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Computational modeling of the drop-weight tear test: A comparison of two failure modeling approaches

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ABSTRACT

We use a void mediated (Modified Gurson–Tvergaard–Needleman) and damagemechanics-based approaches (Modified Xue–Wierzbicki) to model fracture of pipeline steel in the drop-weight tear test. Both of the approaches provide a reasonable account of the experimental force–displacement records and the Crack-Tip Opening Angles (CTOAs) obtained though the analysis of the records; however, for the mesh densities considered in this work, the void-based fracture modeling it does not capture tunneling-to-slant transition. We also use results of the models to address the issue of transferability of CTOA measured in lab-scale samples to larger scales.

1. Introduction

The Drop-Weight Tear Test (DWTT) is commonly used to characterize the dynamic fracture behavior of pipeline steel. At CanmetMATERIALS, the Crack-Tip Opening Angle (CTOA), computed by an analysis of the force–displacement curve recorded in the DWTT, has been investigated with regard to use as a failure parameter that may serve to characterize the capacity of the steel to arrest rapidly propagating cracks in pipes conveying gas; see, for instance, the article by Xu et al. [1]. We may also use the force–displacement curve and the observed fracture-surface morphology to calibrate and validate computational failure models. In this paper, we contrast a previously-developed damage-mechanics-based approach (Simha et al. [2]-hereafter designated as Article I) to model failure with an approach based on void growth, nucleation and coalescence.

In Article I, the failure modeling approach incorporates rate effects for damage evolution and strength dependence, and is a modification of the model advanced by Xue and Wierzbicki [3] (see also [4]) which comprises a damage evolution law that depends on both the hydrostatic state of stress and the Lode angle. A highlight of Article I is the modeling of the transition from tunneling to slant fracture in X70 grade pipeline steel; in addition, the model obtained good agreement with computational and experimental force–displacement curves. The damage-mechanics approach uses a scalar damage variable $D \in [0,1]$ to model failure so that when $D = 1$, the material element can no longer support any load. Models are specified for the degradation of both the elastic modulus as well as the material strength. However, analysis of fracture surfaces has shown that the failure is void-based (see, for instance, Fig. 1). In contrast to damage mechanics, wherein damage is an abstract variable, a physically appealing alternative is to use a model wherein the failure is mediated by voids.

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Nomenclature

$\mathbf{1}$	second order identity tensor
A	Gaussian amplitude (used in nucleation model)
A^*	dimensionless geometric factor
$\boldsymbol{C}$	fourth order elastic tensor
C_1	hardening constant in strength model
C_2	rate constant in strength model
C_p	specific heat capacity
d	DWTT notch depth
E	Young's modulus
f	void volume fraction
f^*	derived void volume fraction
f_c	void volume fraction at coalescence
f_f	void volume fraction at failure
f_N	fraction of second-phase particles that nucleate voids
G	Shear modulus
H	DWTT sample height
h	weighting function for non-locality
$\boldsymbol{I}$	fourth order symmetric identity tensor
i, j, k	indices ranging from 1 to 3
J_3	third invariant of deviatoric tensor
k_ω	constant in lode-angle dependence of void growth
L	DWTT sample length
$\boldsymbol{n}$	plastic flow direction
n	hardening exponent in strength model
P	load
P_{max}	maximum load
q_1, q_2, q_3	GTN constants
R	radius of non-local sphere
r	radius
$\boldsymbol{r}$	plastic flow direction
$\boldsymbol{s}$	deviator tensor
S	DWTT sample span
s_N	standard deviation in void nucleation model
T	temperature
t	time
T_M	melting temperature
T_R	reference temperature
V	volume
V_p	non-local volume
w	DWTT notch width
$\mathcal{H}$	normalizing function in non-local integral
$\mathcal{K}$	bulk modulus
$\mathcal{L}$	lode parameter
χ	Taylor-Quinney coefficient
$\boldsymbol{\epsilon}$	strain tensor
$\epsilon_\circ$	fracture envelope constant
$d\epsilon_p$	increment of equivalent plastic strain
ϵ_f	fracture envelope
ϵ_N	nucleation strain in normal distribution
$\boldsymbol{\epsilon}^p$	plastic strain tensor
ϵ_p	equivalent plastic strain
$\dot{\epsilon}_p$	equivalent plastic strain rate
$\dot{\epsilon}_\circ$	reference strain rate
$d\lambda$	plastic flow proportionality constant
ϕ	yield function
ρ	density
$\bar{\sigma}$	effective strength
$\boldsymbol{\sigma}$	stress tensor
$\sigma_\circ$	yield strength