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A Lode-dependent enhanced Lemaitre model for ductile fracture prediction at low stress triaxiality

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ABSTRACT

The present paper deals with a modification of the stress triaxiality-based Lemaitre damage model to predict the ductile fracture at low stress triaxiality and shear-dominated loadings. The influence of the third stress invariant on damage evolution is introduced through the Lode parameter to form the Lode-dependent Enhanced Lemaitre (LEL) model. The enhanced model is then employed to predict fracture at different loading configurations and for two materials. For each material, the hardening law is first identified using both J_2 and J_2–J_3 plasticity criteria depending on material. A methodology to obtain the damage model parameters is then presented and applied to two different materials. Good agreement between the experimental and numerical results is obtained, which shows the interest of the proposed model to predict the ductile fracture for various loading configurations at both low and high stress triaxialities.

1. Introduction

Fracture prediction in real size structures subjected to complex loading conditions has been of utmost interest in the scientific and engineering community in the past century. With the increasing computational power of modern computers, numerical simulations with non-linear finite element (FE) codes allow investigating various complicated problems for damage and fracture prediction in real scale models, which is an important topic in many industries, such as aerospace, automotive, nuclear and forming industries. For all industrial cold forming processes, understanding and modeling ductile damage mechanisms remains a major issue in view of obtaining defect-free products. The ability of numerical modeling to predict ductile fracture is indeed crucial. However, this ability is still limited because of the complex loading paths (multi-axial and non-proportional loadings) and important shear effects in several forming processes where the stress triaxiality is nearly zero in the danger zone. The ability of damage models to capture the ductile fracture mechanisms under low stress triaxiality and shear-dominated stress state is vital. Microscopically, damage is associated with voids nucleation, growth and coalescence in high and moderate stress triaxiality or shear band formation in low stress triaxiality. Macroscopically, damage is represented as the progressive degradation of material, which exhibits a decrease in material stiffness and strength. The role of microvoids in ductile failure was first modeled by McClintock et al. [1], who analyzed the evolution of an isolated cylindrical void in a ductile elastoplastic matrix. Rice and Tracey [2] studied the evolution of spherical voids in an elastic-perfectly plastic matrix. These results showed that the void growth is governed by the stress triaxiality ratio, which is the ratio of the

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Nomenclature

$C_s,\ C_{ax},\ C_t,\ C_c,\ k$	material constants in the J_2–J_3 yield criterion
$E,\ \nu$	Young's modulus and Poisson's ratio
$E_M,\ \sigma_M$	Young's modulus and flow stress of undamaged material
$J_2,\ J_3$	second and third invariants of deviatoric stress tensor
$K,\ \epsilon_0,\ n$	material constants in the Swift hardening law
$Y,\ w(D)$	energy density release rate and weakening function (Lemaitre model)
$\alpha_1,\ \alpha_2,\ \eta_1,\ \eta_2,\ \epsilon_{D0},\ A$	additional material constants in the LEL model
$\dot{\bar{\boldsymbol{\epsilon}}}^p$	equivalent plastic strain rate tensor
$\dot{\bar{\epsilon}}^p$	equivalent plastic strain rate
$\eta,\ \eta_{ini}$	stress triaxiality and initial stress triaxiality
$\bar{\epsilon}_p,\ \bar{\epsilon}^p$	equivalent plastic strain
$\overline{\sigma}$	von Mises equivalent stress
$\overline{\theta}$	Lode parameter
σ_0	flow stress
$f,\ F_D$	plastic potential (yield function in associative flow) and damage dissipative potential
p	hydrostatic pressure
$s,\ S,\ D_c,\ h,\ \epsilon_D$	material constants in the Lemaitre model

mean stress to the von Mises equivalent stress. In these studies, the interaction between microvoids, the coalescence process and the hardening effects were neglected and failure was assumed to occur when the cavity radius would reach a critical value specific for each material. Gurson [3], in an upper bound analysis of a finite sphere containing an isolated spherical void in a rigid perfectly plastic matrix, employed the void volume fraction f (or porosity) as an internal variable to represent damage and its softening effect on material strength. This micromechanical model was then improved to account for different aspects: prediction accuracy [4], void nucleation [5], void coalescence [6,7], void shape effect (e.g. [8–10]), void size effect (e.g. [11]), void/particle interaction (e.g. [12]), isotropic strain hardening (e.g. [13]), kinematic hardening (e.g. [13,14]), plastic anisotropy (e.g. [15,16]), rate dependency (e.g. [17]), shear effect (e.g. [18,19]).

On the other hand, uncoupled phenomenological models have been increasingly developed, especially for industrial applications. The uncoupled models employ an indicator variable to predict material failure when its critical value is reached. This variable is often taken as a weighted cumulative plastic strain, in which the weighting function accounts for the effect of stress state on the fracture initiation. However, this type of approach does not allow accounting for the impact of damage on material strength. This can be erroneous when a large amount of voids is developed.

In addition to the uncoupled phenomenological models and micro-mechanical based damage models, the Continuum Damage Mechanics (CDM) models have been developed within a consistent thermodynamic framework, in which the evolution of the phenomenological damage parameter is obtained through a thermodynamic dissipation potential. Starting from the early work of Kachanov [20], this class of models has been continuously developed [21–24] and widely used to predict ductile fracture for high stress triaxiality. The Lemaitre model allows incorporating the influence of damage on material behavior and ensuring positive damage dissipation energy. In addition, the identification of this model is straightforward with conventional mechanical tests (often tensile tests), which enables its use for high stress triaxiality industrial applications (e.g. [25]). However, under shear-dominated and complex loadings at low stress triaxiality, this model sometimes cannot provide a good prediction of damage localization (see e.g. [26,27] for the applications of this model to predict ductile fracture occurring in forming processes). In this case, the stress triaxiality-dependent term in damage evolution is nearly deactivated in the damage accumulation law, which depends only on the von Mises equivalent stress.

The early ductile damage models used only the stress triaxiality to account for the influence of stress state. From their experimental results, Bao and Wierzbicki [28] showed that the stress triaxiality is not enough to formulate ductile fracture models. Several recent studies demonstrated the importance of the third stress invariant on the material ductility (e.g. [29–31]), especially at low stress triaxiality; the Lode angle parameter is generally used to include it [18,32–36]. The common idea of these works is to account for the whole stress state in damage model formulation, which is defined by the stress triaxiality, the von Mises equivalent stress, and the Lode parameter.

The present work aims at enhancing the Lemaitre coupled damage model to predict ductile fracture under shear-dominated loading by incorporating the influence of the Lode parameter in its formulation. In the first part, the Lemaitre damage model is revisited and enhanced to form the phenomenological Lode-dependent enhanced Lemaitre (LEL) model. The parameters of this model are then identified and applied to predict fracture of various mechanical tests (tensile test, shear tests on butterfly specimen, torsion test) for two different materials: a high elastic limit (HEL) steel and a zirconium alloy. For each material, plastic hardening is identified prior to damage, using the J_2–J_3 plasticity criterion developed in [37] for the HEL steel, and J_2 plasticity criterion for the zirconium alloy. The comparison with experimental results shows the validity of the proposed LEL model to predict the ductile fracture for both high and low stress triaxiality mechanical tests, with two different materials.