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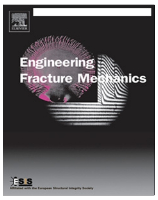

Three-dimensional finite element analysis of crack-tip fields of clamped single-edge tension specimens – Part I: Crack-tip stress fields

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ABSTRACT

A systematic study has been carried out based on three-dimensional finite element analyses to investigate the impact of the in-plane and out-of-plane dimensions on the crack-tip stress fields of clamped SE(T) specimens. Both plane-sided and side-grooved specimens with a wide range of thickness-to-width ratios ($B/W = 1/2$, 1, 2 and 4), crack lengths ($a/W = 0.3$, 0.4, 0.5, 0.6 and 0.7) and strain hardening exponents ($n = 5$, 10 and 20) are included in this study. The through-thickness distributions of J and CTOD as well as the distribution of the opening stress ($\sigma_{\theta\theta}$) ahead of the crack tip at different crack front locations are presented. The distributions of J and CTOD over the crack front and those of $\sigma_{\theta\theta}$ ahead of the crack tip are impacted by a/W, B/W, n and the type of specimens (i.e. plane-sided or side-grooved). In addition, the empirical equation for calculating CTOD from J for SE(T) specimens developed by Shen and Tyson based on two-dimensional plane-strain finite element analyses is found inadequate to be applied to three-dimensional SE(T) specimens except for the plane-sided specimens with $n = 10$ and side-grooved specimens with $n = 5$.

1. Introduction

The strain-based design (SBD) method [1–4] is being increasingly used to address demanding loading conditions in offshore and onshore pipeline applications, such as offshore pipe laying and large ground movements imposed on onshore pipelines due to, for example, frost heave, thaw settlement and mine subsidence. In the strain-based design method, the fracture toughness resistance curve, i.e. the J-integral (J)–R or crack tip opening displacement (CTOD)–R curve, is a key input to the evaluation of the tensile strain capacity [3–7], which is defined as the allowable longitudinal tensile strain in the pipeline and generally exceeds the yield strain. It is well known that the toughness resistance curve depends on the crack-tip constraint level [8–10]: a high level of crack-tip constraint results in a low toughness resistance curve and vice versa. The use of the single-edge tension (SE(T)) specimen to determine the resistance curve has gained much attention in the pipeline industry over the last decade, mainly because the SE(T) specimen is more relevant to the full-scale pipe containing surface cracks under internal pressure and/or longitudinal tension than the standard single-edge bend (SE(B)) and compact tension (C(T)) specimens as far as the crack-tip stress field and constraint level are concerned [2–4,8,11–17].

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Nomenclature

2/3D	two/three dimensional
a	crack depth
A_2	in-plane constraint parameter
b	remaining ligament
B	specimen thickness
B_N	specimen net thickness
CMOD	crack mouth opening displacement
C(T)	compact tension
CTOD	crack tip opening displacement
δ_{90}	local CTOD measured based on the 90° intersection method
δ_J	CTOD estimated from J based on Eq. (2)
ε	true strain
ε_0	yield strain
E	Young's modulus
FEA	finite element analysis
h	out-of-plane constraint parameter
H	specimen daylight distance
HRR	Hutchinson–Rice–Rosengren
J	J-integral
J_{ave}	average J-integral
J_{loc}	local J-integral
J_{mid}	mid-plane J-integral
LLD	load line displacement
m	factor relating *CTOD* to J
n	strain hardening exponent
P_Y	reference load
Q	in-plane constraint parameter
ρ	crack tip radius
r	crack distance
R curve	resistance curve
σ	true stress
σ_0	yield strength
$\sigma_{\theta\theta}$	opening stress
σ_{UTS}	ultimate tensile strength
σ_Y	effective yield strength
SBD	strain-based design
SE(B)	single-edge bend
SE(T)	single-edge tension
t	pipe wall thickness
T_z	out-of-plane constraint parameter
v	Poisson ratio
VCE	virtual crack extension
W	specimen width
z	z-direction (through-thickness) coordinate

Two types of SE(T) specimens have been reported in the literature, namely the pin-ended [18,19] and clamped specimens [2,3,15,16,20,21]. Nyhus et al. [22] reported that J and the crack-tip constraint level for pin-ended SE(T) specimens are independent of the specimen daylight distance (H), whereas J and the crack-tip constraint level for clamped SE(T) specimens are significantly influenced by H. Chiesa et al. [23] pointed out the similarity between the crack-tip constraint levels of the clamped SE(T) specimen and non-pressurized pipeline containing circumferential surface cracks under longitudinal tension based on results of the finite element analysis (FEA). In [23], the SE(T) specimen and pipeline were modeled by adopting the two-dimensional (2D) plane-strain and shell-line-spring elements, respectively. Cravero and Ruggieri [12] also carried out plane-strain FEA and compared the crack-tip constraint levels of the pin-ended and clamped SE(T) specimens with those of the pressurized pipelines containing longitudinal surface cracks. They reported that the crack-tip constraint levels of pin-ended SE(T) specimens correlate well with those of the longitudinally cracked pipeline, if the relative crack length (a/W) for the specimen equals that (a/t) for the pipeline, where t is the pipe wall thickness. Shen et al. [13] carried out plane-strain FEA of pin-ended and clamped SE(T) specimens as well as full-scale non-pressurized pipes containing circumferential surface cracks under tension. They indicated that the crack-tip constraint levels of both pin-ended and clamped