Annual Report
2015

Chair of Applied Mechanics
Prof. Dr.-Ing. Paul Steinmann
Prof. Dr.-Ing. Kai Willner
PD Dr.-Ing. Julia Mergheim
Friedrich-Alexander-Universität Erlangen-Nürnberg

Prof. Dr.-Ing. P. Steinmann
Prof. Dr.-Ing. K. Willner
PD Dr.-Ing. J. Mergheim
Lehrstuhl für Technische Mechanik
Friedrich-Alexander-Universität Erlangen-Nürnberg
Egerlandstraße 5
91058 Erlangen
Tel.: 09131 8528501
Fax.: 09131 8528503
www: http://www.ltm.uni-erlangen.de

Editors: S. Hürner

Contents

1 Preface

This annual report briefly documents the scientific, teaching and social activities at the Chair of Applied Mechanics at the University of Erlangen-Nuremberg during 2015. At the scientific side the never ending enthusiasm of all members of the Chair did indeed result in exciting research and correspondingly in an internationally recognized output in terms of publications and conference contributions. Likewise the demanding teaching load, e.g. some several thousand written exams that require correction, could only be carried due to the amazing level of dedication exhibited by all members of the Chair. Of course all these efforts in turn fully justify team building activities in terms of excursions, summer barbecues and various types of parties that characterize the social life at the Chair. In summary we hope that this report convinces the reader of the level of academic achievements at the Chair of Applied Mechanics during the past year.

Paul Steinmann, Kai Willner, Julia Mergheim

2 Members of the Chair of Applied Mechanics

Professorship Continuum Mechanics:
Prof. Dr.-Ing. habil. Paul Steinmann (Head of the Chair)

Professorship Structural Mechanics:
Prof. Dr.-Ing. habil. Kai Willner

Working group Computational Mechanics:
PD Dr.-Ing. Julia Mergheim

Emeritus:
Prof. Dr.-Ing. habil. Günther Kuhn

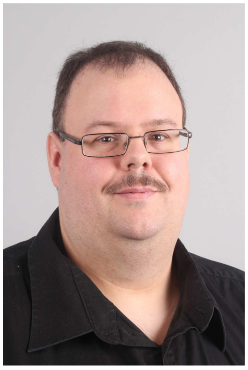

P. Steinmann


K. Willner


J. Mergheim

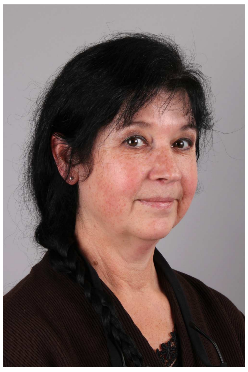
Technical and Administrative Staff

Christian Bänsch
Agnes Brütting
Dipl.-Ing. (FH) Dieter Pausewang
Dipl.-Betriebswirtin (FH) Ingrid Welsing


C. Bänsch


A. Brütting


D. Pausewang


I. Welsing

Scientific Staff

Maximilian Volkan Baloglu, M.Sc.(hons.)	
Dipl.-Ing. Florian Beyer	
Benjamin Brands, M.Sc.	
Silvia Budday, M.Sc.	
Denis Davydov, Ph.D.	
Dipl.-Ing. Florian Endres	
Ali Esmaeili, M.Sc.	
Dipl.-Ing. Sebastian Fillep	
Dipl.-Math. Jan Friederich	
Dr.-Ing. Sandrine Germain	(until 30.05.2015)
Dr.-Ing. Mokarram Hossain	(until 31.08.2015)
Dipl.-Ing. Simone Hürner	
Dipl.-Ing. Martin Jerschl	
Hesam Kandelousi, M.Sc.	
Andreas Kergaßner, M.Sc.	
Dipl.-Ing. Stefan Käßmair	
Dipl.-Technomath. Philipp Landkammer	
Dipl.-Ing. Vera Luchscheider	(until 30.06.2015)
Markus Mehnert, M.Sc.	
Jean-Paul Pelteret, Ph.D.	
Dr.-Ing. Sebastian Pfaller	
Dr. Ing. Dipl.-Math. techn. Gunnar Possart	
Dmytro Pivovarov, M.Sc.	
Daniel Riedlbauer, M.Sc.	
Dipl.-Ing. Stefan Riehl	
Saba Saeb, M.Sc.	
Dipl.-Ing. Stefan Schindler	
Dipl.-Ing. Stefan Schmaltz	(until 28.02.2015)
Dipl.-Technomath. Oliver Schmitt	
Benjamin Söhngen, M.Sc.	
Dominic Soldner, M.Sc.	(since 01.12.15)
Dipl.-Ing. Dominik Süß	
Bastian Walter, M.Sc.	
Tim Weidauer, M.Sc.	
Jiong Wang, Ph.D.	
Reza Zabihyan, M.Sc.	

V. Baloglu

F. Beyer

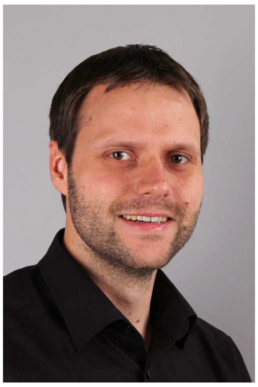
B. Brands

S. Budday

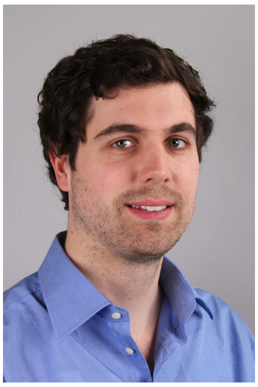
D. Davydov

F. Endres

A. Esmaeili



S. Fillep



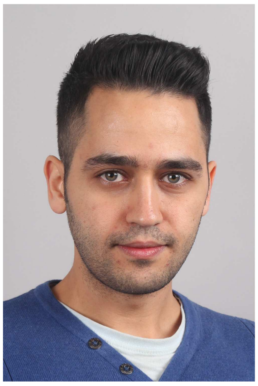
J. Friederich

S. Germain

M. Hossain

S. Hürner

M. Jerschl



H. Kandelousi

A. Kergaßner

S. Käßmair

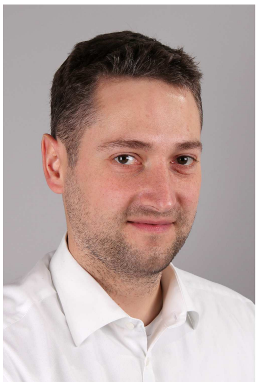

P. Landkammer


V. Luchscheider


M. Mehnert

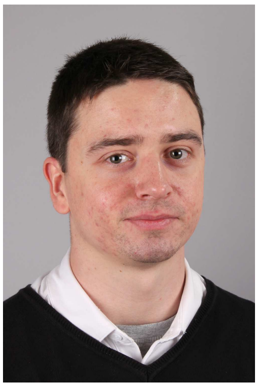

J.-P. Pelteret

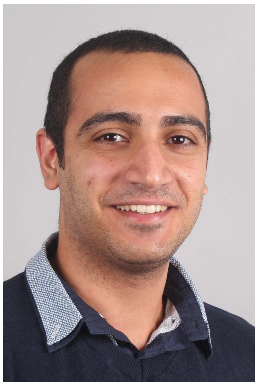

S. Pfaller

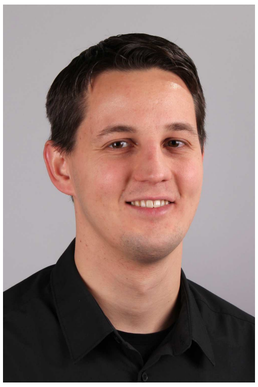

G. Possart


D. Pivovarov


D. Riedlbauer


S. Riehl

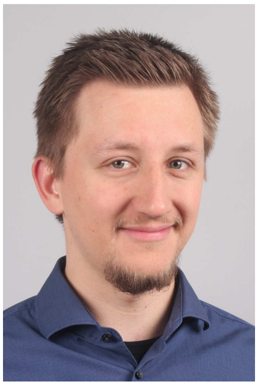

S. Saeb


S. Schindler


S. Schmaltz


O. Schmitt

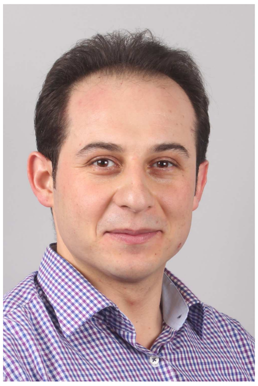

D. Süß


B. Söhngen


D. Soldner


B. Walter


T. Weidauer


R. Zabihyan

External Postgraduates

Dipl.-Ing. Jürgen Metzger
Dipl.-Phys. Patrick Schmitt
Dipl.-Ing. (FH) Paul Wilhelm

Guest Scientists and international Co-operation Partners

Prof. Dr. Ryszard A. Bialecki
Prof. Dr. Ghodrat Karami
Prof. Dr. Gennady Mishuris
Prof. Dr. Zoran Ren
Prof. Dr. Leopold Skerget
Prof. Dr. Matjaz Hribersek
Andrew McBride, Ph.D.
Amirtham Rajagopal, Ph.D.
Prof. Dr. Bozidar Sarler

Assistant lecturer

Dr.-Ing. Karsten Kolk
PD Dr.-Ing. Ralf Meske

Student Assistants

Ach, Theresa	Ahmadi, S. Shahabeddin	Alappat, C. Louis
Amin Ghaziani, Milad	Bader, Tobias	Bauer, Christof
Bauer, Philipp	Benedikter, Andreas	Bitsch, Daniel
Bitterwolf, Moritz	Bugert, Larissa	Caspari, Michael
Chennupati, Srikanth	Demling, Stefan	El Haouari, Abdellah
Fellner, Dorian	Göllner, Stefan	Großmann, Alexander
Hauser, Daniel	Hay, Manon	Heidenreich, Thomas
Jahansouz, Venus	Kellner, Michael	Kergaßner, Andreas
Kieser, Christoph	Knoll, Matthias	Kram, Judith
Krause, Daniel	Lechner, Timo	Lion, Antonia
Münch, Hannes	Oberleiter, Thomas	Oswald, Tancrède
Phutane, Uday	Pourtavakoli, Hamzeh	Primus, David
Qureshi, Mohammed	Reiter, Nina	Ries, Maximilian
Rösel, Uta	Schlegel, Nicolai	Schlichting, Marie-Louise
Schöttner, Jakob	Schwegler, Benjamin	Sheikholeslami K., Hesam
Soldner, Dominic	Speidel, Cornelia	Sperber, Christian
Stauber, Michael	Sultani, Darius	Tausendpfund, Theresa
Tuchnitz, F. Jan	Wagner, Andreas	Wicke, Martin
Winkel, Claudius	Wurmer, Florens	Zilker, Julian
Zobel, Pascal		

Student assistants are mainly active as tutors for young students in basic and advanced lectures at the BA- and MA-level. Their indispensable contribution to high quality teaching at the Chair of Applied Mechanics is invaluable, thus financial support from various funding sources is gratefully acknowledged.

3 Scientific Reports

The following pages allow a short overview on the various ongoing research projects pursued at the Chair of Applied Mechanics during 2015. These are mainly financed by third-party funding of various (public and industrial) funding sources and are in addition supported by the core support of the university. Topicwise we have a nice mix of continuations of previous projects with projects that started afresh in 2015. Also the complementing expertise as displayed in the three professorships/working groups for continuum mechanics, structural mechanics and computational mechanics established at the Chair of Applied Mechanics is reflected by the variety of research that is performed. This spans from atomistic approaches to material modeling, from experimental investigations to computational challenges and from frictional contact to structural problems. Of course the research on these topics constantly produces new insights, thus the following reports can only shed a spot-light on the current state of affairs.

Material modelling of a sheet-layered lamination stack by homogenization

Maximilian Volkan Baloglu, Kai Willner

In electrical machines, the main components consist of sheet-layered lamination stacks, which play an important role for the mechanical response of the system. Especially the nonlinear contact behaviour between individual sheets has a severe influence on the structure. It is furthermore responsible for the fact that an FE-simulation of such a model with standard continuous elements would lead to inappropriate results when omitting the contact.

Nevertheless, in the context of performance and computational effort, it is desirable to avoid a full FE-simulation of the contact zone. Therefore, homogenization techniques are employed to identify a more complex material model to cover the real physical behaviour of a lamination stack. The basic approach is oriented on the description in [2] and schematically shown in Fig. 1.

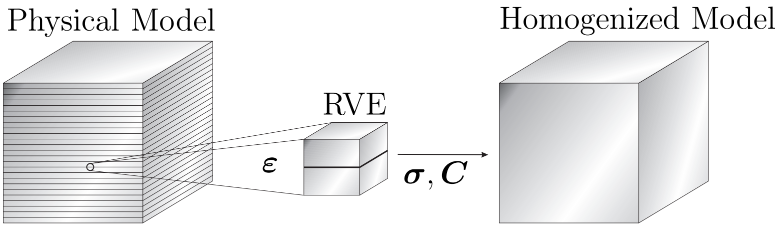


Figure 1: Schematic illustration of identifying a homogenized material law for a lamination stack with the help of a representative volume element (RVE).

As a first step, the material is assumed to be transversely isotropic. For this case, five independent parameters have to be identified to derive a material law of the form

$$\boldsymbol{\sigma} = \boldsymbol{C}\boldsymbol{\varepsilon}, \tag{1}$$

where the strain $\boldsymbol{\varepsilon}$ serves as the input and the stress $\boldsymbol{\sigma}$ as the output for the RVE of the homogenization. By applying different load cases, the elasticity tensor $\boldsymbol{C}$ can be identified, which is needed for the homogenized model.

For the implementation of the homogenization, a static condensation of the stiffness matrix is utilized due to periodic boundary conditions, cf. [3]. The contact zone inside of the RVE is covered by using Zero-Thickness elements, which are explained in [1].

References

[1] Johannes Geisler. “Numerische und experimentelle Untersuchungen zum dynamischen Verhalten von Strukturen mit Fügestellen”. PhD thesis. Universität Erlangen-Nürnberg, 2010.

[2] Vera Luchscheider, Kai Willner, and Mischa Maidorn. “A material model for lamination stacks based on rough contacts”. In: *Electric Drives Production Conference (EDPC), 2014 4th International*. IEEE. 2014, pp. 1–6.

[3] Ulrike Schmidt. “Identifikation mikroskopischer Materialparameter im Rahmen einer Zwei-Skalen-Modellierung”. PhD thesis. Universität Erlangen-Nürnberg, 2014.

Contact Simulation For Sheet-Bulk Metal Forming

Florian Beyer, Kai Willner

Sheet-Bulk Metal Forming (SBMF) is a well-established process to form steel sheets with a thickness between 1 mm and 5 mm into hight quality components with local functional elements. The complex interaction between the tool and workpiece is dominated by locally varying 2- and 3-dimensional stress and strain rates as well as highly diversified contact conditions. As a consequence, one of the major challenges of SBMF processes is the control of the material flow during the metal forming.

The research group 'tools' of the transregional collaborative research 73 'Sheet-Bulk metal forming' is focused on the impact of locally adapted friction conditions by means of structured tool surfaces on the material flow. Different surface modifications have been investigated to optimize SBMF processes. For instance, Fig. 1 shows a structure, which was produced by micromilling, and Fig. 2 depicts a structure, which was machined by high-feed milling.

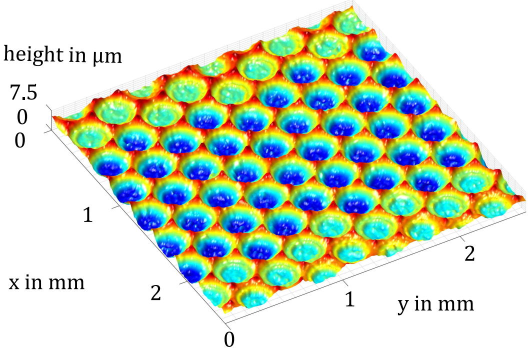


Figure 1: Surface produced by micromilling

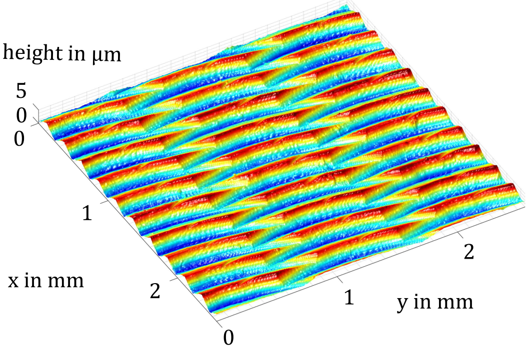


Figure 2: Surface produced by high-feed milling

Technical surfaces initially get into contact with their surface peaks, which characterize the real contact area A_{real}. As A_{real} is small for initial contact, the local contact pressure is large enough to plastically deform the surface asperities – even for low contact loads. A_{real} is an important parameter for friction, as tangential contact loads are only transferable in A_{real}. The identification of this parameter was performed numerically at the Chair of Applied Mechanics. The accurate representation of the multi-scale character of technical surfaces needs both a very fine resolution and a large area, which has to be discretized. An elastic-plastic half-space model, which is explained in detail in [1], is chosen for the numerical identification, because it only requires a discretization of the contacting surfaces and thus, has the advantage of significantly reduced computing time compared to conventional FEM. Additionally, the model was applied with an integrated mechanical-rheological model, which makes it able to take into account the contact interactions due to surface asperities and simultaneously consider the presence of lubrication. A detailed explanation of the study and its results is given with [2].

References

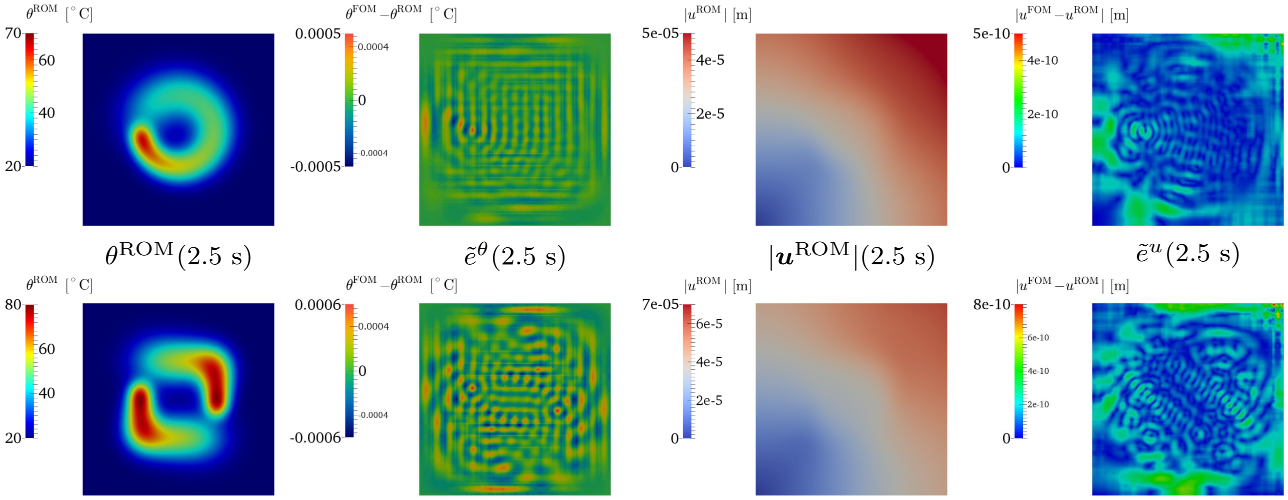
[1] F. Beyer, F. Hauer, and K. Willner. "Development of a Constitutive Friction Law based on the Frictional Interaction of Rough Surfaces". *Tribology in Industry* 37.4 (2015).

[2] P. Kersting, D. Gröbel, M. Merklein, P. Sieczkarek, S. Wernicke, A.E. Tekkaya, E. Krebs, D. Freiburg, D. Biermann, T. Weikert, S. Tremmel, D. Stangier, W. Tillmann, S. Matthias, E. Reithmeier, M. Löffler, F. Beyer, and K. Willner. "Experimental and numerical analysis of tribological effective surfaces for forming tools in Sheet-Bulk Metal Forming". *Production Engineering* (2016).

ROM applied to Thermoelasticity

Benjamin Brands, Julia Mergheim, Paul Steinmann

The goal of reduced-order modelling [3] is to significantly decrease the computational cost of numerical simulations in the context of multi-query and real-time applications. We apply Galerkin projection based ROM using proper orthogonal decomposition (POD) to the transient equations of thermoelasticity (adiabatic split) in 2D with a moving circular heat source like e.g. encountered in laser or electron beam melting processes.
Fig. 1 displays the temperature θ and the displacement field $\boldsymbol{u}$ for two paths of a heat source at certain time instances for the reduced model (ROM). The errors between the FE and the reduced model for the temperature and the displacement field are acceptably small considering the reduction of $148225 + 296450$ DoFs (FOM) to $400 + 250$ (ROM) for θ and $\boldsymbol{u}$, respectively. The position of the heat source center is introduced into the PDEs of thermomechanics via a time-dependent parameter, rendering a system of parameterised PDEs. For the sake of computational efficiency we tackle the non-affine parameter dependency with DEIM [1] using an empirical decomposition of the parameter domain, yielding more than 30 times decrease in the duration of computations.



$\theta^{\mathrm{ROM}}(2.5\text{ s})$ $\tilde{e}^{\theta}(2.5\text{ s})$ $|\boldsymbol{u}^{\mathrm{ROM}}|(2.5\text{ s})$ $\tilde{e}^{u}(2.5\text{ s})$

$\theta^{\mathrm{ROM}}(2.25\text{ s})$ $\tilde{e}^{\theta}(2.25\text{ s})$ $|\boldsymbol{u}^{\mathrm{ROM}}|(2.25\text{ s})$ $\tilde{e}^{u}(2.25\text{ s})$

Figure 1: Simulation of arbitrary heat source paths based on one global POD basis ($n^{\boldsymbol{u}} = 250$ and $n^{\theta} = 400$) computed using a nested POD approach [2].

One future challenge is the application of ROM to non-linear thermomechanics employing reliable and efficient *a posteriori* error estimators.

