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DAMAGE MECHANICS AND MICROMECHANICS OF LOCALIZED FRACTURE PHENOMENA IN INELASTIC SOLIDS

EDITED BY

GEORGE Z. VOYIADJIS
LOUISIANA STATE UNIVERSITY, BATON ROUGE, LA, USA

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PREFACE

This book resulted from a series of lecture notes presented in CISM, Udine. It has two major contributions: Damage Mechanics and Localization in Inelastic Deformation. The course is intended to provide researchers and graduate students with a clear and thorough presentation of the recent advances in continuum damage mechanics for both metals and metal matrix composites as well as the micromechanics of localization in inelastic solids.

Damage Mechanics and Applications: *The major goal of this part of the course is to present many of the different constitutive damage models that have recently appeared in the literature. Another goal is to clearly present the different approaches to this topic in a single complete course that is easily accessible to researchers and graduate students in civil engineering, mechanical engineering, engineering mechanics, aerospace engineering, and material science. The course material was delivered in well-organized lectures that started with the preliminaries and proceeded to advanced topics.*

Micromechanics of Localization in Inelastic Solids and Applications: *The main objective of this contribution is to discuss very efficient procedures of the numerical investigation of localized fracture in inelastic solids generated by impact-loaded adiabatic processes. Particular attention is focused on the proper description of a ductile mode of fracture propagating along the shear band for high impact velocities. This procedure of investigation is based on utilization the finite element or finite difference methods for regularized thermo-elasto-viscoplastic constitutive model of damage material using both rate dependency and non-local approaches.*

It is noteworthy to stress that all considered numerical examples are motivated by recent experimental observations. Qualitative comparison of numerical results with experimental observation data is presented. The numerical results obtained have proven the usefulness of the thermo-elasto-viscoplastic theory in the numerical investigation of dynamic shear band propagation and localized fracture using rate dependency and nonlocal formulations.

Invited Lecturers:
Tomasz Lodygowski (Poznan University of Technology, Poland), Piotr Perzyna (Institute of Fundamental Technological Research, Poland), Antonio Rinaldi (University of Rome "Tor Vergata", Italy), and George Z. Voyiadjis (Louisiana State University, USA).

Coordinator: *George Z. Voyiadjis*

The authors present in **Part I** the micro-mechanical damage model that accounts for the nonlocal microscopic interactions in the simulation of metal/composite impact and severe contact stress problems. This is achieved by introducing the contributions of damage and its corresponding gradients in the virtual power relations as measures of micro motion of damage within the bulk. By using these internal state variables together with displacement and temperature, the constitutive model is formulated with state laws based on the free energies and the complimentary laws based on the dissipation potentials.

In this work also the mechanics of small damage is presented using a consistent mathematical and mechanical framework based on the equations of damage mechanics. In this regard, the new scalar damage variable is investigated in detail. The investigation in this work has been carried out for seeking a physical basis is sought for the damage tensor □M□that is used to link the damage state of the material with effective undamaged configuration. The approach presented here provides for a strong physical basis for this missing link. In particular, the authors have made an important link between the damage tensor and fabric tensors.

Computational aspects of the presented theory are also discussed. Numerical integration algorithms, verification and validation process of the theory are discussed. The finite element simulations are also performed by implementing the presented model in the commercial finite element code ABAQUS □6.8.3□as a user defined subroutine (VUMAT).

The outline of the material presented in **Part I** is as follows: in section 2, general mechanisms of the perforation and penetration mechanisms are discussed. A coupled rate-dependent (viscoplasticity) continuum damage theory is presented. In section 3, mechanics of small damage in fiber reinforced composite material is presented. In section 4, a comparative study has been made on the damage variables of the continuum. In section 5, computational aspects of the theory are discussed. The elastic predictor and coupled viscoplastic-viscodamage corrector algorithm that allows for total uncoupling of geometrical and material nonlinearities are presented. The nonlinear algebraic system of equations is solved by consistnt linearization and the Newton□Raphson iteration. A derivation of a new definition for the consistent tangent stiffness matrix that is essential to maintaining the asymptotic quadratic rate of convergence is also presented in section 5. In section 6, numerical simulations of material instability are introduced in order to validate and test the proposed finite strain approach along with the proposed algorithm and its implementation in the ABAQUS finite element code. In section 7, various numerical examples are presented in order to validate the reliability and capability of the theory in simulating various impact and contact stress problems. Experimental comparisons of the adiabatic shear localizations between the proposed model simulations and other independent results are presented. Effect of initial temperatures and loading rates on the development of shear localizations is also *investigated in this section. Model capabilities are preliminarily illustrated for the dynamic localization of inelastic flow in adiabatic shear bands and compared with the experimental results of steel plates by deformable blunt projectiles at various impact speeds.*

A handful of methodologies can be pursued in alternative to (and in combination with) continuum mechanics to develop advanced damage models that are intrinsically suited to address complex issues, such as strain localization phenomena and sample-size dependence of structural failure, which are intimately related to microscale phenomena. Statistical Damage Mechanics (SDM) is one of them.

