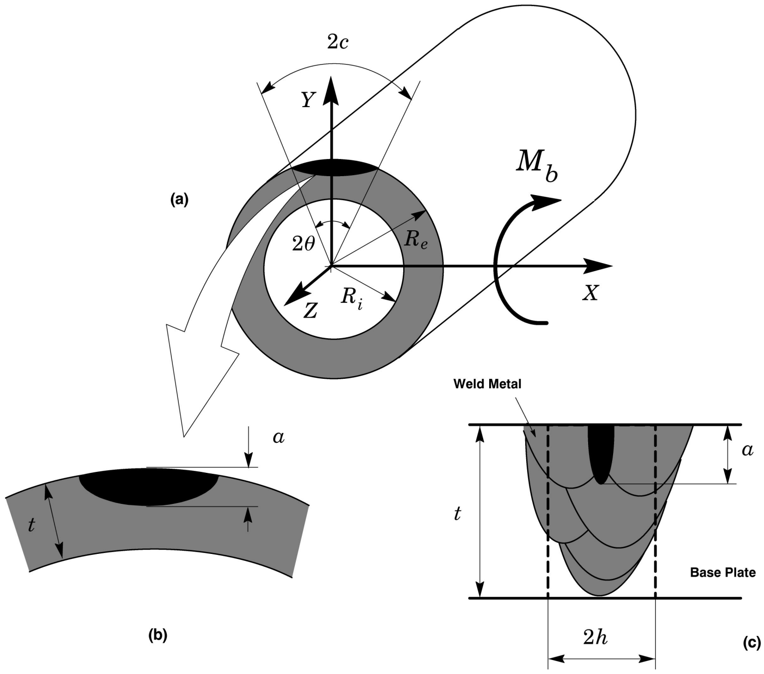


Figure 1. Circumferentially cracked pipe under bending and weld centerline defect geometry

3. FAD-BASED DEFECT ASSESSMENT METHODOLOGIES

3.1 Fundamental FAD Assessment Curve

ECA procedures of crack-like defects based upon the FAD philosophy have undergone extensive developments in the past decade to form the basis for industrial codes and guidelines for structural integrity assessments. A fundamental approach, derived from the early work by Dowling and Townley (Dowling and Townley, 1975) and Harrison et al. (EDF Energy Nuclear Generation, 2009), to address the potential interaction between brittle fracture and plastic collapse adopts the concept of a two-criteria failure assessment diagram to describe the mechanical integrity of flawed components. Here, a geometry and material independent failure line is constructed based upon a relationship between the normalized crack-tip loading, K_r, and the normalized applied (remote) loading, L_r, in the form

$$K_r = \left[1 - 0.14(L_r)^2\right]\left\{0.3 + 0.7\exp\left[-0.65(L_r)^6\right]\right\} \tag{9}$$

for $L_r \leq L_r^{max}$ in which the cut-off parameter, L_r^{max}, is most often given by

$$L_r^{max} = \frac{1}{2}\left(1 + \frac{\sigma_{uts}}{\sigma_{ys}}\right) \tag{10}$$

where σ_{ys} and σ_{uts} are the material's yield stress and tensile strength. Further, ECA procedures more applicable to submarine pipelines, such as DNV F101 (Det Norske Veritas, 2010), also define the cut-off parameter, L_r^{max}, simply as

$$L_r^{max} = \frac{\sigma_{uts}}{\sigma_{ys}} \quad . \tag{11}$$

In the above expression (9), the toughness ratio, K_r, and the load ratio, L_r, are simply defined as

$$K_r = \frac{K_I}{K_{mat}} \tag{12}$$

and

$$L_r = \frac{\sigma_{ref}}{\sigma_{ys}} \tag{13}$$

where K_I is the (Mode I) elastic stress intensity factor, K_{mat} denotes the material's fracture toughness and the reference stress, σ_{ref}, characterizes the plastic collapse load for the cracked component. Current defect assessment procedures based on Eq. (9) include BS7910 Level 2A (British Institution, 2013) and API 579 Level 2 (American Petroleum Institute, 2007) procedures which have arguably emerged as the engineering codes most widely used in integrity assessments of structural components containing crack-like flaws. Structural integrity assessments of a cracked component is based on the relative location of the assessment point with respect to the FAD curve defined by each procedure. The component is simply considered safe if the assessment point lies below the FAD line whereas it is considered potentially unsafe if the assessment point lies on or above the FAD curve. An increased load or larger crack will move the assessment point along the loading path towards the failure line.

