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Strain-based *J*-estimation scheme for fracture assessment of misaligned clad pipelines with an interface crack

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ABSTRACT

A reference strain *J*-estimation formulation is developed to perform the fracture assessment of misaligned clad pipelines containing a circumferential part-through crack located at the interface of weld metal and outer pipe. An extensive parametric study including a total of 896 finite element (FE) models is carried out to investigate the effects of various parameters (pipe diameter, crack depth, crack length, centreline offset, strength mismatch level, and strain hardening exponent) on the *J*-integral. Then, the estimation formulation characterizing the linear relationship between the *J*-integral and the applied displacement loading is proposed using the standard least square fitting, and a goodness of fit for the *J*-integral values obtained from the formulation and the FE analysis is endorsed. Finally, the application range of the estimation formulation is mostly extended by conducting further comparative study.

1. Introduction

With the dramatically increasing demand for recoverable corrosive hydrocarbons, the clad C-Mn steel pipelines metallurgically-bonded with an inner corrosion resistant alloy (CRA) layer have become major transportation tools for oil and natural gases. These pipelines are connected together by joining one end of the pipe to the other end by girth welding procedure, and during the procedure, crack-like defects are often introduced into the pipelines, especially into the welds [1–5]. Moreover, the pipelines are subjected to complicated loading conditions during the installation or in-service operation [6], which poses tremendous challenge to the reliability of the pipelines. Therefore, it is of great importance to find a suitable fracture assessment methodology for these offshore pipelines under large plastic deformation. Current codes and standards for fracture assessment such as BS7910 [7] and R6 [8] are usually obtained from the load-controlled conditions [9,10]. However, in several circumstances, the pipelines are subjected to displacement- or strain-controlled loading deforming into the plastic regime [11], such as in the reeling installation [6]. In this case, strain-based approach is preferably employed for the fracture assessment.

In 1990s, Schwalbe [12] proposed a strain-based engineering treatment model on the crack tip opening displacement (CTOD) and *J*-integral for fully plastic conditions. However, the model can only be used for small strain levels and plane stress problem. As an extension of reference stress method, a reference strain *J*-estimation procedure was developed by Linkins et al. [13] to deal with strains directly based on the un-cracked body strain. With the advances in computing power, 3-D finite element (FE) analysis has become an alternative for conducting fracture assessment of cracked pipelines subjected to large plastic deformation. Jayadevan et al. [1] and Østby et al. [2] investigated the fracture responses of homogeneous pipelines with a surface crack based on 3-D FE analysis, and it is noted that the CTOD varies linearly with the global strain. The variation tendency of CTOD with the global strain for the welded clad pipelines with an external surface crack was studied by Zhang et al. [5], while the proposed assessment equation is only

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Nomenclature

a	crack depth
b	uncracked ligament length
D_e	pipe outer diameter
e	centreline offset
E	Young's modulus
F	dimensionless constant depending on structure geometry and loading mode
h	weld root opening width
h_1	dimensionless parameter depending on crack size, structure geometry and hardening exponent
J_{el}	elastic component of total J-integral
J_{pl}	plastic component of total J-integral
K	stress intensity factor
L	pipe length
M_F	weld strength mismatch factor
n	strain hardening exponent
n_{out}	strain hardening exponent of outer carbon steel
n_w	strain hardening exponent of weld metal
P	applied load
P_0	reference load
t	pipe wall thickness
t_{CRA}	CRA layer thickness
u	tensile displacement
α	dimensionless constant
β	rotation angle
ε_{nom}	applied nominal strain
ε_{pl}	plastic strain
ε_{ref}	reference strain
ε_{uc}	uncracked-body equivalent strain
ε_y	yield strain
θ/π	crack length ratio
σ_{nom}	applied nominal stress
σ_{ref}	reference stress
σ_{uc}	uncracked-body equivalent stress
σ_y	yield strength
σ_y^{out}	yield strength of outer carbon steel
σ_y^{w}	yield strength of weld metal
υ	Poisson's ratio
ϕ	weld groove angle

Abbreviations

BS	British Standard
CRA	corrosion resistant alloy
CTOD	crack tip opening displacement
EPRI	Electric Power Research Institute
FE	finite element
HAZ	heat affected zone
SGC	small geometry change
WCL	weld centre line

suited to a specific pipe configuration. Based on a strain-based J-estimation scheme in conjunction with the equivalent stress-strain relationship method, Souza and Ruggieri [14] provided a concise fracture assessment framework for under-matched pipe girth welds by considering a wide range of pipe geometries, crack sizes and material properties.

During the welding process, weld misalignment such as centreline offset, angular or both is invariably introduced into the pipeline [15–17], which induces an additional bending moment along the pipe section (Fig. 1). Due to the stress concentration effect caused by the misalignment, the maximum bending moment is obtained at the weld toe, while no bending moment is observed at the weld centre line (WCL) [4]. Hence, the weld toe is a more critical location of crack initiation and propagation. It is worth noting that the aforementioned research works [1–3,5,10,14] are all about fracture analyses of aligned pipelines with a surface crack located at the WCL, and few investigations are involved in the fracture assessment of misaligned clad pipelines containing a crack located at the

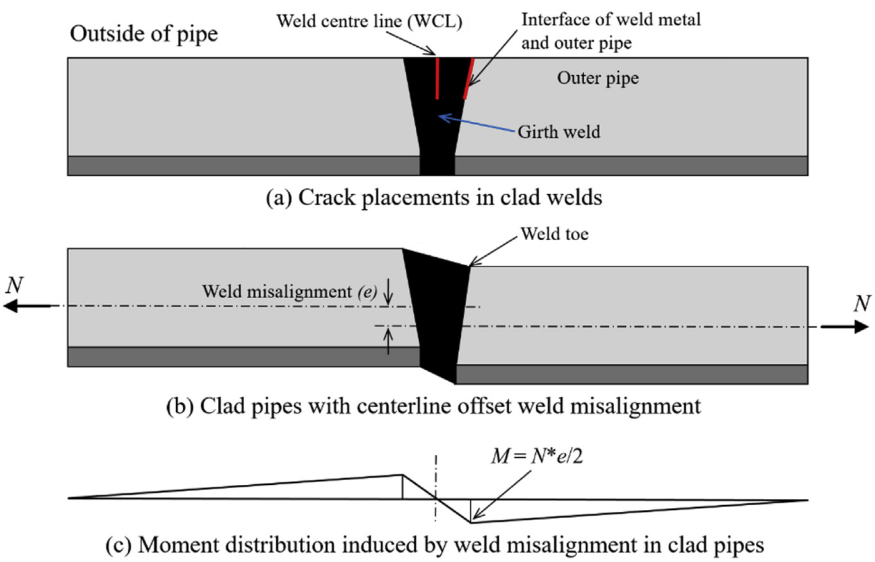

Fig. 1. (a) Crack placements in clad welds [27]; (b) clad pipes with centreline offset weld misalignment; (c) moment distribution induced by weld misalignment in clad pipes.