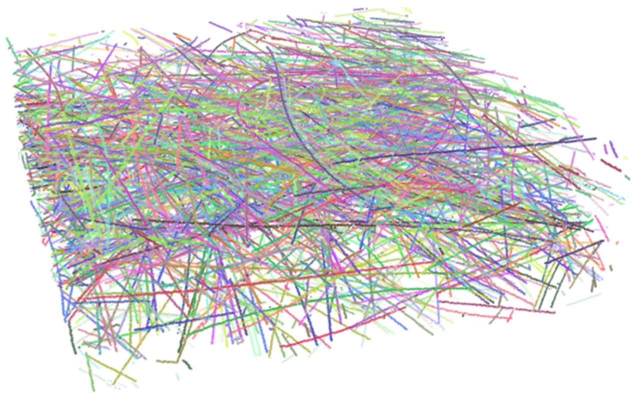
Karlsruhe Institute of Technology
Institute of Engineering Mechanics

University of Paderborn
Chair of Engineering Mechanics

GRK 2078 International Research Training Group

29th International Workshop
Research in Mechanics of Composites



Bad Herrenalb, Germany
December 6-8, 2016

Karlsruhe Institute of Technology

Objective of the Workshop

Modern fiber reinforced polymers (FRP) show a macroscopic material behavior depending sensitively on the fiber orientation distribution and arrangement as well as on the generally nonlinear material behavior of the constituents. Additionally, the overall composite behavior is influenced by fluid-structure interaction, by curing during the production process as well as by the interface properties. Understanding the correlation of both the microstructure and the micromechanical behavior on the one side, and the macroscopic composite behavior on the other side, is of fundamental interest for the design of materials, the optimization of production processes as well as the dimensioning and optimization of construction parts. In this workshop, new approaches for the material modeling of **short and long fiber reinforced composites**, corresponding numerical solution strategies, and experimental techniques are discussed. Special emphasis is given to the modeling of process chains. The International Research Training Group "Integrated Engineering of continuous-discontinuous long fiber reinforced polymer structures", funded by the German Research Foundation (DFG), provides a structured educational program for several PhD students focusing on research in the areas of materials science, product engineering, mechanics, production science and light-weight technologies.

The Organizers

Prof. Dr.-Ing. habil. Thomas Böhlke
Prof. Dr.-Ing. habil. Rolf Mahnken
GRK 2078 International Research Training Group

Graphic on front page:
Reference-graphic by Pascal Pinter, A novel Method for Determination of Fiber Length Distributions from μCT-data, P. Pinter, B. Bertram, K. Weidenmann (KIT), Karlsruhe, Germany

Program for Tuesday, December 6, 2016

Time	
from 18:00 on	Registration and Welcome, Informal Meeting

Program for Wednesday, December 7, 2016

Time	Authors	Title of Lecture
08:30 - 09:00	P. Pinter and K. A. Weidenmann	Microstructure Characterization of fiber reinforced polymers based on parametrized space curves derived from CT Data
09:00 - 09:30	J. Niedermeyer and C. Redenbach	Investigating the fibre length distribution from CT images using fibre endpoints
09:30 - 10:00	M. Schneider	Generating fiber-filled volume elements with high volume fraction and prescribed fourth order fiber orientation tensor
10:00 - 10:30	Coffee break	
10:30 - 11:00	C. Röhrig and S. Diebels	Characterization of a short fiber-reinforced polymer
11:00 - 11:30	M. Schemmann, B. Brylka and T. Böhlke	Characterization and parameter identification of damage in sheet molding compounds
11:30 - 12:45	Lunch	
12:45 - 13:30	M. Kabel and M. Schneider	Keynote: Efficient hourglass control in FFT-based computational homogenization
13:30 - 14:00	F. Göküzüm and M.-A. Keip	Consistent macroscopic tangent computation for FFT-based homogenization
14:00 - 14:30	X. Ju and R. Mahnken	Error-controlled homogenization for a class of linear elastic disordered materials
14:30 - 15:00	N. Goldberg, F. Ospald, M. Schneider, and J. Ihlemann	Considering the fiber orientation for the computation of the hyperelastic Tucker average for short fiber reinforced composites
15:00 - 15:30	Coffee break	
15:30 - 16:00	R. Bertóti and T. Böhlke	Effective and efficient modeling of viscous SFRP flow
16:00 - 16:30	C. Liebold, A. Haufe, and Peter Middendorf	Questions Regarding the Development of Mapping Algorithms for Short Fiber Reinforced Composite Modeling
16:30 - 17:15	S. Wulfinghoff, M. Fassin, and S. Reese	Keynote: Conditions for phenomenological anisotropic damage models derived from micromechanics
19:00	Conference Dinner	

