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Technical Note

Geometric and material property dependencies of the plastic rotation factor in the drop-weight-tear test

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ABSTRACT

We carry out significance testing on experimental and computational data sets to determine which material and geometric parameters affect the plastic rotation factor (which is used to estimate the crack-tip-opening angle based on the plastic hinge model) for pipeline steels. It is shown, using the Xue-Wierzbicki damage mechanics model and a statistical analysis, that the rotation factor mainly depends on the Charpy V-notch energy, and empirical fits for the rotation factor are proposed.

1. Introduction

The measurement of the Crack-Tip Opening Angle (CTOA) for ductile, ferritic steels has been investigated with the aim of using it as a measure of the fracture propagation toughness or as a failure criterion for crack extension in finite element computations. CanmetMATERIALS has been developing the Simplified-Single Specimen (S-SSM) CTOA procedure to estimate the CTOA based on the force–displacement history measured in a Drop-Weight Tear Test (DWTT) based on the plastic hinge model [5]. The only adjustable constant in the CTOA estimation procedure is the plastic rotation factor.

In the S-SSM procedure, for CTOA estimation, the force–displacement curve yields a slope, which in combination with a plastic rotation factor yields the CTOA [6].

$$2\gamma = \frac{8r_p}{\xi} \cdot \frac{180}{\pi} \tag{1}$$

where 2γ is the CTOA, and ξ is the slope of the $\ln(\frac{P}{P_m})$ vs $\frac{(y-y_i)}{S}$ curve in the steady-state region; see Fig. 1(b) for an example. P_m is the peak force observed during the test, y_i is the displacement when the peak force occurs. The steady-state region of crack growth occurs when $-1.21 < ln(\frac{P}{P_m}) < -0.51$, which corresponds to crack length between 25 mm and 40 mm for a 10 mm deep notch DWTT specimen.

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Nomenclature

ϵ_f	plastic strain at failure
ϵ_p	plastic strain
γ	half the CTOA
σ_y	yield strength
ξ	slope of the normalized DWTT force–displacement curve plotted on a logarithmic scale
a	distance from the surface of the specimen to the crack tip
B	initial thickness of the DWTT specimen
$b = W - a$	remaining ligament
C_v	Charpy V-notch energy
$CTOA = 2\gamma$	crack tip opening angle
$d\epsilon_p$	increment of plastic strain
D_e	DWTT energy
dD	increment of damage
m	material parameter in damage evolution model
n	hardening exponent
P	force in the DWTT
$P^* = \frac{P}{P_m}$	non-dimensional DWTT force
P_m	peak force in the DWTT
r_p	plastic rotation factor
S	distance between the anvils in the DWTT test
W	width of the DWTT specimen
y	vertical displacement of hammer (at load point) in the DWTT
$y^* = \frac{y - y_i}{S}$	non-dimensional DWTT displacement
y_i	vertical displacement of hammer (at load point) at peak load in the DWTT
y_{na}	distance from the neutral axis to the crack tip

The question of the dependency of r_p on material properties such as yield strength (σ_y), Charpy V-Notch Energy (C_v), and geometrical parameters such as specimen thickness (B) was drawn to our attention during discussion within the ASTM committee considering a draft standard for measurement of CTOA based on the S-SSM procedure.

In this note, we study empirical dependencies of r_p on the above variables through two approaches – using computations and using experimental results. The obtained relationships were subjected to statistical assessments to identify the most significant variables, and finally, empirical fits are proposed. It is important to note that the computational results are used to assess general trends and to propose a functional form for the dependence of r_p on relevant variables; the values of the constants in the function have been derived from empirical fits to experimental results.

2. Experimental details and results

In order to determine r_p experimentally the geometry change of the specimens is taken into account. Assuming that the work hardening is equal in tension and compression, and that the cross section is trapezoidal, r_p is obtained by measuring the center of gravity of the trapezoidal section [6].

The experimental results for typical pipe steels are summarized in Table 1.

3. Computational details and results

Finite element computations of both the DWTT and Charpy test were carried out, and the computations were used to access variables and material properties that may not be accessible in practise. For instance we investigated what the rotation factor is in the case of a material with the hardening parameters of X52 steel with damage parameters chosen such that it exhibits a low C_v, or, conversely, X80 steel with a very high C_v. This was a purely theoretical exercise and no attempt to match experimental results was made.

Along the lines of the approach in Simha et al. [3], a damage mechanics approach was used with element removal to grow the crack, using a non-local implementation to mitigate mesh dependence. The damage evolution model reads:

$$dD = m\left(\frac{\epsilon_p}{\epsilon_f}\right)^{m-1}\frac{d\epsilon_p}{\epsilon_f} \tag{2}$$

Since $dD \propto \epsilon_f^{-m}$, ϵ_f is useful for varying the C_v values of the simulations.