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Non-local phenomenological damage-mechanics-based modeling of the Drop-Weight Tear Test

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ABSTRACT

We modify the Xue–Wierzbicki damage mechanics model to include strain rate effects, implement it in an explicit finite element code and use it to model the dynamic response and failure of X70 pipe steel in the Drop-Weight Tear Test (DWTT). The damage evolution depends on Lode angle, hydrostatic pressure, and strain rate. Strength of the steel is assumed to depend on strain hardening, strain rate and thermal softening. To mitigate the expected mesh dependence of results, we use the non-local integral formulation due to Bazant and Pijaudier-Cabot. A highlight of the computational results is the ability to model the fracture mode transition between impact and static loading: slant fracture for impact loading and flat fracture for static loading of the DWTT specimen. Furthermore, the measured experimental force–displacement curves are in excellent agreement with the computed curves. We estimate the Crack Tip Opening Angle and compare with experimental measurements. Our results also provide insight into the influence of the Lode-angle-dependent damage evolution on modeling slant fracture.

1. Introduction

The dynamic fracture response of pipe steels may be characterized using the Drop-Weight Tear Test (DWTT). Force and displacement histories measured in the test can be used to compute quantitative measures of fracture resistance such as fracture energy and Crack-Tip Opening Angle (CTOA); see, for instance, Xu and Tyson [1]. Force–displacement measurements and fracture surface observations in the DWTT may also be used to calibrate and validate constitutive models for the pipe steel in finite element (FE) computations. Constitutive model, here, is intended to include both a description of the steel's strength (strain hardening, strain rate and thermal dependence) and failure. Results of computations wherein the steel is described by such a constitutive model provide insights into the DWTT, and more importantly, allow assessment of the material's response to stress states and loading conditions not accessible through the DWTT. In the present work, we develop a constitutive model and use it to model the response and failure of a typical pipe steel in the DWTT.

To date, failure in finite element models of the DWTT has been modeled using the Gurson-Tvergaard-Needleman model or the Cohesive Zone approach. In the former, the strength of the ductile matrix is degraded based on void nucleation and growth, and when a threshold void volume fraction is reached, the finite element is removed from the calculation thereby simulating crack growth. The articles by Wang et al. [2] and Nonn and Kalwa [3] are representative examples. The Cohesive Zone approach relies on a traction-separation law specified for cohesive zone elements that are placed in the finite element mesh along the crack path; the elements separate when some fracture-mechanics-based criterion is satisfied and free

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Nomenclature

$\mathbf{1}$	second order identity tensor
a	thermal diffucivity
$\boldsymbol{C}$	fourth order elastic tensor
C_1	hardening constant in strength model
C_2	rate constant in strength model
C_p	specific heat capacity
D	damage
d	displacement in DWTT
d_{max}	displacement corresponding to maximum load
E	Young's modulus
G	shear modulus
$g(\dot{\epsilon}_p)$	function modifying damage evolution
h	weighting function for non-locality
$\boldsymbol{I}$	fourth order symmetric identity tensor
i, j, k	indices ranging from 1 to 3
J	J integral
J_3	third invariant of deviatoric tensor
K	fracture toughness
k	exponent in lode angle function
$\boldsymbol{n}$	plastic flow direction
n	hardening exponent in strength model
P	impact load
p	hydrostatic pressure
p_{lim}	tensile pressure limit. Above this pressure $D = 1$.
P_{max}	maximum impact load
q	constant in pressure dependence function μ_p
R	radius of non-local sphere
r	radius
$\boldsymbol{s}$	deviator tensor
T	temperature
t	time
T_M	melting temperature
T_R	reference temperature
V	volume
v	crack speed
V_p	non-local volume
$w(D)$	weakening function
$\mathcal{H}$	normalizing function in non-local integral
$\mathcal{K}$	bulk modulus
$\mathcal{L}$	lode parameter
β_e	exponent in elastic weakening function
β_p	exponent in plastic weakening function
χ	Taylor–Quinney coefficient
δ	rate parameter in strain rate function modifying damage evolution
$\boldsymbol{\epsilon}$	strain tensor
$\epsilon_\circ$	fracture envelope constant
$d\epsilon_p$	increment of equivalent plastic strain
ϵ_f	fracture envelope
$\boldsymbol{\epsilon}^p$	plastic strain tensor
ϵ_p	equivalent plastic strain
$\dot{\epsilon}_p$	equivalent plastic strain rate
$\dot{\epsilon}_\circ$	reference strain rate
γ	weighting constant in Lode angle function
κ	thermal conductivity
$\mu_p(p)$	pressure dependence function in fracture envelope
Φ	yield function
ρ	density
$\bar{\sigma}$	effective strength
$\boldsymbol{\sigma}$	stress tensor