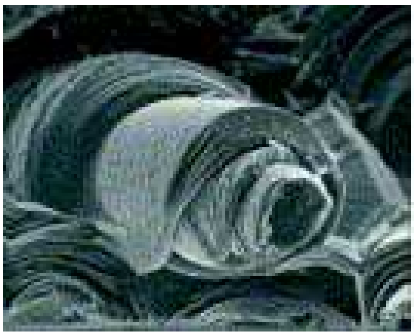
Karlsruhe Institute of Technology
Institute of Engineering Mechanics

University of Paderborn
Chair of Engineering Mechanics

23rd International Workshop

Research in Mechanics of Composites



Bad Herrenalb, Germany
29th Nov. - 1st Dec. 2010

Objective of the Workshop

Modern and classic composites display a macroscopic material behavior depending on their nanostructure, microstructure, and mesostructure in a complex way. The mechanisms and size scales relevant for the macroscopic material behavior depend, among others, on the mechanical or physical sizes considered and on the thermomechanical process conduct. Understanding the correlation of both the microstructure and micromechanical behavior and the macroscopic material behavior of components is of fundamental interest for a number of composite utilization problems such as the selection and the design of materials as well as the dimensioning and optimization of construction parts.

In this workshop, new approaches for the material modeling of composites are introduced and discussed with respect to the multiscale properties of the material type. This workshop serves young researchers and well-established scientists to discuss their research experiences and allows for interdisciplinary discussions covering the fields of applied mathematics, mechanics and materials science.

Prof. Dr.-Ing. habil. Thomas Böhlke — Prof. Dr.-Ing. habil. Rolf Mahnken

Prof. Igor Tsukrov — Dr.-Ing. Dipl.-Math. Romana Piat

Program for Monday, 29th November 2010

Time	
from 18:00	Registration and Welcome

Program for Tuesday, 30th November 2010

Time	Authors	Title
		Characterization
08:30 - 09:00	D. Leguillon	Detection of a debonding between two substrates from a full field measurement
09:00 - 09:30	S. Dietrich, K. A. Weidenmann	Characterisation of carbon-carbon composites using micro-computed tomography (μ-CT) and 3D Image Analysis
09:30 - 10:00	H. Altendorf, O. Wirjadi	3D-Characterization of fibre-reinforced composites
10:00 - 10:30	Coffee break	
10:30 - 11:00	B. Reznik	Spatial organization of pyrolytic carbon
11:00 - 11:25	T. S. Gross, N. Timoshchuk, I. Tsukrov, B. Reznik, R. Piat, T. Böhlke and O. Deutschmann	Proposed mechanisms of localized damage in pyrolitic carbon caused by nanoindentation
11:25 - 12:05	J.-M. Gebert, A. Wanner	Elastic constants of high-texture pyrolytic carbon and CVI-infiltrated carbon/carbon composites measured by Ultrasound Phase Spectroscopy
12:05 - 12:30	T. S. Gross, N. Timoshchuk, I. Tsukrov, B. Reznik, R. Piat, T. Böhlke, and O. Deutschmann	On the ability of sharp indentation to capture anisotropy of pyrolytic carbon materials
12:30 - 13:30	Lunch	
		Modeling
13:30 - 14:15	I. Tsukrov, B. Drach, T. S. Gross, R. Piat, T. Böhlke	Effective stiffness and thermal expansion coefficients of CVI-infiltrated unidirectional carbon fibers
14:15 - 14:45	T.-A. Langhoff, T. Böhlke, K. Jöchen, S. Lin, R. Piat, I. Tsukrov, T. S. Gross, B. Reznik, O. Deutschmann	On thermoelastic bounds for pyrolytic carbon based on image processing
14:45 - 15:15	G. Stasiuk, R. Piat, T. Böhlke, B. Drach, I. Tsukrov	Micromechanical modeling of CFCs for arbitrary fibers distributions
15:15 - 15:45	F. Hankeln, R. Mahnken	Simulation of deep-drawing for carbon-fibre-prepregs
15:45 - 16:15	Coffee break	
16:15 - 16:45	F. Fritzen, C. Engelhardt, T. Böhlke	Influence of the fiber clustering on the apparent and effective elastic properties of short fiber reinforced composites
16:45 - 17:15	S. Sanwald	Evolution of the fibre orientation in discontinuously reinforced thermoplastic melting
17:15 - 17:45	J. Stránsk, J. Vorel, J. Zeman, M. Šejnoha	Mori-Tanaka based estimates for effective conductivity of various engineering materials
17:45 - 18:15	K.-U. Widany, R. Mahnken	Error indicator for parameter identification of constitutive laws with adaptive FEM for polymers
19:30	Conference Dinner	

