Parametric Finite-Volume Micromechanics of Uniaxial Continuously-Reinforced Periodic Materials With Elastic Phases

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The finite-volume direct averaging micromechanics (FVDAM) theory for periodic heterogeneous materials is extended by incorporating parametric mapping into the theory's analytical framework. The parametric mapping enables modeling of heterogeneous microstructures using quadrilateral subvolume discretization, in contrast with the standard version based on rectangular subdomains. Thus arbitrarily shaped inclusions or porosities can be efficiently rendered without the artificially induced stress concentrations at fiber/matrix interfaces caused by staircase approximations of curved boundaries. Relatively coarse unit cell discretizations yield effective moduli with comparable accuracy of the finite-element method. The local stress fields require greater, but not exceedingly fine, unit cell refinement to generate results comparable with exact elasticity solutions. The FVDAM theory's parametric formulation produces a paradigm shift in the continuing evolution of this approach, enabling high-resolution simulation of local fields with much greater efficiency and confidence than the standard theory. [DOI: 10.1115/1.2931157]

Keywords: finite-volume theory, parametric mapping, homogenization, heterogeneous materials, local stiffness matrix

1 Introduction

A major objective of micromechanics is to predict average (also called effective or homogenized) elastic moduli from a knowledge of the elastic moduli, shapes and distribution of the individual phases that make up the heterogeneous material. Just as important is the ability to accurately predict the local stress and strain fields that may produce local inelastic behavior, damage, and ultimately failure. Such capability, if sufficiently accurate, can be used at both the structural and material design and optimization levels. Specifically, it can be used to efficiently identify the proper combination of materials for the desired overall properties, thus reducing considerably the large expense associated with the traditional trial-and-error approach based on the actual fabrication and laboratory testing.

Two distinct micromechanical modeling approaches based on two types of material microstructure representation can be identified, Drago and Pindera [1]. One representation is based on material microstructures with statistically homogeneous distribution of phases for which a representative volume element (RVE) with the same statistical information representative of the material at large can be identified at each continuum point. Its average properties are determined by solving the RVE boundary-value problem under homogeneous displacement or traction boundary conditions, which produce homogeneous stresses and deformations in the equivalent or homogenized material. The second representation is based on microstructures that are periodic, Fig. 1. Periodic materials are composed of building blocks called repeating unit cells (RUCs) that admit arbitrary internal microstructures. Since one RUC is indistinguishable from another, the response of the entire array under macroscopically uniform loading is identical to the response of an arbitrary RUC under the same loading. This loading is specified by periodic boundary conditions that involve both surface displacements and tractions.

Methods for the analysis of periodic materials have become dominant in the past 20 years due to the difficulty of simultaneously satisfying homogeneous displacement and traction boundary conditions, necessary in fulfilling the RVE requirement, for subvolumes with arbitrary microstructures. In particular, the homogenization theory has emerged as a powerful technique in the analysis of periodic materials. This technique employs a multiscale displacement representation in the solution of the RUC problem, which leads to the determination of the effective or homogenized elastic moduli and the internal strain and stress fields, see Sanchez-Palencia [2] and Suquet [3]. The solution of the RUC boundary-value problem, however, is typically generated using the finite-element method.

An attractive alternative to the finite-element approach in the solution of periodic RUC problems is the finite-volume theory developed by Bansal and Pindera [4,5]. As recently demonstrated by Pindera and Bansal [6], many microstructural features and response characteristics of real unidirectional composites are efficiently simulated by this method. The method's development is rooted in the so-called higher-order theory for functionally graded materials originally developed by Aboudi, Pindera, and Arnold in a sequence of papers published in the 1990s and summarized in a review article by Aboudi et al. [7]. Incorporation of periodic boundary conditions into this higher-order theory within the homogenization framework has produced a micromechanics model for periodic materials called high-fidelity generalized method of cells (HFGMC), Aboudi et al. [8,9]. Subsequent reconstruction of this micromechanics model based on a substantially simplified RUC volume discretization, and the use of the local/global stiffness matrix approach, see Bufler [10] and Pindera [11], has demonstrated this theory to be a finite-volume, direct-averaging, micromechanics (FVDAM) model. This reconstruction was motivated by a similar reconstruction of the original higher-order theory for functionally graded materials by Zhong et al. [12] and