3.2 Advanced FAD Assessment Methods Including Weld Strength Mismatch

A more advanced FAD formulation including the effects of weld metal strength mismatch can be derived by defining the toughness ratio as

$$K_r = \sqrt{\frac{J_e}{J}} \tag{14}$$

where J is the total value of the applied J-integral and J_e represents its elastic component. Now, by making use of the connection between J and K and following API 579 (American Petroleum Institute, 2007) to define the reference stress, σ_{ref},

$$\sigma_{ref} = \frac{M_b}{2R_m^2 t\left(2sin\beta - \frac{a}{t}sin\theta\right)} \tag{15}$$

an improved form of toughness ratio, K_r, yields

$$K_r = \sqrt{\frac{J_e}{J_e + J_p}} = \sqrt{\left[1 + \frac{H_{wm}}{J_e}\left(L_r^{wm}\right)^{n_{wm}+1}\right]^{-1}} \tag{16}$$

in which the fully plastic solution to describe J_p is given by previous Eq. (5) with H_{wm} then written as

$$H_{wm} = \alpha_{wm}\epsilon_{ys}^{wm}\sigma_{ys}^{wm} b\left[h_1(a/t,\ D_e/t,\ \theta,\ 2h/t,\ M_y,\ n_{wm})\right] \quad . \tag{17}$$

where the load ratio, L_r^{wm}, is defined is terms of the yield stress of the weld metal.A key feature of the above methodology is that it derives entirely from elastic-plastic J solutions based upon detailed finite element analyses thereby incorporating virtually any geometry and material dependence in the FAD procedure.

4. TOLERABLE CRACK SIZE ESTIMATES FOR CRA CLAD PIPES WITH UNDERMATCH GIRTH WELD

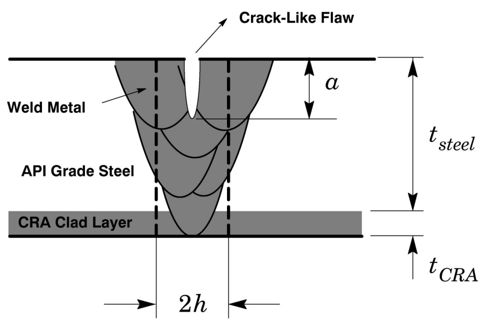
To demonstrate the effectiveness of the methodology presented previously in advanced defect assessment procedures for cracked structural components, this section examines the prediction of critical flaw sizes for a typical clad pipe employed in subsea flowlines having a girth weld made of UNS N06625 Alloy 625. Conducted as part of a collaborative program between the University of São Paulo and Petrobras (Brazilian State Oil Company), the verification studies conducted here compare estimates of tolerable crack sizes based upon an ECA procedure incorporating the fully plastic solutions described previously with crack size estimates obtained directly from a conventional FAD methodology derived from API 579 (American Petroleum Institute, 2007).

4.1 Pipe Geometry and Material Properties

The verification analyses consider the girth weld for a typical C-Mn pipe internally clad with UNS N06625 Alloy 625 (American Society for Testing and Materials, 2009, 2011). Figure 2(a) shows the idealized girth weld geometry illustrating the crack depth, a, the steel pipe wall thickness, t_{steel}, and the clad liner thickness, t_{CRA}. Experimental work conducted by Hippert (Hippert, 2013) shows that a typical macro section of the CRA girth weld clearly reveals the dissimilar character of weld metal in sharp contrast with the base plate material. The analyzed pipe has outside diameter, $D_e = 203.2$ mm (8 in), steel pipe thickness, $t_{steel} = 15$ mm and clad liner thickness, $t_{CRA} = 5$ mm thereby resulting in $D_e/t = 10.2$ with $t = t_{steel} + t_{CRA}$ denoting the overall pipe wall thickness. The effects of through thickness heterogeneity are not addressed in this case study.