Program for Wednesday, 1st December 2010

Time	Authors	Title
		Fracture and Fatigue
09:00 - 09:30	O. Voloshko, F. Labesse-Jied, Y. Lapusta, V. Loboda	Analysis of pre-fracture zone for a crack in an adhesive layer between two isotropic materials
09:30 - 10:00	B. Brylka, F. Fritzen, T. Böhlke, K. Weidenmann	Influence of microstructure on fibre delamination test
10:00 - 10:30	J. Kreikemeier, U. Gabbert	A two scale finite element approach for the fracture and damage analysis of composite materials
10:30 - 11:00	Coffee break	
		Multiscale Methods
11:00 - 11:30	G. Rousset, E. Martin	A multi-scale approach for fatigue life prediction of unidirectional SiC/Ti composites
11:30 - 12:00	G. Couégnat, E. Martin	Multiscale modelling of the mechanical behaviour of woven ceramic-matrix composites
12:00 - 12:30	K.-H. Sauerland, R. Mahnken	A multiscale model for coated forming tools under thermal shock loading
12:30 - 13:00	C. Chambon, S. Diebels	Mechanical modelling of hybrid sandwich composite with homogenisation methods
13:00 - 13:30	Final discussion	
13:30	Lunch	

3D-Characterization of Fibre-Reinforced Composites

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Abstract. Composite materials are used in an increasing number of automotive and aerospace applications. One important material class are fibre-reinforced polymers. Application examples include carbon or glass fibre-reinforced polymers to reduce the weight of fuselages in modern aircraft. Using tomographic imaging, the complete 3D-microstructure of these functional materials can be captured. Their fibre system, which accounts for much of these materials' strength, can be characterized in terms of fibre densities, fibre direction distributions and fibre diameter. To this end, we can apply either methods from integral geometry to characterize the entire fibre system [1], algorithms based on linear filters to extract information about local fibre directions [2,3] or mathematical morphology to analyse fibre orientations and thickness [4]. In this talk several approaches for calculating fibre orientations based on 3D image data are introduced, compared and discussed.

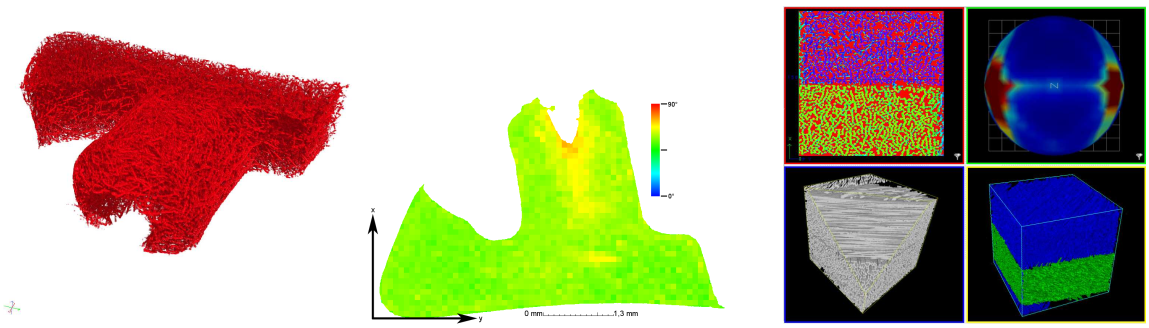

Fig. 1. Local analysis of a glass (left) and carbon (right) fibre-reinforced polymer.