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Finite Volume Micromechanics Of Heterogeneous Periodic Materials An Attractive Alternative To The Finite Element Based Homogenization Of Heterogeneous Media

Valeriy A. Buryachenko

Finite Volume Micromechanics Of Heterogeneous Periodic Materials An Attractive Alternative To The Finite Element Based Homogenization Of Heterogeneous Media:

Micromechanics of Heterogeneous Materials Valeriy Buryachenko,2007-09-20 Here is an accurate and timely account of micromechanics which spans materials science mechanical engineering applied mathematics technical physics geophysics and biology The book features rigorous and unified theoretical methods of applied mathematics and statistical physics in the material science of microheterogeneous media Uniquely it offers a useful demonstration of the systematic and fundamental research of the microstructure of the wide class of heterogeneous materials of natural and synthetic nature

Computational Methods in Micromechanics Somnath Ghosh,Martin Ostoja-Starzewski,1995 Contains 11 papers presented at the November 1995 symposium addressing new methods of computational micromechanics and their applications Some methods include multiresolution analysis with reproducing kernel particle method the asymptotic homogenisation method the Voronoi cell FEM and more **Computational Homogenization of Heterogeneous Materials with Finite Elements** Julien Yvonnet,2019-06-11 This monograph provides a concise overview of the main theoretical and numerical tools to solve homogenization problems in solids with finite elements Starting from simple cases linear thermal case the problems are progressively complexified to finish with nonlinear problems The book is not an overview of current research in that field but a course book and summarizes established knowledge in this area such that students or researchers who would like to start working on this subject will acquire the basics without any preliminary knowledge about homogenization More specifically the book is written with the objective of practical implementation of the methodologies in simple programs such as Matlab The presentation is kept at a level where no deep mathematics are required *Finite Volume Direct Averaging Micromechanics of Heterogeneous Media* Yogesh Bansal,2005 *Applied RVE Reconstruction and Homogenization of Heterogeneous Materials* Yves Remond,Said Ahz,Majid Baniassadi,2016-02-01 Applied RVE Reconstruction and Homogenization of Heterogeneous Materials contains the basic principles underlying the main continuum mechanical partial differential equation models used in practice together with numerical methods to approximately solve them This book offers a unified presentation of continuum mechanical models and their discrete counterparts providing a deeper understanding of the relationship between the main numerical methods finite element methods finite volume methods and the advantages and shortcomings of each In addition the book shows by way of Matlab code snippets how to implement the methods described for all types of different problems including linear and nonlinear and stationary and time dependent also covering solids and fluids and the typical common finite element finite volume and time stepping methods **Heterogeneous Media** Konstantin Markov,Luigi Preziosi,2000-02-02 Most materials used in contemporary life and industry are heterogeneous composites and multicomponent possessing a rich and complex internal structure This internal structure or microstructure plays a key role in understanding and controlling the continuum behavior or macroscopic of a wide variety of materials The modeling process is a critical tool for scientists and engineers studying the analysis and experimentation for the micromechanics and behavior of these materials Heterogeneous Media is a critical in depth edited survey of the major topics surrounding the modeling and analysis of problems in micromechanics of multicomponent systems including conceptual and practical aspects The goal of this extensive and comprehensive survey is to provide both specialists and nonspecialists with an authoritative and interdisciplinary perspective of current ideas and methods used for modeling heterogeneous materials behavior and their applications Topics and Features all chapters use interdisciplinary modeling perspective for investigating heterogeneous media Five chapters provide self contained discussions with background provided Focuses only upon most important techniques and models fully exploring micro macro interconnections extensive introductory survey chapter on micromechanics of heterogeneous media microstructure characterization via statistical correlation functions micro scale deformation of pore space wave fields and effective dynamical properties modeling of the complex production technologies for composite materials The book is ideal for a general scientific and engineering audience needing an in depth view and guide to current ideas methods and