The material of the external pipe is an API 5L Grade X70 pipeline steel with a higher yield stress, $\sigma_{ys} = 551$ MPa, tensile strength, $\sigma_{uts} = 660$ MPa, and relatively low hardening properties ($\sigma_{uts}/\sigma_{ys} \approx 1.20$). The inner clad layer is made of a nickel-chromium alloy 625 (UNS N06625) with the girth weld fabricated using the GTAW process with a filler metal having essentially similar metallurgical composition and mechanical properties as the clad material (Hippert, 2013). Tensile tests performed on the girth weld material (Hippert, 2013) provide the yield stress, $\sigma_{ys} = 495$ MPa and tensile strength, $\sigma_{uts} = 828$ MPa, with high hardening properties ($\sigma_{uts}/\sigma_{ys} \approx 1.67$). Based on Annex F of API 579 (American Petroleum Institute, 2007), the Ramberg-Osgood strain hardening exponents describing the stress-strain response for both material is estimated as $n_{bm} = 14.2$ and $n_{wm} = 6.5$. The higher mechanical strength and superior resistance to a wide range of corrosive environments of unusual severity for this material derive from the combination of the nickel-chromium matrix with other microalloying elements such as molybdenum and niobium. Figure 2(b) shows the measured true stress *vs.* true strain for both materials. It can be seen that, while the yield stress for the weld metal undermatches the yield stress for the base plate material, the higher hardening behavior of the weld metal material causes the girth weld to overmatch the base plate material after deformation levels of ~ 1 %.

The fracture toughness value for the girth weld metal is estimated based upon DNV F108 (Det Norske Veritas, 2006) which requires fracture mechanics testing using single edge notched tensile SE(T) specimens to generate crack growth resistance data ($J - R$ curves) for ECA procedures applicable to reeling installation. Guided by preliminary fracture tests of the girth weld material (Hippert, 2013) we take the J-value at onset of crack growth defined by $J = 400$ kJ/m^{2}as the material's elastic-plastic toughness, J_{mat}. This toughness value is well in accord with previous reported crack growth resistance data for Alloy 625 materials, including weld metal and heat affected zone region.



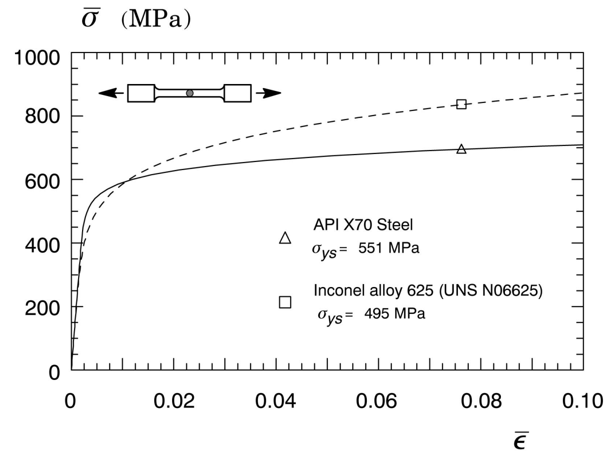


Figure 2. (a) Representative CRA girth weld of the pipe with $D_e = 203.2$ mm (8 in), $t_{steel} = 15$ mm and clad liner thickness, $t_{CRA} = 5$ mm; (b) Measured true stress *vs.* true strain response of the girth weld for the C-Mn pipe internally clad with UNS N06625 Alloy 625.

4.2 Prediction of Critical Flaw Sizes

Prediction of critical flaw sizes for the CRA girth weld follows from constructing the loading path (which derives from the procedure outlined previously) for each crack configuration on the K_r *vs.* L_r plot. Within the present context, the intersection of the loading path with the FAD assessment line defines the predicted failure condition for the analyzed CRA clad pipe with undermatch girth weld. Moreover, to provide a consistent basis of comparison for the integrity assessments, the safety factors which would be applied to flaw dimensions, acting stresses and fracture toughness are set to unity.