References

[1] S. Chaturantabut and D.C. Sorensen. “Nonlinear model reduction via discrete empirical interpolation”. *SIAM Journal on Scientific Computing* 32.5 (2010), pp. 2737–2764.

[2] A. Paul-Dubois-Taine and D. Amsallem. “An adaptive and efficient greedy procedure for the optimal training of parametric reduced-order models”. *International Journal for Numerical Methods in Engineering* 102.5 (2015), pp. 1262–1292. ISSN: 1097-0207. DOI: `10.1002/nme.4759`. URL: `http://dx.doi.org/10.1002/nme.4759`.

[3] A. Quarteroni, A. Manzoni, and F. Negri. *Reduced Basis Methods for Partial Differential Equations: An Introduction.* Vol. 92. Springer, 2015.

The role of mechanics during brain development

Silvia Budday, Ellen Kuhl, Paul Steinmann

Mammalian brains display a wide variety of shapes and surface morphologies which are closely correlated to neuronal activity. The folding pattern serves as clinical indicator for physiological and pathological conditions. Based on the hypothesis that growth-induced mechanical instabilities drive brain folding, we establish a continuum model of differential growth by multiplicatively decomposing the deformation gradient $\boldsymbol{F} = \boldsymbol{F}^{\mathrm{e}} \cdot \boldsymbol{F}^{\mathrm{g}}$ and the volume change $J = \det(\boldsymbol{F}) = J^{\mathrm{e}} J^{\mathrm{g}}$ into a reversible elastic part and an irreversible growth part. For simplicity, we assume that growth is purely isotropic and the growth tensor is parameterized in terms of a scalar-valued growth multiplier ϑ, $\boldsymbol{F}^{\mathrm{g}} = \vartheta \boldsymbol{I}$. We let the outer gray matter grow morphogenetically at a constant rate $\dot{\vartheta}_{\mathrm{c}} = G_{\mathrm{c}}$. The inner white matter only grows when stretched $(J^{\mathrm{e}} > 1)$ at a stretch-dependent rate $\dot{\vartheta}_{\mathrm{s}} = G_{\mathrm{s}}(J^{\mathrm{e}} - 1)$ [3], which mimics the chronic elongation of nerve fibres when stretched beyond their physiological limit.

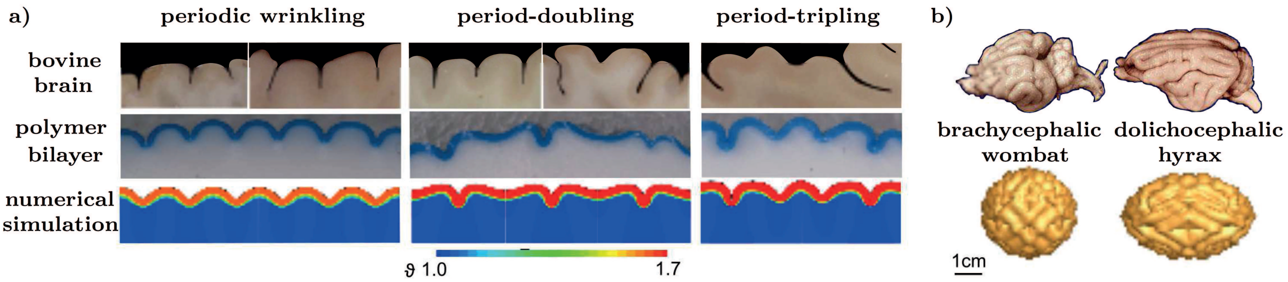


Figure 1: a) Primary and secondary instabilities in a bovine brain, a polymer bilayer, and numerical simulations. b) Influence of ellipticity on folding patterns in mammalian brains.

Within this computational framework, we simulate the evolution of the folding pattern in the highly nonlinear post-buckling regime. While moderate growth evokes periodic sinusoidal wrinkles, further continuing growth induces secondary instabilities - the surface bifurcates into increasingly complex morphologies. Advanced wrinkling modes such as period-doubling and period-tripling as illustrated in Figure 1a can explain the increasing complexity of our brain surface as we age [2]. We show how extrinsic mechanical factors including brain size, cortical thickness, and cortical curvature regulate pattern selection [1]. Our simulations explain why longer brains tend to fold more longitudinally than radially (figure 1b). We experimentally validate our numerical results (Figure 1a bottom row) by examining buckling of a compressed polymer film on a soft foundation (Figure 1a middle row). Understanding the process of cortical folding in the mammalian brain has direct implications on the diagnostics of neurological disorders such as schizophrenia and autism.

References

[1] S. Budday, P. Steinmann, A. Goriely, and E. Kuhl. "Size and curvature regulate pattern selection in the mammalian brain". *Extreme Mechanics Letters* (2015). DOI: `10.1016/j.eml.2015.07.004`.

[2] S. Budday, P. Steinmann, and E. Kuhl. "Secondary instabilities modulate cortical complexity in the mammalian brain". *Philosophical Magazine* 95 (28–30 2015), pp. 3244–3256. DOI: `10.1080/14786435.2015.1024184`.

[3] S. Budday, P. Steinmann, and E. Kuhl. "The role of mechanics during brain development". *Journal of the mechanics and physics of solids* 72 (2014), pp. 75–92.

Adaptive Finite Element solution of the Kohn-Sham equations

Denis Davydov, Paul Steinmann

Properties of matter, such as electric conductivity, magnetizm, and mechanical response under applied loads are ultimately determined by its electronic structure. The latter can be obtained by solving the Schrödinger wave equation: $\hat{H}\psi_\alpha = \lambda_\alpha \psi_\alpha$, that represents a quantum mechanical many-body eigenvalue problem. The exact solution to this problem can be obtained for a single hydrogen atom only. Many of the physical properties of condensed matter systems are dictated by its ground state. One of the most successful and widely adopted approaches to obtain the ground state of electronic structure theoretically, is within the context of Density Functional Theory (DFT) of Kohn and Sham [3].

The adaptive Finite Element (FE) analysis of the Kohn-Sham equations was implemented [2] using the open-source Differential Equations Analysis Library (`deal.ii`) [1]. A FE basis set has a number of significant advantages: (i) It can account for arbitrary geometries and arbitrary boundary conditions; and (ii) the strict locality of the FE basis, and the sparse matrices that arise from it, facilitates parallelization of the problem and distributed computing.

The ultimate goal of this project is to develop an adaptive FE solution of the KS equations that not only provides good accuracy at modest numerical cost, but also scales well to large problems, thus making calculations on super computers more efficient. Scaling of different eigensolvers is currently under investigation for a test problem of an isolated carbon nanotube (Fig. 1).

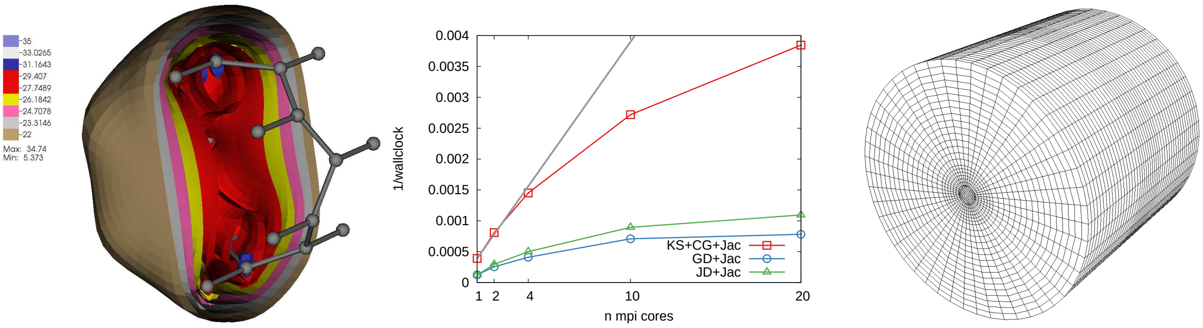


Figure 1: DFT-FE calculations of carbon nanotube. (left) electron-electron elestrostatic interaction energy; (middle) scaling of different eigensolvers; (right) the FE mesh.

References

[1] W. Bangerth, R. Hartmann, and G. Kanschat. “deal.II—A general-purpose object-oriented finite element library”. *ACM Transactions on Mathematical Software* 33.4 (Aug. 2007), pp. 1–27. DOI: `10.1145/1268776.1268779`.

[2] Denis Davydov, Toby Young, and Paul Steinmann. “On the adaptive finite element analysis of the Kohn-Sham equations: Methods, algorithms, and implementation.” *International Journal for Numerical Methods in Engineering* (2015), n/a–n/a. ISSN: 1097-0207. DOI: `10.1002/nme.5140`. URL: `http://dx.doi.org/10.1002/nme.5140`.

[3] W. Kohn and L. J. Sham. “Self-consistent equations including exchange and correlation effects”. *Physical Review* 140.4A (1965), A1133–A1138.

Atomistic simulations of domain configuration in ferroelectric functional materials

Florian Endres, Paul Steinmann

Ferroelectric materials are of significant importance in science and industry due to the electromechanical coupling. Therefore, ferroelectrics are simulated on different length scales using different models and algorithms in order to predict and understand the complex material behavior. Today smart material structures, e.g. multiferroic nanofilms, are manufactured with only very few nanometers thickness [3]. Most continuum descriptions are not able to capture the highly anisotropic, size dependent material behavior on such small length scales. There are continuum models, such as phase field models, that also describe ferroelectric material at the nano length scale. However, these models need specific input parameters like domain wall energies that are usually calculated by atomistic simulations. Consequently atomistic simulations are indispensable to simulate structures on the nanoscale.

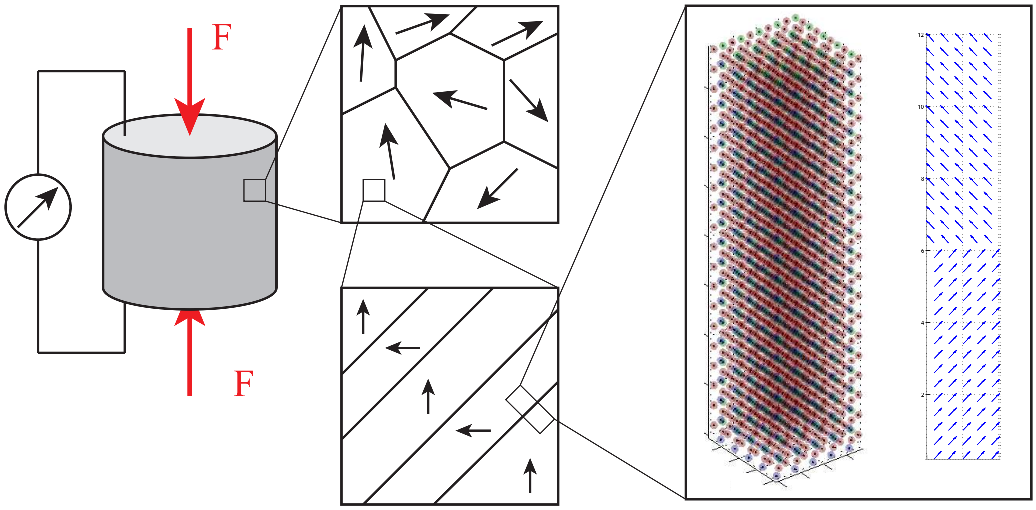


Figure 1: Ferroelectric crystal at different length scales.

We simulate ferroelectric domain configuration on the atomistic length scale [2] using a recently developed extended molecular statics algorithm [1]. The aim of this project is to improve the fundamental understanding of ferroelectric material behavior on the atomistic length scale and identify material parameters for continuum models.

References

[1] F. Endres and P. Steinmann. “An extended molecular statics algorithm simulating the electromechanical continuum response of ferroelectric materials”. *Computational Mechanics* 54.6 (2014), pp. 1515–1527.

[2] F. Endres and P. Steinmann. “Molecular statics simulations of head to head and tail to tail nanodomains of rhombohedral barium titanate”. *Computational Materials Science* 97 (2015), pp. 20–25.

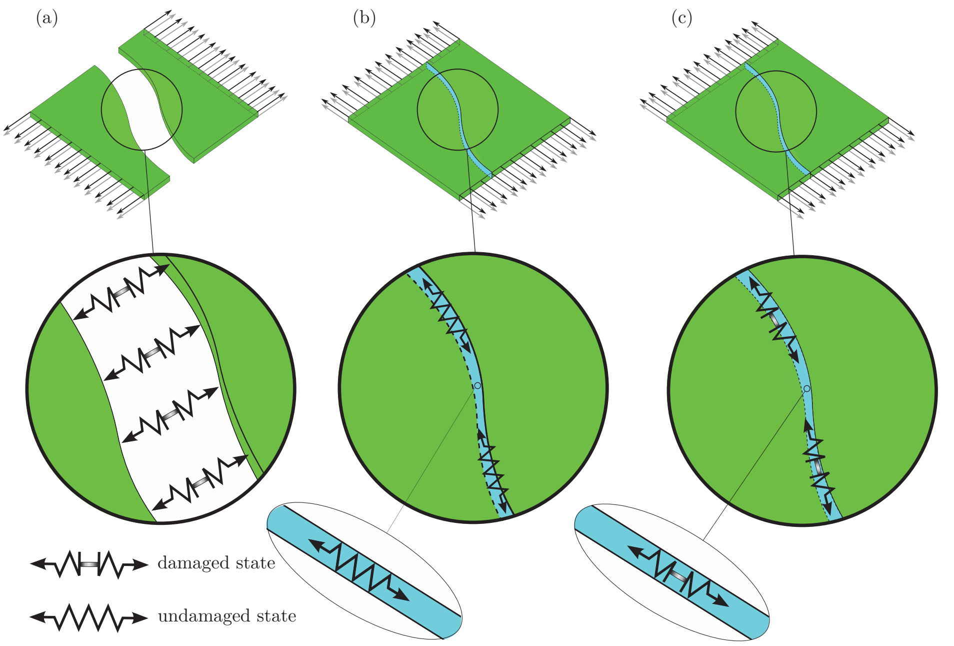
[3] Carolin Schmitz-Antoniak, Detlef Schmitz, Pavel Borisov, Frank MF de Groot, Sven Stienen, Anne Warland, Bernhard Krumme, Ralf Feyerherm, Esther Dudzik, Wolfgang Kleemann, et al. “Electric in-plane polarization in multiferroic CoFe2O4/BaTiO3 nanocomposite tuned by magnetic fields”. *Nature communications* 4 (2013).

Interface elasticity with damage

Ali Esmaeili[1], **Ali Javili**[2], **Paul Steinmann**[1]

[1] Chair of Applied Mechanics, University of Erlangen–Nuremberg, 91058 Erlangen, Germany
[2] Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305, USA

Interfaces can play a dominant role in the overall response of a body, particularly at small length scales. This scale-dependent characteristic can be captured by endowing a coherent interface with its own elastic resistance as proposed by the interface elasticity theory. This theory proves to be an extremely powerful tool to explain size effects and to predict the behavior of nano-materials. To date, interface elasticity theory only accounts for the elastic response of coherent interfaces and obviously lacks an explanation for inelastic interface behavior such as damage or plasticity [2]. The objective of this contribution is to extend interface elasticity theory to account for damage of coherent interfaces. To this end, a thermodynamically consistent interface elasticity theory with damage is proposed. A local damage model for the interface is presented and is extended towards a non-local damage model of integral-type [1].



cohesive zone model

interface elasticity theory without damage

interface elasticity theory + CDM current contribution

Figure 1: (a) classical cohesive non-coherent interface damage model, (b) interface elasticity theory, (c) interface elasticity theory accounting for damage.

References

[1] A. Esmaeili, A. Javili, and P. Steinmann. “Interface elasticity theory accounting for damage on coherent interfaces”. *Computer Methods in Applied Mechanics and Engineering* (2015).

[2] A. Javili and P. Steinmann. “A finite element framework for continua with boundary energies. Part II: The three-dimensional case”. *Computer Methods in Applied Mechanics and Engineering* 199.9 - 12 (2010), pp. 755 –765.

An efficient two-scale approach to model technical textiles

Sebastian Fillep, Julia Mergheim and Paul Steinmann

Technical textiles show a nonlinear constitutive behavior that differs from the underlying fiber material and is significantly influenced by heterogeneities on the micro level, e.g. the structural assembly of the fibers and appearing contact zones.

A specific homogenization scheme is introduced that connects a macroscopic homogeneous shell continuum to a representative volume element that is explicitly modeled by means of a heterogeneous, volumetric sample. Thereby, the macroscopic power density and the microscopic averaged power density are considered to be equal [1, 2].

During the two scale simulation both the macroscopic stress state and the tangent in a Newton scheme is needed. The tangent is approximated by a forward differentiation scheme. To improve the efficiency of the scheme a tabulated macro constitutive model is computed a priori that provides the macro-level with the macroscopic tangent and the macroscopic stress resulting from the RVE calculations. The macroscopic components are interpolated between the explicitly evaluated data points.

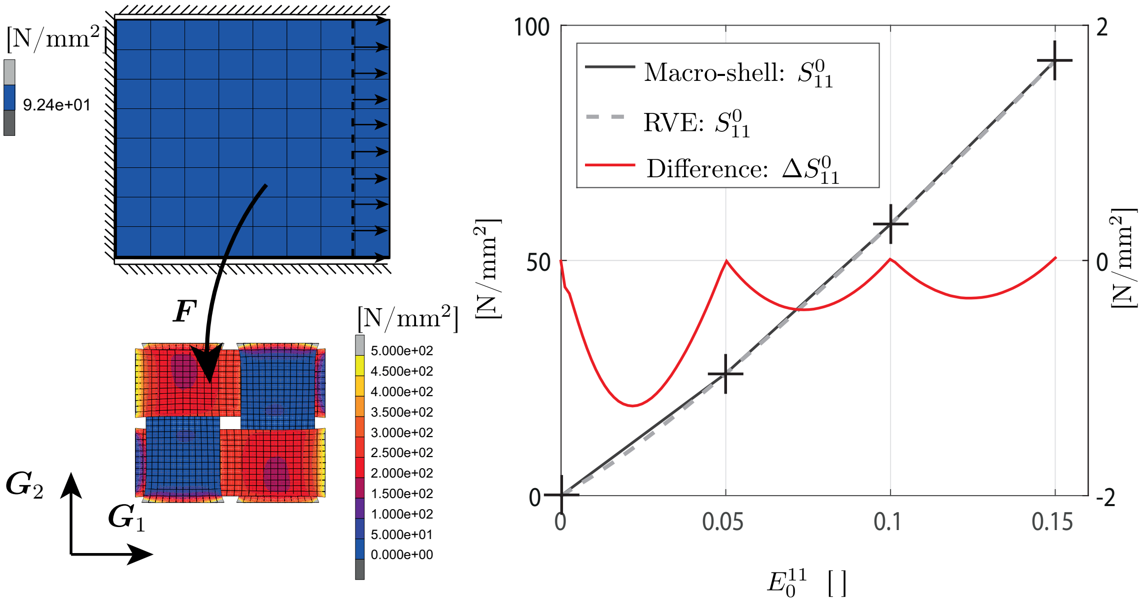


Figure 1: Plot of the stress components S_0^{11} and $\bar{S}_0^{11}$ on the macro-model (top left) and the RVE (bottom left) in the deformed state. Comparison of the stresses (right) of a uniform tension on macro scale evaluated with the tabulated macro constitutive model (black), a direct calculation with a RVE (grey) and the difference ΔS^0_{11} (red).

The capability of this method to capture nonlinearities depends on the discretization of the tabulated macro constitutive model. For the described example the results are in very good agreement, see Figure 1.

References

[1] S. Fillep, J. Mergheim, and P. Steinmann. “Computational homogenization of rope-like technical textiles”. *Computational Mechanics* 55 (2015), pp. 577–590.

[2] S. Fillep, J. Mergheim, and P. Steinmann. “Computational modelling and homogenization of technical textiles”. *Engineering Structures* 50 (2013), pp. 68–73.

Interactive visualization of the analytical solution for the infinite plate with an elliptical hole under simple tension: www.ltm.fau.de/plate

Jan Friederich, Sebastian Pfaller, Paul Steinmann

The infinite plate with a circular or elliptical hole under simple tension is one of the basic and most studied problems in solid mechanics. The general setting and an illustrating example are depicted in Fig. 1. The solution of this problem provides insight into the concentration of stresses at the boundary of cut-outs such as rivet holes and has furthermore served as a vital ingredient for research on cracks. The analytical solution of this problem dates back more than 100 years; for a historical overview and a comprehensive mathematical exposition covering the general case of an arbitrary elliptical hole we refer to [2] and references therein.

We have developed a web-based software tool for the interactive visualization of the analytical solution of this problem for the use in education and research. For geometrical parameters of the ellipse provided by the user, the stresses are instantaneously evaluated and displayed. Based on HTML5 and the WebGL 1.0 standard, the software runs in mordern browsers on desktop or mobile devices. In particular, making use of WebGL allows for efficient pixel-wise evaluation and real-time rendering by employing shader programs, which are executed on the graphics adapter. For further details on the theoretical background and our implementation we refer to [1].

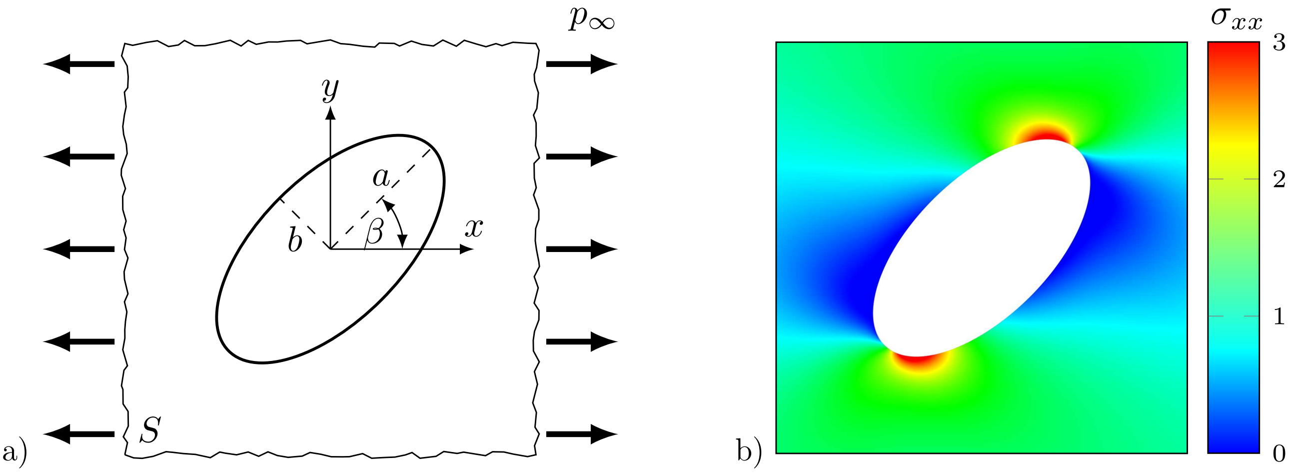


Figure 1: a) Infinite plate S with elliptical hole under simple tension in x-direction. The half-axes of the ellipse are denoted by a and b, respectively; the orientation of the major axis of the ellipse with respect to the x–axis is given by β. b) Resulting stresses σ_{xx} for $a = 1$, $b = 0.5$, $\beta = 45°$, and $p_\infty = 1$.