Program for Thursday, December 8, 2016

Time	Authors	Title of Lecture
09:00 - 09:30	F. Ongaro	Theoretical modeling of biologically inspired composite materials
09:30 - 10:00	J. Hund, C. Leppin, T. Böhlke, J. Rothe	Stress-strain characterization and damage modeling of glass fiber reinforced polymer composites with vinylester matrix
10:00 - 10:30	M. Schmerbauch, F. Erler, and A. Matzenmiller	Comparison of the Micromechanical Crack Orientation in Longfiber-Reinforced Composites to Puck's Theory
10:30 - 11:00	Coffee break	
11:00 - 11:30	U. Ehlenbröker, M. Petersmann, T. Antretter, and R. Mahnken	Transformation strains and variant interaction for bainitic variant evolution
11:30 - 12:00	C. Dammann, R. Mahnken, and P. Lenz	(n)- and (n+1)-layered composite sphere models for thermo-chemo-mechanical effective properties
12:00 - 12:30	Final discussion	
13:00	Lunch	

Effective and efficient modeling of viscous short-fiber reinforced polymer flow

Róbert Bertóti and Thomas Böhlke

Chair for Continuum Mechanics,
Institute of Engineering Mechanics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Abstract. For the effective modeling of viscous short-fiber reinforced polymer flow, so called Fiber Orientation Tensors (FOTs) are used [1]. The FOTs describe the microstructure of a fluid-fiber mixture on the macro scale in an effective manner. In the current work, Fiber Orientation Vectors (FOVs) are also used which describe the microstructure of the fluid-fiber mixture on the micro scale in a discrete manner. The evolution equations of the FOVs and the FOTs are all based on Jeffery's equation [2]. The effectiveness and efficiency of the FOTs vs. the FOVs is shown in this work on the example of a numerical implementation for simple flow cases.

Not only the fluid-fiber interaction, but also the fiber-fluid interaction is described in an effective way. A two step homogenization method, based on a Hashin-Shtrikman bound [3], is used to calculate the flow induced anisotropic viscosity of the fluid-fiber mixture. This method is compared numerically to the Dinh-Armstrong constitutive model [4] by means of simple flow cases.

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(n)- and $(n+1)$-layered composite sphere models for thermo-chemo-mechanical effective properties

Christian Dammann, Rolf Mahnken, and Peter Lenz

Chair of Engineering Mechanics,
Paderborn University, Paderborn, Germany

Abstract. Our work presents extensions of multi layered *composite sphere models* known from the literature [1, 2, 3] to temperature-dependent elastic effects accompanied by curing. Effective properties in dependence on the degree of cure are obtained by homogenization for a representative unit cell (micro-RVE) on the heterogeneous microscale. To this end, analytical solutions for (n)- and $(n+1)$-layered composite sphere models, [3, 4], are derived, in addition to Voigt and Reuss bounds resulting from the assumption of a homogeneous mixture. For simplification, we restrict the material behavior of the micro-RVE to a thermo-chemo-mechanical coupling with linear elasticity. In a numerical study we compare different effective material properties including bounds.

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Transformation strains and variant interaction for bainitic variant evolution.

Ulrich Ehlenbröker[1], Manuel Petersmann[2], Thomas Antretter[2], and Rolf Mahnken[1]

[1] Chair of Engineering Mechanics,
Paderborn University , Paderborn, Germany
[2] Institute of Mechanics,
Montanuniversität Leoben, Leoben, Austria

Abstract. The evolution of the baintic phase in steel is of particular relevance especially in industrial production processes encompassing hot-forming and quenching of larger components. For that reason a multi-scale model for bainitic phase transformation in multi-variant polycrystalline low alloy steels has been developed [1].

In order to yield relasitic simulation results, the microscopic conversion procedures for the austenite-to-bainite transformation have to be described in an appropriate way. To that end, the transformation strains for the crystallographic variants in the model have been adjusted. For the calculation of transformation strains, different theories can be applied, e.g. a hierarchical block-structure as described in [2] for the martenstic phase transformation in a 9Ni-steel, or a theory solely based on the lattice parameters of the two phases (austenite and bainite) and the assumption that the transformation leaves a close packed plane and a close packed direction in that plane unrotated, in other words the measured orientation relationship for the transformation (see [3]). Further, a mechanism for the simulation of variant interaction between the different crystallographic variants, based on the theory of transformation hardening, has been introduced into the model (see [4]).

