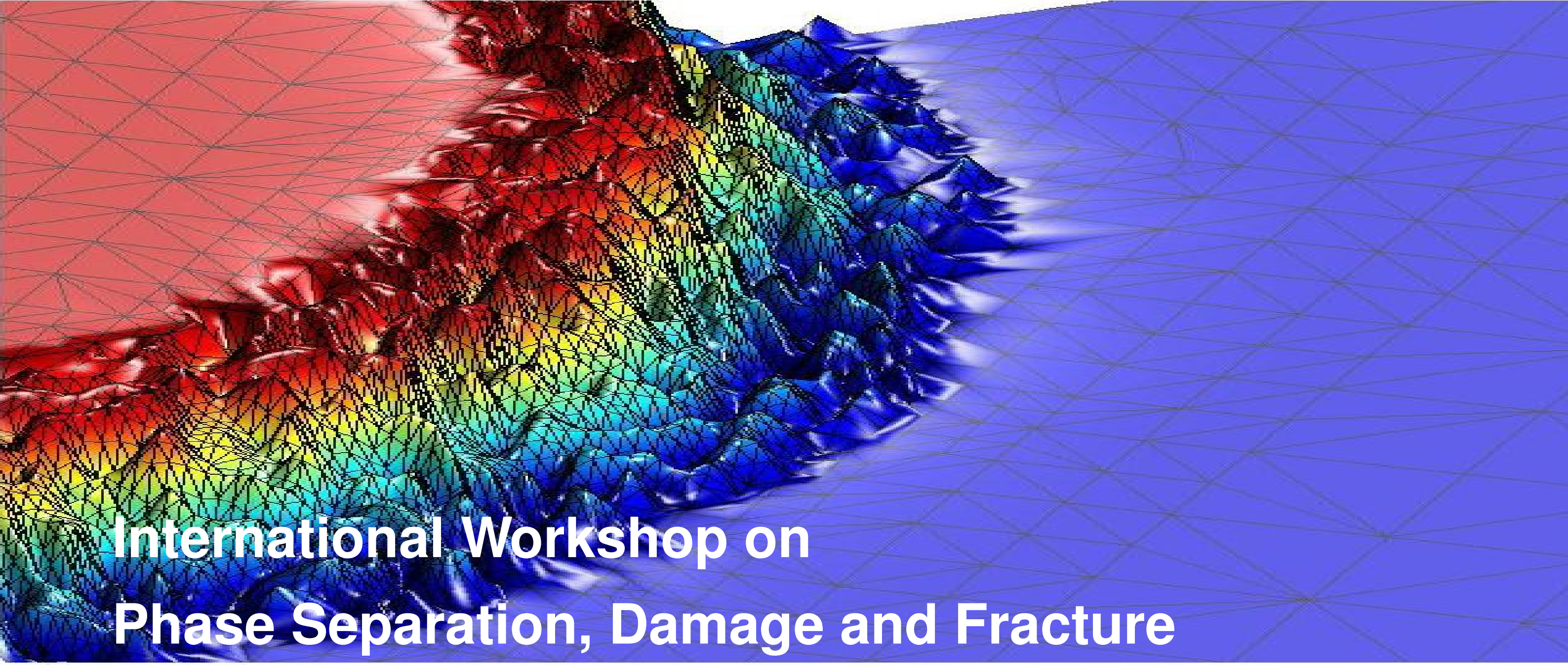

International Workshop on Phase Separation, Damage and Fracture

Weierstrass Institute for Applied Analysis and Stochastics
September 21 – 23, 2011

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International Workshop on

Modeling and Analysis of Phase Separation, Damage and Fracture

WIAS, September 21–23, 2011
Berlin, Germany

Organizers

Dorothee Knees, Christiane Kraus

Local Organizing Committee

Jens André Griepentrog, Hauke Hanke, Christian Heinemann, Ina Hohn, Rüdiger Müller

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Weierstrass Institute for Applied Analysis and Stochastics (WIAS)

Scope

Phase separation processes, damage phenomena and crack propagation occur in many materials and devices of every day life. They can lead to a reduced functionality up to the failure of the complete structure. The knowledge and modeling of the mechanisms inducing phase separation, damage and fracture is of great importance for technological applications. In this way, predictions can be made on the lifetime of the structure and material properties can be optimized.

Damage phenomena are caused by different physical processes (e.g. mechanical loading, change of temperature, chemical processes, phase separation) and take place on different time and length scales. Phenomenological damage models are often formulated by means of phase field models which are coupled with other physical processes. There are various challenges concerning the modeling, the analysis and the numerical simulation of such coupled systems.