References

[1] J. Friederich, S. Pfaller, and P. Steinmann. “A web-based tool for the interactive visualization of stresses in an infinite plate with an elliptical hole under simple tension: www.ltm.fau.de/plate”. *Archive Of Applied Mechanics* (2015), pp. 1–9. DOI: `10.1007/s00419-015-1049-9`.

[2] N. I. Muskhelishvili. *Some basic problems of the mathematical theory of elasticity*. Leyden: Nordhoff International Publishing, 1975.

Interaction of particles in viscous flows

Simone Hürner, Paul Steinmann

In recent years, nanoparticles have emerged as important players in modern medicine. For instance, magnetic drug targeting is a very promising candidate to treat cancer efficiently. Thereby, magnetic particles are injected into the bloodstream and steered to cancer cell by an external magnetic field [2]. Obviously for optimizing this method, the motion of nanoparticles in viscous flows has to be predictable. Therefore, numerical simulations are widely used. But, for this, it is necessary to carry out further investigations on the behaviour of nonspherical particles in viscous flows. Hence, the particles are assumed to be rigid bodies, so there translational motion can be estimate by Newton's Second Law:

$$m\frac{d\boldsymbol{u}}{dt} = \sum \boldsymbol{F}$$

With $\boldsymbol{F}$ is the sum of the body, surface and contact forces acting on the particle, m is the particle mass and $\boldsymbol{u}$ is the translational velocity of the particle. The rotational motion is given by:

$$\boldsymbol{I}\frac{d\boldsymbol{\omega}}{dt} = \sum \boldsymbol{M}$$

With $\boldsymbol{M}$ is the sum of the torques acting on the particle, $\boldsymbol{I}$ is the moment of inertia and $\boldsymbol{\omega}$ is the angular velocity of the particle, in relation to a body-fixed coordinate system. As illustrated in Fig. 1, for the motion of nonspherical particles it is required to consider the position and the orientation of a body-fixed coordinate system of the particle to the global coordinate system. This can be done by using Euler angles [1]. By now, the modells describing the forces are implemented and the motion of nonspherical particles in viscous flows can be calculated. But further investigations on modelling the interactions of nanoparticles have to be carried out. Consequently, we focus on modelling the interaction of particles, described by the contact forces, by discrete element method.

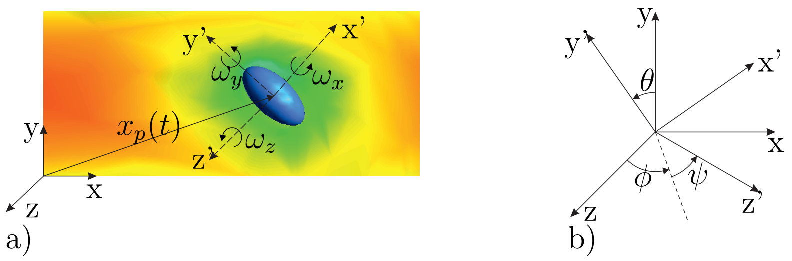


Figure 1: a) The position of an ellipsoid particle with a body-fixed coordinate system [x',y',z']; the global coordinate system is represented by [x,y,z]. b) Definition scetch of the Euler angles θ, ϕ, ψ

References

[1] Stefan Blaser. "Forces on the surface of small ellipsoidal particles immersed in a linear flow field". *Chemical Engineering Science* 57.3 (2002), pp. 515 –526. ISSN: 0009-2509. DOI: `http://dx.doi.org/10.1016/S0009-2509(01)00389-X`. URL: `http://www.sciencedirect.com/science/article/pii/S000925090100389X`.

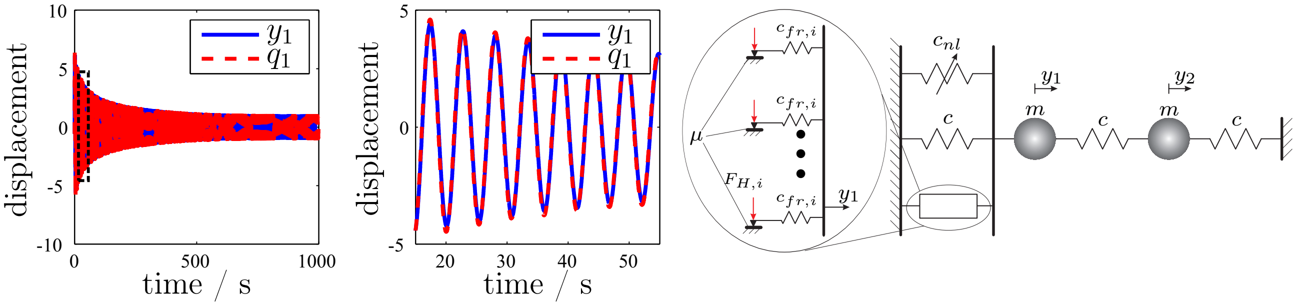
[2] E. M. Cherry and J. K. Eaton. "Simulation of Magnetic Particles in the Bloodstream for Magnetic Drug Targeting Applications". *International Journal for Numerical Methods in Engineering* (2013).

Studies of a geometrically nonlinear friction damped system using NNMs

Martin Jerschl, Kai Willner

Within the design process it is often sufficient to treat real-life applications as linear systems for the structural dynamic analysis because only small strains and displacements are considered. Since structures have to provide higher speed performances (e.g. turbines), the trend is towards lightweight constructions and consequently the system often undergoes larger displacements while the strains remain small. This fact leads for example to geometrical nonlinearities and loss of some comfortable properties of linear systems. For instance the resonance frequency of the system is dependent on the energy.

In this project a geometrically nonlinear system is investigated numerically concerning the possibility to restrict this frequency-energy dependence. Therefore another nonlinearity in the shape of a dry friction damper is added to the system (see figure 1 (c)). The system properties are described in [1]. As foundation of this research approach the concept of NNMs (nonlinear normal modes) is used, which describes an extension of LNMs (linear normal modes) to the nonlinear regime. In contrast to LNMs the frequency-energy dependence can be described with this tool. During numerical experiments with different parameter sets the system is driven into resonance to isolate a single NNM followed by the evaluation of decay processes. This is motivated by the invariance property which also holds for nonlinear systems: If a dynamic flow is initiated on a NNM it remains there for all time. Further explanations can be found in [1, 2]. System parameters for the friction damper can be identified such that no frequency-energy dependence occurs any more and a *modal* ansatz with energy dependent damping can be used as an equivalent one. Several decay processes initiated on an isolated resonance are investigated with this identified modal approach. The modal solution q_i shows congruence with the numerically integrated (NEWMARK method) solutions y_i (see figure 1(a),(b)).



(a) (b) (c)

Figure 1: Decay process initiated on isolated resonance with identified parameters (first DOF). Comparison between the numerically integrated solution and the modal solution. (a) complete decay process, (b) zoom, (c) model description.

References

[1] M. Jerschl, D. Süß, and K. Willner. "Studies of a Geometrical Nonlinear Friction Damped System Using NNMs". In: *Conference Proceedings of the Society for Experimental Mechanics Series*. Springer International Publishing, 2016 (accepted).

[2] M. Krack. *The concept of nonlinear modes applied to friction-damped systems.* Vol. 2014/5. Berichte aus dem IDS. Garbsen: PZH Verl., TEWISS - Technik und Wissen GmbH, 2014. ISBN: 3944586956.

The Mechanics of Wrinkling Skin

Hesam Kandelousi, Paul Steinmann

The skin is mainly made up of three layers: the epidermis, dermis and hypodermis. Each layer of the skin possesses different material properties and it also differs from one person to another according to age, race, gender, body site and environmental influences [2]. During aging, the dermis is atrophied as a result of volume reduction in glycosaminoglicans and collagen fibers. In the face this process is progressed with environmental effects such as sunlight. In addition, hypodermis (which is a fat layer) is also progressively atrophied which can further reduce the stiffness of the skin [2]. Two relatively recent hyper-elastic constitutive models proposed by Limbert [1] and Rubin-Bodner [3] proved to be efficient in considering almost all the complexities associated with modeling the skin behavior under various loading conditions. In the first model which is a mesostructurally-based anisotropic model, stress responses are fully decoupled to volumetric, deviatoric fiber, cross-fiber and fiber-to-fiber/fiber-to-matrix components and individual tropocollagen molecules are used in agreement with physical and molecular-dynamics-based experiments to capture and predict the mechanical responses of the skin. The second model is a phenomenological elasto-viscoplastic model which uses a combination of elastic and dissipative components. The elastic part (E) is responsible for long term stiffness of the tissue whereas the dissipative part (D) is responsible for the short time tissue deformation and able to capture creep and relaxation effects (fig 1). The combination of these models and the introduction of a damage parameter to weaken the long term elasticity in the matrix and the fiber part of the elastic components (E) along with realistic three layer geometry can give a good insight into the aging process.

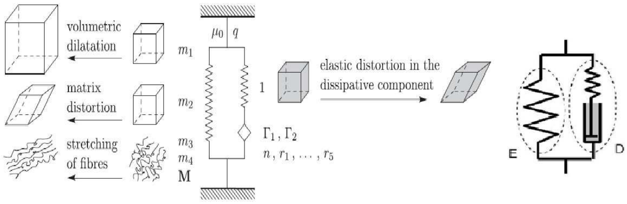


Figure 1: Pictorial representation of the Rubin-Bodner model [4] in the long term elastic response (left) and dissipative components (right). The diamond shows the rate of inelasticity. E stands for Elasticity components and D for Dissipative components.

References

[1] G. Limbert. "A mesostructurally-based anisotropic continuum model for biological soft tissue-decoupled invariant formulation". *Mech Behav Biomed Mater* 4.8 (2011), pp. 1–21. ISSN: 1637-57. DOI: `10.1016/j.jmbbm.2011.07.016.`.

[2] E. Mazza, O. Papes, M. B. Rubin, S. R. Bodner, and N. S. Binur. "Simulation of the aging face". *J Biomech Eng* 129.4 (2007), pp. 619–623. DOI: `10.1115/1.2746388`.

[3] S.R. Bodner M.B. Rubin. "A three-dimensional nonlinear model for dissipative response of soft tissue". *International Journal of Solids and Structures* 39.19 (2002), 5081–5099. ISSN: 0020-7683. DOI: `10.1016/S0020-7683(02)00237-8`.

[4] O. Papes. "Nonlinear Continuum Mechanics In Modern Engineering Applications (Doctoral dissertation)" (2011), pp. 1–190. DOI: `10.3929/ethz-a-007139775`. (Visited on 2012).

Computational Aspects of the Cahn-Hilliard equation in Elastic Solids

Stefan Kaessmair, Paul Steinmann

The Cahn–Hilliard equation plays an important role in the modelling of binary mixtures since it accounts for down- and uphill diffusion. Both mechanisms aim to minimize the free energy of the system consisting of a non-convex configurational part and an interface contribution. At the beginning, the mixture rapidly decomposes followed by coarsening of the obtained microstructure.
Due to the occurrence of fourth-order operators, the numerical treatment of the Cahn-Hilliard equation is nonstandard. To address this issue higher-order continuous interpolation methods are employed allowing a direct implementation in terms of the primal variable. On the other hand, the introduction of an auxiliary field allows to rephrase the original problem as set of two coupled second-order equations, which is solved using standard C^0 finite elements. Comparing C^1-continuous methods, i.e. natural element analysis (NEA) and isogeometric analysis (IGA), to C^0 finite elements (FEA), the IGA is superior in accuracy whereas the FEA performs best in runtime. The NEA is numerically to expensive. See [1] for details.
Based on that, the Cahn-Hilliard equations is coupled to elastic deformations in order to describe more complex phenomena, e.g. the lithiation in Li-ion batteries [2]. Fig 1 depicts the phase decomposition and coarsening of a binary mixture in a hyperelastic solid.

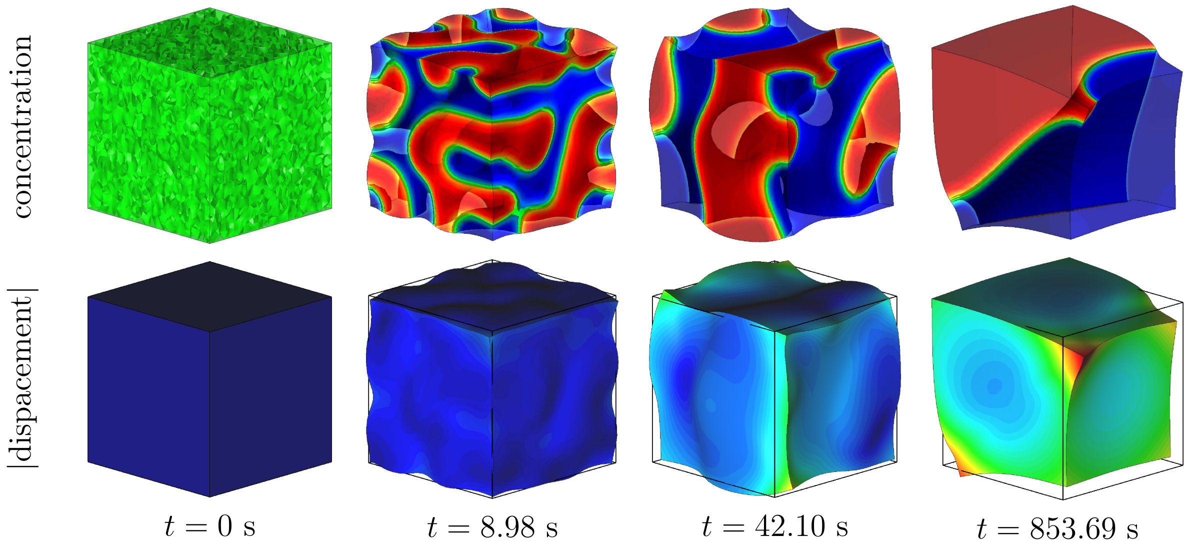


Figure 1: Evolution of species concentration and displacement in a unit cube. The reference configuration of the body is indicated by the black frame.

References

[1] S. Kaessmair and P. Steinmann. “Comparative Computational Analysis of the Cahn-Hilliard Equation with Emphasis on C^1-Continuous Methods”. *Journal of Computational Physics* (2015), submitted.

[2] C. Miehe, H. Dal, L.-M. Schänzel, and A. Raina. “A phase-field model for chemo-mechanical induced fracture in lithium-ion battery electrode particles”. *International Journal for Numerical Methods in Engineering* (2015). ISSN: 1097-0207. DOI: `10.1002/nme.5133`.

Modelling of additive manufactured materials using crystal plasticity and numerical homogenisation

Andreas Kergaßner, Julia Mergheim, Paul Steinmann

In additive manufaturing complex parts are built from thin layers of powder material. In the process called selective electron beam melting (SEBM), the powder is fused by the energy of an electron beam. By using different scan strategies it is possible to control the resulting mesostructure in the material. Figure 1 shows two different resulting grain structures. In the left one long grains are oriented along the building direction. This is why anisotropic behaviour is expected. In the right figure the behaviour is isotropic because the grains are uniformly shaped.

In this project a macroscopic model for the behaviour of additive manufactured materials should be identified. For this purpose, a gradient-enhanced crystal plasticity formulation [1] is used on the mesoscale and the mesoscopic variables are transferred by means of numerical homogenization to the macroscale. This is done for both, the isothermal behaviour after the process as well as for the cooling period during the process, which results in residual strains and accompanying residual stresses.

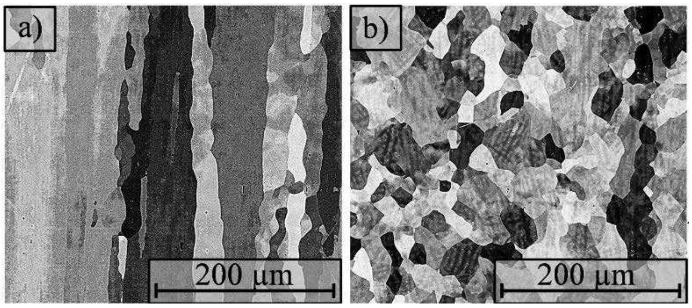


Figure 1: Different grain structures of SEBM manufactured materials [2].

References

[1] M. E Gurtin, L. Anand, and S. P Lele. "Gradient single-crystal plasticity with free energy dependent on dislocation densities". *Journal of the Mechanics and Physics of Solids* 55.9 (2007), pp. 1853–1878.

[2] C. Körner, H. Helmer, A. Bauereiß, and R. F Singer. "Tailoring the grain structure of IN718 during selective electron beam melting". In: *MATEC Web of Conferences*. Vol. 14. EDP Sciences. 2014, p. 08001.

Inverse form finding with application to forming processes

Philipp Landkammer, Paul Steinmann

The aim is to determine - relating to a given forming process - the optimal material (undeformed) configuration of a workpiece when knowing the target spatial (deformed) configuration. Therefore, the nodal positions of a discretized setting based on the finite element method (FEM) are the discrete free parameters of the form finding problem, see Fig. 1. A new algorithm, which is purely based on the nodal data of each iteration, is proposed in [1] to determine the discretized optimal material configuration. *(Collaborative research project: SFB/TR73, www.tr-73.de)*

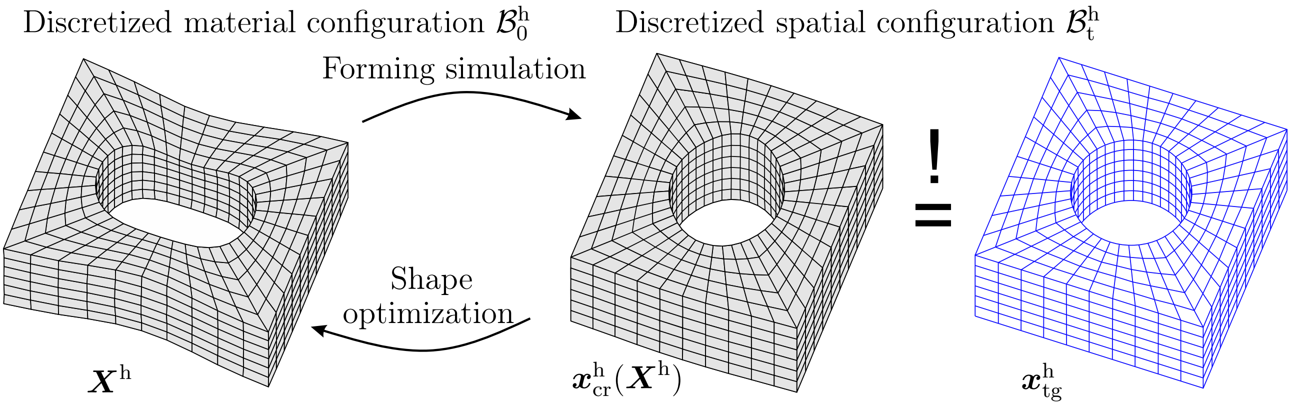


Figure 1: The optimization problem: The nodal positions $\boldsymbol{x}_{\mathrm{tg}}^{I}$ of the target spatial configuration are given, while the optimal nodal positions $\boldsymbol{X}^{I}$ of the material configuration are sought

The iterative strategy can be easily coupled in a non-invasive fashion via subroutines with arbitrary external FEM software. Consequently, the user has not to struggle with the underlying optimization theory and can perform the preprocessing, the solving and the postprocessing within his habitual software. A benchmark comparison with parameter-based sensitivity methods (DDM) from literature for multibody frictional contact problems shows highly promising convergence results when using the new non-inasive method, see Fig. 2. The determination of an optimum workpiece design is of great interest especially for metal forming applications.

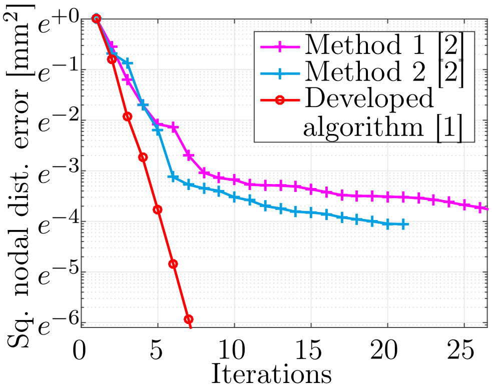


Figure 2: Comparison with literature [2]: Within the non-invasive approach the objective function decreases continuously in each iteration without slowing down.

References

[1] P. Landkammer and P. Steinmann. "A non-invasive heuristic approach to shape optimization in forming". *Comp. Mech., accepted* (2015).

[2] S. Stupkiewicz, J. Lengiewicz, and J. Korelc. "Sensitivity analysis for frictional contact problems in the augmented Lagrangian formulation". *Comp. Meth. Appl. Mech. Engrg.* 99 (2010), pp. 2165–2176.

Continuum thermo-electro-mechanical modeling of a thick walled tube

Markus Mehnert, Mokarram Hossain, Paul Steinmann

This work presents a fully coupled thermo-electro-elastic continuum model for the material behavior of isotropic electro-active elastomers under the influence of a temperature gradient. This class of electro-active polymers is composed of a rubber-like basis material combined with electro-active particles resulting in material properties that can be significantly influenced both by the application of an electric field and a change in temperature. As an analytical example we present the inflation and stretch of a thick walled cylindrical tube (figure 1, left), which is well established in the literature ([1], [2]). The influence of an axial electrical field and radial heating is analysed by the resulting pressure P on the internal surface and the axial force at the end of the tube.