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Consistent macroscopic tangent computation for FFT-based homogenization

Felix Selim Göküzüm and Marc-André Keip

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

Abstract. Lately, the FFT-based method suggested by MOULINEC & SUQUET [1] has increased in popularity due to its superior computational speed. The present work gives a computational framework for evaluating the consistent tangent for FFT-based homogenization. It is inspired by the works on multiscale FEM, see e.g. MIEHE ET AL. [2]. The proposed consistent tangent for FFT-based approaches offers an alternative to numerical tangents calculation, which are carried out by perturbing the single strain components. Especially in the context of multi-scale methods, e.g. FE^2 or FE-FFT [3,4], the computation of a consistent macroscopic tangent is crucial. Computing the tangent numerically can be costly with respect to computational time and might even surpass the computational time needed for solving the initial mechanical equilibrium. We will show that the use of an algorithmic tangent offers a more efficient and faster calculation of the macroscopic tangent, however, it comes with the drawback of an increased memory storage demand. The viability of the method holds for linear as well as for nonlinear material behaviour, including viscoelasticity and large strains as discussed in KABEL ET AL. [5].

References

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Considering the fiber orientation for the computation of the hyperelastic Tucker average for short fiber reinforced composites

Niels Goldberg[1], Felix Ospald[2], Matti Schneider[3], and Jörn Ihlemann[1]

[1] Professorship of Solid Mechanics, Faculty of Mechanical Engineering, TU Chemnitz, Chemnitz, Germany
[2] Professorship of Partial Differential Equations, Faculty of Mathematics, TU Chemnitz, Chemnitz, Germany
[3] Fraunhofer ITWM, Kaiserslautern, Germany

Abstract. In this contribution we apply a fiber orientation-adapted integration scheme to the computation of the Tucker average of non-linear material laws for short fiber reinforced composites based on angular central Gaussian fiber orientation distributions. We establish a reference scenario for fitting the Tucker average of a transversely isotropic hyperelastic energy to microstructural simulations, obtained by FFT-based computational homogenization. We carefully discuss ideas for accelerating the identification process, leading to a tremendous speed-up compared to a naive approach. The resulting hyperelastic material map turns out to be surprisingly accurate, simple to integrate in commercial finite element software and fast in its execution. We demonstrate the capabilities of the extracted model by a finite element analysis of a fiber reinforced chain link.

Stress-strain characterization and damage modeling of glass fiber reinforced polymer composites with vinylester matrix

Jonas Hund[1], Christian Leppin[2], Thomas Böhlke[3], and Jan Rothe[2]

[1] Institute of Mechanics,
Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[2] Suisse Technology Partners AG,
Neuhausen am Rheinfall, Switzerland
[3] Institute of Engineering Mechanics,
Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Abstract. Beyond a certain loading threshold, glass fiber reinforced polymer composites with vinylester matrix exhibit considerably nonlinear deformation behavior due to damage of the matrix material. To model such nonlinear deformation properties, an approach of a fully anisotropic damage model suggested by Govindjee et al.[1] is considered. In addition, the inter-fiber fracture criterion introduced by Puck[2] is used for the damage function which defines the damage initiation and the material strength. For identifying the material properties as well as validating the model three GFRP laminates with different layups are tested in tension under different loading orientations, assuming laminate theory to be reasonably well fulfilled. Further experiments are compared with corresponding simulation results to demonstrate the performance of the model.

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Efficient hourglass control in FFT-based computational homogenization

Matthias Kabel and Matti Schneider

Department of Flow and Material Simulation, Fraunhofer ITWM, Kaiserslautern

Abstract. The FFT-based homogenization method of Moulinec and Suquet [1] is a fast and memory-efficient solver posed on regular voxels grids and is well adapted for elastic simulations on complex microstructures of fiber reinforced plastics. Originally, the method used Fourier polynomials to discretize the continuous version of the Lippmann-Schwinger equation, which lead to convergence problems at high material contrasts (e.g. pores and defects). Recently, many groups are working on using alternative discretizations in combination with the FFT-based method: Voxelwise constant strains [2], finite differences on a staggered grid [3], trilinear hexahedral elements with reduced integration [4] and trilinear elements with full integration [5].