Heterogeneous Media Konstantin Markov,Luigi Preziosi,2011-09-26 Most materials used in contemporary life and industry are heterogeneous composites and multicomponent possessing a rich and complex internal structure This internal structure or microstructure plays a key role in understanding and controlling the continuum behavior or macroscopic of a wide variety of materials The modeling process is a critical tool for scientists and engineers studying the analysis and experimentation for the micromechanics and behavior of these materials Heterogeneous Media is a critical in depth edited survey of the major topics surrounding the modeling and analysis of problems in micromechanics of multicomponent systems including conceptual and practical aspects The goal of this extensive and comprehensive survey is to provide both specialists and nonspecialists with an authoritative and interdisciplinary perspective of current ideas and methods used for modeling heterogeneous materials behavior and their applications Topics and Features all chapters use interdisciplinary modeling perspective for investigating heterogeneous media Five chapters provide self contained discussions with background provided Focuses only upon most important techniques and models fully exploring micro macro interconnections extensive introductory survey chapter on micromechanics of heterogeneous media microstructure characterization via statistical correlation functions micro scale deformation of pore space wave fields and effective dynamical properties modeling of the complex production technologies for composite materials The book is ideal for a general scientific and engineering audience needing an in depth view and guide to current ideas methods and **Heterogeneous Media** Konstantin Z. Markov,Luigi Preziosi,2000 *Local and Nonlocal Micromechanics of Heterogeneous Materials* Valeriy A. Buryachenko,2021-11-16 This book presents the micromechanics of random structure heterogeneous materials a multidisciplinary research area that has experienced a revolutionary renascence at the overlap of various branches of materials science mechanical engineering applied mathematics technical physics geophysics and biology It demonstrates intriguing successes of unified rigorous theoretical methods of applied mathematics and statistical physics in material science of microheterogeneous media The prediction of the behaviour of heterogeneous materials by the use of properties of constituents and their microstructure is a central problem of micromechanics This book is the first in micromechanics where a successful effort of systematic and fundamental research of the microstructure of the wide class of heterogeneous materials of natural and synthetic nature is attempted The uniqueness of the book lies in its development and expressive representation of statistical methods quantitatively describing random structures which are at most adopted for the forthcoming evaluation of a wide variety of macroscopic transport electromagnetic strength and elastoplastic properties of heterogeneous materials