The plot in figure 1 shows the pressure for selected values of the ratio λ_i of the inner radius of the cylinder before and after the inflation at a reference temperature of 293 K. If a radial temperature gradient is applied by heating/cooling of the outer surface of the tube the material softens/stiffens. The application of an axial electric field leads to a further softening of the material (dashed lines).

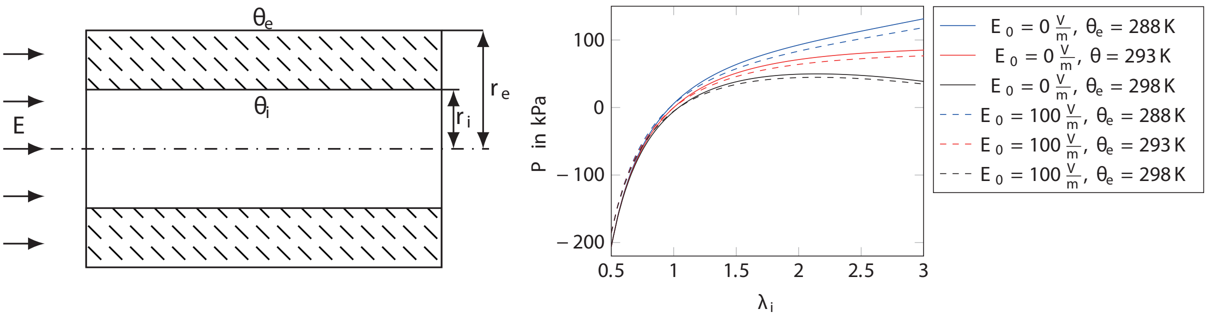


Figure 1: Sketch of the analytical example (left) and plot of the pressure at the inner surface of the tube for selected values of λ_i (right)

References

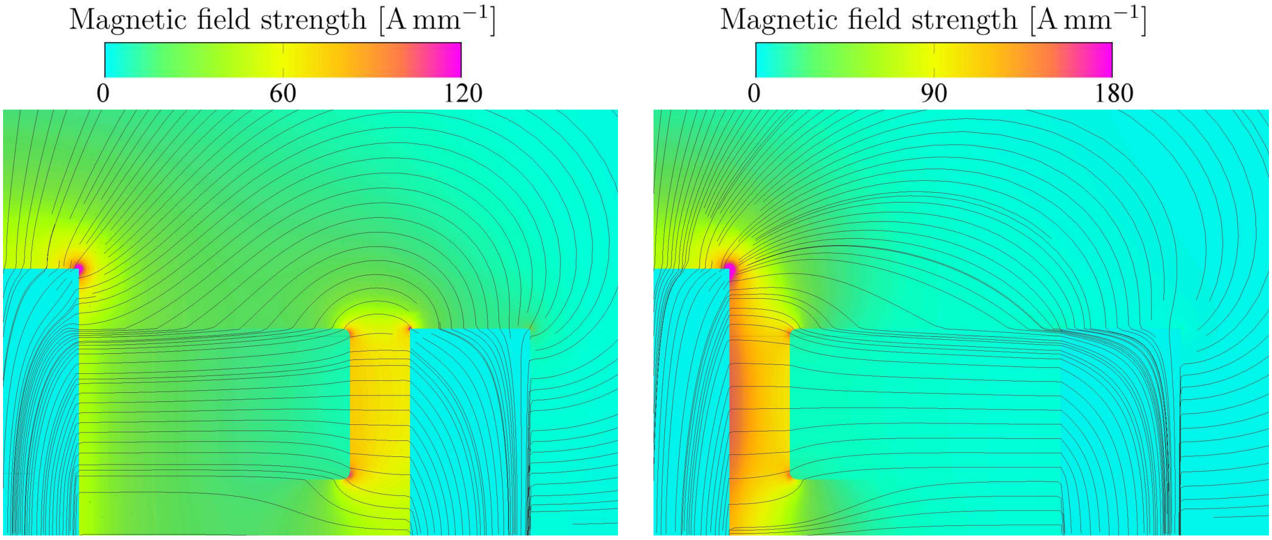
[1] R. Bustamante. "Transversely isotropic nonlinear magneto-active elastomers" (2010).

[2] P. Vu D.K.; Steinmann. "Numerical Modeling of Non-Linear Electroelasticity" (2007).

A framework for computational modelling of magneto-sensitive polymers

Jean-Paul Pelteret, Paul Steinmann

The ERC advanced grant MOCOPOLY (multi-scale, multi-physics modelling and computation of magneto-sensitive polymers) project consists of numerous individual components of research working towards the characterisation of the multi-scale behaviour of magneto-sensitive polymers. Within each field of research exist numerous challenges with respect to the simulation of these materials as their behaviour is highly non-linear and the description of the multi-physics problem is challenging. The matrix is a soft, viscous, incompressible polymer. Its response is affected by the distribution and alignment of stiff embedded particles and the magnetic field that permeates the material.



Contours of magnetic field strength and flux lines for two different designs of magneto-active polymer valves

To this end, a computational framework aimed at connecting the various components of research is under development. A coupled multi-physics FEM framework that incorporates incompressible finite-strain elasticity together with electric/magnetic fields, as well as the free-space surrounding the media, has been developed [1]. It has been used to evaluate and understand both theoretical [2] and practical applications (see figure) in electro- and magneto-elasticity. Current work is focussed on developing a tool-set to perform parameter identification for constitutive models based on both experimental [3] and numerical analysis of rate-dependent, field-responsive materials with complex micro-structures.

References

[1] J-P. V. Pelteret, D. Davydov, A. McBride, D. K. Vu, and P. Steinmann. “Computational electro- and magneto-elasticity for quasi-incompressible media immersed in free space”. *Submitted* (2015).

[2] P. Saxena, J-P. V. Pelteret, and P. Steinmann. “Modelling of iron-filled magneto-active polymers with a dispersed chain-like microstructure”. *European Journal of Mechanics A/Solids* 50 (2014), pp. 132–151. DOI: `10.1016/j.euromechsol.2014.10.005`.

[3] B. Walter, J-P. V. Pelteret, P. Steinmann, J. Kaschta, and D. Schubert. “Detecting wall slip of elastomers in oscillatory shear measurements using parallel-plate rotational rheometry”. *Journal of Rheology, accepted* (2015).

A novel method for particle- and continuum-based simulations: the Capriccio method

Sebastian Pfaller, Paul Steinmann

Plastics usually consist of the actual polymer matrix and quite frequently of various additives. In recent years, very small filler particles, so-called “nanofillers“, have attracted increasing interest. Their size amounts to some nanometres and is thus in the same range as the typical dimensions of the polymer chains. As evident from experiments, they have significant influence on plastics: such ”nanocomposites“ may not only exhibit improved toughness and prolonged fatigue lifetime, but can be employed even as in situ sensors to measure for instance moisture or damage. To capture their specific effects in simulations, we have developed the Capriccio method as a novel numerical tool to combine molecular dynamics techniques with the finite element method [1, 2].

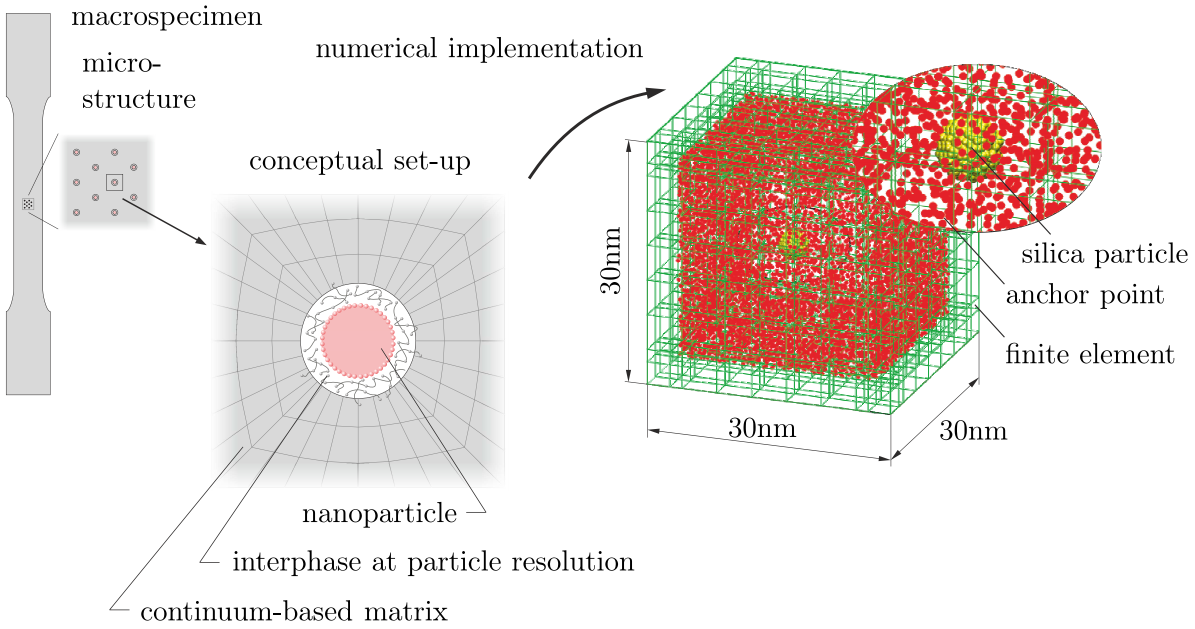


Figure 1: Conceptual set-up (left): the specific microstructure of a macrospecimen is treated by continuum mechanics (pure polymer matrix) combined with particle-based techniques (interphase between nanoparticle and polymer matrix). Numerical implementation (right): a silica nanoparticle is embedded into a polystyrene matrix (both described by molecular dynamics), which is coupled to a finite element region representing pure polystyrene

References

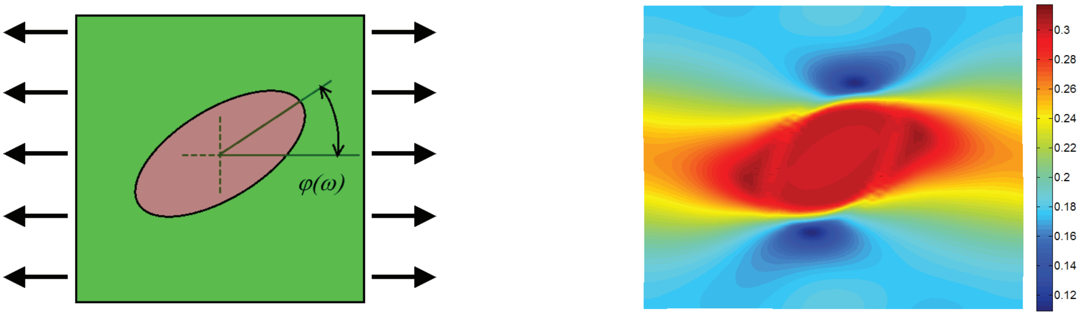
[1] S. Pfaller, M. Rahimi, G. Possart, P. Steinmann, F. Müller-Plathe, and M. C. Böhm. “An Arlequin-based method to couple molecular dynamics and finite element simulations of amorphous polymers and nanocomposites”. *Computer Methods in Applied Mechanics and Engineering* 260 (2013), pp. 109–129.

[2] S.Pfaller, G. Possart, P. Steinmann, M. Rahimi, M. C. Böhm, and F. Müller-Plathe. “Molecular Dynamics Meets Finite Elements: An Approach for Coupled Simulations of Nanocomposites”. In: ed. by Martin Müser, Godehard Sutmann, and R. G. Winkler. Vol. 46. NIC Series. Jülich: John von Neumann Institute, 2013.

SFEM application to computational homogenization

Dmytro Pivovarov, Paul Steinmann

We study stochastic Representative Volume Elements (RVE) of elastic heterogeneous materials. Thereby uncertainties in the geometry of the microstructure (Fig. 1a) result in the random nature of the solution fields (Fig. 1b) thus requiring the use of the stochastic version of the Finite Element Method [2, 1]. The subject of this study is to analyze the influence of uncertainties in the geometry of the micro structure on the stress distribution over the volume of the RVE (Fig. 1b) and on the homogenized stress (Fig. 2).



a)

b)

Figure 1: a) Stochastic RVE of a heterogeneous material with centered elliptic inclusion. The orientation of the major axis is random and is given by the angle $\varphi(\omega)$. b) The mean value of the von Mises stress distributed over the volume of the RVE.

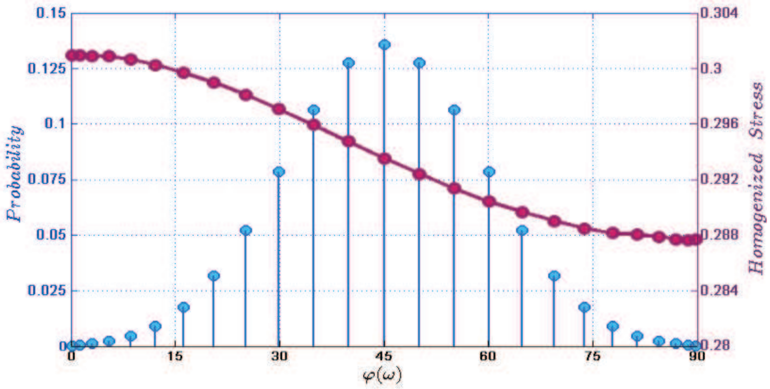


Figure 2: Homogenized (macroscopic) von Mises stress and the correspondent probability distribution function versus random variable $\varphi(\omega)$.

References

[1] Ghanem R. G. and Spanos P. D. *Stochastic finite elements: a spectral approach*. New York: Dover Publications, inc, 2003. ISBN: 0-486-42818-4.

[2] Dmytro Pivovarov and Paul Steinmann. “Modified SFEM for Computational Homogenization of Heterogeneous Materials with Microstructural Geometric Uncertainties”. *Computational Mechanics* (in press). DOI: `10.1007/s00466-015-1224-4`.

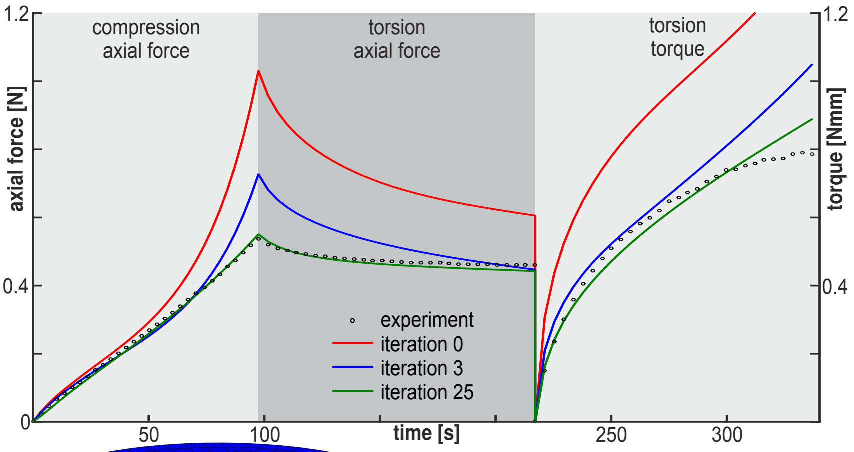
Inverse parameter identification of viscoelastic gels based on combined compression-torsion experiments

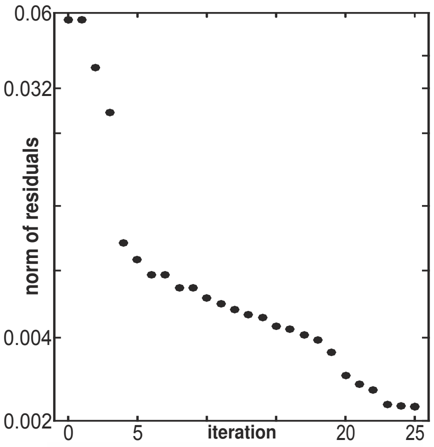
Gunnar Possart, Jan Friederich, Paul Steinmann

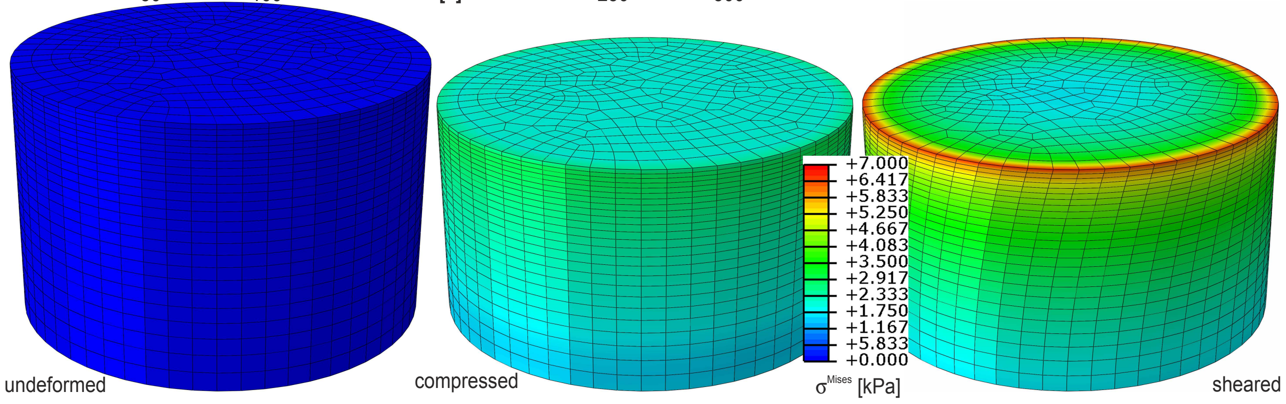
The mechanical properties of a polymer gel are investigated using deformation tests in a rotational plate rheometer. To activate different deformation modes, an axial compression step is followed by torsional shear. The histories of the resultant axial force during both compression and shear as well as the resultant torque are then used for inverse parameter identification, which is based on a gradient descent method and nonlinear finite element simulations.
For the constitutive description of the gel, a modified two-terms hyperfoam model is used. Its energy density in terms of principal stretches λ_i and Jacobian $J = \det \mathbf{F}$

$$\Psi = \sum_{i=1}^{2} \frac{2\mu_i^\infty}{\alpha_i^2} \left[\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3\right] + \frac{J^{\alpha_1\beta} - 1}{\beta} \quad \text{with} \quad \beta = \frac{\nu}{1 - 2\nu} \, ,$$

is governed by two shear moduli μ_i^∞, Poisson's ratio ν and two coefficients α_i. To capture viscoelastic stress relaxations, which are evident e.g. from the decrease in the axial force during torsion, the constitutive description is extended by a two terms Prony series, governed by two relaxation moduli c_i and relaxation times τ_i. The list of ten parameters to be identified with respect to the experimental data is completed by the Coulomb friction coefficient μ acting between gel and rheometer walls.







it.	μ_1^∞[kPa]	α_1[-]	μ_2^∞[kPa]	α_2[-]	ν[-]	c_1[%]	τ_1[s]	c_2[%]	τ_2[s]	μ[-]
0	0.37	81.81	6.85	7.96	0.242	26.03	6.61	35.12	65.85	0.040
25	5.15	16.86	0.02	8.57	0.302	17.14	9.89	20.20	17.95	0.103

Interphases in silica-polystyrene-nanocomposites simulated by a novel hybrid MD-FE framework

Sebastian Pfaller, Gunnar Possart, and Paul Steinmann

The mechanical behavior of silica - polystyrene nanocomposites is investigated using our novel Capriccio method [2]. It couples a particle domain to a continuum, whereby regions of specific interest, as e.g. interphases around nanoparticles, are described at molecular length scale. The polymer matrix that surrounds the nanoparticle is treated continuum-based by the FE-method. With such a set-up it is possible to simulate agglomerating nanoparticles in a large amount of polymer matrix. This kind of investigations usually exceeds the capability of pure particle-based approaches due to the huge number of degrees of freedom that would have to be considered. In our recent publication [1] we investigate strain-like quantities in systems containing two silica nanoparticles at different initial distances and compare them to pure continuum descriptions. The coupled simulation is able to reveal interphase effects due to the large resolution in the MD region. This can be used to substitute physical experiments to characterize polymer interphases around particles: The differences in the behaviour of coupled and purely continuum simulations of the same configuration could be employed to calibrate e.g. cohesive zone models in an extended continuum description also considering interphases.

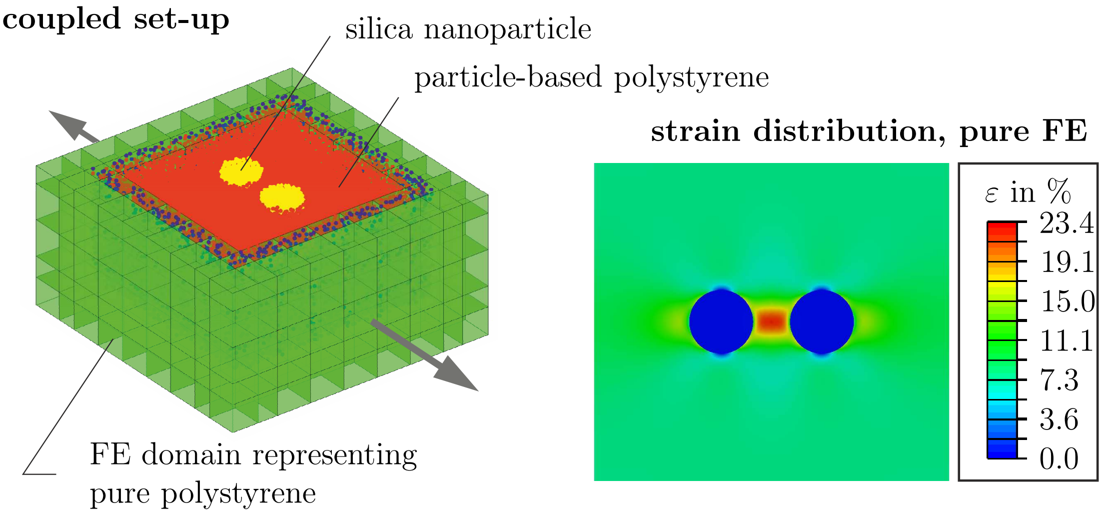


Figure 1: The coupled system consists of two silica nanoparticles embedded into a polystyrene matrix, both described by molecular dynamics and enclosed by a finite element domain (left). The distribution of the local tensile strain ε in the center plane of a corresponding pure FE system (overall strain $\varepsilon^{MD} = 7.75\%$) shows significant inhomogeneities (right).

