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A HYBRID MODEL OF DUCTILE FAILURE ACCOUNTING FOR STRAIN HARDENING

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Abstract

Existing ductile failure models such as the Gurson-Tvergaard-Needleman (GTN) model as well as more recent physics-based models (for instance, the Benzerga-Leblond coalescence model from 2014) were all derived using classical limit analysis for perfectly plastic porous materials, with plastic flow in the matrix being described by J_2 flow theory. When extended heuristically to hardenable materials, these models do not account for the heterogeneity of plastic strain in the matrix, and are unable to capture the effect of hardening on the evolution of porosity, the primary damage variable.

This work uses "sequential limit analysis" (SLA) to first derive a hardening-sensitive void coalescence criterion for a cylindrical cell containing a coaxial cylindrical void of finite height, by discretizing the intervoid ligament into a finite number of shells in each of which the quantities characterizing isotropic hardening are considered to be homogeneous. Next, this new criterion is combined with a recently formulated hardening-sensitive void growth criterion (also derived using SLA) to obtain a hybrid model of ductile failure. The new constitutive formulation's ability to remedy the two aforementioned shortcomings of existing models is examined, and a set of finite-element micromechanical unit cell calculations is used to further assess the model's predictive capabilities.

1. Introduction

For axisymmetric loading, stable and diffuse plastic flow in a porous matrix would lead to void impingement at strains that are, in general, far in excess of measured or computed strains to failure. Ductile failure ultimately takes place because of plastic flow localization in the intervoid matrix, with cell model studies having clearly established the transition from diffuse to localized plastic flow. This transition to localized plastic flow is conventionally referred to as the onset of void coalescence. Thus, void coalescence is inherently directional, resulting from inhomogeneous yielding.

In this work, first, a void coalescence criterion is formulated for ductile porous rigid-hardenable materials exhibiting isotropic hardening, for the case of axisymmetric loading. For this analysis, a cylindrical unit cell subjected to uniaxial straining is taken to contain a coaxial cylindrical void of finite height, with plastic flow in the intervoid matrix being described by J_2 (Von Mises) flow theory while regions above and below the void are assumed to remain rigid (a consequence of elastic unloading which characterizes coalescence). This hardening-sensitive criterion is based on "sequential limit analysis" of the cylindrical cell with a rigid-hardenable matrix, which takes into account the evolution of the void geometry as well as the heterogeneity of hardening in the matrix by discretizing the intervoid ligament into a finite number of cylindrical shells in each of which the quantities characterizing hardening are considered to be homogeneous. This is in contrast to the classical limit analysis (CLA) used to derive, for a rigid-perfectly plastic matrix, existing void coalescence criteria which have since been heuristically extended to hardenable materials. Unlike the new model which accounts for the spatial variation in plastic strain throughout the matrix, the existing heuristic models calculate an ``average" plastic strain homogenized over the matrix.

The new coalescence model is then combined with the hardening-sensitive diffuse void growth model devised recently by Lacroix, Leblond and Perrin (2016), thereby creating a two-surface (hybrid) formulation to model ductile failure for axisymmetric loading. This new hardening-sensitive hybrid model is assessed through comparison of its predictions with those of the existing hybrid model (GT-BL) combining the heuristic extension of the Gurson-Tvergaard (GT) void growth model and the Benzegra–Leblond (BL) coalescence model from 2014, and also with those of the 1984 Gurson–Tvergaard–

Needleman (GTN) model. Besides their inability to account for the heterogeneity of plastic strain in the matrix, a significant shortcoming of the latter models derived using CLA is that they are unable to predict variation in the evolution of porosity with varying hardenability of the matrix. The extent to which this shortcoming is corrected by the new hybrid model is examined in detail here for a number of cases, by varying triaxiality (for proportional loading) and initial porosity besides, of course, the hardenability of the matrix. Furthermore, the new hybrid model is assessed through comparison of its predictions with the results of micromechanical finite element simulations (unit cell calculations), with regard to the stress-strain response as well as porosity evolution.

2. Results

Simulations were performed to achieve the following objectives:

a. Implementation of the new hybrid model
b. Comparison of the new hybrid model with micromechanical unit cell calculations (FE)
c. Comparison of the new hybrid model with existing heuristic hybrid models (GTN and GT-BL)

3. Conclusions

For one, unlike the heuristic models mentioned previously, the new model is able to show an effect of hardening on porosity evolution, especially at high triaxialities.