Micromechanics S. Nemat-Nasser,M. Hori,2013-10-22 A comprehensive overview is given in this book towards a fundamental understanding of the micromechanics of the overall response and failure modes of advanced materials such as ceramics and ceramic and other composites These advanced materials have become the focus of systematic and extensive research in recent times The book consists of two parts The first part reviews solids with microdefects such as cavities cracks and inclusions as well as elastic composites To render the book self contained the second part focuses on the fundamentals of continuum mechanics particularly linear elasticity which forms the basis for the development of small deformation micromechanics In Part 1 a fundamental and general framework for quantitative rigorous analysis of the overall response and failure modes of microstructurally heterogeneous solids is systematically developed These expressions apply to broad classes of materials with inhomogeneities and defects While for the most part the general framework is set within linear elasticity the results directly translate to heterogeneous solids with rate dependent or rate independent inelastic constituents This application is specifically referred to in various chapters The general exact correlations obtained between the overall properties and the microstructure are then used together with simple models to develop techniques for direct quantitative evaluation of the overall response which is generally described in terms of instantaneous overall moduli or compliance The correlations among the corresponding results for a variety of problems are examined in great detail The bounds as well as the specific results include new observations and original developments as well as an in depth account of the state of the art Part 2 focuses on Elasticity The section on variational methods includes some new elements which should prove useful for application to advanced modeling as well as solutions of composites and related heterogeneous bodies A brief modern version of elements in vector and tensor algebra is provided which is particularly tailored to provide a background for the rest of this book The data contained in this volume as Part 1 includes new results on many basic issues in micromechanics which will be helpful to graduate students and researchers involved with rigorous physically based modeling of overall properties of heterogeneous solids Parametric Finite Volume Theory for Periodic Heterogeneous Materials Mahendra Gattu,2007 **An Introduction to Computational Micromechanics** Tarek I. Zohdi,Peter Wriggers,2008-03-15 In this its second corrected printing Zohdi and Wriggers illuminating text presents a comprehensive introduction to the subject The authors include in their scope basic homogenization theory microstructural optimization and multifield analysis of heterogeneous materials This volume is ideal for researchers and engineers and can be used in a first year course for graduate students with an interest in the computational micromechanical analysis of new materials Micromechanics in Practice Michal Šejnoha,Jan Zeman,2013 The book will concentrate on the application of micromechanics to the analysis of practical engineering problems Both classical composites represented by carbon carbon textile laminates and applications in Civil Engineering including asphalts and masonry structures will be considered A common denominator of these considerably distinct material systems will be randomness of their internal structure Also owing to their complexity all material systems will be studied on multiple scales Since real engineering rather than academic problems are of the main interest these scales will be treated independently from each other on the grounds of fully uncoupled multi scale analysis Attention will be limited to elastic and viscoelastic behaviour and to the linear heat transfer analysis To achieve this the book will address two different approaches to the homogenization of systems with random microstructures In particular classical averaging schemes based on the Eshelby solution of a solitary inclusion in an infinite medium represented by the Hashin Shtrikman variational principles or by considerably simpler and more popular Mori Tanaka method will be compared to detailed finite element simulations of a certain representative volume element RVE representing accommodated geometrical details of respective microstructures These are derived by matching material statistics such as the one and two point probability functions of real and artificial microstructures The latter one is termed the statistically equivalent periodic unit cell owing to the assumed periodic arrangement of reinforcements carbon fibres carbon fibre tows stones or masonry bricks in a certain matrix carbon matrix asphalt mastic mortar Other types of materials will be introduced in the form of exercises with emphases to the application of the Mori Tanaka method in the framework of the previously mentioned uncoupled multi scale analysis **Microstructural Modeling and Computational Homogenization of the Physically Linear and Nonlinear Constitutive Behavior of Micro-heterogeneous Materials** Felix Fritzen,2014-08-22 Engineering materials show a pronounced heterogeneity on a smaller scale that influences the macroscopic constitutive behavior Algorithms for the periodic discretization of microstructures are presented These are used within the Nonuniform Transformation Field Analysis NTFA which is an order reduction based nonlinear homogenization method with micro mechanical background Theoretical and numerical aspects of the method are discussed and its computational efficiency is validated Homogenization of Coupled Phenomena in Heterogenous Media Jean-Louis Auriault,Claude Boutin,Christian Geindreau,2010-01-05 Both naturally occurring and man made materials are often heterogeneous materials formed of various constituents with different properties and behaviours Studies are usually carried out on volumes of materials that contain a large number of heterogeneities Describing these media by using appropriate mathematical models to describe each constituent turns out to be an intractable problem Instead they are generally investigated by using an equivalent macroscopic description relative to the microscopic heterogeneity scale which describes the overall behaviour of the media Fundamental questions then arise Is such an equivalent macroscopic description possible What is the domain of validity of this macroscopic description The homogenization technique provides complete and rigorous answers to these questions This book aims to summarize the homogenization technique and its contribution to engineering sciences Researchers graduate students and engineers will find here a unified and concise presentation The book is divided into four parts whose main topics are Introduction to the homogenization technique for periodic or random media with emphasis on the physics involved in the mathematical process and the applications to real materials Heat and mass transfers in porous media Newtonian fluid flow in rigid porous media under different regimes Quasi statics and dynamics of saturated deformable porous media Each part is illustrated by numerical or analytical applications as