The workshop aims to bring together researchers from mathematics and material science in order to discuss and compare different techniques and to develop new approaches in the above field. The following topics will be addressed:

- Modeling and analysis of phase separation and damage processes
- Modeling of microstructure evolution, coupling with further physical processes
- Sharp interface and crack propagation models
- Numerical issues in this field

Wednesday, September 21, 2011, 08:00 - 17:00

08:00 - 09:00	REGISTRATION
09:00 - 09:15	OPENING
09:15	Cyclic fatigue in an oscillating elastoplastic body **Pavel Krejčí**
10:00	Rate-independent approach to non-associated decohesion models **Martin Kružík**
10:30 - 11:00	COFFEE BREAK
11:00	Models of adhesive contacts delaminating at mixed modes **Tomáš Roubíček**
11:30	Delamination in viscoelastic materials with thermal effects **Marita Thomas**
12:00	Non-local damage models at high strain rates **Dietmar Klingbeil**
12:30 - 14:00	LUNCH BREAK
14:00	A dynamical system approach to high cycle fatigue life-predictions **Stefano Bosia**
14:30	Energy release rate caused by crack propagation in a composite material -Part I- **Maria Specovius-Neugebauer**
15:00	Energy release rate caused by crack propagation in a composite material -Part II- **Martin Steigemann**
15:30 - 16:00	COFFEE BREAK
16:00	Crack Propagation in Mode I-II by an approximated PLS **Matteo Negri**
16:30	Some remarks on the second derivative of the elastic energy with respect to crack length **Rodica Toader**

Program

Thursday, September 22, 2011, 09:00 - 21:00

09:00	On dynamic Griffith fracture **Christopher J. Larsen**
09:45	A toy model for dynamic debonding **Giuliano Lazzaroni**
10:15 - 10:45	COFFEE BREAK
10:45	The hybrid model as a phase field model for crack propagation **Hans-Dieter Alber**
11:15	A vanishing viscosity approach to a rate-independent damage model **Chiara Zanini**
11:45	A variational principle for gradient flows in metric spaces **Antonio Segatti**
12:15 - 13:45	LUNCH BREAK
13:45	A thermomechanic mesoscopic model of SMA as a limit of microscopic models **Barbora Benešová**
14:15	Young-measure quasi-static damage evolution **Alice Fiaschi**
14:45	Fading memory effects induced by upscaling viscoelastic and porous media **Eduard Rohan**
15:15	Derivation of an effective damage model based on micro-structure evolution **Hauke Hanke**
15:35 - 16:00	COFFEE BREAK
16:00	Analysis of a model for adhesive contact with friction **Riccarda Rossi**
16:30	Analysis of a complete model for damage in solids **Elena Bonetti**
17:00	To the identification of planar cracks in linear piezoelectric material **Peter Steinhorst**
19:00 - 21:00	DINNER

Friday, September 23, 2011, 09:00 - 13:00

09:00	Thermophoresis and diffusion induced decomposition in blends and alloys **Kerstin Weinberg**
09:45	Solvability of a model of phase separation with nonlinear mechanics **Donat Wegner**
10:15 - 10:45	COFFEE BREAK
10:45	Existence results for Cahn-Hilliard equations coupled with elasticity and damage **Christian Heinemann**
11:15	Numerical Simulation of Coarsening in Binary Alloys **Uli Sack**
11:45	Finite Element Simulation of Damage and Phase Separation **Rüdiger Müller**
12:15	A derivation of a Griffith-type energy functional **Anja Schlömerkemper**
12:45 - 13:00	CLOSING

The hybrid model as a phase field model for crack propagation

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Recently we have proposed a phase field model for the propagation of phase interfaces in elastic solids, which differs from the Allen-Cahn model by a term containing the absolute value of the gradient of the order parameter. We call this model the hybrid model, since the evolution equation for the order parameter has properties both of a parabolic and a hyperbolic equation. An advantage of this model is that the constitutive relations in the evolution equation for the order parameter and in the limit sharp interface model coincide, even if this constitutive relation is nonlinear. Because of this property a modification of this model can be used to simulate crack propagation. With the "damage variable" $\varphi(t,x)$, which varies between 0 and 1, the resulting model equations are

$$\begin{aligned} -\operatorname{div}_x T &= \mathsf{b}, \\ T &= \big(\varphi D + (1-\varphi)\kappa\big)\varepsilon(\nabla_x u), \\ \partial_t \varphi &= -f\big(\psi_S(\varepsilon(\nabla_x u),\varphi) - \nu \Delta_x \varphi\big)\nabla_x \varphi. \end{aligned}$$

Here κ, a and c are positive constants and the nonlinear function $f : \mathbb{R} \to \mathbb{R}$ is defined by

$$f(s) = \begin{cases} 0, & s < a, \\ c(s-a), & s \geq a. \end{cases}$$

This model will be discussed in the talk.

References

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[2] — *Evolution of phase boundaries by configurational forces.* Arch. Rational Mech. Anal. **185**(2), 2007, pp. 235 –286, DOI 10.1007/s00205-007-0054-8.

