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A numerical study on the crack tip constraint of pipelines subject to extreme plastic bending

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ABSTRACT

This study investigates the fracture response and crack tip constraint of thick wall pipelines subject to large plastic bending. Such a circumstance frequently occurs during the installation of offshore pipelines (such as the reeling method), and accidental overloading, both inducing inelastic bending. The near-tip stress and strain fields are obtained through the fully nonlinear 3D finite element models constructed to examine the response of a practical range of cracked pipeline geometries and material properties. It is observed that throughout the loading history (up to the large scale yielding of the pipeline), by incorporation of the J–Q two parameter fracture theory, the near crack tip fields do indeed resemble those obtained from a K–T modified boundary layer formulation. This analogy provides sufficient proof for the applicability of the similitude concept inherent and fundamental to any fracture assessment procedure. All the pipelines considered in this study, which had realistic crack sizes, exhibited low constraint behavior (i.e. $-1.4 < Q < -0.4$). Additionally, Q was observed to decrease as a linear function of the global bending strain. Based on this correlation, simplified design equations are presented by which the constraint of such pipelines could be effectively estimated. The equations would be suitable for incorporation in the constraint-matched integrity assessment procedures that would in turn overcome the overt conservatism produced by the use of single parameter fracture mechanics approaches. Suitability of the low constraint laboratory specimens for fracture toughness measurements is also confirmed.

1. Introduction

With the ever-rising cost of energy and also depletion of most resources in reasonably benign environments, the oil and gas industry is compelled to move into more demanding environments (i.e. into deeper waters and into more hostile environments such as the Arctic). Reliable pipelines capable of operating in these environments and withstanding the associated extreme loadings are a key factor in such developments. The Limit State Design (LSD), together with the Strain Based Design (SBD), provides cost-effective pipeline design strategies, as manifested in most major design codes (e.g. API [1] and DNV [2]).

Pipelines, either onshore or offshore, are subjected to bending due to a variety sources, including pipelines conforming to the curvature of a stinger, reel drums and/or bathymetry of a rough seabed. Buried pipelines can also be subjected to seabed/ground motion caused by subsidence, mudslides, seismic activity and uneven settlements. Among these, reeled pipelines are subjected to the most severe inelastic bending, which induces strains up to 3%, well into the materials plastic range. For such pipelines, the potential for fracture of the girth weld on the tensile side is one of the governing limit states. Assessment of

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Nomenclature

δ_{ij}	Kronecker's delta
ε_g	global bending strain at the outermost pipe fiber
ε_p	equivalent plastic strain
ε_y	$=\sigma_y/E$, yield strain
σ_{ij}	stress tensor components
σ_{11}	crack opening stress
σ_e	$=(1.5 \times \underline{S}:\underline{S})^{0.5}$, equivalent Mises stress invariant
σ_h	$= \sigma_{kk}/3$, hydrostatic stress invariant
σ_u	ultimate tensile strength
σ_y	yield stress
υ	Poisson's ratio
$2c$	crack length
a	crack depth
b_1	intercept in the constraint estimation equation
B	width of SENT specimen
CTOD	crack tip opening displacement
d	$= CTOD/(J/\sigma_y)$ = crack opening parameter
D	pipeline diameter
E	modulus of elasticity
J	the *J*-Integral computed numerically
J_{ave}	spatially averaged *J*-Integral
K_I	Mode-I stress intensity factor
L	length of pipeline symmetric FE model
n	strain hardening index
Q	constraint parameter
Q_{ave}	spatially averaged constraint parameter
r, θ	polar coordinates based at the crack tip
R	radius in the MBL model
R_x	rotation applied at pipeline end (Rad)
s	curved coordinate along crack length (Fig. 2)
$\underline{S}$	deviator stress tensor
t	pipe wall thickness
T	*T*-stress
u_x, u_y	displacement components
W	thickness of SENT specimen

this limit state consists of conducting a fracture mechanics analysis of a hypothetical defect, which is assumed to have been caused due to welding imperfections, and is termed Engineering Criticality Assessment (ECA) in the literature. An ECA proceeds by comparing the crack-driving force of a flawed pipeline to the fracture toughness of the material obtained from a suitable test specimen. The concept of "similitude" in fracture mechanics is implicit in such an approach; that is, it is assumed that the near-tip stress and strain fields that govern the micro-structural fracture processes, are similar in any two cracked bodies (e.g. in this case, the flawed pipeline and the respective test specimen). Traditionally, these fields were assumed to be uniquely described by a single parameter (i.e. the crack-driving force), which, depending on the level of loading, could be either of *K*, *J* or *CTOD*. Later on, it was shown that such a single parameter description is only valid for certain configurations that exhibit high levels of crack-tip stress triaxiality [3,4].

Two-parameter formulations have been therefore developed, which utilize an additional "constraint" parameter, in addition to the crack-driving force, to describe the near-tip fields. Most notable of such formulations are the J–T [5,6], J–A_2 [7] and J–Q [8,9] formulations. The additional constraint term is closely related to the stress triaxiality, and can satisfactorily describe the scatter in the toughness data obtained from different test configurations. In general, higher constraint/triaxiality configurations exhibit lower fracture toughness and vice versa. Moreover, high constraint configurations usually undergo brittle cleavage fracture, while ductile tearing fracture is observed in low-constraint configurations. Despite the constraint dependency of the toughness data, historically, guidelines have recommended the use of high constraint test specimens, such as the deeply cracked Single Edge Notch Bend (SENB) specimen, which produces the lowest toughness data, thus adding to the conservatism of the ECA. However, recently, the provision to utilize constraint-matched test specimen is recommended by some codes. For instance, DNV [10] accepts the use of low-constraint Single Edge Notch Tensile (SENT) specimen for the assessment of reeled pipelines, based on its constraint similarity to that of circumferentially flawed reeled pipes [11,12]. Similar studies [13,14], have shown the suitability of SENT specimens for ECA of high pressure pipelines with axial flaws based on close examination of J–Q trajectories in the two bodies.