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Effect of Strain-Gradient Plasticity in Engineering Fracture Assessments

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Abstract

This study implements the conventional mechanism-based strain gradient plasticity (CMSG) in the engineering fracture assessment of structural steels, to estimate both the near-tip opening displacements and the probability of brittle fracture. The CMSG theory recognizes the dependence of the material hardening on both the strain and its gradient, for plastic deformations occurring at micron or sub-micron levels, through a material length scale. The CMSG presents a more realistic description of the stress, strain and displacement field in the immediate vicinity of the crack tip, than does the classical plasticity. This study therefore examines the near-tip opening displacement, commonly used in the assessment for ductile fracture in structural steels. This study also integrates the CMSG theory in calculating the microscopic crack driving force in a cleavage fracture assessment framework, namely the Weibull stress approach. The accuracy of the scalar Weibull stress relies significantly on the gradient-dependent, near-tip stress field, which subsequently impinges on the failure probability estimated using the Weibull stresses.

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Keywords: strain gradient plasticity; crack-tip opening displacement; material length scale; indentation.

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1. Introduction

The magnitude of the stresses and displacements at the immediate vicinity of the crack tip depends significantly on the accurate description of the material constitutive relationship. Recent research efforts (Gao et al. 1999) have discovered that the hardening of the materials depends not only on the strain values but their gradients when plastic deformation occurs at micron or sub-micron levels. Previous researchers (Chen et al. 1999) have demonstrated that the near-tip stresses computed from the mechanism-based gradient (MSG) plasticity remain much higher than the classical HRR solutions (Hutchinson 1968, Rice and Rosengren 1968). Huang et al. (2004) have further proposed a conventional mechanism-based strain gradient plasticity (CMSG) model to reduce the computational requirement in solving the higher-order stresses in the original MSG theory. Swaddiwudhipong et al. (2005) have subsequently implemented the CMSG theory in C^0 type elements to describe the gradient-based plastic deformation.

Nomenclature

E	elastic modulus
K_I	stress-intensity factor
N	hardening exponent
P_f	probability of fracture
R	radius
T	T-stress
l	material length scale
m	Weibull exponent
u,v	displacements in x- and y- directions
Θ	temperature
δ	near-tip displacement
ε^p	effective plastic strain
η^p	effective plastic strain gradient
θ	angle around the crack tip
σ_w	Weibull stress

Recent research efforts have extended the CMSG theory to a wide range of engineering applications, including the fatigue and fracture analysis of metals (Stamoulis and Giannakopoulos 2012), the assessment of nano-indentation tests (Haghshenas and Klassen 2013), thermo-mechanical assessment of metals (Voyiadjis and Faghihi 2013), and cleavage fracture analysis of ferritic steels (Qian et al. 2011). The strain gradient plasticity theory prescribes the material hardening as a function of the gradient of the strain over an intrinsic material length scale. This study reports effect of the strain gradient plasticity in computing the near-tip opening displacement and the Weibull stress assessment in the probabilistic fracture assessment of Euro-steels.

2. Conventional Mechanism-Based Strain Gradient Plasticity

In the conventional mechanism-based strain gradient plasticity theory, the flow stress, σ_f, depends on both the strain and strain gradient over a material length scale, as follows,

$$\sigma_f = \sigma_y \sqrt{f^2(\varepsilon^p) + l\eta^p} \quad (1)$$

where σ_y refers to the material yield strength and $f(\varepsilon^p)$ defines the classical strain hardening law,