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A model for ductile damage prediction at low stress triaxialities incorporating void shape change and void rotation

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ABSTRACT

Ductile fracture at the high triaxiality regime is well-known to be controlled by void nucleation, growth and coalescence. However, under low stress triaxiality conditions and general three dimensional finite deformations, damage is still poorly predicted due to the complex loading state and microstructural changes under such a condition. Experimental results have revealed not only void growth, but also important void shape change and void rotation under shear-dominated loading. The ability of ductile damage models to predict both void growth with shape change and void rotation is thus crucial for complex loading applications. In the present study, a Gurson-like nonlinear homogenization-based model (namely GVAR) is proposed and compared with the constitutive models for elasto-plastic porous materials developed in Kailasam and Ponte Castañeda (1998) (VAR model) and Danas and Aravas (2012) (MVAR model). The proposed model is based on *ad hoc* modifications of the VAR model, to give sufficiently accurate results for void growth at both low and high stress triaxialities and keeping the functional form of the original Gurson model. The VAR and MVAR models were based on rigorous linear comparison composite (LCC) homogenization methods, which can describe the evolution of microstructure of porous materials, represented by the void volume fraction, the aspect ratios and the orientations of general ellipsoidal voids. The proposed GVAR model thus inherits these characteristics and provides a sufficiently accurate void growth formulation (and simple at the same time). In addition, the loading direction is not necessary aligned with the ellipsoidal void axes. These models are implemented in an object-oriented finite element (FE) code. The identification of model parameters and the assessment of the proposed model are then carried out via 3D periodic unit-cell computations subjected to different stress states. Comparative results show that the present model predicts relatively accurately the evolution of void volume fraction, void aspect ratios and void rotation for different initial void shapes, void volume fractions and under different stress triaxiality levels. A qualitative application to a tensile test on a notched round bar shows the efficiency of the model to predict microstructure evolution (i.e. voids volume, shape and orientation) in a real-scale model simulation. This model with few parameters to be identified is thus promising to predict damage under complex loading paths and ready to be applied to complex FE simulations.

Notation

Boldface capital letters denote fourth-rank tensors (e.g. $\mathbf{\Pi}$); undertilded symbols denote second-order tensors (e.g. $\underset{\sim}{\epsilon}$); underlined symbols denote vectors (e.g. $\underline{v}$). All tensor components are written in a fixed Cartersian coordinate system with base vectors $\underline{e}^{(k)},\ k = 1,2,3$ unless otherwise indicated. The following products are used in the text: $(\underline{n}^{(1)} \otimes \underline{n}^{(2)})_{ij} = n_i^{(1)} n_j^{(2)}$; $(\underline{n} \cdot \underset{\sim}{a})_i = n_k a_{ki}$; $(\underset{\sim}{a} \cdot \underline{n})_i = a_{ik} n_k$; $\underset{\sim}{\sigma} : \boldsymbol{M} : \underset{\sim}{\sigma} = \sigma_{ij} M_{ijkl} \sigma_{kl}$; $(\boldsymbol{A} : \boldsymbol{B})_{ijkl} = A_{ijpq} B_{pqkl}$.

1. Introduction

Ductile fracture at high stress triaxiality – the ratio of the mean stress to the von Mises equivalent stress – has been the subject of numerous studies in the literature and is well-known to be controlled by void nucleation, growth and coalescence. Starting from early studies of McClintock (1968) and Rice and Tracey (1969), subsequent works have contributed to clarify different mechanisms leading to final failure under high triaxiality regime.

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Nomenclature

p	accumulated plastic strain in the matrix
p_h	hydrostatic pressure
η	stress triaxiality
L	Lode parameter
σ_m	mean or hydrostatic stress, $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$
$\sigma_1, \sigma_2, \sigma_3$	three principal stresses, $\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$
w_1, w_2	ellipsoidal voids aspect ratios defined via $w_1 = a_3/a_1,\ w_2 = a_3/a_2$
$\underline{n}^{(1)}, \underline{n}^{(2)}, \underline{n}^{(3)}$	orientation vectors of an ellipsoid
a_1, a_2, a_3	three orthogonal semi-axes of an ellipsoid
σ_y	flow stress of matrix material
$\sigma_\star$	the effective stress
$\boldsymbol{K}$	the hydrostatic part of the fourth-order identity tensor $\boldsymbol{I} : K_{ijkl} = 1/3\delta_{ij}\delta_{kl}$
$\boldsymbol{I}$	the fourth-order identify tensor $\boldsymbol{I} = 1/2(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk})$
$\boldsymbol{J}$	the deviatoric part of the fourth-order identify tensor $\boldsymbol{I} : J_{ijkl} = I_{ijkl} - 1/3\delta_{ij}\delta_{kl}$
f, f_0	the void volume fraction and its initial value
E_c	critical mesoscopic strain at coalescence onset
σ_{eq}	von Mises equivalent stress
δ_{ij}	the standard Kronecker symbol
$\boldsymbol{M}, \boldsymbol{M^m}$	tensors used to define effective stresses in VAR and MVAR models
$\boldsymbol{Q}$	microstructural tensor
$\underset{\sim}{\dot{\epsilon}^p}, \underset{\sim}{\dot{\epsilon}}^v$	overall average plastic strain and average plastic strain in the vacuous phase
$\underset{\sim}{\omega}, \underset{\sim}{\omega^v}$	overall average spin and average spin in the vacuous phase