All of these discretization have major drawbacks: No explicit formula for the Green's operator, material function has to be evaluated on a double fine grid, hourglassing or high computational effort. In our talk we will propose a computational efficient way to insert an artificial stiffness to the hourglass deformation modes [6] utilizing the reference material and assess the solution quality as well as the computational efficiency of this new discretization.

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Questions regarding the development of mapping algorithms for short fiber reinforced composite modeling

Christian Liebold[1], Dr. André Haufe[1], and Prof. Dr.-Ing. Peter Middendorf[2]

[1] DYNAmore GmbH,
Industriestraße 2, Stuttgart, Germany
[2] Institute of Aircraft Design,
University of Stuttgart, Germany

Abstract. This work will emphasis the importance of a proper data transformation from the process simulation to the finite element mesh for structural analysis. As an example, two modeling approaches for short fiber reinforced composites within a commercial finite element code will be compared. Thereby, different homogenization, averaging and interpolation techniques will be introduced and discussed. In [1], interpolation and averaging techniques for scalar values such as strains and thicknesses based on the finite element integration methods have been developed, not covering the topic of a proper consideration of tensorial data. This is crucial since standard averaging methods will lead to the loss of information about the tensors' shape being described by its eigenvectors and eigenvalues and thereby, the loss of information about the degree of anisotropy. A method to overcome this problem is introduced in [2] and will be discussed within this work. Averaging and interpolation techniques for scalar values such as they are described in [3] will be introduced as well, trying to identify the most reliable averaging method. The gained knowledge about proper data transformation and homogenization shall be applicable for further processing techniques such as continuous fiber reinforced composites or metal forming.

The influence of scattering data from process simulation on the results of structural analysis will be discussed as well.

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Investigating the fibre length distribution from CT images using fibre endpoints

Jan Niedermeyer and Claudia Redenbach

TU Kaiserslautern, Kaiserslautern, Germany

Abstract. Estimating the fibre length distribution in fibre reeinforces polymers from CT data is still a challenge. Image quality usually does not allow a full fibre segmentation.

Using Gaussian curvature we can segment the fibre endpoints from a CT image. By interpreting these endpoints as a point process we can then use point process statistics to investigate properties of the underlying fibre process.

[1] proposed a method to estimate the fibre length distribution from an endpoint process. We further investigate Ripleys K function and the pair correlation function to receive information of the fibre length distribution.

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Theoretical modeling of biologically inspired composite materials

Federica Ongaro

School of Engineering and Materials Science (SEMS),
Queen Mary University of London, London, UK

Abstract. Many efforts have been devoted to the prediction of the effective properties of regular cellular materials with empty cells [1]. In reality, at the microscale, many biological tissues display a peculiar cellular structure having the internal volumes filled with fluids, fibers, or other bulk materials. Similar composite solutions are found, for example, in the natural tubular structures like plant stems or animal quills. In these systems, the inner honeycomb or foam-like core behaves like an elastic foundation supporting the dense outer cylindrical shell and makes it more performant [2]. Though some authors numerically and theoretically analyzed the morphology, composition and mechanical behavior of filled cellular materials, up to date closed-form expressions for the effective elastic moduli and constitutive equations have not been derived. To contribute filling this research gap and to provide some useful tools for practical applications, I will initially present a continuum model for two-dimensional cellular materials having a hexagonal microstructure and the cells filled by a generic elastic material, modeled as a series of closely spaced, independent linear-elastic springs (Winkler foundation). The analysis is then extended to the case of elongated hexagonal cells to study the mechanics of orthotropic composite cellular materials, inspired by the keel tissue of the ice plant [3]. Finally, in the last part of my talk, I will investigate the effects of adding structural hierarchy [4] into a composite cellular material. Specifically, I will focus on composite cellular materials composed by structural elements which themselves have a structure. The proposed approach is general enough to be applied to a very wide range of materials, including long fiber reinforced composites.