[3] — *Comparison of a rapidely converging phase field model for interfaces in solids with the Allen-Cahn model.* Submitted, (Preprint Nr. 2631, Fachbereich Mathematik, TU Darmstadt, June 2011)

A thermomechanic mesoscopic model of SMA as a limit of microscopic models

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In this talk we present a thermomechanic mesoscopic model of SMA featuring the heat equation and thermo-mechanic coupling where the microstructure is represented by means of Young measures whereas the phases are characterized by a phase-field variable. We further rigorously prove that this model can be obtained by a limiting procedure from microscopic models that are again thermo-mechanically coupled and take (a vanishing) interfacial energy into account.

Analysis of a complete model for damage in solids

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A model for damage in solids is discussed in terms of a phase-field system. Indeed, the degeneracy of the rigidity of the material is related to a damage parameter playing the role of a phase variable. In particular, some internal constraint (given by a non-smooth multivalued operator) ensures the physical consistency of this damage quantity. In particular, the material is assumed to react differently in damage/non-damage regimes. More precisely, the stress tensor is given by two contributions associated to the damaged and non-damaged states, vanishing, respectively, when the material is completely damaged or not damaged. Note that the resulting power of internal forces represents a (nonlinear) source for the damage evolution. We are able to prove global existence for a weak solution of the resulting PDE system. This work is in collaboration with Christiane Kraus (WIAS-Berlin) and Antonio Segatti (University of Pavia).

A dynamical system approach to high cycle fatigue life-predictions

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In this talk we will propose a model for predicting the lifetime of a continuum in high-cycle fatigue (HCF). The model we will consider is grounded on a multiscale approach and on an analysis based on nonlinear dynamics. Based on the Dang Van HCF theory (see [1]), we consider that at the macroscopic scale the material is in elastic shakedown while at the mesoscopic scale it presents an elastic shakedown, a plastic shakedown or ratcheting. In the finite lifetime domain we will encounter a plastic shakedown at the mesolevel. As in the model proposed by Morel [2], we consider at the small scale a law for isotropic hardening governed by the mesoscopic accumulated plastic strain and involving an initial hardening followed by a softening phase ending in the failure of the material. The very long quasi-periodic behaviour exhibited by samples in HCF is mathematically mirrowed by the presence of a ghost saddle-node bifurcation in the dynamical behaviour of the system (e.g. see [3]). Using tools from the theory of dynamical systems, an analytical effective a-priori estimate for the time-to-failure is derived. The efficiency of the model will finally be illustrated with numerical simulations as well as with other benchmark methods to estimate fatigue-life.

Refences

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[2] F. Morel. *A fatigue life prediction method based on a mesoscopic approach in constant amplitude multiaxial loading*. Fatigue & Fracture of Engineering Materials & Structures, **21**(3), 241–256 (1998).

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Young-measure quasi-static damage evolution

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An existence result for the quasi-static evolution of incomplete damage in elastic materials is presented. The absence of gradient terms in the damage variable causes a critical lack of compactness. Therefore, the analysis is developed in the framework of Young measures, where a notion of solution is defined, presenting some improvements with respect to previous contributions. This is a joint work with D. Knees and U. Stefanelli.

Derivation of an effective damage model based on micro-structure evolution

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This lecture is addressed to the question of deriving an effective damage evolution model by investigating the limit process of damage models with a “simple” micro-structure. Thereto, microscopic damage models are introduced, where there are only two phases of material - damaged and undamaged. This microscopic structure is scaled by a parameter $\varepsilon > 0$, where the structure is getting finer if ε goes to zero. Then, regularization and two-scale homogenization techniques lead to an effective damage model, wherein the damage is described by a damage variable $z : [0, T] \times \Omega \to [0, 1]$ reflecting the micro-structure induced by the ε-dependent models. Here, $z(t, x) = 1$ means that no damage occurs in point x at the time t and $z(t, x) = 0$ means the material cannot take any more damage but is still allowed to perform elastic deformations (i.e. no complete damage).
This approach suggests in which way phenomenological damage models could depend on the damage variable. Furthermore, anisotropy is allowed in the microscopic damage models, which leads to an anisotropic limit damage model.

Existence results for Cahn-Hilliard equations coupled with elasticity and damage

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The Cahn-Hilliard system is a well established model to describe phase separation and coarsening in alloys. To account for elastic effects, the Cahn-Hilliard system is coupled with an elliptic equation for the deformation field, the so-called Cahn-Larché system.

In this talk we present a new model where the Cahn-Larché system is coupled with a damage phase-field. The coupling takes place in the elastic energy density of the system, which now depends on the strain, the chemical concentration and the damage variable. We assume that the damage process influences its local surrounding and that the damage process is uni-directional, which leads to a differential inclusion for the internal variables.

We introduce a suitable notion of weak solutions and provide an existence result under appropriate growth conditions for the free energy. The proof of the existence result is based on a time-incremental minimization scheme. Several regularization and approximation techniques are discussed to establish suitable variational inequalities for the limit problem.

We also consider several generalizations of the new introduced model including multi-component alloys, Allen-Cahn equations for the phase-field, logarithmic forms for the chemical energy and quadratic energy forms with respect to the gradient of the damage variable.