The structural integrity analysis described here focus on critical flaw size estimates derived from two related FAD procedures and already outlined previously: (1) Standard FAD assessment based on API 579 Level 2 (American Petroleum Institute, 2007) using linear elastic fracture mechanics to define the crack driving force in terms of K_I as described in (American Petroleum Institute, 2007) and (2) Advanced FAD formulation incorporating the GE-EPRI evaluation methodology for J described by Eq. (14). Within the present context, the integrity assessment based on API 579 Level 2 (American Petroleum Institute, 2007) is interpreted as a baseline estimate against which other critical flaw size estimates can be compared.

Souza and Ruggieri (Souza, 2015) provide the h_1-factors for the circumferentially cracked pipes with varying geometries and strength mismatch levels needed to estimate the J_p-values entering into Eq. (16). Building upon extensive nonlinear 3D analyses of detailed finite element models, they arrived at functional dependence of factor h_1 on crack geometry (as characterized by a/t and θ/π) for a given D_e/t-ratio and mismatch level, M_y, including the strain hardening exponent for the weld metal, in the form

$$h_1 = \xi_0 + \xi_1(a/t) + \xi_2(a/t)^2 + \xi_3(a/t)^3 + \xi_4(\theta/\pi) + \xi_5(\theta/\pi)^2 \quad (18)$$

where a multivariate polynomial fitting is adopted to describe the variation of factor h_1 with crack geometry, which is essentially valid in the range $0.1 \le a/t \le 0.4$ and $0.04 \le \theta/\pi \le 0.20$.

In the above, evaluation of the applied bending moment follows from using a moment-strain relationship determined for the uncracked pipe configuration. The longitudinal bending strain, ϵ_z^b, for a pipe with outside diameter, D_e, under pure bending is given by

$$\epsilon_z^b = \frac{D_e/2}{R_b + D_e/2} \quad (19)$$

where R_b is the bending radius representing the reel drum radius in the context of ECA procedures applicable to reeling installation. Here, the moment-strain trajectories for cracked pipes are essentially similar to the corresponding trajectory for an uncracked pipe (Ostby *et al.*, 2005; Chiodo and Ruggieri, 2010). Further, within the present methodology, the longitudinal bending strain, ϵ_z^b, is effectively interpreted as a *global* measure of the applied loading that would be conventionally utilized in routine ECA applications thereby neglecting any potential effects of the mismatched girth weld on the moment-longitudinal strain response for the analyzed pipe configuration.

Using now the ECA procedures just outlined, our exploratory analyses generate predictions of critical flaw sizes in terms of flaw depth, a_{cr}, for the CRA clad pipe with undermatch girth weld with varying crack length, $2c$ = 50, 100, 150 and 200 mm, based on different assessment methodologies. Predictions of the critical crack depth with varying crack length follow from constructing the loading path corresponding to increased crack depth (which derives from the procedure outlined in the previous sections) for each crack configuration on the K_r vs. L_r plot. Within the present context, the intersection of the loading path with the failure line described by each integrity assessment methodology defines the predicted value of a_{cr} for the analyzed cracked pipes. To illustrate the procedure, Fig. 3 displays the FAD curves and the loading paths (increasing crack depth) corresponding to a crack length of $2c = 100$ mm - the procedure to determine the a_{cr}-values for other crack lengths are similar.