References

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Mircrostructure characterization of fiber reinforced polymers based on parametrized space curves derived from μCT data

Pascal Pinter and Kay André Weidenmann

Institute for Applied Materials,
Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Abstract. Microstructural data is crucial for modelling of fiber reinforced polymers. There are many image features that can be used to describe the fiber architecture using micro computed tomography analysis. Since it is difficult to track fibers in volumetric images, it is even possible to calculate fiber orientations voxel based [1] without knowing about the connection to adjacent voxels. This method is state of the art and is implemented in many commercial toolkits like e.g. VGStudio Max. In recent years, micro computed tomography has gained image quality intensively. This enables to acquire high resolution images which are necessary to track fibers correctly from one end to the other. But most of the currently available software is only applicable for short fiber reinforced polymers [2] or there is no possibility to evaluate fiber curvature [3].

In this work, an algorithm is introduced to parametrize a space curve for each fiber within the scanned sample. This method offers the full information about fiber architecture and allows for deriving orientation tensors or curvatures directly from the parametrized curves.

References

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Characterization of a short fiber-reinforced polymer

Céline Röhrig and Stefan Diebels

Lehrstuhl für Technische Mechanik,
Universität des Saarlandes, Saarbrücken, Germany

Abstract. This contribution presents ideas, how composite materials can be characterized with respect to experimental testing. Due to the huge number of possible combinations of matrix and filler, each composite material has its own characteristics. In this work a polybutylene terephthalate (PBT) reinforced by short glass fibers is characterized. An overview of the properties of the investigated material is obtained from results of cyclic uniaxial tensile tests at constant strain rate. The short fiber reinforced PBT shows elasto-plasticity and damage. These properties depend on a fiber orientation angle, which is investigated by testing specimens with different angles compared to the main fiber orientation. For the evaluation the complete strain information in all directions is obtained by an optical area analysis over the whole surface using a digital image correlation (DIC) software. The optical system uses four cameras to realize a 360°-3D-measurement by a two-sided stereography. A final aim of this work is to realize a verification experiment representing the three-dimensional forming process as realistically as possible. Therefore a deep-drawing based testing device, a Nakajima test for polymeric materials is presented and first results of the experimental investigations are shown. Thereby an optical deformation measurement system is also used for the evaluation of the specimen deformation. Finally a first idea for a one-dimensional modeling description based on the experimental results of the uniaxial tensile tests is presented for further research.

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Characterization and parameter identification of multi-axial behavior in sheet molding compounds

Malte Schemmann and Thomas Böhlke

Chair for Continuum Mechanics,
Institute of Engineering Mechanics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Abstract. Due to their high lightweight potential, economical mass-production and excellent formability, discontinuous fiber reinforced composites are increasingly used for nonstructural components in the automotive sector. The application of this class of materials is however hindered by a lack of an understanding for robust modeling the whole process chain as well as the process related thermo-mechanical process-dependent properties. The material class under consideration is SMC (sheet molding compound), a thermoset matrix reinforced with glass fibers.

The damage behavior of SMC is characterized in uniaxial and biaxial tensile tests, whereas multiple loading ratios are considered to identify damage initiation and evolution. An optimization of the cruciform specimen geometry was performed to observe damage in the area multiaxial stresses. The multi-objective optimization criterion ensures a damage localization in the area of interest instead of the specimen arms, as well an as homogeneous as possible stress state in that area [1].

In experiments the full strain field is measured with digital image correlation. Due to the inhomogeneity of the stress and strain fields an inverse parameter identification is required to obtain the material properties [2, 3]. Hereby a Gauss-Newton type Algorithm is used to identify parameters of a FEM simulation in a way, such that the simulated and measured strain fields deviation is minimal.

References

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Comparison of the micromechanical crack orientation in longfiber-reinforced composites to Puck's theory

Mario Schmerbauch, Felix Erler, and Anton Matzenmiller

Institute of Mechanics,
University of Kassel, Kassel, Germany

Abstract. The micromechanical crack orientation in longfiber-reinforced composites is compared to the crack angle prediction of PUCK's fracture criterion. PUCK's model is one of the best performing macroscopic criteria in the *World-Wide Failure Exercise I* [1] and *II* [2]. As a unique feature among phenomenological failure conditions, it provides the orientation of the fracture plane in the inter-fiber failure mode for a single ply, which is characterized by a fracture angle. Before a macroscopic crack occurs in a lamina, cracks evolve on the fiber-matrix level. Hence, a microscopic approach by using a single-fiber *Repeating Unit Cell (RUC)* is used to investigate this mechanism on the finer scale and its influence on the effective properties. In this approach, interfaces with an elasto-damage constitutive model are inserted into the discretized *RUC* along the interelement boundaries to represent matrix cracking and fiber-matrix debonding. The distribution of failed interface elements is analyzed and compared to PUCK's results for uniaxial stress states as well as for in-plane biaxial loading. The microscopic boundary value problem is solved with the *High-Fidelity Generalized Method of Cells* [4].