References

[1] S. Pfaller, G. Possart, M. Rahimi, F. Müller-Plathe, P. Steinmann, and M. C. Böhm. "Investigation of Interphase Effects in Silica-Polystyrene-Nanocomposites Based on a Novel Hybrid MD-FE Simulation Framework". *submitted to Physical Review E* (2015).

[2] S. Pfaller, M. Rahimi, G. Possart, P. Steinmann, F. Müller-Plathe, and M. C. Böhm. "An Arlequin-based method to couple molecular dynamics and finite element simulations of amorphous polymers and nanocomposites". *Computer Methods in Applied Mechanics and Engineering* 260 (2013), pp. 109–129.

Thermomechanical modelling and simulation of selective beam melting processes

Daniel Riedlbauer, Paul Steinmann, Julia Mergheim

Selective beam melting processes are used to additively build geometrical complex parts from thin layers of metal powder material. The energy of an electron or laser beam fuses the powder in defined, locally- restricted points in the current layer to melt the powder into the already fused and recongealed material of the previous processed layers. Therefore the beam energy causes the powder particles to undergo an irreversible phase change from a powder particle to melt and then to solid. To build up the part thousands of layers have to be processed since the thickness of one powder layer is in the range from $50\mu m$ to $100\mu m$. Hence selective beam melting processes as selective laser melting (SLM) or selective electron beam melting (SEBM) belong to the class of additive manufacturing processes. In the SLM process for the polymer PA12 and in the SEBM process for the metal alloy TiAL6V4 very high temperatures of 290°C and 3000°C occur, respectively, and might result in residual stresses and warpage of the produced part.

To predict and reduce the residual stress and warpage a simulation tool is developed, which is based on a thermomechanical model. The model describes the powder material not as single powder particles, but as a continuum and the strong nonlinear temperature dependency of the material parameters is included [2]. For the discretization in time a very stable and computationally efficient implicit Runge-Kutta method is used. The implementation of the model is done by using the finite element library deal.II [1]. For describing the temperature-dependent mechanical behaviour of the TiAl6V4 powder material, a thermo-elasto-visco-plastic material model is developed. Similarly a thermo-visco-elastic material model is used to characterize the material behaviour in the SLM process of PA12. To obtain more precise results from the simulation the finite element mesh in the vicinity of the beam is adaptively refined due to the extreme temperature gradients induced by the beam.

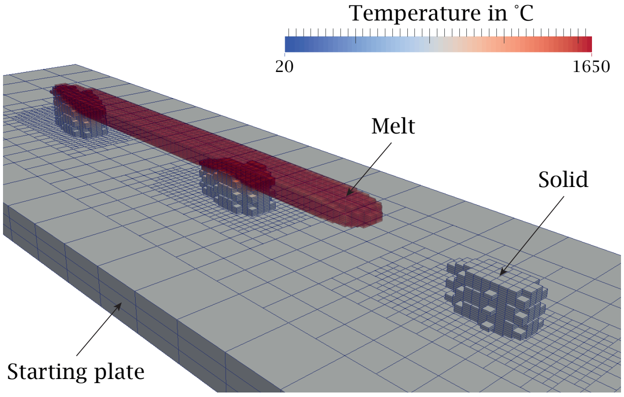


Figure 1: Selective electron beam melting of Ti-6Al-4V

References

[1] W. Bangerth, R. Hartmann, and G. Kanschat. “deal.II – a general purpose object oriented finite element library”. *ACM Trans. Math. Softw.* 33 (2007), pp. 24/1–24/27.

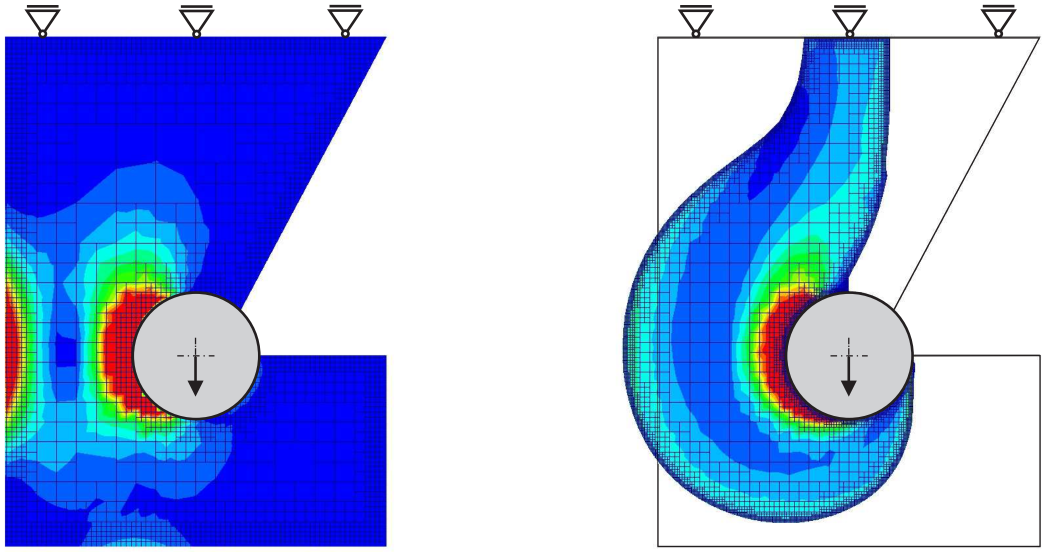
[2] D. Riedlbauer, M. Drexler, D. Drummer, P. Steinmann, and J. Mergheim. “Modelling, simulation and experimental validation of heat transfer in selective laser melting of the polymeric material PA12”. *Computational Materials Science* 93 (2014), pp. 239–248.

Structural shape optimization using a fictitious domain discretization technique

Stefan Riehl, Paul Steinmann

This contribution is concerned with the formulation and implementation of a method for structural shape optimization within a fictitious domain setting [1]. Thereby, the main consideration is to embed the evolving structural component into a uniform finite element mesh which is then used for the structural analyses throughout the course of the optimization.

A boundary tracking procedure based on adaptive mesh refinement is used to identify interior and exterior elements, as well as such elements that are intersected by the physical domain boundary of the structural component. By this mechanism, we avoid the need to provide an updated finite element mesh that conforms to the boundary of the structural component for every single design iteration [2].



a) b)

Figure 1: Optimal shape design problem for a hook-like structure. **a** Initial design and mechanical boundary conditions. **b** Optimal design arrived at. The contour plot shows the distribution of the strain energy density for the initial and the optimal design, respectively.

In order to account for the geometric mismatch between the boundary of the structural component and its non-conforming finite element representation within the fictitious domain setting, a selective domain integration procedure is employed for all elements that are intersected by the physical domain boundary, cf. the optimal design problem depicted in Fig. 1.

References

[1] E. Nadal, J. J. Ródenas, J. Albelda, M. Tur, J. E. Tarancón, and F. J. Fuenmayor. “Efficient Finite Element Methodology Based on Cartesian Grids: Application to Structural Shape Optimization”. *Abstract and Applied Analysis* 2013 (2013), pp. 1 –19.

[2] Stefan Riehl and Paul Steinmann. “An integrated approach to shape optimization and mesh adaptivity based on material residual forces”. *Computer Methods in Applied Mechanics and Engineering* 278 (2014), pp. 640 –663.

Multi-scale modeling of heterogeneous materials

Saba Saeb[1], **Ali Javili**[2], **Paul Steinmann**[1]

[1] Chair of Applied Mechanics, University of Erlangen-Nuremberg
[2] Department of Civil and Environmental Engineering, Stanford University

The aim of this project is to present a unifying framework to capture the mechanical behavior of heterogeneous materials at finite strains using computational homogenization, thereby elaborating on computational aspects of the finite element method. The underlying assumption of computational homogenization is the separation of length scales and hence, the material response at the macro scale is computed from averaging the micro-sample (RVE) behavior. In doing so, the equivalence of the stress power between the two scales, the Hill–Mandel condition, should be satisfied via imposing proper boundary conditions. Among variety of boundary conditions fulfilling this condition, here we report on Dirichlet (DBC), periodic displacement and anti-periodic traction (PBC) and Neumann boundary conditions (NBC).

While computational algorithms to implement DBC and PBC are well-established, special care should be taken to deal with the stiffness matrix singularity when prescribing pure Neumann boundary conditions on the RVE to implement NBC. A novel geometrically independent yet computationally inexpensive algorithm to implement NBC for finite deformation analysis is presented and its robustness is demonstrated through providing numerical examples [1].

The influence of the choice of the boundary conditions on the overall response of a RVE corresponding to the microstructure of a uniformly arranged particle reinforced composite is investigated. It is observed that regardless of the type and value of the deformations and also material properties, the results obtained under DBC and NBC overestimates and underestimates the ones from PBC, respectively.

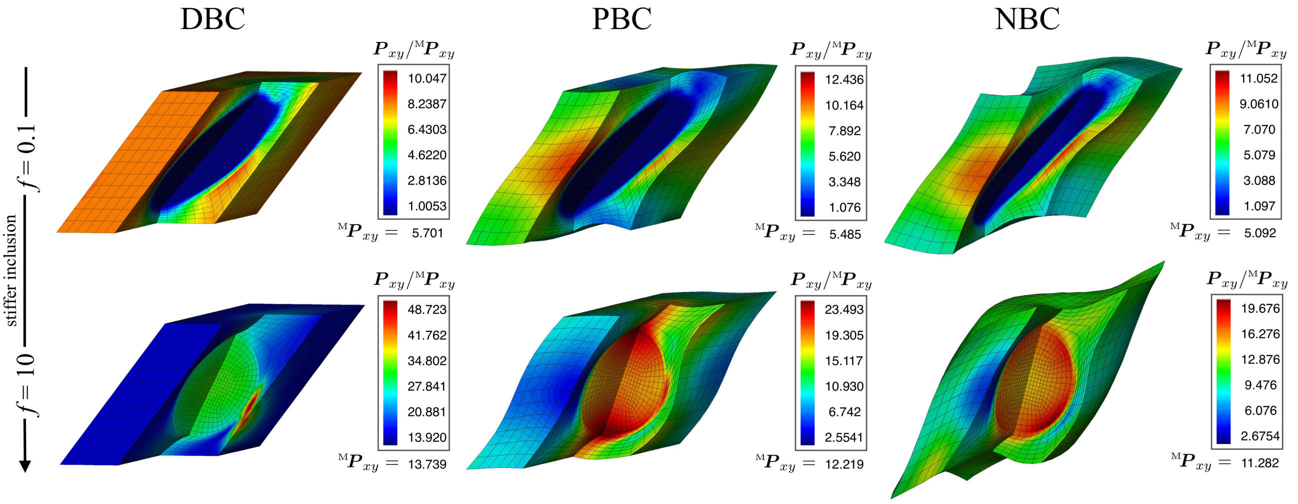


Figure 1: Distribution of the microscopic Piola stress (xy-component) normalized by its macroscopic counterpart.

References

[1] S. Saeb, A. Javili, and P. Steinmann. "Aspects of computational homogenization at finite deformations. A unifying review from Reuss' to Voigt's bound. submitted". *Applied Mechanics Reviews* (2015).

A thermo-viscoplastic constitutive model for low and high temperatures and strain rates

Stefan Schindler, Paul Steinmann

The plastic behavior of metals depends not only on the strain but also on the current temperature and strain rate. Seidt and Gilat [2] investigated these dependencies via compression tests at low strain rates for various constant temperatures, and via adiabatic compression tests at high strain rates (see Fig.1). The function defining the yield stress is usually - like for instance in the Johnson-Cook model - multiplicatively decomposed into three functions, each capturing one of the phenomena strain hardening, strain rate hardening, and thermal softening. Consequently, the evolution of strain hardening stays constant for arbitrary constant temperatures or arbitrary constant strain rates and thus allows one to capture some but not all of the measured effects at the same time.

The novel constitutive law described in [1] is based on the von Mises equivalent stress and decomposes the function defining the yield stress additively into an initial yield stress depending on temperature and strain rate and a stress evolution which considers a combined dependency on strain, strain rate, and temperature. The new model is suitable to describe the material behavior over a large range of loading conditions, in detail from small to large plastic strains, low and high strain rates, and from room temperature to melting temperature (see Fig.1). It is particularly promising for applications with combined loading conditions, like high strain rates and high temperatures at the chip formation of cutting processes. Furthermore, with the use of just one material model lots of applications could be modeled, e.g. bulk forming, hot working, or crash simulations.

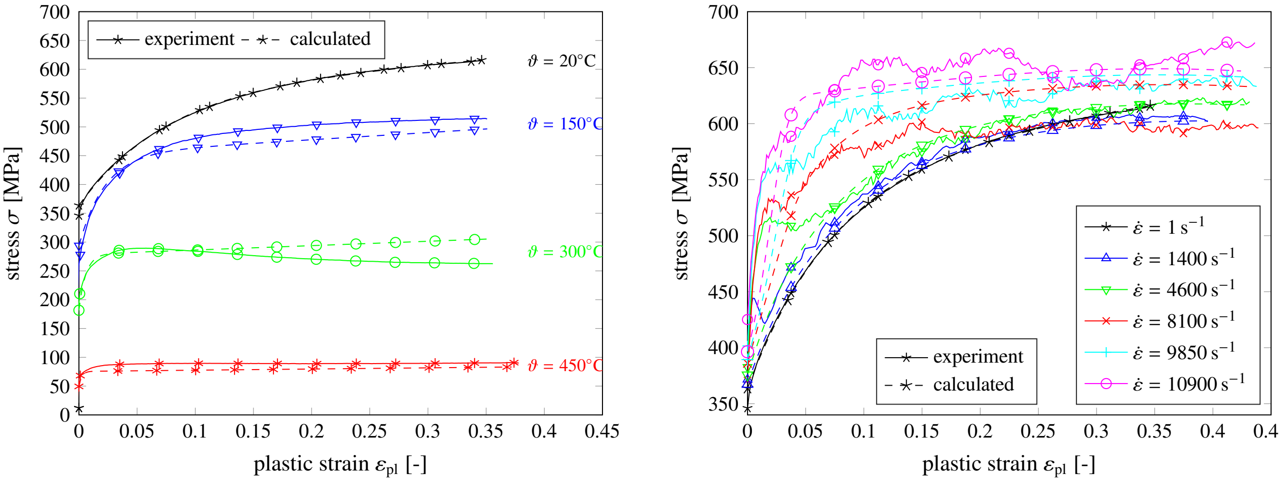


Figure 1: temperature dependency (left) and strain rate dependency (right) of the yield stress

References

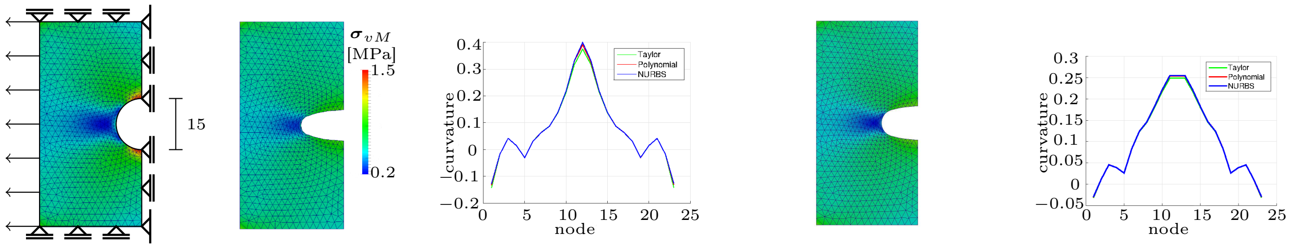
[1] S. Schindler, P. Steinmann, J.C. Aurich, and M. Zimmermann. “A viscoplastic constitutive model for low and high strain rates and temperatures”. *IJSS* (Submitted 2015).

[2] J.D. Seidt and A. Gilat. “Plastic deformation of 2024-T351 aluminum plate over a wide range of loading conditions”. *IJSS* 50.2 (2013), pp. 1781–1790.

Curvature approximation on FE–meshes for node–based shape optimization

Oliver Schmitt and Paul Steinmann

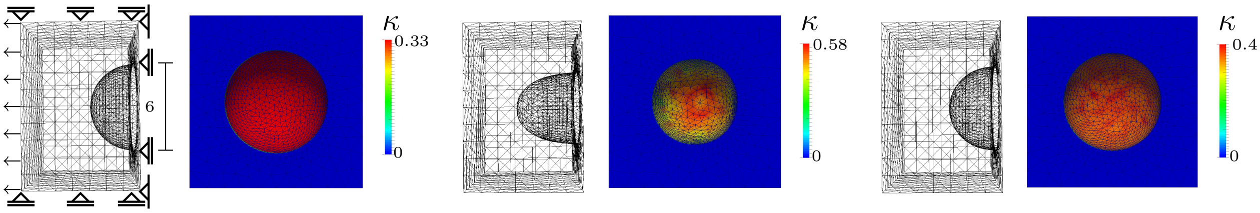
With regard to manufacturing constraints in shape optimization problems, e.g. for milling processes, the control of the curvature of the considered domain is of interest. However, in node–based shape optimization the boundary of the considered body is given by the boundary nodes of the FE discretization. In two space dimensions, these are employed to describe the boundary of the FE system by smooth curves, such as the graph of a function, a NURBS curve or a general curve parameterized by its arc–length [2], and thereby approximate its curvature. In figure 1, an application of the curvature approximations on a half model of an infinite plate with a circular whole is illustrated.



(a) (b) (c) (d) (e)

Figure 1: (a) Initial geometry and problem definition, (b) geometry after a compliance optimization with volume constraint without curvature control and (c) the resulting curvature distribution in the half circle, (d) geometry after a compliance optimization with volume and curvature constraint ($\kappa_{max} = 0.25$) and (e) the resulting curvature distribution in the half circle.

In the case of three space dimensions, the curvature describes the rate of change of a tangential plane at a point on the surface. Therefore the embedded Weingarten map [1], which can be represented as a matrix, is approximated using the FE–node coordinates. The maximum eigenvalue of this matrix equals the maximum directional curvature of the surface in the respective FE–node. In figure 2 the curvature approximation is demonstrated on a half model of a cube with a circular whole.



(a) (b) (c) (d) (e) (f)

Figure 2: (a) Initial geometry and (b) initial curvature distribution, (c) geometry and (d) curvature distribution after a compliance minimization with volume constraint and (e) geometry and (f) curvature distribution after a compliance minimization with volume and curvature constraint ($\kappa_{max} = 0.4$).

References

[1] Jörg Peters and Ulrich Reif. *Subdivision surfaces*. Springer, 2008.

[2] Oliver Schmitt and Paul Steinmann. “On curvature control in node–based shape optimization”. In: *PMM-J Appl Math Mec+*. 2015.

Parameter identification for sheet-bulk metal forming

Benjamin Söhngen, Kai Willner

The manufacturing of near-net-shape sheet metal components is part of current research. As part of the Collaborative Research Centre (Transregio) 73, which approaches the challenge of sheet-bulk metal forming, this work addresses the identification of sheet metal parameters.

For the identification process the so called Finite-Element-Model-Updating (FEMU) strategy is used. Here the displacement field from a biaxial tension test obtained by digital image correlation (DIC) is compared to the results from a numerical experiment conducted with the finite element method. Further information and results can be found in [1], [3] and [2].

Besides the inverse identification of the material parameters it is crucial to obtain the yield surface through experiments as well. It is therefore necessary to define a measure of plasticity that is applicable to both uni- and mutliaxial stress states. The approach that is used in this work is based on the plastic work W which is defined by the integral of the true (Cauchy) stress σ over the plastic strain $\varepsilon_{\mathrm{pl}}$. As a reference value the plastic work from uniaxial tension W_0 is evaluated for different amounts of plastic strain (e.g. 0.2%, 1.0%, 2.0%, 3.0%, ...), cf. Fig. 1. The yield stresses in biaxial stress states are then determined by enforcing the equality $W_0 = W_1 + W_2$, where W_1 and W_2 are defined as the plastic works for axis A1 and A2 (cf. Fig. 2). With this method the evolution of the yield surface can be identified by varying the force ratios A1:A2 as depicted in Fig. 3

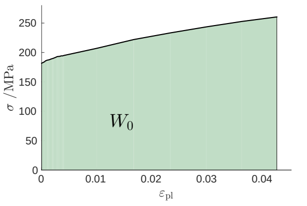


Figure 1: Plastic work from uniaxial tension test

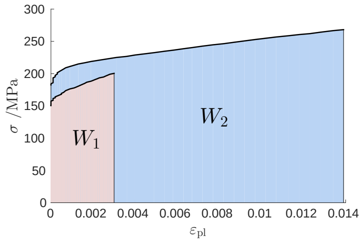


Figure 2: Plastic work from biaxial tension test with a force ratio A1:A2 of 3:4

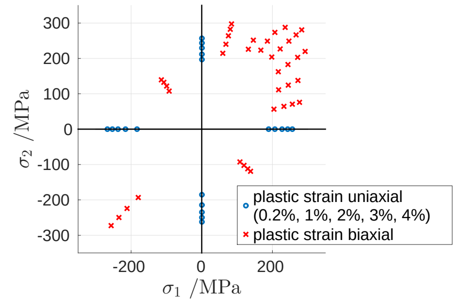


Figure 3: Evolution of the yield surface

References

[1] Söhngen B. and Willner K. "Inverse Parameter Identification for Orthotropic Elasto-Plastic Sheet-Steel". In: *Special Issue: 86th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM).* (Aachen). Ed. by Zavarise G., Cinnella P., and Campiti M. Vol. 15. 1. WILEY-VCH Verlag, 2015, pp. 361–362.

