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A Lode-dependent Gurson model motivated by unit cell analyses

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ABSTRACT

In this study, the effects of including a dependency on the third deviatoric stress invariant in the void evolution equation of the Gurson model are examined using unit cell calculations and imperfection band analyses. Finite element analyses of a unit cell model are conducted to approximate the behaviour of the material microstructure. The unit cell was modelled as a cube made from an elastic-plastic matrix governed by J_2 flow theory with a spherical void located at the centre. The results of the unit cell calculations show a monotonic decrease in void growth when the stress state changes from generalized tension to generalized compression. To mimic the resulting evolution of the void volume fraction, an extension of the Gurson model based on the shear modification proposed by Nahshon and Hutchinson (2008) is proposed. This Lode-dependent void evolution term is further qualitatively assessed through comparisons with the unit cell simulations and through strain localization predictions using imperfection band analyses. The assessment demonstrates that the proposed modification of the void evolution equation is consistent with the evolution of the unit cell in the case of moderate and high stress triaxiality ratios. Furthermore, the imperfection band analyses exhibit a greater difference between the failure strain values in generalized tension and generalized compression using this Lode-dependent void evolution term compared to similar analyses that employ the original Gurson model or the shear-modified Gurson model. The Lode-dependent void evolution term thus renders the ductility predictions more consistent with previously reported studies based on unit cell calculations for the set of material parameters employed in this study.

1. Introduction

The experiments performed by Bao and Wierzbicki [2] indicated that stress triaxiality alone is not sufficient to quantify ductile fracture. This result has subsequently been corroborated by experiments under a variety of macroscopically imposed stress states using carefully designed tubular specimens [3,23,36,40] or combinations of different test specimens [6,16]. Although such experiments certainly prove that the deviatoric stress state affects the measured failure strain, they are difficult to use for quantifying inherent material ductility since the local loading paths generally deviate from the globally applied loading paths. The non-uniqueness of the ductile fracture locus under the application of non-proportional loading has been shown from both physical experiments [5] and from numerical analyses [7,12,44]. In general, it is extremely

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Nomenclature

Symbols

κ	Scaling function of Lode-dependent porosity term
ϕ, Φ	Microscopic and macroscopic yield function
$\boldsymbol{\sigma}, \boldsymbol{\Sigma}$	Microscopic and macroscopic stress tensor
σ_{eq}	von Mises equivalent stress
σ_h	Hydrostatic stress
$\sigma_I, \sigma_{II}, \sigma_{III}$	Principal stress components
σ_M	Matrix flow stress
σ_0	Initial yield stress
θ	Deviatoric angle
$\mathbf{C}^t$	Material tangent stiffness
$\mathbf{d}, \mathbf{D}$	Microscopic and macroscopic rate-of-deformation
D_{eq}	Equivalent rate-of-deformation
E_{eq}	Equivalent strain
E, ν	Elastic material parameters
f	Void volume fraction/porosity
I_1	First principal invariant of the stress tensor
J_2	Second principal invariant of the deviatoric stress tensor
J_3	Third principal invariant of the deviatoric stress tensor
k_s	Parameter of Lode-dependent porosity term
$\mathbf{L}$	Velocity gradient
L	Lode parameter
$\mathbf{n}$	Imperfection band normal
$\mathbf{N}$	Nominal stress tensor
p	Matrix accumulated plastic strain
$\dot{\mathbf{q}}$	Velocity non-uniformity
Q, C	Isotropic hardening parameters
q_1, q_2	Tvergaard parameters
T	Stress triaxiality

Abbreviations

FE	finite element
GC	generalized compression
GS	generalized shear
GT	generalized tension
RVE	representative volume element

difficult to construct test specimens that yield exactly proportional loading paths in regions where failure initiates. Moreover, local stress measurements are not available from experimental data and must be acquired from numerical analyses. The stress measurements extracted from numerical simulations thus rely heavily on the adopted constitutive model. Some uncertainty regarding the predicted local loading path remains due to the hybrid experimental-numerical procedure, and whether physical experiments can be used to determine an intrinsic failure locus for a given material is questionable [5].

The Gurson model [21] is an extensively used porous plasticity model that incorporates material softening due to the growth of microscopic voids. This model is derived from an upper-bound plastic limit analysis of a hollow sphere with a rigid perfect-plastic matrix governed by J_2 flow theory. Consequently, there is only a single microstructural variable associated with the model, which is referred to as the void volume fraction or porosity. The void volume fraction is treated as an internal variable, and an evolution law is obtained from the condition of matrix incompressibility. However, the resulting porosity evolution law lacks the ability to predict the influence of the deviatoric stress state on the void growth. Numerical studies involving unit cell simulations [8,18,24,52] have shown that these effects of the deviatoric stress state are persistent at moderate and high stress triaxiality levels. Specifically, for a matrix material governed by J_2 flow theory, stress states corresponding to generalized tension are found to promote more rapid void growth, with the growth rate successively decreasing towards generalized compression loading. Moreover, the voids evolve into general ellipsoidal shapes that are dictated by the deviatoric stress state. Such arbitrary ellipsoidal void shapes are not consistent with the representative volume element (RVE) used in the Gurson model. Since void growth is of key importance for ductile failure in the case of moderate and high levels of stress triaxiality, the influence of the deviatoric stress state on the evolution of the void volume fraction is considered to be important in the context of porous plasticity modelling.

Several models that account for more general void shapes have been proposed over the past decades. In particular, Gologanu et al. [19,20] included prolate and oblate void shapes, while Madou and Leblond [27,28] more recently derived a

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