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Influence of microstructure on fibre delamination test

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Abstract. The experimental determination of interface properties of fibrous composite materials by fibre push- or pull-out tests is a challenging task. It requires adequate preparation of specimens on very small length scales (typically 50 μm and smaller) and with additional constraints, e. g. on the orientation of the fibres relative to the cutting plane.

Thus, in practice the number of experiments is limited. Consequently, the efficiency and the robustness of the experiment highly contribute to the success of the investigations of material properties.

Based on a finite element modeling, we investigate different experimental settings for glass fibre reinforced polypropylene with respect to their robustness (in terms of measuring possibilities and uncertainties) and their versatility for the identification of interface properties. The uncertainty of the material properties is accounted for by consideration of statistically distributed material properties. The presented methodology can be transferred to other materials, e. g. fibre reinforced metal ceramic composites.

References

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Mechanical Modelling of Hybrid Sandwich Composite with Homogenisation Methods

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Abstract. Hybrid Composites are widely used in the field of transport industry and especially for aerospace applications because of their high stiffness at relatively limited weight. Since this class of materials presents a high complexity, a numerical modelling is of interest.
The modelling of hybrid sandwich composites can be based on three different strategies: a classical 3D (FEM) volumetric modelling, the classical plate (or shell) theory or a numerical homogenisation for plates [1,2]. In the frame of this work, we are interested in the last solution. Its principle is to model on the macroscopic scale a 2D plate (or shell) by finite elements and to project the deformations from each integration point to a 3-dimensional Representative Volume Element (RVE) resolving the microstructure of the laminate. The local boundary value problem will be solved for the RVE and the stress resultants will be projected back on the macroscale with help of a modified Hill-Mandel condition. Further considerations will be taken into account for the multi-scale modelling for plates, especially concerning plate kinematics [3].
A further part will include the presentation of some results of such modelling and will include a discussion of them. Further improvements of the presented model can be made, like for example take the fluctuations into account, or include non-linear material behaviour, e. g. plasticity, in the model. The influence of the interfaces between the individual layers will be handled in a forthcoming work.

References

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Multiscale modelling of the mechanical behaviour of woven ceramic-matrix composites

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Abstract. This paper presents a multiscale approach for the mechanical modelling of woven ceramic-matrix composites (CMC). The DMD (Discrete Micro Damage) model developed in this work is based on (i) a realistic description of the microstructure of the material, and (ii) a discrete representation of the damage mechanisms.

Dedicated numerical tools have been developed for the generation and the meshing of representative unit cells at both micro and meso scale [1]. The effect of the damage development on the macroscopic properties of the material is evaluated numerically: a finite number of damage states is introduced into representative unit cells, and the effective properties are eventually computed using a finite-element based homogenization scheme. These results are used to identify a damage model which is formulated in the framework of continuum damage mechanics. The DMD model has been applied to a woven C/SiC composite. Its predictive capabilities have been evidenced on generic structural tests and compared to a reference phenomenological macrosopic model.

References

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Characterisation of Carbon-Carbon Composites using Micro-Computed Tomography ($\mu - CT$) and 3D Image Analysis

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Abstract. The structural properties and configuration of C/C composites have a strong influence on their mechanical and thermal behaviour. Therefore it is necessary to gain insight into the distribution of size, orientation and further characteristic descriptors of the microstructure. For most composites absorbtion- or phase-contrast tomography provides excellent access to the inner material structure. The combination of modern 3D imaging and image processing techniques allows for a comprehensive evaluation of the materials characteristics. We present a framework of image processing and analysis steps which can be applied to a broad range of composite materials like fibrous preforms or infiltrated porous bulk materials. The algorithms are entirely based on the open source libraries ITK and VTK [1, 2] and the framework comprises noise and artifact reduction in image raw data, different automatic binarization procedures as well as orientation and shape analysis of image objects. The results extracted in form of distribution functions or representative principal shape types provide a substantial foundation for homogenization procedures or finite-element simulations.

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[2] W. Schroeder, K. Martin, B. Lorensen: *The VTK Toolkit* Kitware Inc., (2004).