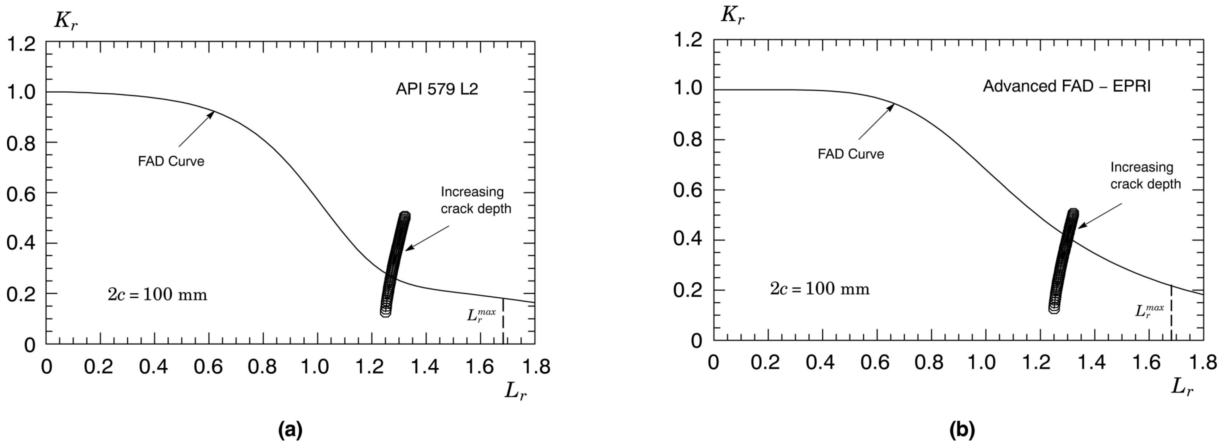


Figure 3. FAD curves and the loading paths corresponding to a crack length of $2c = 100$ mm for each integrity assessment procedure: (a) Standard FAD Assessment Based on API 579 Level 2; (b) Advanced FAD Assessment Based on GE-EPRI.

Table 1 compares the critical flaw sizes, a_{cr}, for the undermatch girth weld made of UNS N06625 Alloy 625. The trends are unmistakable. Integrity assessments based on the more refined and accurate FAD procedure incorporating the GE-EPRI approach yield much larger tolerable crack size estimates. Consider for example, predictions of critical crack size for $2c = 100$ mm. The standard FAD assessment based on API 579 Level 2 (American Petroleum Institute, 2007) provides $a_{cr} = 2.15$ mm whereas the advanced FAD formulation incorporating the GE-EPRI evaluation methodology for J gives $a_{cr} = 4.32$ mm which is twice the former crack depth size. Moreover, the crack length, $2c$, has a relatively weak effect on the predicted critical crack size (depth), a_{cr}; for example, doubling $2c$ causes a relatively small decrease in a_{cr}.

Table 1. Predicted critical flaw sizes for the analyzed CRA clad pipe with undermatch girth weld.

	Critical Crack Size, a_{cr} (mm)	
$2c$ (mm)	API 579 L2	Mismatch-Based EPRI
50	2.3	4.9
100	2.1	4.3
150	2.0	4.1
200	2.0	3.9

5. CONCLUDING REMARKS

This work describes an evaluation procedure based upon the GE-EPRI methodology to determine elastic-plastic crack driving forces (as characterized by the J-integral) in pipeline girth welds with circumferential weld centerline cracks subjected to bending load for a wide range of crack geometries and weld strength mismatch levels. Verification studies of typical clad pipe employed in subsea flowlines having an undermatch girth weld made of a UNS N06625 Alloy 625 (American Society for Testing and Materials, 2009, 2011) compare estimates of tolerable crack sizes based upon an ECA procedure incorporating the methodologies developed here with crack size estimates obtained directly from conventional FAD methodologies. These exploratory analyses demonstrate that an advanced FAD formulation incorporating the GE-EPRI evaluation methodology reduces significantly the conservatism that would arise from critical crack size estimates derived from a standard FAD formulation. Moreover, the present work shows that a material specific FAD curve yields tolerable crack size estimates which are comparable, albeit slightly more conservative, to the corresponding critical crack size predictions derived from the advanced FAD procedure based on the GE-EPRI approach. Overall, our investigation demonstrates the effectiveness of the proposed advanced FAD approach in defect assessment procedures while, at the same time, enabling additional understanding of the potential applicability of fully plastic solutions in cracked structural components. Additional studies are in progress to further validate the proposed methodology as a predictive tool for ECA procedures, including development of plastic collapse solutions for pipeline girth welds with circumferential surface cracks.

6. ACKNOWLEDGEMENTS

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