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Generating fiber-filled volume elements with high volume fraction and prescribed fourth order fiber orientation tensor

Matti Schneider

Department of Flow and Materials Simulation
Fraunhofer Institute for Industrial Mathematics ITWM, Kaiserslautern, Germany

Abstract. The digital material cycle for fiber reinforced plastics crucially depends on microstructures capturing the fiber volume fraction and the fiber orientation. Short fiber composites used in the industry generally feature a large volume fraction and high fiber aspect ratio.
In this talk I will introduce a fast and robust method to generate volume elements including straight cylindrical fibers of equal length. It is based on a reformulation of the microstructure generation problem for prescribed fourth order fiber orientation tensor in terms of an energy minimization problem, which is then solved numerically. In contrast to existing methods, high accuracy (five significant digits for the fiber orientation tensor), large fiber aspect ratios (up to 150) and large volume fractions (50 volume$-\%$ for isotropic orientation and aspect ratio of 30) can be reached. The talk closes with a small study on the effective linear elastic properties of the resulting microstructures, depending on fiber orientation, volume fraction as well as aspect ratio.

Conditions for phenomenological anisotropic damage models derived from micromechanics

Stephan Wulfinghoff, Marek Fassin, and Stefanie Reese

Institute of Applied Mechanics,
RWTH Aachen, Aachen, Germany

Abstract. The talk investigates the modeling of irreversible anisotropic brittle and ductile damage based on second and fourth order damage tensors and its connection to micromechanical material models. In particular, the conditions for strictly increasing damage are discussed. Restrictions on the form of the free energy function and the damage evolution law are proposed. These are motivated by energetical, scale-bridging considerations for growing cracks and pores. Moreover, conclusions are drawn related to the damage-induced evolution of the yield surface in plasticity.

Error-controlled homogenization for a class of linear elastic disordered materials

Xiaozhe Ju and Rolf Mahnken

Chair of Engineering Mechanics,
University of Paderborn, Paderborn, Germany

Abstract. The notion of model adaptivity has been well established, aiming at adaptive selection of mathematical models from a well defined class of models (model hierarchy) to achieve a preset level of accuracy (see e.g. [1,2]). The present contribution addresses its application to a class of linear elastic composite problems. We will show that the classical bounding theories according to [3,4] can provide a model hierarchy in a natural and theoretically consistent manner, without combination of different methods using a priori knowledge. As a further benefit, the resulting computational scheme reduces to a single-scale one. To arrive at computable higher order bounds, the classical singular approximation following [5] is made. As a new finding, this may, under certain circumstances, give rise to an overlap effect. To overcome this, a correction is proposed. Additionally, the model adaptivity is coupled to the well established adaptive finite element method (FEM), such that both macro model and macro discretization errors are controlled. The proposed adaptive procedure is driven by a goal-oriented a posteriori error estimator based on duality techniques. For efficient computation of the dual solution, a patch-based recovery technique is proposed, where a comparison with other existing methods is also given. For illustration, numerical examples are presented.

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Participants

Title, Name	Institution	E-Mail-Address
M.Sc. Róbert Bertóti	Institute of Engineering Mechanics Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	robert.bertoti@kit.edu
Prof. Dr.-Ing. Thomas Böhlke	Institute of Engineering Mechanics Karlsruhe Institute for Technology (KIT) Karlsruhe, Germany	thomas.boehlke@kit.edu
Robert Böhm	Student Assistant at the Institute of Engineering Mechanics Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	
Dipl.-Math. Christian Dammann	Chair of Engineering Mechanics University of Paderborn Paderborn, Germany	dammann@ltm.upb.de
Christian Dorn	Student Assistant at the Institute of Engineering Mechanics Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	
Dipl.-Math. Ulrich Ehlenbröker	Chair of Engineering Mechanics University of Paderborn Paderborn, Germany	ehlenbroeker@ltm.uni-paderborn.de
M.Sc. Felix Erler	Institute for Mechanics University of Kassel Kassel, Germany	mario.schmerbauch@uni-kassel.de

