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A modified strain-controlled reference stress approach for submarine pipelines under large-scale plastic strain

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ABSTRACT

The reel-lay approach is widely applied in submarine pipelines. During the process of reeling and unreeling, pipelines are subjected to nominal strain of 1–4%. In this study, various pipeline geometries and crack dimensions were calculated using a finite element analysis and analytical solution under strain-controlled boundary conditions. A modified reference stress approach was applied under strain-controlled boundary conditions using a derived implicit analytical solution of the nominal stress. The limit load solution was modified through a γ factor based on the finite element analysis under strain-controlled boundary conditions. A regression analysis of γ was conducted and an empirical formula was determined. The modified strain-controlled reference approach is in contrast to other ECA methods and proved to be closer to the finite element analysis results.

1. Introduction

With an over-exploitation of land resources, large reserves of marine resources have received attention in recent years. Submarine exploitation is being gradually applied to industry. However, for complex submarine surroundings, high-quality long-distance pipelines are required [1–3], and some common exploitation methods such as J-lay [4,5], S-lay [6,7], and reel-lay [8] have been applied. With traditional J-lay and S-lay methods, it is difficult to guarantee the quality control during the process of offshore welding and nondestructive testing (NDT). The latest reel-lay method does not require offshore welding, and the pipelines are instead welded on land, reeled onto a huge roller, and then unreeled at the laying sites. During the reeling and unreeling process, the pipelines are subjected to 1–4% plastic strain [9–11]. Some micro-defects might not be found through NDT, or the repair process may be expensive. Therefore, an engineering critical assessment (ECA) is crucial in this type of case.

Some common ECA methods such as EPRI estimation [12], a reference stress approach [13], and a reference strain approach [14] have been applied. EPRI estimation was derived from the electric power research institute's J integral manual. The reference stress approach comes from the EPRI approach under the assumption of $h(n) \approx h(1)$ [13], and therefore the accuracy is sacrificed. However, the reference stress approach can be applied to materials not corresponding to Ramberg–Osgood's constitutive model. One of the most frequently input parameters of the reference stress approach are the limit load solution, P_L. The selection of P_L largely influences the accuracy of the evaluation. Another input parameter is the applied load, P. However, submarine pipelines are subjected to large-scale plastic strain during the reel-lay process. Therefore, reference stress approach is inaccurately applied directly to submarine pipelines under strain-controlled conditions. To apply the reference stress approach, the nominal strain should be transformed into the nominal stress. Chen et al. [15] conducted a numerical analysis of defective pipelines under complex loading systems through a reference stress approach. Kim et al. [16] conducted a comparison between an analytical solution and an experimental solution for circumferential through-wall cracked pipes. Østby et al. [17] applied a 3D finite element analysis of pipelines with surface cracks under large deformations. The relationship between the bending moment and strain was used to determine the bending moment of a specified strain, and relationship between CTOD and the bending moment was studied. Kamaya and Machida [18] conducted a numerical analysis of pipe containing inner circumferential cracking under a bending load. A comparison between the finite element analysis (FEA) and R6 Option 2 was applied, the results of which proved their good agreement. Based on numerical analyses [15–18], the boundary conditions are all load-controlled rather than strain-controlled. It is over conservative for a strain-controlled condition to be replaced with a load-controlled condition [19]. The reference strain approach is based on a strain-controlled or displacement-controlled condition, which was first proposed

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Nomenclature

a	surface crack depth
$2b$	average pipe perimeter
c	half of the surface crack length
D	external diameter of pipeline
D_r	abscissa of reference strain approach
D_a	average pipeline diameter
ECA	engineering critical assessment
EPRI	Electric Power Research Institute
E	Young's modulus
f_w	finite width correction factor
FEA	finite element analysis
FAD	failure assessment diagram
FAC	failure assessment diagram
h	factor of EPRI J approach
J	J integral
J_e	elastic component of J integral
K_I	stress intensity factor
K_{mat}	fracture toughness
K_r	ordinate of reference stress and reference strain approach
L_r,	abscissa of reference stress approach
L_r^{max}	plastic collapse limit
L_r^M	modified L_r
M	expansion correction factor
M_m	stress intensity amplification factor
n	strain hardening exponent
NDT	non-destructive testing
P	applied load
P_L	limit load
P_L^M	modified limit load
t	thickness of pipeline
ε_{ref}^m	modified reference strain
γ	correction factor of limit load
σ_0	yield strength
σ_n	nominal stress
σ_{ref}	reference stress
σ_{true}	true stress
σ_u	tensile strength
ε_{true}	true strain
ε_{true}^p	plastic component of true strain
$\varepsilon_{true}^{total}$	total true strain
ε_{true}^e	elastic component of true strain
ε_n	nominal strain
ε_{ref}	reference strain
ε_0	yield strain
ν	Poisson's ratio

