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Christian Miehe, M. Hofacker, Lisa Schänzel, F. Aldakheel

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Phase Field Modeling of Fracture in Multi-Physics Problems. Part II. Coupled Brittle-to-Ductile Failure Criteria and Crack Propagation in Thermo-Elastic-Plastic Solids

Christian Miehe*, M. Hofacker, Lisa Schänzel, F. Aldakheel

Institute of Applied Mechanics (Civil Engineering), Chair I, University of Stuttgart, Pfaffenwaldring 7, 70569 Stuttgart, Germany

Abstract

This work presents a generalization of recently developed continuum phase field models from brittle to *ductile fracture* coupled with *thermo-plasticity* at finite strains. It uses the *geometric approach* to the diffusive crack modeling based on the introduction of a *balance equation for a regularized crack surface* and its modular linkage to a multi-physics bulk response developed in the first part of this work. This evolution equation is governed by constitutive crack driving force. In this work, we supplement the energetic and stress-based forces for brittle fracture by additional forces for ductile fracture. These are related to state variables associated with the inelastic response, such as the amount of plastic strain and the void volume fraction in metals, or the amount of craze strains in glassy polymers. To this end, we define driving forces based on *elastic and plastic work densities*, and *barrier functions* related to critical values of these inelastic state variables. The proposed thermodynamically consistent framework of ductile phase field fracture is embedded into a formulation of gradient thermo-plasticity, that is able to account for material length scales such as the width of shear bands. It is applied to two constitutive model problems. The first is designed for the analysis of *brittle-to-ductile failure mode transition* in the dynamic failure analysis of *metals*. The second is constructed for a quasi-static analysis of *crazing-induced fracture* in glassy *polymers*. A spectrum of simulations demonstrates that the use of barrier-type crack driving forces in the phase field modeling of fracture, governed by accumulated plastic strains in metals or crazing strains in polymers, provide results in very good agreement with experiments.

Keywords: ductile fracture, dynamic fracture, crack propagation, phase field modeling, ductile-to-brittle failure mode transition, crazing, thermo-plasticity, finite strains

1. Introduction

1.1. A Phase Field Approach to Ductile Fracture

Recently developed phase field approaches to fracture regularize sharp crack discontinuities within a pure continuum formulation. This diffusive crack modeling allows the resolution of complex failure topologies, such as crack branching phenomena in dynamic fracture of brittle solids. In contrast to computational models which model sharp cracks, the phase-field-type diffusive crack approach is a spatially smooth continuum formulation that avoids the modeling of discontinuities and can be implemented in a straightforward manner by coupled multi-field finite element solvers. The works Francfort and Marigo [1], Bourdin et al. [2], Hakim and Karma [3], Miehe et al. [4], Borden et al. [5], Verhoosel and de Borst [6] provide alternative approaches to regularized fracture, see Miehe et al. [7] for a more detailed review. These approaches are restricted to the modeling of *brittle fracture in elastic solids* at quasi-static and dynamic conditions. The phase field models by Miehe et al. [4] and Borden et al. [5] combine gradient damage theories with ingredients of fracture mechanics by incorporating the regularized crack surface as a central object. In

*Corresponding author. Tel.: +49-711-685-66379
Email address: cm@mechbau.uni-stuttgart.de (Christian Miehe)
URL: www.mechbau.uni-stuttgart.de/ls1/ (Christian Miehe)