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Cleavage fracture assessment for surface-cracked plates fabricated from high strength steels

Shuang Chen, Xudong Qian *, Aziz Ahmed

Department of Civil and Environmental Engineering, Centre for Offshore Research and Engineering, National University of Singapore, Singapore 117576, Singapore

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ABSTRACT

This paper presents a combined experimental and numerical investigation to assess the probability of cleavage fracture for surface-cracked plates, using the Weibull stress framework. The proposed procedure defines a critical crack-front segment as the fracture initiation zone using the computed energy release rate. The Weibull-stress based local approach introduces a modified constraint correction function, which allows bidirectional scaling of the fracture toughness in surface-cracked specimens and the idealized 1T small-scale yielding condition. The proposed procedure predicts closely the probability of fracture for surface-cracked specimens made of three different types of steel materials.

1. Introduction

Structural steels have observed increasing applications in conditions with a low ambient temperature, for example, in offshore facilities in the Arctic which covers about 25% of the world's undiscovered petroleum reserve. At low ambient temperatures, ferritic structural steels often experience unstable brittle failure with barely noticeable prior deformations, which leads subsequently to catastrophic consequences. As revealed by previous studies [1,2], cleavage fracture initiates with the rapid propagation of a crack along specific crystallographic planes. The trigger of the cleavage fracture failure, which often exhibits pronounced scatters in the experimentally measured toughness values [3–5], originates from the statistical distribution of the microscopic defects in the near-tip material [6,7]. Thus the assessment of cleavage fracture often utilizes a probability-based treatment to describe the scatter of the experimental data in contrast to a deterministic approach used for ductile fracture failure.

The assessment of the cleavage fracture failure for steel materials has led to the development of both a global approach [8–10] based on the experimentally measured fracture toughness values from standard laboratory specimens, and a local approach [11–13] using a Weibull stress calculated from the highly stressed materials ahead of the crack front. ASTM E-1921 [14] summarizes such a global approach in estimating the probability of cleavage fracture for high-constraint, small-scale yielding crack-front conditions. The global Weibull model quantifies the temperature dependence of the fracture toughness over the DBT region through a Master Curve concept [3,15,16]. The Master Curve defines the relationship between the median fracture toughness and the temperature for one-inch (25.4 mm) thick high-constraint specimens, via a reference temperature T_0 determined from the explicit procedures outlined in ASTM E-1921 [14].

* Corresponding author. Tel.: +65 6516 6827; fax: +65 6779 1635.
E-mail address: qianxudong@nus.edu.sg (X. Qian).

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Nomenclature

A_{pl}	area under the load versus plastic displacement or moment versus plastic rotation curve
A_{net}	net intact area of the cracked section in a surface-cracked specimen
B	thickness of a through-thickness fracture specimen
B_{FZ}	length of the critical crack-front segment representing the fracture initiation zone
B_{total}	total crack-front length for a surface crack
C	constant
E	elastic modulus
J	energy release rate
J_{avg}	average energy release rate along the curved crack front
J_c	critical energy release rate
J_{pl}	plastic component of J
K_0	macroscopic Weibull scale parameter
K_{Jc}	critical plane-strain fracture toughness
K_J	plane-strain crack driving force under mode I loading $\left(=\sqrt{EJ/(1-\upsilon^2)}\right)$
K_{min}	threshold fracture toughness
M	non-dimensional loading parameter $(= b\sigma_0/J)$
N	total number of specimens in a dataset
P	load
P_f	cumulative probability of fracture
$P_{i\text{-}rank}$	rank probability
R	radius of modified boundary layer model
R_0	initial root radius
S	loading span
T	temperature
T_0	reference temperature at which the median fracture toughness equals 100 MPa$\sqrt{\text{m}}$
U	strain energy
V_0	a reference volume (1 mm^3 in this paper)
V_f	volume of the fracture process zone
W	width of a specimen
a_0	initial crack depth
b_0	initial remaining ligament in a specimen
d	coefficient in rotation angle of a surface-cracked specimen
$g(M)$	constraint function
h	thickness of the knife-edge attachment on the surface of the plate
l	arc length along the crack front measured from the free surface
m	Weibull modulus
r	number of valid data
t	thickness of the surface-cracked plate
u	displacement along x-axis
υ	displacement along y-axis
xT	thickness of the fracture specimen (as multiples or fractions of 1 inch or 25.4 mm)
α	anti-clockwise angle
η	coefficient in J calculation
θ	rotation angle of a specimen
σ_0	yield strength of the material
σ_1	maximum principal stress
σ_u	Weibull scale parameter
σ_{ult}	ultimate strength of the material
σ_w	Weibull stress
$\sigma_{w\text{-}min}$	threshold Weibull stress
υ	Poisson's ratio
ϕ	crack-front angle

The local approach, represented by the Weibull stress model pioneered by the Beremin's group [17], estimates the local crack driving force using a scalar Weibull stress based on an assumed distribution of the microscopic flaw sizes in the near-tip materials. The cumulative probability of failure predicates on the weakest-link model, which assumes that the cleavage failure of the entire specimen triggers from a failure in a local volume of material ahead of the crack tip. Previous researchers [18,19] have incorporated a threshold Weibull stress in the two-parameter Weibull stress model to reflect the experimental observation that cleavage fracture does not occur below a specific global crack driving force, in line with the global Weibull