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A modified reference strain method for engineering critical assessment of reeled pipelines

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ABSTRACT

Reel-lay is a highly efficient method employed to install small or medium diameter offshore pipelines that play a key role in transportation of crude oil and natural gas. However, pipelines are subjected to 1–3% plastic straining during the process of reel-lay; thus engineering critical assessment (ECA) must be carried out to obtain the crack-like defect acceptance criteria. In our work, the effects of pipe geometry, crack geometries, and material properties on the reference strain are investigated. Furthermore, an empirical formula is proposed to estimate the reference strain. By incorporating the reference strain, the application range of the strain-based failure assessment diagram method is extended to ECA of severe circumferential surface cracks in reeled pipes.

1. Introduction

The reel-lay method has been adopted by offshore industries to install small or medium diameter pipelines that play a key role in transportation of crude oil and natural gas. Contrary to the traditional S-lay and J-lay methods, most fabrication processes for the reel-lay method (assembly, welding, inspection, and coating) are conducted at onshore facilities; thus the installation time and overall investment of projects are reduced. The installation process of reel-lay is briefly described as follows. At first, the pipes are joined by girth welding into a pipeline several kilometers in length in an onshore facility. Then, the pipeline is spooled onto a large diameter reel installed on a vessel. Third, the vessel travels to the installation site. Finally, the pipeline is installed by spooling off from the reel, as shown in Fig. 1.

However, during reel and unreel, the pipe is subjected to large-scale plastic strain on the order of 1–3%. The magnitude of the nominal uncracked strain ε_{unc} can be calculated by [2]:

$$\varepsilon_{unc} = \frac{D}{D+2R_{reel}} \tag{1}$$

where D is the outer diameter of the pipe and R_{reel} is the radius of the reel.

Since the offshore pipelines are joined by a girth welding method, welding flaws such as cracks and lack of penetration may be introduced into welds; thus engineering critical assessment (ECA) must be conducted accurately to avoid fracture failure of girth welds during installation by the reel-lay method.

At present, the fundamental approach applied in fitness-for-service flaw assessment procedures, such as BS 7910 [3] and R6 [4], is the reference stress method [5] proposed by Ainsworth. For large plastic strains, a slight variation of reference stress (σ_{ref}) will dramatically change the reference strain (ε_{ref}) which causes a significant change in the right-hand side of

$$J_p/J_e \approx E\varepsilon_{ref}/\sigma_{ref} \tag{2}$$

where J_p and J_e are the plastic and elastic components of the J-integral. In order to ensure the accuracy of the ECA result of reeled pipelines, the reference stress (σ_{ref}) must be accurately calculated for the reason mentioned above. Tkaczyk et al. [6] used the modified reference stress approach proposed by Kim and Budden [7] to optimize the limit load solution of Kastner et al. [8], which is commonly used in the offshore industry. Although the approach leded to more accurate result, it still did not take directly advantage of the natural boundary condition of strain or displacement.

The crack driving force, in terms of the J-integral, is much more sensitive to bend moment than to strain under large-scale yield conditions [9,10]. For the relation of the J-integral and the bending moment, the J-integral increases dramatically in the stress range typical of the reel-lay method. Under these conditions, even small errors in the calculation of applied loads can lead to large errors in the estimation of the J-integral, potentially compromising the accuracy of traditional load based ECA procedures under

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Nomenclature

a	crack depth
A–H	fitting factors
b, c	characteristic length
c	half-length of crack
D	outer diameter of pipe
D_r	abscissa in the strain-based FAD
E	Young's modulus, $E' = E$ for plane stress and $E' = E/(1-\nu^2)$ for plane strain
f_1, f_2	non-dimensional functions of the reference strain method
f_w	finite width correction factors
h_1, g_1	normalized value of J-integral
J_p , J_e	plastic and elastic components of J-integral, respectively
K_r	ordinate in the FAD
K_{mat}	fracture toughness
K_I	Mode-I stress intensity factor
L_r	abscissa in the stress-based FAD
L_r^{max}	plastic collapse limit
M	bulging correction factors
M_m	stress intensity magnification factor
n	strain hardening exponent
P_0	generalized limit load
P	generalized applied loading
R_{reel}	radius of reel
t	wall thickness of pipeline
ν	Poisson coefficient
ε	strain
ε_0	normalizing strain
ε_{ref}	reference strain
ε_p	plastic strain
ε_y	yield strain
ε_{unc}	uncracked strain
$\Delta\varepsilon$	safety margins
σ	stress
σ_0	normalizing stress
σ_{max}	maximum tensile stress
σ_{ref}	reference stress
σ_y, σ_u	yield strength and ultimate strength, respectively
CTOD	crack tip opening displacement
ECA	engineering critical assessment
FAC	failure assessment curve
FAD	failure assessment diagram
SENT	edge notch tensile specimen