Influence of the fiber clustering on the apparent and effective elastic properties of short fiber reinforced composites

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Abstract. The apparent and effective elastic properties of short fiber reinforced composites are investigated. The focus is on the determination of the influence of fiber clustering on the response of the heterogeneous material. Similar approaches have been pursued by [1] for circular or spherical particles.

Periodic artificial microstructures are generated and the a high quality discretization based on Netgen [2] is created for the use with the finite element model. A Monte Carlo type study based on the finite element method is carried out to provide estimates of the influence of microstructural changes onto the elastic parameters.

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Elastic Constants of High-Texture Pyrolytic Carbon and CVI-infiltrated Carbon/Carbon Composites Measured by Ultrasound Phase Spectroscopy

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Abstract. The elastic constants of a high-texture pyrolytic carbon (PyC) as well as of different porous carbon/carbon composites are determined experimentally via ultrasound phase spectroscopy (more details on the experimental method can be found in [1, 2]). All independent elastic constants for the high-texture PyC could be determined and show transverse isotropy ($C_{11} = 40$, $C_{12} = 20$, $C_{13} = 13.1$, $C_{33} = 18.2$ and $C_{44} = 1.8$ GPa, $\rho = 2.178$ g/cm^3 [3]).

Two different substrates of C/C composites were studied: A C/C-felt with a fiber content of 7.1% and a 2D-C/C-laminate with a fiber content of 22.5%. The CVI infiltration parameters were chosen to yield a high-texture pyrolytic carbon [4, 5] and the porosity varied in the range of 10% to 90% depending in the infiltration time. For the felt, all five elastic constants could be determined for specimens of higher densities (about 1 g/cm^3). The 2D-C/C-laminate shows a wave-length dependency in certain directions, that results from an inhomogeneous wave propagation within the composite.

References

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Proposed Mechanisms of Localized Damage in Pyrolitic Carbon Caused by Nanoindentation

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Abstract. We used a cube corner nanoindenter to estimate the anisotropic elastic constants of a sample of pyrolytic carbon where the anisotropic elastic constants were previously characterized using ultrasound and strain gage methods. Significant discontinuities were observed when indentations were performed normal to the growth plane yet none were observed when indentations were performed normal to the growth direction. Nanoindentations in carbon typically do not leave a residual indentation as the loading unloading curve is usually fully elastic. However, raised features were observed at the indents that exhibited discontinuities by scanning probe and scanning electron microscopy. The discontinuities are typically associated with the growth of cracks from the corners of the indents but none were observed. The origin of the observed features is discussed in the body of the paper.

On the Ability of Sharp Indentation to Capture Anisotropy of Pyrolytic Carbon Materials

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Abstract. We used a Vickers microindenter and three different nanoindenter types to estimate the anisotropic elastic constants of a sample of pyrolytic carbon where the anisotropic elastic constants were previously characterized using ultrasound and strain gage methods. Indentations were performed normal to the growth plane and normal to the growth direction to determine if either indentation method could capture the anisotropic elastic response. An axisymmetric finite element model of an indenter penetrating a sample with transverse isotropic behavior was also created to estimate the expected response. The model predicted that the elastic response for a given indenter should depend weakly on the transverse elastic properties and, in principle; an indentation test should be able to independently detect the elastic modulus in a given direction. However, the elastic constants estimated from the microindentation response and the response for the Berkovich and conical indenters was the approximately same for both orientations and both were substantially different from the macroscopic response. The elastic constant estimated from the cube corner indenter response was approximately half the value obtained by the other indenters when measured normal to the growth direction and was much lower than that predicted by ultrasound and strain gage measurements. The elastic constants normal to the growth plane were between the strain gage and ultrasound predictions.

Simulation of Deep-Drawing for Carbon-Fibre-Prepregs

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Abstract. In automotive industry research is done to replace high strength steel by combinations of steel and carbon-fibre prepregs (pre-impregnated fibres). It is planned to form both steel and uncured prepregs in one step followed by the curing process under pressure in the forming die. The ability to simulate the mechanical behaviour during forming and curing would allow more economical processes.