Non-local damage models at high strain rates

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Engineering applications are the motivation for dealing with metals at high strain rates. Typical examples are the safety of containments of flight turbines or the crash worthiness of cars. Classical continuum mechanics offers as a typical tool for such applications local models, i.e. the mechanical equilibrium holds and state dependent variables do not directly depend on their neighbourhood. The finite element application of such models leads to the well known effect that the results depend strongly on the element size, if a certain amount of damage is exceeded.

In contrast to that, non-classical continuum mechanics, such as non-local or gradient models, exhibit a different nature and a different behaviour. Beside the classical mechanical equilibrium, one or more additional field equations are introduced, where the variables are the damage, accumulated plastic strain or similar variables. Once such concepts are introduced into the finite element procedures the observed behaviour is different to that of local models and the mesh dependence is remarkably reduced.

The underlying mathematical structure of the local and non-local models is shown in detail. A stability analysis in Ljapunow's sense is performed and explains the observed behaviour in parts. Nevertheless, a consistent mathematical analysis is still missing.
This is a joined work with Bob Svendsen and Arnd Flatten.

Cyclic fatigue in an oscillating elastoplastic body

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For the evaluation of cyclic fatigue accumulation in elastoplastic materials under uniaxial loading regimes, the rainflow method is perhaps the most popular engineering tool. It sums up individual contributions of each closed loop in the strain-stress diagram. The rainflow count cannot be extended to the multiaxial case, as multidimensional loading paths exhibit no closed loops. The observation that the rainflow algorithm evaluates in fact the mechanical energy dissipated during the loading and unloading process, leads to the modeling hypothesis that dissipation can be used as fatigue indicator in multiaxial processes as well. This is confirmed by experiments manifesting a strong heat release in the areas of highest fatigue. We propose here a temperature dependent model for fatigue accumulation in an oscillating elastoplastic body based on these observations. The full PDE system consists of the momentum and energy balance equations, and an evolution equation for the fatigue rate. In nontrivial cases, the process develops a thermal singularity in finite time. The main result consists in proving the existence and uniqueness of a strong solution before the material failure occurs.

Rate-independent approach to non-associated decohesion models

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The overall behavior of the vast majority of engineering materials and structures is significantly affected or even dominated by the presence of interfaces (i.e. internal boundaries). This is particularly true for heterogeneous materials, where interfaces provide weak spots from which damage initiates at multiple levels of resolution. Therefore, in the engineering community, considerable research efforts have been focused to adequately describe and simulate the interfacial behavior under general loading conditions.

The aim of this contribution is to extend the existing rate-independent approaches to decohesion to incorporate a wide class of mixed-mode interfacial models developed in the engineering literature. To this goal, we introduce a general energy-based delamination model. We outline results related to the time-discrete incremental problem, including an existence proof and necessary conditions for the energetic solution in the form of energy inequalities. These are employed to propose a fully discrete scheme based on the finite element method. Numerical examples will be presented. This is a joint work with Jan Zeman and Pavel Gruber (Prague).

On dynamic Griffith fracture

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We first briefly discuss models for dynamic Griffith fracture, and then describe issues concerning the preliminary question of existence for wave equations off of arbitrary growing cracks. The main difficulties come first from the fact that, since the crack might be dense even if its measure is finite, only unusually weak solutions are possible, and second, the space of test functions must grow in time, which rules out many methods of analysis. Finally, we discuss some properties of dynamic fracture solutions.

A toy model for dynamic debonding

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We present a model for the debonding of a one-dimensional inextensible film, subject to a monotonic loading with vanishing speed. We consider a homogeneous material containing a small defect where the toughness is lower than the one of the matrix. In this case the dynamic solutions do not converge to a quasistatic one if the loading speed tends to zero. This is due to the presence of kinetic energy, which can be estimated by an optimal bound. Moreover, using an exact numerical solution of the wave equation, we study the case of many defects, modelling a homogenized material.
Joint work with R. Bargellini, P.E. Dumouchel, and J.J. Marigo.

Finite Element Simulation of Damage and Phase Separation

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In this talk, a finite element method for a combined model of phase separation and damage is derived and results of numerical experiments are discussed. Rate dependent damage is modeled as a phase field like order parameter. For the temporal evolution, this leads to a partial differential equation similar to the Allen-Cahn equation. An additional nonsmooth constraint is introduced that excludes healing of material. The resulting variational inequality is solved by the primal dual active set method. Phase separation is modeled by a Cahn Hilliard equation with linear elasticity. Smooth and singular logarithmic potentials are considered as well as possibly anisotropic and inhomogeneous elasticity tensors.

