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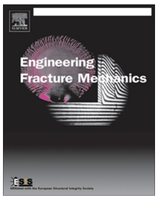

A model for arrest of rapid cracks in gas-pressurized ductile steel line pipe

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ABSTRACT

Modifying and adding to elements of Schindler's model, a model to predict arrest of rapidly propagating cracks in gas-pressurized steel pipe is presented. A bulging factor models the flaring of the crack flaps and contributes to the crack driving force. The crack tip, a structural hinge in each flap, a traveling neck ahead of the crack tip, and soil backfill contribute to the plastic dissipation rate. Model inputs are yield and ultimate strength, hardening exponent, crack-tip opening angle, soil density and Charpy V-Notch energy. Model predictions for steel grades ranging from X52 to X120, display modest non-conservatism.

1. Introduction

Field tests show that gas-pressurized, high-grade, steel line pipe specified using the Charpy V-Notch (CVN) energy computed through the Battelle Two-Curve Model (BTCM) may not arrest a rapidly propagating crack. Alternatively stated, for grades that have CVN energies greater than 100 J, the BTCM may obtain non-conservative predictions. Modifications to the BTCM that increase the conservatism of the predictions do exist, but the modifications rely on results of field tests to adjust empirical parameters in models. This article presents an alternative to the BTCM or its variants – model inputs are parameters that can be obtained using routine laboratory experiments.

Crack arrest in steel line pipe depends on the fracture and flow properties of the steel, speed of the decompression front in the gas, interaction between the expanding gas and the flaring surfaces of the crack flaps, and the presence of backfill. Subsuming these complex phenomena into a set of three equations, the BTCM yields a toughness requirement for the line pipe, given the line pressure, gas composition and depth of back fill (or no backfill).

Because of the complexity of the relationship between the fracture resistance and the driving force, the BTCM relies crucially on empirical calibrations. For ease of use, parametric studies were carried out using the BTCM to obtain an empirical relationship for the CVN and this is known as the Batelle One-Curve Model (BOCM); see the report by Eiber et al. [9]. The BOCM is given by

$$C_{V(2/3)B} = 2.382 \cdot 10^{-2} \sigma_h^2 (Rt)^{1/3}, \tag{1}$$

where the hoop stress σ_h is expressed in MPa, radius R and thickness t are expressed in mm, and $C_{V(2/3)B}$ energy in Joules. Scaling the energy obtained in this expression by 1.4925 (ratio of the cross-sectional areas of the full size and two-third size

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Nomenclature

$a_\circ$	initial notch of CVN sample
A_g	fracture strain expressed as a percentage
Δa	crack growth
B	thickness of CVN sample
c	half length of crack
c_d	factor for dynamic strength
$C_{V(2/3)B}$	Charpy V-Notch energy for two-thirds size sample from the BOCM
$C_{V(BTCM)}$	Charpy V-Notch energy for full size sample using the BTCM
$C_{V(LE)}$	Charpy V-Notch energy for full size sample using the Leis–Eiber correction
D	total plastic dissipation rate
D_f	energy of fracture (rate)
D_{ph}	energy dissipation rate in plastic hinge
D_{pn}	energy dissipation rate in neck
D_{ps}	energy dissipation rate for soil evacuation
E	Young's modulus
G	elastic energy release rate
J	Joule
$\mathcal{J}$	J-integral
$\mathcal{J}_{0.2}$	J-integral at 0.2 mm of crack growth
K	hardening coefficient
K_d	dynamic fracture toughness
K_I	mode I stress intensity factor
l_p	plastic zone size
M	moment acting on flanks of crack
m	exponent in resistance curve
M_T	bulging factor
n	hardening exponent in power law
p	internal pressure
R	radius
t	wall thickness of pipe
T_p	time of travel of wedge of soil per increment of crack growth
V	crack speed
W	height of CVN sample
W_{CVN}	CVN energy
W_{ext}	rate of external work (work input per unit area of crack extension)
W_f	fracture energy
W_p	rate of plastic dissipation (plastic work dissipated per unit area of crack extension)
W_{ph}	rate of plastic dissipation in hinges in crack flanks
W_{pn}	rate of plastic dissipation in neck preceding the crack tip
W_{ps}	rate of plastic dissipation due to soil
α	crack-tip opening angle
β	rotation angle of the hinge
δ	angle used in the hinge model
Δ	symbol for increment
ϵ_f	localization strain
$\bar{\epsilon}$	effective plastic strain
η	η factor
ψ	used in bulging factor definition
γ	angle used in the hinge model
γ_p	surface energy (energy per unit area)
λ	used in bulging factor
ν	Poisson's ratio
ρ	root radius of notch in CVN sample
ϱ	density of soil
σ_f	flow stress – average of yield and ultimate strength
σ_y	yield strength
σ_u	ultimate strength
$\bar{\sigma}$	effective stress
σ_h	hoop stress
σ_{RDT}	hoop stress at crack arrest