The simulation of prepregs must regard highly anisotropic, viscoelastic and thermal-chemical properties. For this the model is split into an anisotropic elastic part, which represents the fibre fraction and an isotropic, viscoelastic part, representing the matrix. This part also contains curing, causing a dependency on time and temperature. This is done for small deformations. The results are compared to experimental data.

During deep-drawing large deformations are occurring, so an approach is in progress. This model contains an anisotropic elastic part based on a neo-Hooke law enhanced by an anisotropic part. A viscoelastic part is added, with parameters dependent on temperature. These two laws are added building a combined model for CFK-prepregs.

A two scale finite element approach for the fracture and damage analysis of composite materials

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Abstract. The presentation deals with a two scale finite element model which was developed to describe and analyze the anisotropic damage state of fibre reinforced composite materials. The thermodynamical consistent formulation is based on the standard continuum mechanics framework of finite deformations. The damage onset is measured by means of the maximum principal stress criterion of the true CAUCHY stress tensor. The corresponding eigendirection is used as the crack propagation direction. The coupling of the macro scale and the micro scale is carried out by means of the UMAT utility of the commercial finite element system ABAQUS.
The properties of the viscous regularization, which is necessary to ensure the well posedness of the underlying boundary value problem will be highlighted before further examples show the applicability of the two scale approach.

References

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On thermoelastic bounds for pyrolytic carbon based on image processing

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Abstract. Pyrolytic carbon (PyC) can be used as matrix material for carbon-carbon (C/C) composites which exhibit an attractive combination of high fracture toughness and high-strength to weight ratio. This unique combination leads to their major application as aircraft brake linings in a variety of extreme aerospace refractory materials. C/C composite materials with PyC matrix are of particular interest and can be produced by chemical vapour infiltration of carbon fibers preforms.

The thermoelastic properties of heterogeneous materials depend on both the constitutive properties of the constituents and the microstructural characteristics [1]. In the present paper, the thermoelastic and the heat conduction properties are homogenized from the submicron to the micro scale [2]. The submicrostructure of PyC can be described as a large set of approximately coherent domains having different orientations. The domains themselves are assumed to exhibit a hexagonal material symmetry. The key result of the presentation is that the statistical information necessary for the evaluation of the first and second order thermoelastic bounds [3, 4] is obtained based on new image processing techniques applied to TEM images.

References

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Detection of a debonding between two substrates from a full field measurement

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Abstract. To detect the onset of a delamination crack at the interface between two plies in a laminated composite or more generally the emergence of a debonding between two substrates is an important goal in experimental fracture mechanics. It can be achieved using a full kinematic field measurement. This technique is currently employed for the identification of constitutive laws of materials. Recent developments also allow determining the stress intensity factors at the tip of a crack. It is extended here to the determination of the length of a short new crack at the root of a v-notch, in the generic case, and at an interface in the particular case of a multi-material. The method proposed here falls into the category of direct methods as opposed to inverse approaches. It is based on a matched asymptotic expansions procedure, where the short crack length plays the role of a small perturbation, together with the theory of singularities. The first corrective term of the outer expansion can be straightforwardly expressed as a function of the crack length. Its extraction is achieved through the calculation of the associated generalized stress intensity factors for elastic homogeneous materials as well as bimaterials. Numerical simulations are carried out on a finite element solution disturbed by a random noise. In addition, the method used to compute the generalized stress intensity factors associated with the singularity proved accurate and robust.

Spatial organization of pyrolytic carbon

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Abstract. Recent developments on the relationship between different structural levels of pyrolytic carbon coatings are reviewed [1-6]. Pyrolytic carbon coatings deposited on carbon fibers and non-carbon substrates are studied comparatively by light microscopy, scanning electron microscopy and transmission electron microscopy combined with selected-area electron diffraction [2, 3]. Optically uniform coatings exhibit pronounced gradual changes in texture degree of graphitic crystallites at the sub-micrometer-scale if investigated by electron diffraction [4, 5]. The thickness of the reaction layer at the pyrolytic carbon/carbon fiber interface depends on the carbon fiber crystallization degree [6].