Crack Propagation in Mode I-II by an approximated PLS

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In-plane brittle fracture propagation is generally described by Griffith's criterion [1] together with a directional criterion; among the many we take into account the Principle of Local Symmetry (PLS) [2]. We consider boundary conditions of proportional type and linearized elasticity; this special setting allows indeed to solve first for the crack path (with fixed boundary data) and then for its parametrization in time. Crack paths will be represented by (the graph of) Lipschitz functions, in a suitable system of coordinates. Behind this Lipschitz setting lies a major technical problem since the stress intensity factors (SIFs) in general are not well defined if the crack path is only Lipschitz continuous. According to [3] the SIFs do exist if the path is class $C^{1,1}$. At the present stage this regularity is not affordable for an existence result. Therefore, we employ an integral approximation of the SIFs, inspired by [5], and supported by a higher integrability of displacements at the crack tip. Most important, such a volume integral representation allows to easily approximate also the right limits of the SIFs; thank to this fact it is possible to write a functional differential equation whose solution is a Lipschitz path along which the approximated SIFs satisfy PLS. Technically, existence follows by Schauder Theorem through the Hölder continuity of displacements and approximated SIFs, with respect to variations of the crack set. We also prove that the solutions are indeed of class $C^{1,\alpha}$ for some $\alpha < 1$. Uniqueness is still open. Finally, given a trajectory we will find by standard arguments (e.g. [4]) a non-decreasing, left-continuous parametrization of class BV such that Griffith's criterion (for the approximated stress intensity factors) is satisfied in a weak Kuhn-Tucker form.

References

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Fading memory effects induced by upscaling viscoelastic and porous media

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The paper deals with viscoelasticity in heterogeneous materials featured by periodic microstructure. The standard two scale homogenization can be applied to get the effective, i.e. upscaled constitutive laws relevant to the macroscopic scale. Several examples are presented illustrating different origins of the fading memory behaviour apparent in the upscaled material models.

As a simplest example one may consider the heterogeneous Voigt-Kelvin medium where the material micro-model based on the parallel spring and dashpot arrangement, i.e. without any relaxation feature, leads to fading memory effects apparent at the microscopic scale.

It has been shown that the creep and relaxation effects are obtained also when upscaling weakly permeable fluid-saturated porous media, cf. [2]. In this case the induced viscoelasticity with the fading memory features is caused by the fluid micro flow in the pores. Thus, the hereditary creep of the "macroscopically solid" material results from the homogenization of the Biot poroelastic medium with the dual porosity ansatz which is respected by "ϵ^2-scaling" of the permeability, where $\epsilon \to 0$ is the size of the microstructure. It indicates asymptotically negligible pores and only localized redistribution of the flow due to heterogeneity of the medium at the ”mesoscopic" scale, whereby the tiny pores are distinguishable at the microscopic scale. Similar effects characterize the double porous materials with strong heterogeneities in the permeability coeffcients (again in the sense of the ϵ^2-scaling) [1]; this material model describes e.g. the compact bone tissue where the two systems of pores are associated with the primary Haversian and the secondary canalicular porosities intercommunicating the fluid phase. Also perfusion in deforming tissues can be approximated by this type of model with a more complex topology of the microstructure [3].

Obviously, the fading memory viscoelasticity in porous material can arise due to the fading memory type viscoelasticity of the solid phase, i.e. of the matrix part, whereas the pore fluid does not contribute if pores are large with respect to the scale. Such a model is discussed and it is shown that further fading memory effects appear in the Biot compressibility homogenized coeffcients.

References

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Analysis of a model for adhesive contact with friction

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We address a model for adhesive contact between a viscoelastic body and a rigid support, also accounting for frictional effects. We describe the adhesion phenomenon in terms of a damage surface parameter according to Fremond's theory, and we model unilateral contact by the Signorini conditions, and friction by a nonlocal Coulomb law. All the constraints on the internal variables, as well as the contact and the friction conditions, are rendered by means of subdifferential operators, whence the highly nonlinear character of the resulting PDE system. Existence of a global-in-time solution of the related Cauchy problem is proved by passing to the limit in a time-discretization scheme.

Models of adhesive contacts delaminating at mixed modes

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After introducing a basic concept of quasistatic rate-independent adhesive contacts and surveying some results about it, a refinement by reflection of the mode of delamination will be exposed. As a matter of fact, engineering models distinguish Mode I (=opening, with rather small activation energy needed) from Mode II (=shearing, with usually much bigger activation energy). Mixity mode combining both modes occurs most typically, rather than a pure Mode I or II. Some mixity-sensitive models bear rigorous mathematical and numerical analysis. Two-dimensional computational experiments will be presented, too. Eventually, some rate-dependent effects like healing or viscosity or inertia will be mentioned. The presentation will reflect collaboration with L.Freddi, M.Kružík, A.Mielke, V.Mantič, R.Paroni, R.Rossi, L.Scardia, M.Thomas, and C.Zanini, including computational simulations from M.Kočvara, C.G. Panagiotopoulos, R. Vodička, J. Zeman.

Numerical Simulation of Coarsening in Binary Alloys

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Phase separation phenomena in alloys, such as spinodal decomposition and Ostwald ripening can be described by phasefield models of Cahn-Hilliard-type. Realistic models based on thermodynamically correct logarithmic free energies contain highly nonlinear and singular terms as well as drastically varying length scales (cf. [1]). We present a globally convergent nonsmooth Schur-Newton Multigrid method [2] for Cahn-Hilliard-type equations and a numerical study of coarsening in a eutectic AgCu alloy taking into account elastic effects.