by Linkens et al. [14]. However, there is a limitation to a reference strain approach in that it can only be applied to shallow cracks that do not affect the compliance of the entire component [20]. To date, a theoretical derivation of the reference stress approach based on the strain-controlled boundary condition has yet to be found. A simple nominal strain equivalent to the true strain is inaccurate for large-scale plastic deformation of submarine pipelines.

A series of numerical calculations were conducted in the present study under strain-controlled boundary conditions closer to the process of reel-lay submarine pipelines. The nominal stress σ_n was acquired using the derived implicit equation, $f(\sigma_n, \varepsilon_n) = 0$, according to the relationships among the true stress σ_{true}, true strain ε_{true}, nominal stress σ_n, nominal strain ε_n, and Ramberg–Osgood's constitutive model. Therefore, an applied load P can be acquired using σ_n. A modified γ factor was applied to the reference stress approach to guarantee the accuracy of the limit load. A regression analysis was conducted to acquire an empirical formula of the γ factor. The proposed modified strain-controlled reference stress approach was shown to be in contrast to other ECA methods.

2. ECA methods

2.1. Reference stress approach

In 1984, Ainsworth [13] proposed a new ECA method, which integrates the concept of the reference stress and EPRI J evaluation [21], which is widely known as a reference stress approach. The reference stress σ_{ref} as an input parameter is defined as Eq. (1):

$$\sigma_{ref} = \left(\frac{P}{P_L}\right)\sigma_0 \tag{1}$$

where σ_0 is the yield stress.

A failure assessment diagram (FAD) is a typical application of the reference stress approach, and is widely used in a fitness-for-purpose criterion such as R6 [22], BS 7910 [23], and API 579 [24]. There are three parameters in a FAD approach, namely, L_r, K_r, and L_r^{max}, as shown in Fig. 1, where L_r and K_r are defined through Eqs. (2) and (3), respectively. Here, K_I is the stress intensity factor, K_{mat} is the fracture toughness of the material, and L_r^{max} is the cut-off value of L_r, which is used to prevent a plastic collapse. There are various definitions of L_r^{max}. For example, L_{r1}^{max} is defined through Eq. (4) and corresponds to BS 7910 [23] and DNV-OS-F101 [25]. However, it is occasionally thought to be over conservative, and therefore, L_{r2}^{max} is defined through Eq. (5), which corresponds to DNV-RP-F108 [26].

$$L_r = \frac{\sigma_{ref}}{\sigma_0} = \frac{P}{P_L} \tag{2}$$

$$K_r = \frac{K_I}{K_{mat}} \tag{3}$$

$$L_{r\,1}^{max} = 0.5\left(\frac{\sigma_0 + \sigma_u}{\sigma_0}\right) \tag{4}$$

$$L_{r\,2}^{max} = \frac{\sigma_u}{\sigma_0} \tag{5}$$

A failure assessment curve (FAC) is defined through Eq. (6), which is in accordance with R6 Option 2 [22] and BS 7910 [23].

$$f(L_r) = \left[\frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{L_r^3\sigma_0}{2E\varepsilon_{ref}}\right]^{-\frac{1}{2}} \tag{6}$$

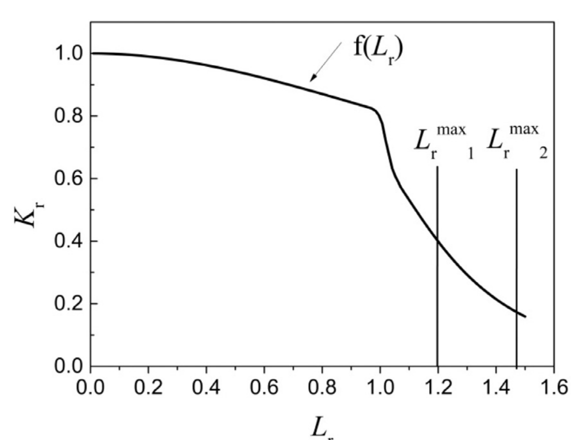

Fig. 1. Schematic of FAD based on reference stress approach.