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A multi-scale approach for fatigue life prediction of unidirectional SiC/Ti composites

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Abstract. Titanium alloys reinforced by silicon carbide monofilaments exhibit high specific stiffness and strength. Those materials are attractive for use in aircraft engine components such as compressor discs [1]. A detailed understanding of their fatigue behaviour under high stress loading is necessary for the industrial developments.

This paper presents a modelling approach for life prediction of a unidirectional SiC/Ti composite in the high cycle fatigue regime. The predominant degradation mechanisms which are taking into account include i) the progressive fibre overloading due to matrix cyclic plasticity, ii) the fibre fractures which induce stress concentration in the neighbouring fibres, iii) the progressive interfacial degradation which results from the cyclic loading near a fibre break.

Micromechanical modelling [2] is used to analyse those mechanisms and to describe statistically the accumulation of filament damage which causes final fracture of the composite. Finally it is shown how this approach can be utilized to analyse a compressor ring reinforced by a titanium matrix composite.

References

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Evolution of the fibre orientation in discontinuously reinforced thermoplastic melting

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Abstract. To take advantage of the whole capability of fibre reinforced plastics suitable physical models have to be developed. Most industrial processes demand in advance a precise knowledge of the material to design the production equipment and the subsequent properties of the desired structural components. One subset of fibre reinforced plastics is the group of discontinuously fibre reinforced thermoplastics. In this study we focus on the impact of the fabrication process of glass fibre reinforced thermoplastics on the component properties. Because the evolution of the composite melting imposes huge effects on the local fabrication and component-specific material properties. For the construction of the mould and design of the structural part basically the rearrangement of the fibre-framework due to the own properties during the manufacturing process plays an important role. Because of the prevailing dependency of the local material properties on the fibre-orientation the numerical solution of the necessary conservation equations will be discussed. The numerical results of the implemented fibre orientation model of a basic component will be compared to the data from computer tomographic scans.

A multiscale model for coated forming tools under thermal shock loading

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Abstract. Hybrid-forming processes are processes in which workpieces are specific heated up before forming with the goal of the reduction of forming forces. They are innovative methods for the production of components with graded properties, particularly with regard of tailored material properties and geometrical shape of the semi-finished or finished products [1]. In these forming processes the forming tools are subjected to cyclic thermal shock loading conditions which can result into damage and failure. For improvement of the tool service life in the hybrid-forming process under consideration coated forming tools with multilayered coating systems will be applied in future.

This contribution shows the actual state of work for the development of a multiscale model for the finite element simulation of the multilayered coated forming tool. Within this multiscale model the three-dimensional model of the forming tool builds the macromodel. On the macrolevel the multilayered coating is discretized with one shell element over the coating thickness. The mesomodel of the coating considers the actual layer design with several metallic and ceramic layers. The macro-meso transition is realized with a Taylor-assumption. So far, the microscale is not considered within the multiscale model, which leads to the assumption that each layer is regarded as homogeneous continuum. Within this strategy the constitutive equations are formulated on the mesoscale and the meso-macro transition is done using volume averaging for stresses and the stiffness matrix similar to [2,3]. Furthermore, a damage model will be included for particular layers or interfaces with the goal of the simulation of delamination. The scalar damage variable will be used in a thermo-mechanical coupled model for simulation of a reduced heat transfer through a partially damaged surface.

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Micromechanical Modeling of CFCs for Arbitrary Fibers Distributions

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Abstract. Mechanical behavior of fiber reinforced and porous materials are strongly dependent on the volume fraction, distribution and shapes of fibers and pores. In this work, the three-dimensional structural information obtained by micro computed tomography [1] is used for evaluation of material parameters for carbon/carbon composites.

The effective elastic material properties of the composite were determined by homogenization procedures combined with numerical methods. For the calculation of the compliance contribution tensors of the pores, the methodology proposed in [2] was used.

Verification of the obtained results was provided by comparison with experimental data [1].