Refences

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A derivation of a Griffith-type energy functional

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We start from a chain of atoms interacting through nearest and next-to-nearest neighbour interactions of Lennard-Jones type. We derive an approximation of the corresponding energy functional as the distance between the atoms tends to zero. To this end we study an expansion by Gamma-convergence and apply the so-called notion of uniformly Gamma-equivalent theories introduced by Braides and Truskinovsky. This leads to a functional which is the sum of an elastic energy and a term containing surface energies as well as a parameter that captures the atomistic scale. (Joint work with Lucia Scardia and Chiara Zanini.)

A variational principle for gradient flows in metric spaces

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In this talk I will present some results on an ongoing project with R. Rossi, G. Savaré and U. Stefanelli regarding a novel variational approach to gradient-flow evolutions in metric spaces. In particular, we advance a functional defined on entire trajectories, whose minimizers converge to curves of maximal slope for geodesically convex energies. The crucial step of the argument is the reformulation of the variational approach in terms of a dynamic programming principle, and the use of the corresponding Hamilton-Jacobi equation. The result is applicable to a large class of nonlinear evolution PDEs including nonlinear drift-diffusion, Fokker-Planck, and heat flows on metric-measure spaces.

Energy release rate caused by crack propagation in a composite material -Part I-

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Among the various criteria predicting crack propagation mainly the energy criterion of Griffith can be considered as an axiomatic access: A crack can only propagate, if energy will be released. Of course, then there appears the question what does this mean in praxis. Treating quasi-static crack propagation in brittle materials can be done by calculating the so-called energy release rate using linear elasticity problems. To this end one considers a plane elasticity problem in a domain Ω_0 with an initial crack and a domain Ω_h, where the crack is grown along a path of length h. If the entries of the Hooke-tensor vary smoothly on the domain, by means of asymptotic analysis, the difference ΔU in the potential energy can be calculated to

$$\Delta U = -\frac{1}{2}(\sum_{i,j=1,2} M_{ij} K_i K_j)h + o(h), \quad h \to 0,$$

where K_1, K_2 are the so-called stress intensity factors and M_{ij} are local integral characteristics depending on the material properties at the crack tip and the geometry of the elongated crack. In particular this formula uses the results about the asymptotic behavior of the displacement fields near the crack tip. For a composite of two materials, that is the elasticity coefficients are discontinuous along a line, this behavior may change decisively if the crack tip reaches the interface. However, if the difference in the elastic properties is not too large one may expect that the asymptotic behavior of the displacement field near the crack tip is related to the case of the homogeneous material. In this lecture we present asymptotic formulae for the generalized eigenvalues and eigenfunctions which determine the asymptotic behavior near the crack tip. When they are fixed, it is possible to calculate again the energy release rates in order to predict, for example, whether a crack tip can reach the interface or whether delamination can happen (cf. Part II).

The results are obtained as a joint work with S.A. Nazarov, St. Petersburg, and Martin Steigemann, University of Kassel.

Energy release rate caused by crack propagation in a composite material -Part II-

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This contribution presents ideas, how crack propagation in inhomogeneous materials can be predicted based on the GRIFFITH energy principle for plane problems: A crack can only propagate, if energy will be released. The problem of crack propagation in linear elastic homogeneous materials is extensively discussed in the literature. Since the work of IRWIN the change of potential energy caused by a straight elongation of the crack in an isotropic homogeneous material can be expressed in quadratic terms of the stress intensities at the crack tip. This result was generalized to anisotropic and also (smooth) inhomogeneous materials using methods of asymptotic analysis by MAZYA, PLAMENEVSKY, NAZAROV and other authors. With this so-called energy release rate at hand, quasi-static scenarios of crack propagation can be simulated in linear elastic materials. In combination with experimental data it is also possible, to answer questions such as lifetime prediction or the stability of crack growth.

The situation can completely change, if there is a sharp material interface as in the case of composite structures. If the crack approaches a discontinuity of the elasticity coefficients, different scenarios of crack propagation are possible, depending on the toughness of the interface and the elastic properties of the composite materials itself. For example, the crack can arrest, be deflected into or penetrate the material interface. A key to calculate the change of energy is the asymptotic expansion of the displacement field at the crack tip, which is of square-root type, as long as the material properties depend smoothly on the space coordinates:

$$u \sim r^{\Lambda}\Big(K_I\Phi^1(\varphi) + K_{II}\Phi^2(\varphi)\Big) + \dots, \qquad r \to 0, \qquad \Lambda = \frac{1}{2}.$$