well as comparison with the self consistent approach **Micromechanics of Heterogeneous Materials Under Compressive Loading** George Laird,1993 In mining and mineral processing compressive loading is often encountered during the comminution of ore bearing minerals and in the wear resistant materials used in the comminution circuit A common thread joining many of the materials that are primarily used under compressive loading is the presence of a high modulus reinforcement either fiber or particulate embedded within a lower modulus matrix phase i e a brittle heterogeneous material Many of these heterogeneous materials are designed or manufactured such that an imperfect interface i e an interface that provides less than complete coherency between the reinforcing phase and the matrix exists between the reinforcing phase and the matrix e g tough fiber reinforced ceramics To date most research has focused on the response of these heterogeneous materials with imperfect interfaces to tensile loading however little is known about their response to compressive loading The principal objective of this investigation is to develop a better understanding of the micromechanical behavior of these complex materials under compressive loading Analytical solutions are reviewed and compared with finite element models for the simulation of heterogeneous materials with imperfect interfaces under compressive loading This comparison shows that a nonlinear numerical approach finite element method is necessary to fully simulate the behavior of these materials To validate the nonlinear model laser moire experiments were conducted on a model heterogeneous material loaded under uniaxial and biaxial compression In plane displacements were measured and found to be in fundamental agreement with the nonlinear finite element model Subsequently finite element simulations were developed for a variety of heterogeneous materials with imperfect interfaces Results show that deleterious tensile stress concentrations are primarily influenced by three factors i the nature of the imperfect interface ii the moduli mismatch between the reinforcement and matrix and iii the volume fraction of the reinforcement Finally crack initiation experiments in laboratory models of a heterogeneous material with a frictional imperfect interface were conducted to substantiate the prior work using nonlinear finite element models Experimental results correlate well with the numerically predicted micromechanical behavior of a model heterogeneous system under uniaxial compressive loading Micromechanical Analysis and Multi-Scale Modeling Using the Voronoi Cell Finite Element Method Somnath Ghosh,2011-06-23 As multi phase metal alloy systems and polymer ceramic or metal matrix composite materials are increasingly being used in industry the science and technology for these heterogeneous materials has advanced rapidly By extending analytical and numerical models engineers can analyze failure characteristics of the materials before they are integrat **Matrix-free Voxel-based Finite Element Method for Materials with Heterogeneous Microstructures** Andrea Keßler,2018 **Micromechanics of Heterogeneous Materials** Valeriy Buryachenko,2008-11-01 Here is an accurate and timely account of micromechanics which spans materials science mechanical engineering applied mathematics technical physics geophysics and biology The book features rigorous and unified theoretical methods of applied mathematics and statistical physics in the material science of microheterogeneous media Uniquely it offers a useful demonstration of the systematic and fundamental research of the microstructure of the wide class of heterogeneous materials of natural and synthetic nature **Stochastic Material Characterization of Heterogeneous Media with Randomly Distributed Material Properties** Shen Shang,2012 In the field of computational mechanics there has been a very challenging problem which is the characterization of heterogeneous media with randomly distributed material properties In reality no material is homogeneous and deterministic in nature and it has been well known that randomness in microstructures and properties of materials could significantly influence scatter of structural response at larger scales Therefore stochastic characterization of heterogeneous materials has increasingly received attention in various engineering and science fields In order to deal with this challenging problem two major challenges need to be addressed 1 developing an efficient modeling technique to discretize the material uncertainty in the stochastic domain and 2 developing a robust and general inverse identification computational framework that can estimate parameters related to material uncertainties In this dissertation two major challenges have been addressed by proposing a robust inverse analysis framework that can estimate parameters of material constitutive models based on a set of limited global boundary measurements and combining the framework with a general stochastic finite element analysis tool Finally a new stochastic inverse analysis framework has been proposed which has a novel capability of modeling effects of spatial variability of both linear and nonlinear material properties on macroscopic material and structural response By inversely identifying statistical parameters e g spatial mean spatial variance spatial correlation length and random variables related to spatial randomness of material properties it allows for generating statistically equivalent realizations of random distributions of linear and nonlinear material properties and their applications to the development of probabilistic structural models First a robust inverse identification framework called the Self Optimizing Inverse Method Self OPTIM has been developed Unlike other signal matching approaches used in model updating in the course of two parallel finite element simulations Self OPTIM automatically minimizes an implicit objective function defined as a function of internal full field stresses and strains The performance of Self OPTIM has been proven by both numerical and experimental verifications Second in the stochastic finite element method SFEM the spatially varying random material properties such as linear elastic modulus Poisson s ratio and initial yield strength are discretized by the Karhunen Lo ve expansion This computational tool allows for Monte Carlo simulations considering material uncertainties and their propagations through forward simulations By combining SFEM with Self OPTIM a novel algorithm named as stochastic Self OPTIM for stochastic material characterization of heterogeneous media with randomly distributed material properties is invented Its performance has been verified by applying to reconstruction problems and stochastic inverse identifications of statistical parameters of random fields related to material properties To demonstrate promising applications of the stochastic Self OPTIM a probabilistic low cycle fatigue life prediction model has been developed with considerations of spatial variability of Young s modulus Poisson ratio and the initial yield strength For this purpose a probabilistic surrogate model has also been developed by using the polynomial chaos expansion

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