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Mori-Tanaka based estimates for effective conductivity of various engineering materials

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Abstract. The purpose of this paper is to present a simple micromechanics-based model to estimate the effective thermal conductivities of real-world composites of matrix-inclusion type, which can be regarded as macroscopically isotropic materials. The methodology is based on the well-established Mori-Tanaka method for composite media reinforced with ellipsoidal inclusions [1], extended to account for the Kapitza resistance at the matrix-inclusion interface [2], random orientation of particles and particle size distribution [3]. Using a simple orientation averaging argument, we show that the original Mori-Tanaka relations are still applicable for these complex systems, provided that the matrix conductivity is appropriately modified. Such conclusion is supported by the verification of the model against a detailed finite-element study as well as its validation against experimental data for a wide range of engineering material systems.

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Effective Stiffness and Thermal Expansion Coefficients of CVI - Infiltrated Unidirectional Carbon Fibers

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Abstract. Effective elastic properties and thermal expansion coefficients of unidirectional carbon/carbon composites fabricated by chemical vapour infiltration are predicted taking into account the cylindrical orthotropy of pyrolytic carbon layers around fibers. The methodology is based on the elastic solutions for composite cylinders provided in [1, 2]. The submicron properties of the pyrolytic carbon available from analytical modelling and experimental observations [3, 4] are utilized as an input data. The modelling procedure is illustrated by considering several typical microstructures.

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Analysis of Pre-fracture Zone for a Crack in an Adhesive Layer between Two Isotropic Materials

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Abstract. A plane problem for a crack in a thin adhesive elastic-perfectly plastic layer between two identical isotropic elastic semi-infinite spaces is considered. It is assumed that uniformly distributed normal stress is applied to the substrates at infinity. First, the problem is solved numerically by the finite element method. The distribution of the normal stress at the crack continuation, the crack opening displacement and the values of the J-integral are found. Further, an analytical analysis of the formulated problem is carried out. As a rule, the interlayer is usually weaker than the connected bulk substrate materials. Therefore, we can assume that pre-fracture zones arise in the adhesive interlayer ahead of the crack tip. Using the concept of the model [1, 2], the pre-fracture zones are modeled by the crack continuations with normal stresses prescribed at their faces. In a general case, the distribution of the normal stresses is unknown. In this work, the stress distribution is defined numerically at the first phase of analysis. Further, the numerically obtained distribution of the normal stress is approximated by a piecewise constant function.The interlayer thickness is assumed to be neglected because it is much less than the crack length. In this way, we arrive at the problem of linear fracture mechanics. According to [3], the stresses and derivatives of the displacement jumps at the interface between two isotropic materials were presented via piecewise analytic functions. Satisfying the boundary condition, we obtain the problem of linear relationship, which is solved exactly with use of [4]. The equation for determination of the pre-fracture zone length, expressions for the crack opening displacement and the J-integral are obtained in an analytical form. Finally, a universal approximating function which describes the behavior of the normal stress at the crack continuation is constructed. This function depends on the ratio between the external loading and the yield limit of the interlayer, on the ratio between the Young's modulus of the substrate and interlayer and on the ratio between the interlayer thickness and the crack length. The values of the pre-fracture zone lengths, the crack opening displacement and the J-integral, which were calculated for numerically obtained stress distribution and for the distribution assigned by approximating function, are analyzed and compared between each other.

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Error Indicator for Parameter Identification of Constitutive Laws with Adaptive FEM for Polymers

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Abstract. The identification of parameters in constitutive laws for polymers considering inhomogeneous states of stress and strain is realized by iteratively minimizing a least squares functional. The experimental data which contributes to the least squares functional is typically obtained by optical measurement. In each iterative step of this optimization problem a finite element analysis is carried out which results in a significant higher numerical cost than a single finite element analysis. Consequently, an efficient discretization is required to keep the numerical cost low.

To address the problem of efficient discretization an adaptive mesh refinement is considered which is based on a posteriori error indicators [1]. The error indicators are goal-oriented, e.g. the error in the parameters, leading to refinements appropriate to the parameter identification problem. In this contribution we apply the error indicators to the finite element method for tetrahedral elements of low order which are preferable for adaptive mesh refinements and in addition reduce computational effort. Additional stabilization terms in the element formulation [2] reduce volume locking effects making the elements suitable for (nearly) incompressible material behavior.

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