[2] Landkammer P., Loderer A., Krebs E., Söhngen B., Steinmann P., Hausotte T., Kersting P., Biermann D., and Willner K. "Experimental verification of a benchmark forming simulation". *Key Engineering Materials* 639 (2015), pp. 251–258.

[3] Landkammer P., Söhngen B., Loderer A., Krebs E., Steinmann P., Willner K., Hausotte T., Kersting P., and Biermann D. "Experimentelle Verifizierung eines Benchmark-Umformprozesses". In: *Tagungsband zum 18. Workshop Simulation in der Umformtechnik & 3. Industriekolloquium Blechmassivumformung 2015 - DFG Transregio 73.* (Aachen). Ed. by Tekkaya A. E.; Liewald M.; Merklein M.; Behrens B.-A. Shaker Verlag, 2015, pp. 91–110.

Computational Homogenisation using Reduced-Order Modelling

Dominic Soldner, Paul Steinmann, Julia Mergheim

Computational homogenisation requires the repeated solution of similar microscopic boundary value problems. To reduce computational cost, reduced-order modelling (ROM) techniques can be applied using the Proper Orthogonal Decomposition (POD). Within a POD-based approach for first order computational homogenisation of hyperelastic material, the Discrete Empirical Interpolation Method (DEIM) [1] and the Sparse Matrix DEIM [3] are used to approximate the nonlinear term and its Jacobian, using truncated bases $\mathbf{U^r}_\bullet$, e.g. for the nonlinear term $\mathbf{U^r}_\mathbf{f}$.

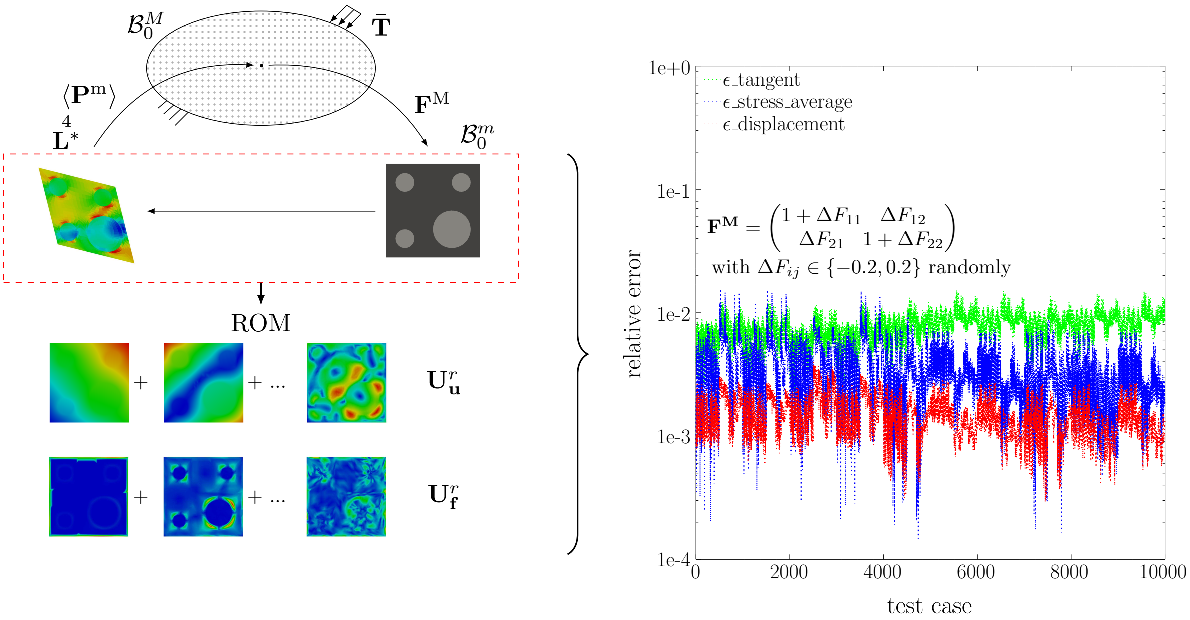


Figure 1: ROM for the BVP on the micro-scale and the errors for different quantities

Considering the snapshots only at a converged state leads to a ill-posed system characterised by a-priori equilibrium. Hence, the nonlinear term and the vector representation of the sparse Jacobian are stored in every iteration step. A more detailed discussion can be found in [2]. For the present example the total number of degrees of freedom (DOF) is reduced from 2802 to 13, while the number of DEIM indices is 57 and 42 for the nonlinear term and its Jacobian respectively. The errors of the displacement field, the averaged Piola-Kirchhoff stress and the tangent modulus are computed for a set of test cases in terms of the L2- and the Frobenius norm respectively.

References

[1] Saifon Chaturantabut and Danny C Sorensen. “Nonlinear Model Reduction via Discrete Empirical Interpolation”. PhD thesis. Rice University, 2011.

[2] Dominic Soldner. “Computationl Homogenisation using Reduced-Order Modelling applied to Hyperelasticity”. MA thesis. Friedrich-Alexander-Universität Erlangen-Nürnberg, 2015.

[3] Răzvan Ştefănescu and Adrian Sandu. “Efficient approximation of sparse Jacobians for time-implicit reduced order models”. *arXiv preprint arXiv:1409.5506* (2014).

Efficient Harmonic Balance Computation of a Resonator Structure

Dominik Süß, Kai Willner

The system investigated here is a resonator including a bolted lap joint. In [3] this system is modeled by a simple 3-DOF model and because of the special design of the structure this works very well. But in order to get a way of predicting the stationary dynamic behavior of jointed structures in general, here the Finite Element Method is applied. A part of the mesh of the chosen FEM model is pictured in figure 1 overlaid to a picture of the real system.

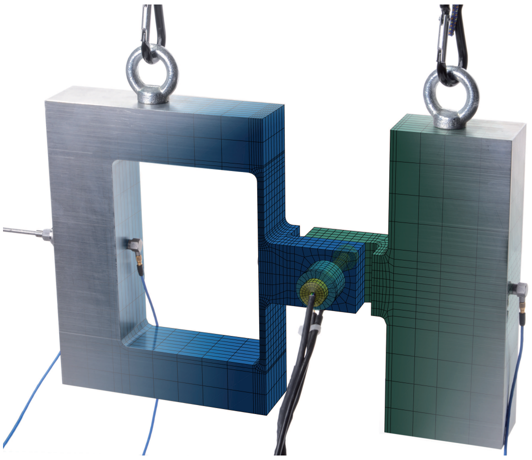


Figure 1: overlay of the real structure and the chosen finite element mesh.

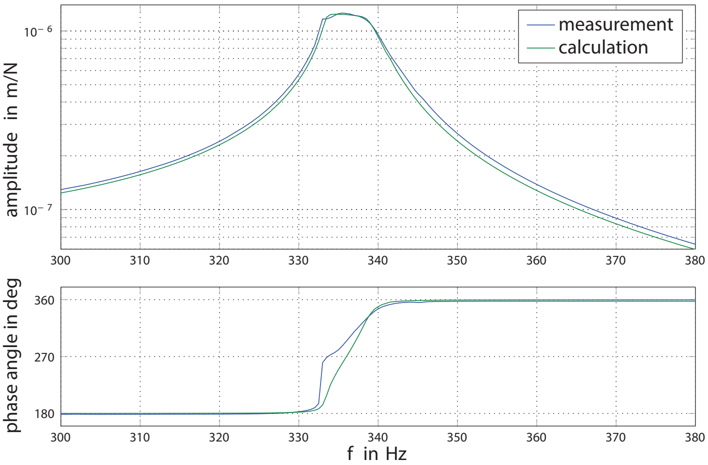


Figure 2: comparison of measured and calculated frequency responses.

The two parts of the system are discretized using hexahedral elements. For discretizing the contact plane (red frame in figure 1) Zero Thickness elements are implemented, see e.g. [1]. In order to compute the stationary behavior of the system in the frequency domain an efficient Adaptive (Multi)Harmonic Balance Method (AHBM) in combination with the Alternating Frequency Time Domain Method (AFT) is applied. For solving the system equations a Newton-Raphson type solver is applied. Using the constitutive law also applied in [2] it is possible to compute the partial derivatives needed for this solver analytically in the framework of the AFT algorithm. The measurements for getting reference FRFs of the real system are recorded using a shaker and performing a stepped sine excitation of the structure. Using a least squares model updating algorithm the calculation results are fitted with respect to the measured curves to identify the contact parameters. The good correlation of a measured and a computed FRF calculated accounting for 11 harmonics can be seen in figure 2.

References

[1] D. Süß, M. Jerschl, and K. Willner. “Numerical Investigation of Jointed Oscillators Using Harmonic Balance Techniques”. In: *Proceedings of ISMA 2014 International Conference on Noise and Vibration Engineering*. Heverlee: KU Leuven, 2014, pp. 3233–3238. ISBN: 9789073802919.

[2] D. Süß and K. Willner. “Investigation of a jointed friction oscillator using the Multiharmonic Balance Method”. *Mechanical Systems and Signal Processing* 52-53.1 (2015), pp. 73–87. ISSN: 08883270. DOI: `\url{10.1016/j.ymssp.2014.08.003}`.

[3] D. Süß and K. Willner. “Parameter Identification for Nonlinear Dynamical Systems using Multi Harmonic Balance Techniques”. *PAMM* 11.1 (2011), pp. 293–294. ISSN: 16177061. DOI: `\url{10.1002/pamm.201110138}`.

Nonlinear viscoelastic behavior of magneto-rheological elastomers

Bastian Walter, Joachim Kaschta[1], Dirk. W. Schubert[1], Paul Steinmann

[1] Institute of Polymer Materials, Friedrich-Alexander-University Erlangen-Nuremberg

Magneto-rheological elastomers (MREs) are smart field-responsive composite materials. Their viscoelastic behavior, as a function of the applied magnetic field, is typically studied using parallel-plate rotational rheometry (amongst other techniques). One point of interest is the field-responsive nonlinear viscoelastic behavior that is closely linked to the change of the particles network at large shear deformation. For this purpose, large amplitude oscillatory shear experiments are commonly conducted with *ex situ* pre-prepared disc-shaped samples at magnetic inductions up to 1 T applied perpendicular to the shear direction.

However, it is most likely that this experimental procedure leads to questionable data (i.e. nonlinear effects) that are due to wall slip, a measuring artifact caused by an adhesive failure at the sample-plate interface. Therefore, a revised sample preparation technique, namely curing within the rheometer (*in situ*), was introduced by Walter et al. [1] to ensure a perfect force transfer onto the sample. Figure 1 showcases a representative example of the nonlinear viscoelastic behavior of an *in situ* cured MRE containing a magnetizable particle volume filler fraction of 30 %. The data are obtained by oscillatory strain sweep experiments performed up to $\gamma_0 = 1$ at $\omega = 10\,\mathrm{rad\,s^{-1}}$ and $T = 45\,°\mathrm{C}$ utilizing the revised sample preparation technique.

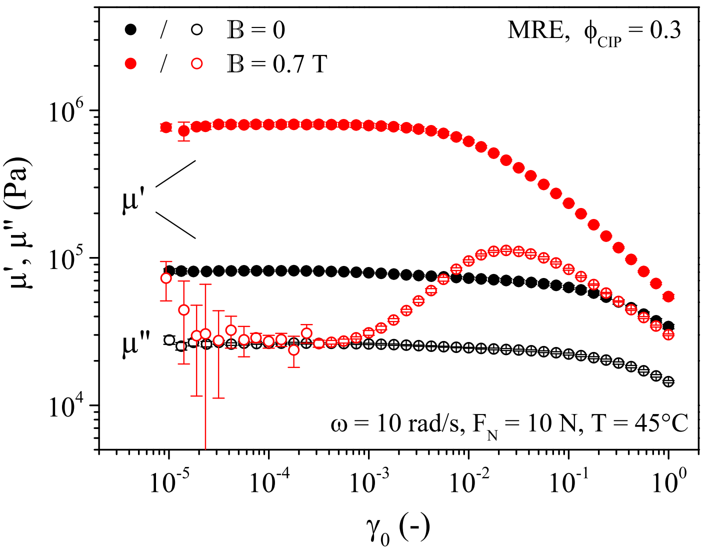


Figure 1: Oscillatory strain sweep experiment on a MRE; without (black) and with (red) the application of a magnetic field.

Although the material composition is above the percolation threshold the nonlinear viscoelastic response related to particle-particle interactions below $\gamma_0 = 0.01$ is hardly visible without the application of a magnetic field. Above $\gamma_0 = 0.01$ both the storage and the loss modulus decrease as expected. For a magnetic induction of $\mathbf{B} = 0.7\,\mathrm{T}$ the magneto-rheological effect, i.e. relative change of the shear modulus within the LVE regime due to strong induced magnetic dipole particle-particle interactions, is evident. With an increasing excitation amplitude (above $\gamma_0 = 0.001$) the polarized particle's interaction in conjunction with the internal microstructural changes leads to a significant decrease in the storage modulus, whereas the loss modulus increases and passes through a pronounced maximum. The latter displays the dissipative nature of the magnetic field induced particle interaction in large amplitude oscillatory shear experiments.

References

[1] B. Walter, J. P. Pelteret, P. Steinmann, J. Kaschta, and D. W. Schubert. “Detecting wall slip of elastomers in oscillatory shear measurements using parallel-plate rotational rheometry”. *Journal of Rheology* accepted (2015).

Eigenpath Analysis of Rotating Mechanical Systems based on ALE-Formulation

Tim Weidauer, Kai Willner

For solving finite element problems subjected to large mesh distortion and movements, a so-called *ALE*-approach (*ALE* = Arbitrary LAGRANGIAN-EULERIAN) as presented in [3] and [1] can be employed. Its basic principle focusses on introducing an arbitrarily moved reference configuration $\mathcal{X}(\mathcal{B})$, which coincides neither with the material nor the spatial configuration $\mathbf{X}(\mathcal{B})$ and $\mathbf{x}(\mathcal{B})$. Thus, the time-dependent map $\boldsymbol{\phi}(\mathbf{X}, t)$ from material to spatial domain can be decomposed into

$$\boldsymbol{\phi} = \hat{\boldsymbol{\phi}} \circ \mathcal{X},$$

where $\mathcal{X}$ yields a reference configuration $\mathcal{X}(\mathcal{B})$ and $\hat{\boldsymbol{\phi}}$ transforms this preliminary state into the body's final spatial positioning $\mathbf{x}(\mathcal{B})$:

$$\mathbf{x}(\mathcal{B}) = \boldsymbol{\phi}(\mathbf{X}, t) = \hat{\boldsymbol{\phi}}(\underbrace{\mathcal{X}(\mathbf{X}, t)}_{\text{ref. config.}}, t), \quad \text{with} \;\; \mathbf{X} = \mathbf{X}(\mathcal{B}).$$

For *rotating* systems, the *ALE*-approach shows a special characteristic since the rigid body rotation in its role as guiding movement $\mathcal{X}$ is known from the start. It enables neglection of the rotational displacements for the mesh, when convection terms in the momentum and continuity equations are considered. This way, the mesh remains still in its initial position, which facilitates coupling of the rotating body with other, static components via frictional contact. As a first step, *JFEM* – an in-house Matlab-FE-code – was expanded by the *ALE*-capabilities for stationary rotating systems and will be further developed towards frictional coupling in the future.

When bodies start to rotate, they alter their dynamic behaviour characterised by the eigenvalues and eigenvectors. One has to account for gyroscopic and inertia effects, whereby the gyroscopic terms lead to asymmetry in the imaginary parts of the formerly conjugated complex eigenvalues. This parameter-dependent asymmetry, unique for every single pair of eigenvalues, induces a split in the eigen frequencies of the system. For tracking the paths of the eigenvalues under increasing spin velocity, e.g. the *eigenpaths*, a continuation algorithm as in [2] was implemented into *JFEM*. In combination with the *ALE*-functionality it enables further research in the field of oscillation behaviour of rotating mechanical systems.

References

[1] Ted Belytschko, Wing Kam Liu, Brian Moran, and Khalil Elkhodary. *Nonlinear finite elements for continua and structures*. John Wiley & Sons, 2013.

[2] Lothar Gaul and Nils Wagner. "Eigenpath dynamics of non-conservative mechanical systems such as disc brakes". *IMAC XXII Dearborn, Michigan, January* (2004), pp. 26–29.

[3] Udo Nackenhorst. "Numerische Analyse der Dynamik rollender Körper mit der Finite Elemente Methode". Habilitation. Institut für Mechanik, Universität der Bundeswehr Hamburg, 2000.

The effect of static strain ageing on the isotropic hardening behaviour of austenitic stainless steel

Paul Wilhelm[1], **Paul Steinmann**[2], **Jürgen Rudolph**[1]

[1] AREVA GmbH
[2] Chair of Applied Mechanics, University of Erlangen-Nuremberg

Static strain ageing refers to the increase in yield stress observed when re-loading a specimen, which has been unloaded some time after pre-straining [1]. The effect depends on steel type, temperature and time. In this project the influence of hold periods at constant stress levels during strain-controlled cyclic loading were examined on austenitic stainless steel specimens (X6CrNiNb18-10). The strain controlled fatigue tests ($R = -1$, $\varepsilon_\mathrm{a} = 0.4\,\%$, $T = 240\,°\mathrm{C}$) were stopped at 450 cycles and the specimens were heat treated in the autoclave at a constant stress level of 170 MPa for three days at 290 °C. After the heat treatment cyclic loading continued under the same conditions as before. At about 900 cycles the fatigue tests were stopped, again, and the specimens were heat treated for a second time. Then the strain controlled cyclic loading continued till specimen failure occured, see Fig. 1.

An evolutionary plasticity model is developed to address the effect of static strain ageing. The constitutive model is a modification of the CHABOCHE [2] visco-plastic material model, which can deal with both cyclic effects, such as combined isotropic and kinematic hardening, and rate-dependent effects, associated with visco-plasticity. A simple 1D formulation of the model without isotropic hardening or softening and with one back stress tensor is published in [3].

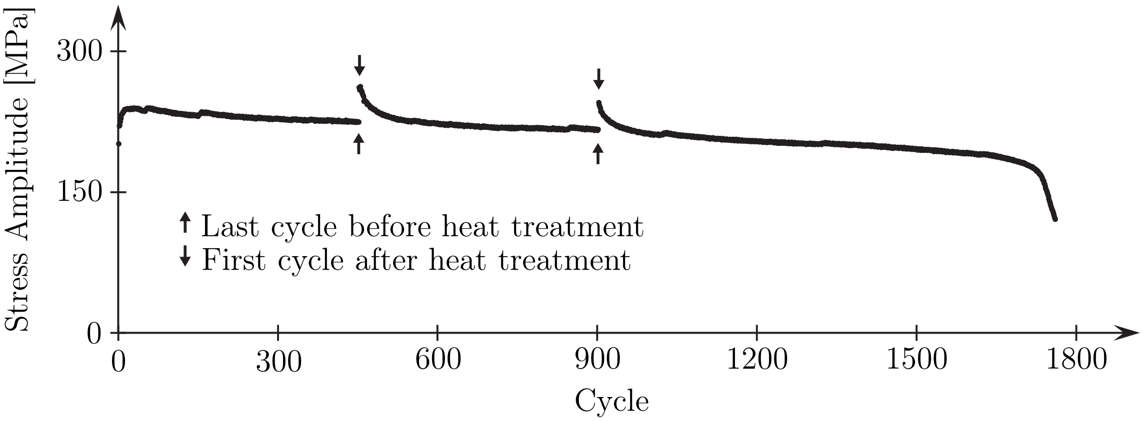


Figure 1: Maximum stress amplitude up to fracture

References

[1] R. Larsson and L. Nilsson. “On the modelling of strain ageing in a metastable austenitic stainless steel”. *Journal of Materials Processing Technology* 212.1 (2012), pp. 46–58.

[2] J. Lemaitre and J.-L. Chaboche. *Mechanics of solid materials.* New York: Cambridge University Press, 2000.

[3] P. Wilhelm, P. Steinmann, and J. Rudolph. *The Effect of Heat Treatments at Different Plastic States on the Isotropic Hardening Behaviour of Austenitic Stainless Steel.* Hamburg: Annual Meeting on Nuclear Technology, 2016.

Computational aspects of homogenization in magneto-mechanics

Reza Zabihyan[1], **Ali Javili**[2], **Julia Mergheim**[1], **Paul Steinmann**[1]

[1] Chair of Applied Mechanics, University of Erlangen–Nuremberg, Germany
[2] Chair of Civil and Environmental Engineering, Stanford University, USA

The behaviour of the heterogeneous magnetorheological elastomers undergoing large deformations under the action of magnetic field is studied. First order computational homogenization is used to derive the effective properties of the macro-structure from the response of the underlying micro-structure. It is assumed that the macroscopic variables are equal to the volume average of their microscopic counterparts. This procedure is based on the solutions of two boundary value problems at the macroscopic and microscopic scales [2, 1]. Different types of boundary conditions have been applied to solve the micro problem where the constitutive law is assumed to be known.

The overall response of various microstructures which are different in volume fraction, size and material properties are studied under different load types and magnetic fields. Results indicate that for an applied magnetic field and large deformations, Dirichlet boundary conditions provide the highest effective Piola Stress $[\overline{\mathbf{P}}]_{xx}$, and effective magnetic induction $[\overline{\mathbb{B}}]_x$. However, Neumann boundary conditions underestimate the results and periodic boundary conditions render intermediate results. The solutions of the different boundary conditions are getting closer to each other by increasing the size of the micro-structure, Fig.1.

