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Influence of yield surface curvature on the macroscopic yielding and ductile failure of isotropic porous plastic materials

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Abstract

Numerical unit cell models of an approximative representative volume element for a porous ductile solid are utilized to investigate differences in the mechanical response between a quadratic and a non-quadratic matrix yield surface. A Hershey equivalent stress measure with two distinct values of the yield surface exponent is employed as the matrix description. Results from the unit cell calculations are further used to calibrate a heuristic extension of the Gurson model which incorporates effects of the third deviatoric stress invariant. An assessment of the porous plasticity model reveals its ability to describe the unit cell response to some extent, however underestimating the effect of the Lode parameter for the lower triaxiality ratios imposed in this study when compared to unit cell simulations. Ductile failure predictions by means of finite element simulations using a unit cell model that resembles an imperfection band are then conducted to examine how the non-quadratic matrix yield surface influences the failure strain as compared to the quadratic matrix yield surface. Further, strain localization predictions based on bifurcation analyses and imperfection band analyses are undertaken using the calibrated porous plasticity model. These simulations are then compared to the unit cell calculations in order to elucidate the differences between the various modelling strategies. The current study reveals that strain localization analyses using an imperfection band model and a spatially discretized unit cell are in reasonable agreement, while the bifurcation analyses predict higher strain levels at localization. Imperfection band analyses are finally used to calculate failure loci for the quadratic and the non-quadratic matrix yield surface under a wide range of loading conditions. The underlying matrix yield surface is demonstrated to have a pronounced influence on the onset of strain localization.

Keywords: Ductile failure; Unit cell; Porous plasticity; Strain localization; Bifurcation analysis; Imperfection band analysis; Third deviatoric stress invariant

1. Introduction

The loading paths exerted on arbitrarily positioned material elements in real structural components are rarely proportional (Dæhli et al., 2016). Metal alloys that have a face-centred cubic (FCC) crystal lattice, such as aluminium-based alloys, are known to display a curved yield surface (Hosford, 1972, 1996), thus imposing a dependence upon the third principal invariant of the stress deviator. The curvature of the yield surface is judged to influence the resulting plastic flow and deformation path, especially when the stress state is allowed to change throughout the loading stage. For instance, in the vicinity of a yield surface corner, rather small changes in the stress state may cause abrupt changes in the strain path of the material. This may in turn trigger localized deformations in the material body which either aids or initiates, and thus influence, the ductile failure process.

An abrupt change from a smoothly varying deformation path into a localized straining mode is a frequent observation for metal alloys subjected to large deformations. Such localization modes may result from small material non-uniformities, such as microvoid-containing bands, or from the decrease in work hardening and material softening of ductile solids when the plastic deformations are sufficiently large. Anand and Spitzig (1980) reported on incipient shear band formation even for positive, although small, work hardening levels in the case of plane deformation specimens under both tension and compression. But even if the material does not exhibit pronounced material softening, localized

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