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A probabilistic fracture mechanics model including 3D ductile tearing of bi-axially loaded pipes with surface cracks

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Abstract

This paper presents a probabilistic fracture mechanics model established from three-dimensional FEM analyses of surface cracked pipes subjected to tension load in combination with internal pressure. The models are particularly interesting for offshore pipelines under operational conditions or during laying, where inelastic deformations may occur. In the numerical models, the plastic deformations, including ductile tearing effects, are accounted for by use of the Gurson–Tvergaard–Needleman model. This model is calibrated to represent a typical X65 pipeline steel behaviour under ductile crack growth and collapse. Several parameters are taken into account, such as crack depth, crack length and material hardening. Another important topic is the examination of the influence of bi-axial loading due to internal pressure on capacity. From the results of the deterministic analyses a probabilistic fracture mechanics model is established using the response surface methodology. Two failure criteria are examined to represent the structural capacity. Based on the established model, we illustrate the methodology by examples employing the two different failure criteria solved with first and second order reliability methods.

Keywords: 3D FEM models; Ductile tearing; Elastic–plastic fracture mechanics; Probabilistic fracture mechanics; CTOD; Response surfaces; Pipelines

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1. Introduction

Under installation and operational conditions of offshore pipelines it is of utmost importance to have calculation procedures to account for different failure modes, such as brittle and ductile fracture and buckling. Additionally, it is important to utilize the pipe capacity to enable a safe and cost effective design. In this paper, we focus on steel pipe materials, such as *X*65, exposed to ductile fracture. In high grade pipeline steels fracture mechanics assessment is important due to the high utilization of the material. Large plastic deformations may be allowed, and a defect positioned in an area with high tension load can result in catastrophic failure. Under

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Nomenclature

t	pipe wall thickness
D	pipe wall diameter
ϕ	angle at the circumference of the pipe
σ_0,$\sigma_{0.2}$	stress at the proportional limit, stress at 0.2% plastic strain
σ_i, σ_TS	flow stress, tensile strength
σ_e, σ_m	von Mises stress, mean stress
σ_h	hoop stress
n	hardening exponent
E	Young's modulus
ν	Poisson ratio
CTOD	crack tip opening displacement
ε	nominal global longitudinal strain
ε_0, ε_p	strain at the proportional limit, plastic strain
ε_lay, ε_app	strain due to laying, strain input to the limit state equation
$\varepsilon_\mathrm{crit}$, $\bar{\varepsilon}_\mathrm{crit}$	critical strain (capacity), critical strain function
ε_s,ε_d	strain due to external static and dynamic load
p_f	probability of failure
$\mathbf{X}$	n-dimensional random vector
$\mathbf{x}$	realizations of $\mathbf{X}$
$f_\mathbf{X}(\mathbf{x})$	joint probability density function of $\mathbf{X}$
$F_\mathbf{X}(\mathbf{x})$	joint probability function
X_i	ith random variable in x-space
$\mathbf{U}$	n-dimensional random vector in $\mathbf{u}$-space
$\mathbf{u}$	realizations of $\mathbf{U}$
U_i	ith uncorrelated standard normal random variable
$G(\mathbf{x})$,$G(\mathbf{u})$	limit state functions in $\mathbf{x}$ and $\mathbf{u}$-space
Φ	univariate standard normal integral
β	safety index
$\alpha, \alpha_\mathrm{i}, \alpha_{ii}, \alpha_{ij}$	polynomial coefficients
f_0, f, f^*	initial, current, and effective void volume fraction
$\dot{f}_\mathrm{growth}$	change in void volume fraction due to void growth
f_F^*	the ultimate value where the microscopic stress carrying capacity vanishes
q_1, q_2, q_3	constants in the Gurson yield function

operational conditions with internal pressure, the external loads may come from free-spans due to seabed topography or lateral snaking due to thermal loads. This means that the loads are often given as applied strain.

Presently, BS7910 [1] and R6 [2] are two examples of common fracture assessment procedures used in pipeline engineering. These procedures are mainly established for elastic global response and do not consider large plastic deformations. It has been shown that BS7910 [1] has restricted applicability where large longitudinal plastic deformations occur, Thaulow et al. [3]. In addition, the stress-based BS7910 procedure is not able to predict safe strain limits for high strain conditions accounting for internal pressure. Therefore, the emphasis in the Joint Industry Fracture Control-Offshore Pipelines project [4] is on large plastic deformations in pipelines and strain-based design. It is believed that a strain-based methodology has the potential to improve the physical prediction of the fracture mechanics response. Strain-based fracture mechanics equations, including the effects of biaxial loading, mismatch, and misalignment, have recently been presented, Østby [5]. These simplified equations are used to establish a strain-based design procedure for laying and operational conditions for offshore pipelines using the partial safety factor format as found in e.g. DNV-OS-F101 [6].