However, under low stress triaxialities and general three dimensional finite deformations, ductile damage is still poorly predicted due to the complex loading state and the induced microstructural changes. In addition to the stress triaxiality effects, recent experimental (e.g. Bao and Wierzbicki, 2004; Barsoum and Faleskog, 2007a), micro-mechanical computation (Barsoum and Faleskog, 2007b; Dunand and Mohr, 2014) and analytical results (Danas and Ponte Castañeda, 2012) reveal the important role of the Lode parameter, which is a function of the second and third deviatoric stress invariants.

Regarding ductile damage, models proposed in the literature can be classified into two groups: phenomenological and micromechanically-based models. The phenomenological models can be further put into two sub-categories: uncoupled (where damage does not affect material strength) and coupled models (where the softening effect of damage is accounted for). In order to better predict ductile fracture at both high and low stress triaxialities, it has been shown that phenomenological models should account for both the stress triaxiality and the Lode parameter in their formulations. Several recent models have been extensively developed and validated for different applications, both for uncoupled models (e.g. Bai and Wierzbicki, 2008; Cao et al., 2015a,b, modified Mohr–Coulomb (Bai and Wierzbicki, 2010; Dunand and Mohr, 2011; Cao et al., 2013)) and coupled models (e.g. Xue model – Xue, 2007; Cao, 2014; Lode-dependent enhanced Lemaitre model – Cao et al., 2014a). However, due to their phenomenological grounds, their application outside the identification domain needs special attention.

Regarding micromechanics-based models, numerous efforts have been devoted to understand the role of micro-voids in ductile damage. Gurson (1977), based on the work of Rice and Tracey (1969), in an upper bound kinematic analysis of a finite sphere containing an isolated spherical void in a rigid perfectly plastic matrix and subjected to affine boundary conditions, employed the void volume fraction f (or porosity) as an internal variable to represent damage and its softening effect on material. The Gurson model, consisting of a plastically compressible yield locus, with the evolution laws for the internal state variables, represents a constitutive model for porous materials. It should be noted that, in this model, spherical voids are assumed to remain spherical. This assumption is only valid for purely hydrostatic stress state, but deficient when general three-dimensional stress states are involved, especially for shear dominated states, where significant void shape changes can be observed. Further extensions of Gurson's framework were devoted to different aspects, especially that of Tvergaard (1981), Tvergaard and Needleman (1984) and Needleman and Tvergaard (1984) to improve the prediction accuracy by accounting for interaction, nucleation and final coalescence of voids (the GTN model); Gologanu et al. (1993) for void shape effect (the GLD model). Gologanu et al. (1993) proposed a constitutive model with aligned spheroidal voids subjected to axisymmetric loadings, aligned with voids symmetry axis (see Benzerga and Leblond, 2010 for a recent review on its derivation and applications). The last model of Madou and Leblond (2012) considered general ellipsoid but there is still no void rotation. This class of models fails for general loading conditions, where loadings are not aligned with voids principal axes and important void rotation is involved. The Gurson framework has also been shown to be insufficient to predict fracture at low stress triaxiality and especially shear-dominated loadings. Several modifications were proposed by Xue (2008) and Nahshon and Hutchinson (2008) to include the influence of the third stress invariant through the Lode angle in the Gurson or GTN models, but these modifications are purely phenomenological. More recently, Cazacu et al. (2013), Benallal et al. (2014) and Leblond and Morin (2014) pointed out that the independence upon the third stress invariant in the classical Gurson model is due to an approximation of this author when calculating the overall plastic dissipation. These authors proposed separately different solutions (e.g. use exact formulations for axisymmetric loading – Cazacu et al. (2013), or use second and third approximations for general loading instead of the first approximation used by Gurson for a term in the derivation of the overall plastic dissipation – Leblond and Morin (2014)). However, the difference between the models proposed by these authors and that of Gurson is small, and can be treated by using the GTN model with additional constitutive parameters q_1 and q_2, at least for quasi-static loadings; while still has the deficiencies at low stress triaxialities. The reason for this is that, all these models are based on the assumption of spherical voids that remain spherical, which is totally incorrect at low stress triaxialities. Regarding GLD-like models, several extensions have been proposed, especially to account for final coalescence stage (Pardoen and Hutchinson, 2000) and void rotation (Scheyvaerts et al., 2011). Pardoen and Hutchinson (2000) constructed a void growth and coalescence model by combining the GLD void growth (extended to hardening materials) with the modified Thomason coalescence model (Thomason, 1968). Recently, Scheyvaerts et al. (2011) used the same approach and added an evolution law for void rotation proposed in Kailasam and Ponte Castañeda (1998), only for plane strain state (i.e. only one void aspect ratio was considered).