If the crack impinges a material interface, this asymptotic expansion can change significantly. As shown in part I of this contribution, the singular exponent Λ depends on the mismatch of the material properties, the geometry of the interface and can especially be complex. Moreover, if one of the materials is anisotropic, the asymptotic expansion can contain logarithmic terms. In this part we will discuss how the energy release rate can be calculated for different scenarios of crack propagation near a material interface. Also here the asymptotic behavior of the displacements has a direct influence. For example, if the singular exponent Λ is complex, the change of potential energy caused by a crack elongation penetrating the interface can be calculated to

$$\Delta U = -\frac{1}{2}\Big(\cos\big(2\log(h)\mathrm{Im}(\Lambda)\big)M_{1,1}K_1^2 + 2M_{1,2}K_1K_2 \\ + \cos\big(2\log(h)\mathrm{Im}(\Lambda)\big)M_{2,2}K_2^2\Big)h^{2\mathrm{Re}(\Lambda)} + \dots .$$

The numbers K_j are the stress intensities at the crack tip on the material interface and $M_{i,j}$ are local integral characteristics depending on the material properties and the crack elongation. Finally we present numerical results.

This is a joint work with S.A. NAZAROV, St. Petersburg, and M. SPECOVIUS-NEUGEBAUER, University of Kassel.

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To the identification of planar cracks in linear piezoelectric material

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An increasing number of technical applications includes piezoelectric components with intrinsic coupling of mechanical and electric behaviour. In the rather brittle piezoelectric ceramics, the danger of cracking has to be kept in mind, especially under situations with extreme or cyclic loads. In worse cases, cracks in piezoelectric components may cause loss of functionality or even the destruction of the whole device. So, an important intention in material control is the detection of cracks. Especially nondestructive test methods for the detection of hidden cracks (cracks without boundary touch) are a challenge.

One basic idea is the use of boundary measurements under certain loads. The knowledge of both Dirichlet and Neumann data, on the outer boundary or at least a part of it, provides additional information about the inner geometry of the domain. The inverse problem here denotes the reconstruction of possible cracks from a Neumann-to-Dirichlet or a Dirichlet-to-Neumann map.

Some approaches of crack detection are discussed in the literature, most authors deal with the Laplace equation where the well-founded theory opens a spectrum of possibilities. We base on an approach for the reconstruction of planar cracks using the reciprocity principle, given by ANDRIEUX, BEN ABDA et.al. in the case of the Laplace equation [1] and in isotropic linear elasticity [2]. An extension of the first step – the identification of the crack plane – has been generalized to linear piezoelectric material behaviour under the assumption of no contact and impermeable semipermeable electric conditions on the crack faces. The generalization of the complete crack identification is not straightforward. We discuss some ansatz points.

A FEM simulation software provides synthetic data instead of boundary measurements. The test of the described method in postprocessing on some 2D numerical examples with known planar cracks allows the comparison between the original crack geometry and its inverse reconstruction. Also such tests enable a numerical test of the sensitivity to data noise, which has always to be considered in practice because of the error level in real-world measurements.

References

[1] S. Andrieux and A. Ben Abda: *Identification of planar cracks by complete overdetermined data: inversion formulae*. Inverse Problems 12, 1996, 553-563

[2] S. Andrieux, A. Ben Abda and H. D. Bui: *Reciprocity principle and crack identification*. Inverse Problems 15, 1999, 59-65

Delamination in viscoelastic materials with thermal effects

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This contribution deals with the analysis of a model describing a rate-independent delamination process along a prescribed interface. The material properties in the bulk are considered to be viscoelastic and temperature-dependent. In the spirit of continuum damage mechanics the delamination process is modeled with the aid of an internal delamination variable z. The related PDE system, which couples the displacements, the absolute temperature and the delamination variable, has a highly nonlinear character and features frictionless Signorini conditions. The goal is to obtain the existence of weak solutions in the setting of brittle delamination, where the delamination variable takes the values 0 or 1, only, and where the crack is described in terms of a transmission condition being a local, nonconvex constraint, which links the displacements and the delamination variable in a very rigid manner. In order to deduce this existence result the brittle model is consecutively approximated by suitably regularized problems: On the one hand, the brittle constraint $z \in \{0, 1\}$ is gained from a Modica-Mortola functional; on the other hand, the rigid transmission condition is approximated by a surface energy term for so-called adhesive contact, which punishes displacement jumps outside the crack set but does not rigidly exclude them.
This is a joined work with Riccarda Rossi (Brescia).

Some remarks on the second derivative of the elastic energy with respect to crack length

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The importance of the energy release rate in modeling crack evolution is well-known, at least since the fundamental contribution of Griffith in 1920. Under suitable assumptions, the energy release rate equals minus the derivative of the elastic energy with respect to crack length and can be expressed in terms of the stress intensity factors. In this talk I shall address the problem of computing the second order derivative of the elastic energy with respect to crack length in the antiplane setting.

Solvability of a model of phase separation with nonlinear mechanics

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In this talk we study a model of phase separation of Cahn-Hilliard type coupled to a quasi-steady mechanical equilibrium. We use a framework based on monotone and pseudomonotone operators to derive existence and uniqueness results involving a generalized notion of weak solutions. The mechanical part is allowed to be nonlinear but monotone and rather general dependencies of the system on the concentration and displacement can be considered. Furthermore, we distinguish two different settings corresponding to the cases of either bounded (quadratic) growth of the potential or unbounded one. But in both cases the magnitude of the coupling between the mechanical part and the diffusion part has to be sufficiently small.