In ***Part II*** *a brief discourse about advances in SDM introduces this methodology and shows its potential. In general, SDM is a multidisciplinary field that seeks to devise non-conventional approaches to fracture and damage by means of discrete damage models accounting for the essential microscale properties of a material or structural system. The ultimate goal is the development of multiscale methodologies that can reliably predict the materials macroscale response in consideration of the microstructural evolution caused by the damage process. Starting from the lower length scale characteristic of the microstructure, the SDM multiscale approach delivers a surprising amount of new insight and makes for a precious companion to the micromechanics methods discussed previously in the book. The bottom-up approach proves to be very effective in understanding the physics of the damage localization process. Although SDM is not yet a mature discipline, by now it has a clear footprint, after nearly two decades of research. This part of the book describes the state of the art and exposes recent trends in SDM for consideration and discussion by the larger solid mechanics community. Some of the concepts discussed herein — yet at their infancy — possess the potential to develop into full blown, innovative, and successful engineering tools. Designing the materials from the microstructure is already a current industry practice to achieve superior damage tolerance, partly driven by widespread usage of composites. SDM may help to do it even better. Another brand new application field for SDM is represented by nanotechnology, especially as far as the design of small (micro- and nano-sized) mechanical systems, such as MEMS and NEMS, where sample-size effects and discreteness are pervasive aspects of the design. After the introductory section 1, Part II unfolds a logical overview of concepts and solutions that begins with simpler one-dimensional models (i.e. the parallel bar system or PBS) in section 2 and ends with multidimensional systems (i.e. spring networks) in section 3. Great emphasis is placed on the derivation of physically-based definitions of the damage parameter for quasi-brittle systems that stem from a pervasive statistical rationale. In section 2, though, a coupled damage-plasticity model is also covered for ductile systems, limited to the one dimensional case. Finally, the last portion of section 3 focuses on sample-size effects in quasi-brittle materials and* *shows how to obtain and harness scaling laws into fractal-based constitutive relations for engineering applications.*

The main objective of ***Part III*** *is to show the broad application of the thermodynamic theory of elasto-viscoplasicity for the description of important problems in modern manufacturing processes, and particularly for meso-, micro-, and nano-mechanical issues. This description is particularly needed for the investigation by using the numerical methods how to avoid unexpected plastic strain localization and localized fracture phenomena in new manufacturing technology.*

In the first part the development of thermo-elasto-viscoplastic constitutive model of a material which takes into consideration the induced anisotropy effects as well as observed contribution to strain rate effects generated by microshear banding is presented. Analysis of recent experimental observations concerning investigations of fracture phenomena under dynamic loading processes suggests that there are two kind of induced anisotropy: (i) the first caused by the residual type stresses produced by the heterogeneous nature of the finite plastic deformation in polycrystalline solids and (ii) the second called the fracture induced anisotropy generated by the evolution of the microdamage mechanisms. It is noteworthy to stress that both these induced anisotropy effects are coupled and this property has to be taken into account in the proposed constitutive description. On the other hand we very well know from recent experimental observations concerning investigation of dynamic loading processes that formation of microshear bands influences the evolution of microstructure of a material. The basic assumption is that microshear banding contributes to viscoplastic strain rate effects.The model is developed within the thermodynamic framework of a unique, covariance constitutive structure with a finite set of the internal state variables. A set of internal state variables consists of one scalar and two tensors, namely the equivalent inelastic deformation, the second order microdamage tensor with the physical interpretation that defines the volume fraction porosity and the residual stress tensor (the back stress). To describe suitably the influence of both induced anisotropy effects and the stress triaxiality observed experimentally the new kinetic equations for the microdamage tensor and for the back stress tensor are proposed. To describe the contribution to strain rate effects generated by microshear banding we propose to introduce certain scalar function which affects the relaxation time in the viscoplastic flow rule. The relaxation time is used as a regularization parameter. Fracture criterion based on the evolution of the anisotropic intrinsic microdamage is formulated. The fundamental features of the proposed constitutive theory have been carefully discussed.

The objective of the second part is to discuss very efficient procedure of the numerical investigation of localized fracture in inelastic solids generated by impact-loaded adiabatic processes. Particular attention is focused on the proper description of a ductile mode of fracture propagating along the shear band for *high impact velocities. This procedure of investigation is based on utilization the finite difference and finite element methods for regularized thermo-elasto-viscoplastic model of damaged material. The viscoplastic regularization procedure assures the stable integration algorithm by using the finite difference or finite element methods. Particular attention is focused on the well-posedness of the evolution problem (the initial□boundary value problem) as well as on its numerical solutions.*

*In **Part I**□ the behavior of selected brittle materials and structures (concrete and masonry) subjected to explosive loadings is discussed. For concrete the accepted Cumulative Fracture*

Criterion (CFC) is exposed. It describes the degradation of the material under fast dynamic processes accompanied by the strong waves propagation phenomenon and large strain rates of deformation. To overcome the computational difficulty in the analyses of such complex problems, the sub-modeling technique as well as splitting of the calculations into two separate parts: analysis of acoustic wave in the air and the propagation of stresses in structures, are used. Some instructive numerical examples of concrete and masonry walls are in focus of the presentation. The numerical tools and computer simulations allow for proper estimation of the structures safety and for taking the design decisions on how to ensure their expected strength.

George □. Voyiadjis , Baton Rouge, 2010

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The authors dedicate this volume to the Memory of Dusan Krajcinovic

a Friend, Mentor and Inspirator

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