Title, Name	Institution	E-Mail-Address
Dr.-Ing. Dipl.-Math. techn. Felix Fritzen	Emmy-Noether-Group EMMA University of Stuttgart Stuttgart, Germany	felix.fritzen@mechbau.uni-stuttgart.de
Sebastian Gajek	Student Assistant at the Institute of Engineering Mechanics Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	
M.Sc. Felix Göküzüm	Institute of Applied Mechanics (Civil Engineering) University of Stuttgart, Stuttgart Stuttgart, Germany	goekuezuem@mechbau.uni-stuttgart.de
M.Sc. Johannes Görthofer	Institute of Engineering Mechanics Karlsruhe Institute for Technology (KIT) Karlsruhe, Germany	johannes.goerthofer@kit.edu
Dipl.-Ing. Niels Goldberg	Professorship of Solid Mechanics, Faculty of Mechanical Engineering TU Chemnitz Chemnitz, Germany	niels.goldberg@mb.tu-chemnitz.de
Dipl.-Ing. Martin Hohberg	Institute of Vehicle System Technolgy Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	martin.hohberg@kit.edu
M.Sc. Jonas Hund	Institute of Mechanics (IFM) Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	jonas.hund@kit.edu
M.Sc. Xiaozhe Ju	Chair of Engineering Mechanics University of Paderborn Paderborn, Germany	xiaozhe.ju@ltm.uni-paderborn.de

Title, Name	Institution	E-Mail-Address
Dr. Matthias Kabel	Department Flow and Material Simulation Fraunhofer ITWM Kaiserslautern, Germany	matthias.kabel@itwm.fraunhofer.de
Constantin Krauß	Student Assistant at the Institute of Engineering Mechanics Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	
Juliane Lang	Institute of Engineering Mechanics Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	juliane.lang@kit.edu
Dr.-Ing. Tom-Alexander Langhoff	Institute of Engineering Mechanics Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	tom-alexander.langhoff@kit.edu
Christian Liebold	DYNAmore GmbH Stuttgart, Germany	christian.liebold@dynamore.de
Prof. Dr.-Ing. Rolf Mahnken	Chair of Engineering Mechanics University of Paderborn Paderborn, Germany	mahnken@ltm.upb.de
Dipl.-Ing. Rudolf Neumann	Institute of Engineering Mechanics Karlsruhe Institute for Technology (KIT) Karlsruhe, Germany	rudolf.neumann@kit.edu
Dipl.-Math. Jan Niedermeyer	Faculty of Mathematics TU Kaiserslautern Kaiserslautern, Germany	niederme@mathematik.uni-kl.de

Title, Name	Institution	E-Mail-Address
Dott. Ing. M.Sc. Frederica Ongaro	School of Engineering and Materials Science (SEMS) Queen Mary University of London London, UK	f.ongaro@qmul.ac.uk
M.Sc. Pascal Pinter	Institute for Applied Materials Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	pascal.pinter@kit.edu
Sebastian Reimann	Student Assistant at the Institute of Engineering Mechanics Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	
M.Sc. Céline Röhrig	Chair of Applied Mechanics Saarland University Saarbrücken, Germany	celine.roehrig@uni-saarland.de
M.Sc. Malte Schemmann	Institute of Engineering Mechanics Karlsruhe Institute for Technology (KIT) Karlsruhe, Germany	malte.schemmann@kit.edu
Dipl.-Ing. Mario Schmerbauch	Institute of Mechanics University of Kassel Kassel, Germany	mario.schmerbauch@uni-kassel.de
Dr. Matti Schneider	Fraunhofer ITWM Kaiserslautern, Germany	matti.schneider@itwm.fraunhofer.de
Prof. Dr.-Ing. Prof. h.c. Jens Schuster	Kaiserlautern University Pirmasens, Germany	jens.schuster@hs-kl.de

Title, Name	Institution	E-Mail-Address
M.Sc. Felix K. Schwab	Institute of Applied Materials Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	felix.schwab@kit.edu
M.Sc. Anna Trauth	Institute of Applied Materials Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	anna.trauth@kit.edu
Daniel Wicht	Institute of Engineering Mechanics Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	daniel.wicht@kit.edu
Dr.-Ing. Stephan Wulfinghoff	Institute of Applied Mechanics RWTH Aachen University Aachen, Germany	stephan.wulfinghoff@ifam.rwth-aachen.de
Tunc Yuzbasioglu	Student Assistant at the Institute of Engineering Mechanics Karlsruhe Institute of Technology (KIT) Karlsruhe, Germany	