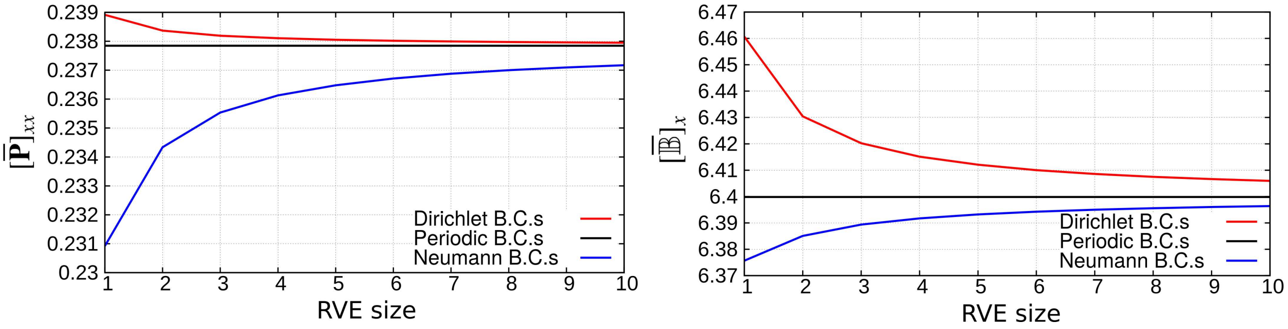


Figure 1: Averaged Piola stress,$[\overline{\mathbf{P}}]_{xx}$, and magnetic induction $[\overline{\mathbb{B}}]_x$ vs. cell size for Dirichlet, periodic and Neumann boundary conditions.($[\overline{\mathbf{F}}]_{xx} = 1.05$, $[\overline{\mathbb{H}}]_x = 10$)

References

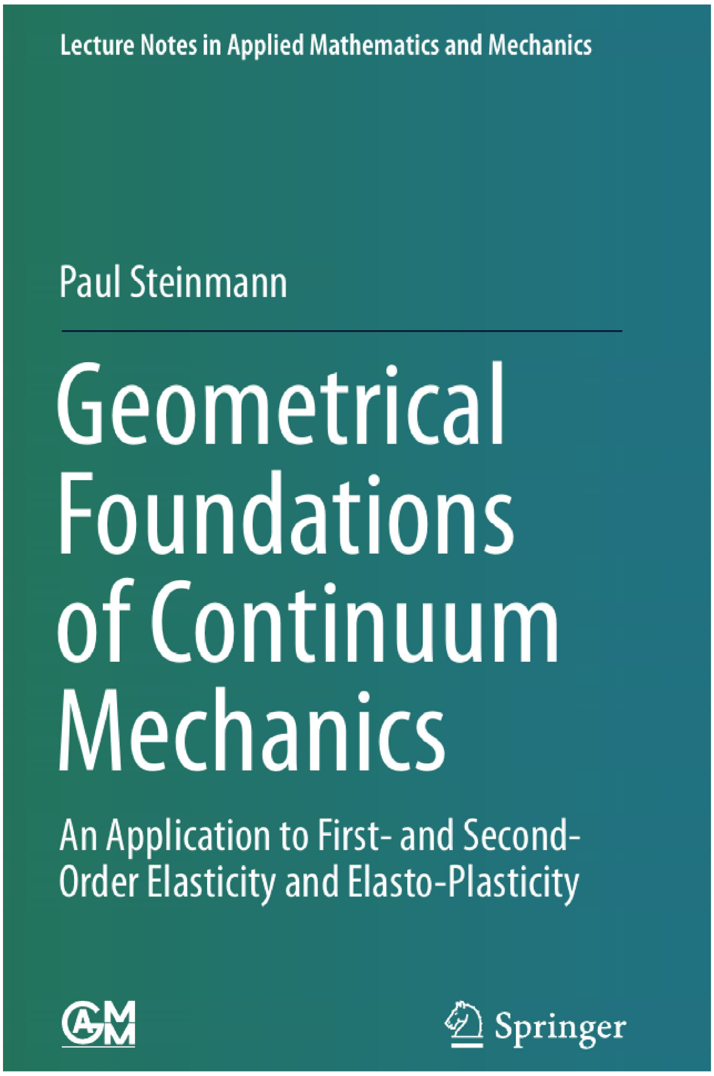
[1] G. Chatzigeorgiou, A. Javili, and P. Steinmann. “Unified magnetomechanical homogenization framework with application to magnetorheological elastomers”. *Mathematics and Mechanics of Solids* 19(2) (2012), pp. 193–211.

[2] A. Javili, G. Chatzigeorgiou, and P. Steinmann. “Computational homogenization in magneto-mechanics”. *International Journal of Solid and Structures* 50 (2013), pp. 4197–4216.

Geometrical Foundations of Continuum Mechanics

Paul Steinmann

This book illustrates the deep roots of the geometrically nonlinear kinematics of generalized continuum mechanics in differential geometry. Besides applications to first- order elasticity and elasto-plasticity an appreciation thereof is particularly illuminating for generalized models of continuum mechanics such as second-order (gradient-type) elasticity and elasto-plasticity. After a motivation that arises from considering geometrically linear first- and second- order crystal plasticity in Part I several concepts from differential geometry, relevant for what follows, such as connection, parallel transport, torsion, curvature, and metric for holonomic and anholonomic coordinate transformations are reiterated in Part II. Then, in Part III, the kinematics of geometrically nonlinear continuum mechanics are considered. There various concepts of differential geometry, in particular aspects related to compatibility, are generically applied to the kinematics of first- and second- order geometrically nonlinear continuum mechanics. Together with the discussion on the integrability conditions for the distortions and double-distortions, the concepts of dislocation, disclination and point-defect density tensors are introduced. For concreteness, after touching on nonlinear first- and second-order elasticity, a detailed discussion of the kinematics of (multiplicative) first- and second-order elasto-plasticity is given. The discussion naturally culminates in a comprehensive set of different types of dislocation, disclination and point-defect density tensors. It is argued, that these can potentially be used to model densities of geometrically necessary defects and the accompanying hardening in crystalline materials. Eventually Part IV summarizes the above findings on integrability whereby distinction is made between the straightforward conditions for the distortion and the double-distortion being integrable and the more involved conditions for the strain (metric) and the double-strain (connection) being integrable. The book addresses readers with an interest in continuum modelling of solids from engineering and the sciences alike, whereby a sound knowledge of tensor calculus and continuum mechanics is required as a prerequisite.



Lecture Notes in Applied Mathematics and Mechanics

Paul Steinmann

Geometrical Foundations of Continuum Mechanics

An Application to First- and Second-Order Elasticity and Elasto-Plasticity

Springer

4 Activities

4.1 Teaching

- Statik (MB)
- Elastostatik und Festigkeitslehre (MB)
- Statik und Festigkeitslehre (CBI, ET, IP, LSE, ME, MT, WING, WW)
- Lineare Kontinuumsmechanik (MB, ME, WING)
- Nichtlineare Kontinuumsmechanik (MB, ME)
- Technische Schwingungslehre (MB, ME, WING)
- Methode der Finiten Elemente (MB, ME, WING)
- Materialmodellierung und -simulation (CE, MB)
- Nichtlineare Finite Elemente (CE, MB, IP)
- Einführung in die Bruchmechanik (MB)
- Mikromechanik (MB, CE)
- Rotordynamik (MB)
- Strukturoptimierung in der virtuellen Produktentwicklung (MB, ME)
- Kontaktmechanik (MB)
- Numerische und experimentelle Modalanalyse (MB, ME, WING)
- Introduction to the Finite Element Method (CE)
- Computational Dynamics (CE)
- Finite-Elemente Praktikum (MB, WING, IP)
- Hauptseminar Technische Mechanik (MB, ME)
- Number of exams - 2401

4.2 Habilitation thesis

- D. K. Vu,
  A study on nonlinear electro-elastostatics: Theory and numerical simulation

4.3 Dissertation theses

- S. Schmaltz,
  Inverse Materialparameteridentifikation von Blechwerkstoffen für ein anisotropes elasto-plastisches Materialmodell bei finiten Deformationen

- S. Pfaller,
  Multiscale Simulation of Polymers

- V. Luchscheider
  Experimentelle und numerische Identifikation eines homogenisierten Materialmodells für Blechpakete elektrischer Maschinen

- S. Diel,
  Charakterisierung und Modellierung des quasi-statischen Verhaltens und der Ermüdung eines zellularen Verbundwerkstoffes

- S. Sitzmann
  Robust Algorithms for Contact Problems with Constitutive Contact Laws

4.4 Diploma theses

- M. Bittner,
  Konzeption eines Texttools zur Analyse komplexer Querverkehrszenarien

4.5 Master theses

- B. Singh,
  Isogeometric contact computation of Roller camshaft contact

- S. Surof,
  Finite-Elemente-Simulation der Kompression und Formgebung von Filamentbündeln

- M. Amin Ghaziani,
  Computational Homogenization in Thermohyperelasticitiy

- A. Kergaßner,
  Kopplung kontinuumsmechanischer und teilchenbasierter Modellierung: Optimierung der Capriccio-Methode

- K. Herberth,
  Investigation of the influence of myelination on the mechanical properties of brain tissue using Abaqus

- A. Lion,
  Experimentelle Untersuchungen zum dynamischen Übertragungsverhalten verschraubter Schrauben

- D. Soldner,
  Computational Homogenisation using Reduced-Order Modelling applied to Hyperelasticity

- J. Hohage,
  Ermittlung des dynamischen Schwingverhaltens von Wickelköpfen von Traktionsantrieben

- M. Stauber,
  Implementation and Computational Aspects of 3D Natural Neighbour Shape Functions

4.6 Bachelor theses

- J. Walter,
  Untersuchungen zum Stabilitä,tsverhalten nichtlinearer Schwingungssysteme

- C. Hartnagel,
  Implementierung von Effekten rotierender Strukturen in einen Finite Elemente Code

- V. Kobler,
  Fininte-Elemente-Simulation des Paketiervorgangs von Blechpaketen

- D. Soldner,
  Reduced-Order Modeling for the one-dimensional heat equation using Proper Orthogonal Decomposition

- I. Moll,
  Numerische Untersuchung des Verbunds aus Bremsscheibe und Radnabe

- C. Schlenk,
  Untersuchungen zur numerischen Integration von Zero-Thickness-Elementen

- C. Oberg,
  Implementierung eines 3D-Balkenelementes zur Tragwerksanalyse in ein bestehendes Finite-Element-Programm (JFEM)

- C. Speidel,
  Mikromechanische Modellierung und Simulation von gewobenen Verbänden

- D. Heilmann,
  Magneto-Statics in Multi-Material Media

4.7 Student research projects theses

- F. Steinbach,
  Performanceoptimierung eines Halbraummodells in Matlab

- J. Hein,
  FEM-Schwingungsanalyse zur Zuverlässigkeitsbewertung eines Radnabenmotoren-Umrichters

- S. Oberleiter,
  Finite-Elemente-Simulation des Kontaktverhaltens von Faserbünden

- S. Gerdhenrichs,
  Auslegung und Konstruktion eines Prüfstands zur Visualisierung der Sprüheigenschaften von spanenden Werkzeugen mit Minimalmengenschmierung
- F. Pilz,
  Modellbildung und Simulation thermischer Interaktionen zwischen temperierten Prozesselementen

- S. Schöllhammer,
  Studie verschiedener Zeitintegrationsverfahren anhand des Doppelpendels
- J. Kram,
  Experimentelle Untersuchung eines dynamischen Systems bei Kopplung von kubischer Steifigkeit mit reibschlüssiger Fügestelle

4.8 Seminar for Mechanics (jointly with LTD)

02.02.2015	Jaroslav Vondřejc, Faculty of Applied Sciences, University of West Bohemia, Plzen, Czech Republic *FFT-based Galerkin method for a reliable determination of homogenized material properties*
16.03.2015	Stephan Rudykh, Department of Aerospace Engineering, Technion - Israel Institute of Technology *Micromechanics of Soft Dielectric Elastomers and Magnetorheological Elastomers*
27.04.2015	Kateryna Plaksiy, Department of Applied Mathematics, NTU Kharkiv Polytechnic Institute, Ukraine *Dynamics of nonlinear dissipative systems in the vicinity of resonance*
15.06.2015	Andrew McBride, Centre of Research in Computational and Applied Mechanics, University of Cape Town, South Africa *Computational and theoretical aspects of a grain-boundary model that accounts for grain misorientation and grain-boundary orientation*
22.06.2015	Valery I. Levitas, Iowa State University, Departments of Aerospace Engineering, Mechanical Engineering, and Material Science and Engineering, Ames, IA 50011, USA *Interaction between phase transformations and dislocations at the nanoscale: Phase field approach*
30.11.2015	Krishnendu Haldar, Institute of Mechanics, TU Dortmund *Discrete Symmetry and Modeling of Magnetic Shape Memory Alloys*

4.9 Editorial activities

GAMM-Mitteilungen

The GAMM-Mitteilungen (GAMM-Proceedings) are published by Wiley-VCH Verlag, Berlin (`www.onlinelibrary.wiley.com`).

Managing Editor:
N. Kondratieva (Chair of Applied Dynamics)

Editor:
P. Steinmann

- Volume 38 Issue 1 2015

  Ferroic Functional Materials

  Guest Editor:

  J. Schröder & D.C. Lupascu, Essen & B. Kiefer, Dortmund & M.-A. Kneip, Stuttgart

- Volume 38 Issue 2 2015

  Pushing the Frontiers of Mechanics: From the Continuum to Atoms and Beyond

  Guest Editor:

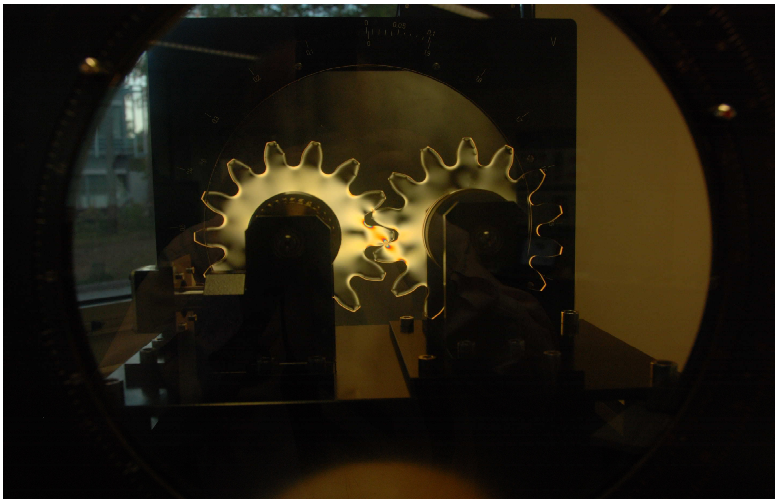
  D. Kochmann, Pasadena & C. Linder, Stanford

Advisory/Editorial Board Memberships (Prof. P. Steinmann)

- **Advanced Modeling and Simulation in Engineering Science**
- **Archive of Applied Mechanics**
- **Archives of Mechanics**
- **Computational Mechanics**
- **Computers and Concrete**
- **Computer Assisted Methods in Engineering and Science**
- **Computer Methods in Applied Mechanics and Engineering**
- **International Journal of Numerical Methods in Engineering**
- **International Journal of Solids and Structures**
- **International Journal of Structural Changes in Solids**
- **Journal of the Mechanical Behaviour of Materials**
- **Mathematics and Mechanics of Complex Systems**
- **Mathematics and Mechanics of Solids**
- **Meccanica**

4.10 Long Night of Science

(mj) Already for the seventh time since 2003, the "Long Night of Science" (Die Lange Nacht der Wissenschaften) took place on October 24th at numerous institutions spread through the metroplitan region of Nuremberg, Erlangen, and Fuerth. Between 6 p.m. and 1 a.m. the audience was invited to "watch, be astonished, understand" (Sehen! Staunen! Verstehen!). The FAU, non-university research institutes, companies and other institutions delivered insight into current trends in research and development. Like recent years, the Chair of Applied Mechanics also participated in this event and opened its doors on Saturday evening to present current research results in the areas of experimental stress analysis, non-linear system dynamics, shape optimization and electro sensitive elastomers. The LTM-guitar demonstrated string waves but brought also Rock'N'Roll into LTM's seminar room. Due to the very positive resonance to our program and the extremely large attendance at our chair, we are encouraged to participate as well in the next "Long Night of Science", which will take place in October 2017.



4.11 Reconstruction measures of the LTM-building at southern campus

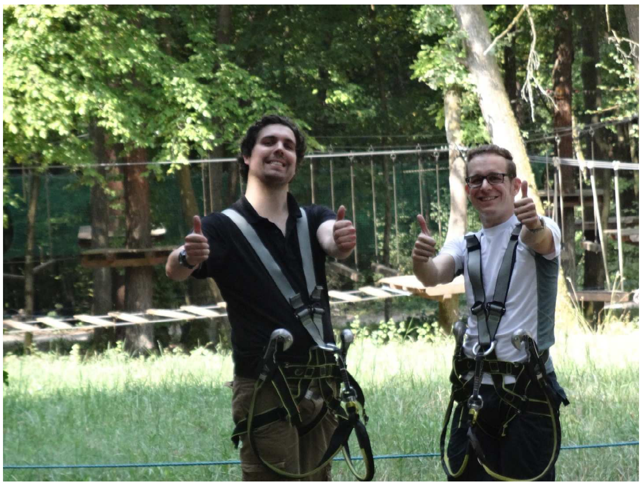
(dp) The university building at southern campus where the Chair of Applied Mechanics is located, was built in 1966. As there was only few maintenance work carried out since that time, the basic structure of the building, especially sanitary facilities as well as structural fire protection, is in bad condition. Furthermore some rooms, such as test fields, laboratories, server and computer rooms, need essential modification. For these reasons extensive reconstruction measures started in April 2015. Due to this construction project the complete building had to be cleared, the chair's staff is moved on an interim basis in rented premises in Erlangen-Tennenlohe, the technical equipment is placed in storage. According to the completion of the LTM-building the removal back to southern campus will take place in February 2016.

Figure 1: Some images of the LTM-building taken during construction project

5 Social events

5.1 Outing in Kletterwald Veilbronn

(bs) Our works outing this year led us into the beautiful Franconian Switzerland to Kletterwald Veilbronn. The weather was perfect and after some difficulties in finding the venue and an unexpectedly exhausting hike for some of us, everybody had arrived at the meeting point and was ready to let the adventure begin. After a short briefing on safety and our gear, we finally started climbing the high ropes on routes of different levels of difficulty. Everyone was full of energy and grew into challenges. Despite initial hesitation or severe fear of heights, eventually the team spirit was stronger and everyone plunged into free fall from 13 m height. After this excitement, we let the event come to an end in a beer garden close by. The typical franconian restaurant had even arranged for additional waiters for our huge group so we pleasurably enjoyed a late lunch and the appropriate beverages in the beautiful surrounding.



5.2 Visit of the Bergkirchweih

(fe) The Bergkirchweih has taken place since 1755 and is one of Germany's biggest beer festivals. Held under elms, chestnuts and oak trees with wooden benches accommodating more than 11,000 people, it is one of Europe's biggest open air beer gardens. Due to the long tradition and the unique atmosphere of the week-long festival, it is no surprise that roughly a million people visit the event every year.

It is tradition that most of the staff of the university's chairs and the FAU students visit the "Berg" at the festival's first Tuesday. Of course, the members of the LTM joined the rest of the university.

The weather had been unsettled but the atmosphere was great as always.

The visit was a great success in cultivating the colleagueship within the chair and beyond.

6 Publications

6.1 Book

[1] *Geometrical Foundations of Continuum Mechanics*. Springer Verlag, Berlin, Heidelberg, 2015. ISBN: 978-3-662-46459-5.

6.2 Contributions to Journals

[1] J.C. Aurich, M. Zimmermann, S. Schindler, and P. Steinmann. “Effect of the cutting condition and the reinforcement phase on the thermal load of the workpiece when dry turning aluminum metal matrix composites”. *International Journal Of Advanced Manufacturing Technology* (2015), pp. 1–18.

[2] J.C. Aurich, M. Zimmermann, P. Steinmann, and S. Schindler. “Fertigungsgenauigkeit beim Drehen steigern - Einfluss der Prozessparameter auf die Maßhaltigkeit bei der Trockenbearbeitung”. *VDI-Z* 157 (2015), pp. 42–45.

[3] F. Beyer, F. Hauer, and K. Willner. “Development of a Constitutive Friction Law based on the Frictional Interaction of Rough Surfaces”. *Tribology in Industry* 37 (2015).

[4] S. Budday, E. Kuhl, and J.W. Hutchinson. “Period-doubling and period-tripling in growing bilayered systems”. *Philosophical Magazine* (2015), pp. 1–17.

[5] S. Budday, P. Steinmann, A. Goriely, and E. Kuhl. “Size and curvature regulate pattern selection in the mammalian brain”. *Extreme Mechanics Letters* 4 (2015), pp. 186–192.

[6] S. Budday, P. Steinmann, and E. Kuhl. “Physical biology of human brain development”. *Frontiers In Cellular Neuroscience* 9 (2015), pp. 1–13.

[7] S. Budday, P. Steinmann, and E. Kuhl. “Secondary instabilities modulate cortical complexity in the mammalian brain”. *Philosophical Magazine* 95 (2015), 3244–3256.

[8] S. Budday, P. Steinmann, E. Kuhl, R. Nay, T. Ovaert, T. Wyrobek, and R. de Rooij. “Mechanical properties of gray and white matter brain tissue by indentation”. *Journal Of The Mechanical Behavior Of Biomedical Materials* (2015), pp. 318–330.

[9] G. Chatzigeorgiou, A. Javili, and P. Steinmann. “Interface properties influence the effective dielectric constant of composites”. *Philosophical Magazine* 95 (2015), pp. 3402–3412.

[10] G. Chatzigeorgiou, A. Javili, and P. Steinmann. “Multiscale modelling for composites with energetic interfaces at the micro- or nanoscale”. *Mathematics and Mechanics of Solids* 20.9 (2015), pp. 1130–1145.

[11] D. Davydov and P. Steinmann. “Reviewing the roots of continuum formulations in molecular systems. Part III: Stresses, couple stresses, heat fluxes”. *Mathematics and Mechanics of Solids* 20.10 (2015), pp. 1153–1170.

[12] D. Davydov, T. Young, and P. Steinmann. “On the adaptive finite element analysis of the Kohn-Sham equations: Methods, algorithms, and implementation.” *International Journal for Numerical Methods in Engineering* (2015).

[13] F. Endres and P. Steinmann. “Molecular statics simulations of ferroelectric barium titanate in the rhombohedral phase”. *GAMM Mitteilungen* 38 (2015), pp. 132–146.

[14] F. Endres and P. Steinmann. “Molecular statics simulations of head to head and tail to tail nanodomains of rhombohedral barium titanate”. *Computational Materials Science* 97 (2015), pp. 20–25.

