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Phase Field Modeling of Fracture in Porous Plasticity: A Variational Gradient-Extended Eulerian Framework For the Macroscopic Analysis of Ductile Failure

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Abstract

This work outlines a rigorous variational-based framework for the phase field modeling of fracture in isotropic porous solids undergoing large elastic-plastic strains. It extends the recent works Miehe et al. [1, 2] to a particular formulation of isotropic porous plasticity. The phase field approach regularizes sharp crack surfaces within a pure continuum setting by a specific *gradient damage modeling* with geometric features rooted in fracture mechanics. A *gradient plasticity model* for porous plasticity with a simple growth law for the evolution of the void fraction is developed, and linked to a failure criterion in terms of the local elastic-plastic work density that drives the fracture phase field. It is shown that this approach is able to model basic phenomena of ductile failure such as *cup-cone failure surfaces* in terms of only two material parameters on the side of damage mechanics: a *critical work density* that triggers the onset of damage and a *shape parameter* that governs the postcritical damage up to fracture. The formulation includes two independent length scales which regularize both the plastic response as well as the crack discontinuities. This allows to design damage zones of ductile fracture to be inside of plastic zones or vice versa, and guarantees on the computational side a mesh objectivity in post-critical ranges. The key aspect that allows to construct a *variational theory for porous plasticity at fracture* is the use of an *Eulerian constitutive setting*, where the yield function is formulated in terms of the *Kirchhoff stress*. Here, we exploit the fact that this stress approximates an *effective stress* that drives the plasticity in the matrix of the porous solid. The coupling of gradient plasticity to gradient damage is realized by a constitutive work density function that includes the stored elastic energy and the dissipated work due to plasticity and fracture. The latter represents a coupled resistance to plasticity and damage, depending on the gradient-extended internal variables which enter the plastic yield function and the fracture threshold function. The canonical theory proposed is shown to be governed by a rate-type minimization principle, which fully determines the coupled multi-field evolution problem, and provides inherent symmetries with regard to a finite element implementation. The robust computational setting proposed includes (i) a general return scheme of plasticity in the spectral space of logarithmic principal strains and dual Kirchhoff stresses, (ii) the micromorphic regularization of the gradient plastic evolution and (iii) a history-field-driven update of the linear phase field equation.

Keywords: porous plasticity, ductile fracture, phase-field modeling, strain gradient plasticity, gradient damage mechanics, variational principles

1. Introduction

Fracture in the form of evolving crack surfaces in ductile solid materials is preceded by significant plastic distortion. The prediction of failure mechanisms due to crack initiation and growth coupled with elastic-plastic deformations

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