Thermophoresis and diffusion induced decomposition in blends and alloys

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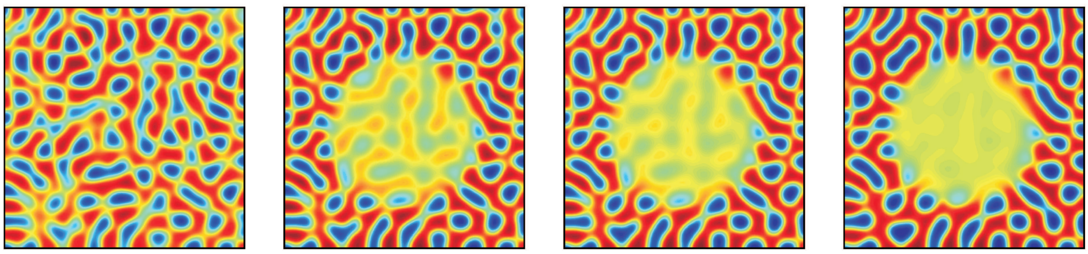
Multicomponent materials show a variety of micro-structural changes such as separation of phases and coarsening (Ostwald ripening). These morphologies influence strength and life expectation of the materials and may be of significant effect, in particular, in very small components such as microelectronic solder joints or thin coatings. In order to analyze the microstructural evolution with a diffusion theory of heterogeneous solid mixtures Cahn-Hilliard phase-field models are applied. The underlying equations involve a bipotential operator and, accordingly, the variational formulation requires approximation functions which are piecewise smooth and globally C^1-continuous. In order to fulfill the continuity requirements we employ here an innovative finite-element concept using B-splines.

Various types of temperature sensitive binary blends are used in modern technical applications, e.g., polymer solutions in adhesives or lubricants. However, comparatively little investigations have been made for the phase behavior of polymer blends subjected to local nonuniform temperature fields. For this reason we present a phase-field model which is extended by an additional thermal flux quantity and study the micro-morphological changes in polymer blends, specifically in a blend of poly(dimethylsiloxane) and poly(ethyl-methyl siloxane). As it can be seen in the Figure, the different temperature sensitivities of the components allows to induce interesting decomposition pattern.



$t^* = 0.03$ $t^* = 0.032$ $t^* = 0.035$ $t^* = 0.04$

Simulation results for a locally super-critical thermal diffusion.

References

[1] D. Anders and K. Weinberg: *Thermophoresis in binary blends. Mechanics of Materials*, submitted for publication, 2011.

A vanishing viscosity approach to a rate-independent damage model

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We focus on the modeling of damage phenomena in elastic bodies as rate-independent, activated processes. While the rate-independent theory seems to be well-established for systems with convex energy functionals, for non-convex energies there are interesting open problems, connected to the lack of regularity of the solutions as functions of time. The latter circumstance makes it necessary to recur to suitable weak solution notions. However, the by-now classical concept of global energetic solutions fails to describe accurately the behavior of the system at jumps. In this talk, we consider rate-independent damage models as limits of systems driven by viscous, rate-dependent dissipation. We illustrate a technique for taking the vanishing viscosity limit, which is based on arc-length reparameterization. In this way, in the limit we obtain a novel formulation for the rate-independent damage model, which highlights the interplay of viscous and rate-independent effects in the jump regime, and provides a better description of the energetic behavior of the system at jumps.

This talk is based on a joint collaboration with Dorothee Knees (WIAS, Berlin) and Riccarda Rossi (Brescia, Italy).

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P R O G R A M

Wednesday September 21	Thursday September 22	Friday September 23
8:00 Registration		
9:00 Opening		
Keynote Lecture 9:15 P. Krejčí 10:00 M. Kružík	*Keynote Lecture* 9:00 C. Larsen 9:45 G. Lazzaroni	*Keynote Lecture* 9:00 K. Weinberg 9:45 D. Wegner
10:30 Coffee Break	10:15 Coffee Break	10:15 Coffee Break
11:00 T. Roubíček 11:30 M. Thomas 12:00 D. Klingbeil	10:45 H.-D. Alber 11:15 C. Zanini 11:45 A. Segatti	10:45 C. Heinemann 11:15 U. Sack 11:45 R. Müller 12:15 A. Schlömerkemper
12:30 Lunch Break	12:15 Lunch Break	12:45 Closing
14:00 S. Bosia 14:30 M. Specovius-Neugebauer 15:00 M. Steigemann	13:45 B. Benešová 14:15 A. Fiaschi 14:45 E. Rohan 15:15 H. Hanke	
15:30 Coffee Break	15:35 Coffee Break	
16:00 M. Negri 16:30 R. Toader	16:00 R. Rossi 16:30 E. Bonetti 17:00 P. Steinhorst	
	19:00 Dinner	