[15] S. Fillep, J. Mergheim, and P. Steinmann. “Computational homogenization of rope-like technical textiles”. *Computational Mechanics* 55 (2015), pp. 577–590.

[16] J. Friederich, S. Pfaller, and P. Steinmann. “A web-based tool for the interactive visualization of stresses in an infinite plate with an elliptical hole under simple tension: www.ltm.fau.de/plate.” *Archive Of Applied Mechanics* (2015), pp. 1–9.

[17] M. Hossain, A.F.M.S. Amin, and M. Nomani Kabir. “Eight-chain and full-network models and their modified versions for rubber hyperelasticity : A comparative study”. *Journal of the Mechanical Behavior of Materials* 24 (2015), pp. 11–24.

[18] M. Hossain, G. Chatzigeorgiou, F. Meraghni, and P. Steinmann. “A multi-scale approach to model the curing process in magneto-sensitive polymeric materials”. *International Journal Of Solids And Structures* 69-70 (2015), pp. 34–44.

[19] M. Hossain, P. Saxena, and P. Steinmann. “Modelling the curing process in magneto-sensitive polymers: Rate-dependence and shrinkage”. *International Journal Of Non-Linear Mechanics* 74 (2015), pp. 108–121.

[20] M. Hossain, P. Saxena, and P. Steinmann. “Modelling the mechanical aspects of the curing process of magneto-sensitive elastomeric materials”. *International Journal Of Solids And Structures* 58 (2015), pp. 257–269.

[21] M. Hossain and P. Steinmann. “Continuum physics of materials with time dependent properties: Reviewing the case of polymer curing”. *Advances In Applied Mechanics* (2015), in press.

[22] M. Hossain, D.K. Vu, and P. Steinmann. “A comprehensive characterization of the electro-mechanically coupled properties of VHB 4910 polymer”. *Archive of Applied Mechanics* 85.4 (2015), pp. 523–537.

[23] A. Javili, G. Chatzigeorgiou, A.T. McBride, P. Steinmann, and C. Linder. “Computational homogenization of nano-materials accounting for size effects via surface elasticity”. *GAMM Mitteilungen* 38.2 (2015), pp. 285–312.

[24] S. Klinge and P. Steinmann. “Inverse analysis for heterogeneous materials and its application to viscoelastic curing polymers”. *Computational Mechanics* 55 (2015), pp. 603–615.

[25] P. Landkammer and P. Steinmann. “A non-invasive heuristic approach to shape optimization in forming”. *Computational Mechanics* (2015), published online.

[26] D. Pivovarov and P. Steinmann. “Modified SFEM for Computational Homogenization of Heterogeneous Materials with Microstructural Geometric Uncertainties”. *Computational Mechanics* (2015), in press.

[27] S. Riehl and P. Steinmann. “A staggered approach to shape and topology optimization using the traction method and an evolutionary-type advancing front algorithm”. *Computer Methods In Applied Mechanics And Engineering* 287 (2015), pp. 1–30.

[28] P. Saxena, J.-P. Pelteret, and P. Steinmann. “Modelling of iron-filled magneto-active polymers with a dispersed chain-like microstructure”. *European Journal Of Mechanics A-Solids* 50 (2015), pp. 132–151.

[29] S. Schindler, M. Zimmermann, J.C. Aurich, and P. Steinmann. "Identification of thermal effects on the diameter deviation of inhomogeneous aluminum metal matrix composite workpieces when dry turning". *Production Engineering* 9 (2015), pp. 473–485.

[30] U. Schmidt, J. Mergheim, and P. Steinmann. "Identification of elastoplastic microscopic material parameters within a homogenization scheme". *International Journal For Numerical Methods In Engineering* 104 (2015), 391–407.

[31] U. Schmidt, P. Steinmann, and J. Mergheim. "Two-scale elastic parameter identification from noisy macroscopic data". *Archive Of Applied Mechanics* (2015), accepted.

[32] O. Schmitt, J. Friederich, S. Riehl, and P. Steinmann. "On the formulation and implementation of geometric and manufacturing constraints in node-based shape optimization". *Structural And Multidisciplinary Optimization* (2015).

[33] D. Schrade, R. Müller, D. Gross, and P. Steinmann. "Phase field simulations of the poling behavior of BaTiO3 nano-scale thin films with SrRuO3 and Au electrodes". *European Journal of Mechanics, A/Solids* 49 (2015), pp. 455–466.

[34] M.H.B.M. Shariff, R. A. Bustamante, M. Hossain, and P. Steinmann. "A novel spectral formulation for transversely isotropic magneto-elasticity". *Mathematics And Mechanics Of Solids* (2015), accepted.

[35] J. Wang and P. Steinmann. "On the modeling of equilibrium twin interfaces in a single-crystalline magnetic shape-memory alloy sample—III: Magneto-mechanical behaviors". *Continuum Mechanics and Thermodynamics* (2015), in press.

[36] P. Wilhelm, J. Rudolph, and P. Steinmann. "Effects of Pressurized Water Reactor Medium on the Fatigue Life of Austenitic Stainless Steels". *Journal Of Pressure Vessel Technology-Transactions Of The ASME* 137 (2015), pp. 061404/1 –061404/7.

[37] P. Wilhelm, P. Steinmann, and J. Rudolph. "Fatigue Approach for Addressing Environmental Effects in Fatigue Usage Calculation". *Atw-International Journal For Nuclear Power* 60 (2015), pp. 245 –250.

Submitted (2015)

[1] S. Kaessmair and P. Steinmann. "Comparative Computational Analysis of the Cahn-Hilliard Equation with Emphasis on C^1-Continuous Methods" (2015).

[2] J-P. V. Pelteret, D. Davydov, A. McBride, D. K. Vu, and P. Steinmann. "Computational electro- and magneto-elasticity for quasi-incompressible media immersed in free space" (2015).

[3] S. Pfaller, G. Possart, M. Rahimi, F. Müller-Plathe, P. Steinmann, and M. C. Böhm. "Investigation of Interphase Effects in Silica-Polystyrene-Nanocomposites Based on a Novel Hybrid MD-FE Simulation Framework" (2015).

[4] D. Riedlbauer, T. Scharowsky, R. F. Singer, P. Steinmann, C. Körner, and J. Mergheim. "Macroscopic simulation and experimental measurement of melt pool characteristics in selective electron beam melting of Ti-6Al-4V" (2015).

[5] B. Walter, J.-P. Pelteret, J. Kaschta, D.W. Schubert, and P. Steinmann. "Detecting wall slip of elastomers in oscillatory shear measurements using parallel-plate rotational rheometry" (2015).

6.3 Contributions to Proceedings

[1] Söhngen B. and Willner K. "Inverse Parameter Identification for Orthotropic Elasto-Plastic Sheet-Steel". In: *Special Issue: 86th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM).* (Aachen). Ed. by Zavarise G., Cinnella P., and Campiti M. Vol. 15. 1. WILEY-VCH Verlag, 2015, pp. 361–362.

[2] F. Beyer, H. Blum, D. Kumor, A. Rademacher, K. Willner, and T. Schneider. "Experimental and Simulative Investigations of Tribology in Sheet-Bulk Metal Forming". In: *Key Engineering Materials.* Vol. 639. 2015, pp. 283–290.

[3] F. Beyer and K. Willner. "Determination of a Constitutive Friction Law Using an Elastic-Plastic Half-Space Model". In: Weinheim, 2015, pp. 173–174.

[4] S. Budday, P. Steinmann, E. Kuhl, and S. Andres. "Primary and secondary instabilities in soft bilayered systems". In: 86^{th} *GAMM Annual Meeting.* Lecce, Italy, 2015, pp. 281–282.

[5] Tekkaya A. E., Liewald M., Merklein M., and Behrens B.-A, eds. *Tagungsband zum 18. Workshop Simulation in der Umformtechnik & 3. Industriekolloquium Blechmassivumformung 2015 - DFG Transregio 73.* (Aachen). Shaker Verlag, 2015.

[6] F. Endres and P. Steinmann. "An atomistic scale analysis of ferroelectric nanodomain interfaces". In: 86^{th} *GAMM Annual Meeting.* Lecce, Italy, 2015, pp. 287–288.

[7] Zavarise G., Cinnella P., and Campiti M., eds. *Special Issue: 86th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM).* (Aachen). Vol. 15. 1. WILEY-VCH Verlag, 2015.

[8] M. Hossain and P. Steinmann. "Towards modelling the curing process in particle-filled electro-active polymers". In: 86^{th} *GAMM Annual Meeting.* Lecce, Italy, 2015, pp. 301–302.

[9] P. Landkammer, A. Loderer, E. Krebs, B. Söhngen, P. Steinmann, T. Hausotte, P. Kersting, D. Biermann, and K. Willner. "Experimental verification of a benchmark forming simulation". *Key Engineering Materials* 639 (2015), pp. 251–258.

[10] P. Landkammer and P. Steinmann. "A global damping factor for a non-invasive form finding algorithm". In: 86^{th} *GAMM Annual Meeting.* Lecce, Italy, 2015, pp. 327–328.

[11] P. Landkammer and P. Steinmann. "Application of a non-invasive form-finding algorithm to the ring compression test with varying friction coefficients". *Key Engineering Materials* 651 (2015), pp. 1381–1386.

[12] Landkammer P., Söhngen B., Loderer A., Krebs E., Steinmann P., Willner K., Hausotte T., Kersting P., and Biermann D. "Experimentelle Verifizierung eines Benchmark-Umformprozesses". In: *Tagungsband zum 18. Workshop Simulation in der Umformtechnik & 3. Industriekolloquium Blechmassivumformung 2015 - DFG Transregio 73.* (Aachen). Ed. by Tekkaya A. E., Liewald M., Merklein M., and Behrens B.-A. Shaker Verlag, 2015, pp. 91–110.

[13] D.-R. Riedlbauer, P. Steinmann, and J. Mergheim. "Thermomechanical simulation of the selective laser melting process for PA12 including volumetric shrinkage". In: *The* 30^{th} *International Conference of the Polymer Processing Society.* Vol. -. Cleveland, USA, 2015.

[14] S. Riehl and P. Steinmann. "A staggered approach to structural shape and topology optimization". In: 86^{th} *GAMM Annual Meeting.* Lecce, Italy, 2015, pp. 575 –576.

[15] S. Riehl and P. Steinmann. “Structural optimization of shape and topology using an evolutionary-type advancing front algorithm”. In: *Conference Proceedings of the YIC GACM 2015*. Aachen, Germany, 2015, pp. 205–208.

[16] O. Schmitt and P. Steinmann. “On curvature control in node-based shape optimization”. In: 86th *GAMM Annual Meeting*. Vol. -. Lecce, Italy, 2015, pp. 579–580.

[17] P. Steinmann and F. Endres. “On molecular statics simulations of ferroelectric functional materials”. In: 86th *GAMM Annual Meeting*. Lecce, Italy, 2015, pp. 15–18.

6.4 Habilitation Thesis

[1] Duc Koi Vu. “A study on nonlinear electro-elastostatics: Theory and numerical simulation”. PhD thesis. Friedrich-Alexander-Universität Erlangen-Nürnberg, 2015.

6.5 Ph.D. Thesis

[1] Sebastian Pfaller. “Multiscale Simulation of Polymers - Coupling of Continuum Mechanics and Particle-Based Modelling”. PhD thesis. Friedrich-Alexander-Universität Erlangen-Nürnberg, 2015.

6.6 Poster

[1] D. Davydov, T. D. Young, and P. Steinmann. *On the adaptive finite element analysis of the Kohn-Sham equations: Methods, algorithms, and implementation.* Sparse Solvers for Exascale: From Building Blocks to applications. Greifswald, Germany, Mar. 23, 2015.

[2] B. Walter, J-P. Pelteret, J. Kaschta, D.W. Schubert, and P. Steinmann. *Nonlinear viscoelastic behavior or measuring artifact? On the wall slip of magneto-sensitive elastomers.* 10th Annual European Rheology Conference. Nantes, France, Apr. 14, 2015.

6.7 Talks

[1] F. Beyer and K. Willner. *A Constitutive Friction Law for Sheet-Bulk Metal Forming.* International Tribology Conference 2015. Tokyo, Japan, Sept. 18, 2015.

[2] F. Beyer and K. Willner. *Determination of a Constitutive Friction Law Using an Elastic-Plastic Half-Space Model.* 86th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM). Lecce, Italy, Mar. 26, 2015.

[3] F. Beyer and K. Willner. *Experimental and simulative investigations of tribology in SBMF.* 16th International Conference on Sheet Metal. Erlangen, Germany, Mar. 17, 2015.

[4] S. Budday, P. Steinmann, A. Goriely, and E. Kuhl. *Extrinsic mechanical factors during brain development: In response to Wilfrid Le Gros Clark 1945.* 9th European Solid Mechanics Conference. Madrid, Spain, July 6, 2015.

[5] S. Budday, P. Steinmann, and E. Kuhl. *A mechanobiological approach to relate neurodevelopmental processes to brain morpholog.* 13th US National Congress on Computational Mechanics. San Diego, USA, July 28, 2015.

[6] S. Budday, P. Steinmann, and E. Kuhl. *Primary and secondary instabilities affect brain morphology.* EMI 2015 - Engineering Mechanics Institute Conference. Stanford, USA, June 18, 2015.

[7] S. Budday, P. Steinmann, and E. Kuhl. *Primary and secondary instabilities in soft bilayered systems.* 86th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM). Lecce, Italy, Mar. 27, 2015.

[8] D. Davydov, J-P. Pelteret, T. D. Young, and P. Steinmann. *On the adaptive finite element approaches applied to PDEs in quantum mechanics.* Scientific Computing Seminar. Heidelberg, Germany, Dec. 10, 2015.

[9] D. Davydov, T. D. Young, and P. Steinmann. *On the adaptive finite element analysis of the Kohn-Sham equations.* deal.II Users and Developers Workshop. College Station, TX, USA, Aug. 5, 2015.

[10] Denis Davydov, Jean-Paul Pelteret, and Paul Steinmann. *Comparison of Several Staggered Atomistic-to-Continuum Concurrent Coupling Strategies.* 13th U.S. National Congress on Computational Mechanics. San Diego, CA, USA, July 29, 2015.

[11] F. Endres and P. Steinmann. *On molecular statics simulations of nanodomain interfaces in ferroelectric functional materials.* 7th International Symposium on Defect and Material Mechanics. Bremen, Germany, Sept. 16, 2015.

[12] S. Fillep, J. Mergheim, and P. Steinmann. *Computational homogenization of one-dimensional textile structures.* Structural Membranes 2015. Barcelona, Spain, Oct. 21, 2015.

[13] S. Kaessmair and P. Steinmann. *A critical comparison of C^1-continuous methods applied to the Cahn-Hilliard equation.* 13th U.S. National Congress on Computational Mechanics. San Diego, USA, July 27, 2015.

[14] P. Landkammer and P. Steinmann. *Application of a non-Invasive form finding algorithm to the ring compression test with varying friction coefficients.* ESAFORM. Graz, Austria, Apr. 17, 2015.

[15] P. Landkammer and P. Steinmann. *The influence of a damping coefficient on a non-invasive strategy for inverse form-finding.* 86th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM). Lecce, Italy, Mar. 25, 2015.

[16] P. Landkammer, B. Söhngen, A. Loderer, E. Krebs, P. Steinmann, K. Willner, P. Hausotte, and D. Biermann. *Experimental Verification Of A Benchmark Forming Simulation.* 16th International Conference on Sheet Metal. Erlangen, Germany, Mar. 17, 2015.

[17] P. Landkammer, B. Söhngen, A. Loderer, E. Krebs, P. Steinmann, K. Willner, T. Hausotte, P. Kersting, and D. Biermann. *Validierung einer Umformsimulation am Beispiel eines Benchmark-Prozesses.* 3rd Industriekolloquium Blechmassivumformung. Dortmund, Germany, Feb. 26, 2015.

[18] M. Mehnert, S. Fillep, and P. Steinmann. *Micromechanical Modeling of Textile Materials by Means of 1-D Structural Elements.* 86th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM). Lecce, Italy, Mar. 27, 2015.

[19] M. Mehnert, M. Hossain, and P. Steinmann. *Continuum Thermo-Electro-Mechanical Modeling of a Thick Walled Tube.* 11th Int. Workshop Direct and Inverse Problems on Piezoelectricity. Paderborn, Germany, Sept. 21, 2015.

[20] J-P. V. Pelteret, P. Steinmann, B. Brands, M. Hossain, D. Pivovarov, B. Walter, and R. Zabihyan. *Magneto-active polymers: Challenges in fabrication, testing, modelling and simulation.* International Conference on Mechanics of Complex Solids and Fluids. Lille, France, Apr. 2015.

[21] J-P. V. Pelteret, B. Walter, J. Kaschta, and P. Steinmann. *Evolutionary algorithms applied to experimental analysis and computational simulation of magnetorheological elastomers.* ECCOMAS Young Investigators Conference. July 2015.

[22] J-P. V. Pelteret, B. Walter, R. Zabihyan, J. Kaschta, and P. Steinmann. *Metaheuristic Algorithms applied to Experimental Analysis and Computational Simulation of Magnetorheological Elastomers.* US National Congress on Computational Mechanics. San Diego, California, USA, July 2015.

[23] S. Pfaller. *Multiscale Simulations of Polymers.* RWTH Aachen, Germany, Jan. 15, 2015.

[24] S. Pfaller. *Multiskalensimulation von Polymeren.* Promotionsvortrag. Erlangen, Germany, May 15, 2015.

[25] S. Pfaller. *The Capriccio Method: Coupled Molecular Dynamics and Finite Element Simulations of Polymers.* EAM A3-ZISC-HPC users seminar, FAU Erlangen. Erlangen, Germany, Apr. 27, 2015.

[26] S. Pfaller and P. Steinmann. *Hybrid Continuum Mechanics and Particle-Based Simulations: the Capriccio Method.* Particle Simulations 2015, FAU Erlangen. Erlangen, Germany, Sept. 24, 2015.

[27] S. Pfaller and P. Steinmann. *The Capriccio Method: An Arlequin-Based Approach to Couple Molecular Dynamics and Finite Element Simulations of Polymers.* GDR Polynano 3661 - Scientific Workshop on Multiscale Modeling, Experimental Characterization and Simulations of Nanocomposites, Université Paris-Est Marne-la-Vallée. Paris, France, June 15, 2015.

[28] P. Riedlbauer D.; Steinmann and J. Mergheim. *Finite element simulation of the thermomechanical material behaviour in the electron beam melting process for Ti6Al4V.* VI International Conference on Coupled Problems in Science and Engineering: Coupled Problems 2015. Venice, Italy, May 18, 2015.

[29] S. Riehl and P. Steinmann. *A staggered approach to structural shape and topology optimization.* 86th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM). Lecce, Italy, Mar. 24, 2015.

[30] S. Riehl and P. Steinmann. *Structural optimization of shape and topology using an evolutionary-type advancing front algorithm.* 3rd ECCOMAS Young Investigators Conference. Aachen, Germany, July 20, 2015.

[31] S. Schindler, P. Steinmann, M. Zimmermann, and J.C. Aurich. *Scale effects in homogenization of metal matrix composites.* Euromech Colloquium 577 - Micromechanics of metal ceramic composites. Stuttgart, Germany, Mar. 3, 2015.

[32] O. Schmitt and P. Steinmann. *On curvature control in node–based shape optimization.* 86th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM). Lecce, Italy, Mar. 24, 2015.

[33] P. Steinmann. *Interplay of Geometry, Generalized Continua and Compatibility.* Seminar, CERECAM, University of Cape Town. Cape Town, South Africa, Jan. 19, 2015.

[34] P. Steinmann, S. Budday, and E. Kuhl. *The Role of Mechanics During Brain Development.* Seminar, Laboratoire de Mécanique des Solides, Ecole Polytechnique. Paris, France, June 4, 2015.

[35] P. Steinmann and F. Endres. *On molecular statics simulations of ferroelectric functional materials.* 86th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM). Lecce, Italy, Mar. 23, 2015.

[36] P. Steinmann, M. Hossain, and P. Saxena. *On materials with time dependent properties : application to the continuum mechanics of curing.* 2nd International Conference on Damage Mechanics (ICDM2, University of Technology of Troyes. Troyes, France, July 8, 2015.

[37] P. Steinmann, A. Javili, and S. Saeb. *Aspects of computational homogenization at finite strains.* Euromech 559: Multi-scale computational methods for bridging scales in materials and structures. Eindhoven, The Netherlands, Feb. 23, 2015.

[38] B. Söhngen and K. Willner. *Inverse Parameter Identification for Orthotropic Elasto-Plastic Sheet-Steel.* 86th Annual Meeting of the International Association of Applied Mathematics and Mechanics (GAMM). Lecce, Italy, Mar. 25, 2015.

[39] B. Walter, J.-P. Pelteret, J. Kaschta, D.W. Schubert, and P. Steinmann. *On the wall slip of magnetorheological elastomers in parallel-plate rotational rheometry.* 7th ECCOMAS Thematic Conference on Smart Structures and Materials. Ponta Delgada, Azores, June 3, 2015.

[40] B. Walter, J.-P. Pelteret, J. Kaschta, D.W. Schubert, and P. Steinmann. *Wall slip of magnetorheological elastomers in parallel-plate rotational rheometry.* 7. TA Anwendertreffen Rheologie - Erlangen. Erlangen, Germany, Oct. 1, 2015.

[41] P. Wilhelm, P. Steinmann, and J. Rudolph. *Statistical Analysis of Fatigue Data for Austenitic Stainless Steels in Water Environments.* 46th Annual Meeting on Nuclear Technology. Berlin, Germany, May 6, 2015.

[42] P. Wilhelm, P. Steinmann, and J. Rudolph. *Statistical Models for Estimating Fatigue Lives of Austenitic Stainless Steels in Light Water Reactor Environments.* 23th Structural Mechanics in Reactor Technology. Manchester, UK, Aug. 14, 2015.

[43] S. Willner K.; Sitzmann and B. Wohlmuth. *Variationally Consistent Quadratic Finite Element Formulations for Contact Problems on Rough Surfaces.* 13th US National Congress on Computational Mechanics. San Diego, USA, July 27, 2015.