significant plasticity. However, the J-integral is almost linearly proportional to the strain imposed on the pipe during the reel-lay process, which makes the strain-based method more attractive.

Because of the reasons outlined above, a strain-based ECA method for reeled pipeline is preferable. Jayadevan et al. [11] and østby et al. [12] investigated the fracture response of pipelines subjected to large plastic strain under tension and bending, respectively. They examined the effects of crack depth, crack length, radius-to-thickness ratio, material hardening and internal pressure on the fracture parameter and obtained a linear CTOD-strain relation when the global deformation in pipeline became plastic. Based on the work mentioned above, Østby [13] proposed a set of strain-based formulas to calculate the fracture parameter (CTOD) of surface cracks in pipelines undergoing plastic strain. Nourpanah and Taheri [9] also took advantage of the linearly proportional relationship between crack driving force and strain and developed a more accurate strain-based approach to estimating J for reeled pipelines.

Linken et al. [14] developed a more straightforward strain-based J-integral estimation formula, which can be directly applied to conduct ECA for strain- or displacement-controlled situations. Based on the work of Linken, Budden [15,16] developed the strain-based failure assessment diagram (FAD) method. However, since a clear definition of reference strain does not exist, the reference strain is taken as the uncracked strain at the location containing cracks, which means the works of Linken et al. and Budden et al. are only suitable to shallow cracks ($a/t < 0.2$).

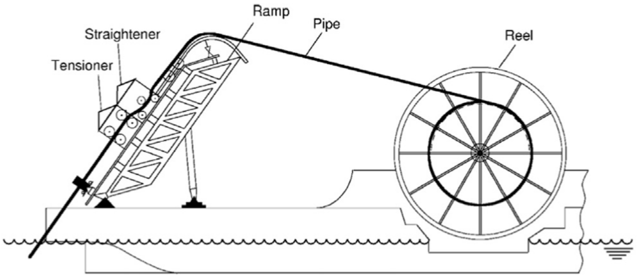

Fig. 1. Illustration of the reel-lay method [1].

In the paper, based on the works of Budden et al. and Nourpanah et al., proposes an empirical formula for evaluating the reference strain, which can extend the application of the strain-based failure assessment diagram method to more severe circumferential surface cracks in reeled pipes compared to the approaches in the literature.

2. *J*-integral estimation schemes

In the context of large-scale yielding, the path-independent J-integral [17] and crack tip opening displacement (CTOD) [18] are the most important fracture parameters which can be employed to characterize the initiation and propagation of cracks in ductile metals. The J-integral is based on a theoretical analysis in characterizing the crack-tip field, which is termed as HRR singularity. Contrary to the J-integral, the concept of CTOD originally was based on experimental observation. Previous work has shown that these two fracture parameters can be well correlated [19].

2.1. *J*-integral estimation methodology of EPRI

Considering a material following the uniaxial stress–strain relation in the Ramberg–Osgood form, represented by Eq. (3), Kumor et al. [20] proposed the EPRI approach to estimate the J-integral via Eq. (4).

$$\frac{\sigma}{\sigma_0} = \frac{\varepsilon}{\varepsilon_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n \tag{3}$$

where σ_0 is the normalizing strength, $\varepsilon_0 = \sigma_0/E$, n is the strain hardening exponent, and α is the material constant. $J_e(a_e)$ and $J_p(a)$ are the elastic and plastic component, respectively.

$$J_p = \alpha\sigma_0\varepsilon_0 c h_1(a/w, n)\left(\frac{P}{P_L}\right)^{n+1} \tag{4}$$

where c is the characteristic length (generally identical to the ligament length or crack size), h_1 is a function of the geometrical sizes of components and the strain hardening exponent, which has been tabulated by Kumor et al. [20] for some standard specimens