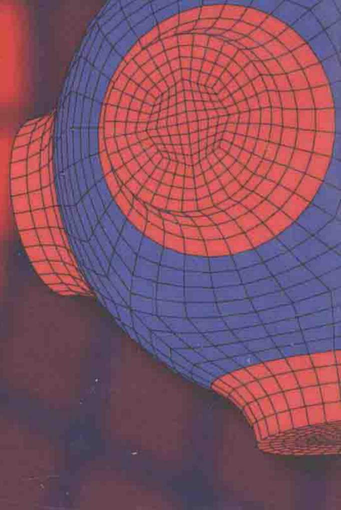
Advanced Structured Materials



Holm Altenbach
Michael Brünig *Editors*

Inelastic Behavior of Materials and Structures Under Monotonic and Cyclic Loading

Springer

Holm Altenbach · Michael Brünig
Editors

Inelastic Behavior of Materials and Structures Under Monotonic and Cyclic Loading

Springer

Editors
Holm Altenbach
Fakultät für Maschinenbau, Institut für Mechanik
Otto-von-Guericke University Magdeburg
Magdeburg
Germany

Michael Brünig
Fakultät für Bauingenieurwesen und Umweltwissenschaften, Institut für Mechanik und Statik
Universität der Bundeswehr München
Neubiberg
Germany

ISSN 1869-8433 ISSN 1869-8441 (electronic)
Advanced Structured Materials
ISBN 978-3-319-14659-1 ISBN 978-3-319-14660-7 (eBook)
DOI 10.1007/978-3-319-14660-7

Library of Congress Control Number: 2014958992

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Preface

This book is a collection of papers devoted to modeling of inelastic material behavior related to structures under normal and advanced conditions. At the moment there exist various approaches, among them phenomenological, mechanism-based, physically motivated, and others. In this sense this book is some kind of a state of the art.

Accurate and realistic modeling of inelastic behavior of advanced materials is essential for the solution of a numerous boundary-value problems occurring in different engineering fields. For example, various microscopic defects cause reduction in strength of materials and shorten the lifetime of engineering structures. Therefore, a main issue in engineering applications is to provide realistic information on the stress distribution within elements of such materials or assessment of safety factor against failure.

During the last years important progress has been observed in the testing practice for monotonic and cyclic behavior delivering important information on deformation patterns and damage evolution in interaction with material microstructure. Great efforts have been made in the attempt to develop more physically based constitutive models for predicting the occurrence of damage and failure in materials and structures under general loading conditions. At the same time, different research fields in solid mechanics and, especially, modeling of advanced materials have evolved due to development of multi-scale approaches. Although some progress has been made in theoretical fields, the application of multi-scale models to numerically analyze real components subjected to monotonic and cyclic loading conditions is still at an early stage. Different research groups around the world have proposed promising approaches and part of them are discussed in the present book.

The aim of the book is not only to consolidate the advances in inelastic material research but also to provide a forum to discuss new trends in damage and fracture mechanics proposing models that are either phenomenological ones or micro-mechanically motivated. Discussion of new multi-scale approaches at several length scales applied to nonlinear and heterogeneous materials have been emphasized from different related disciplines including metal physics, micro-mechanics, as well as mathematical and computational mechanics.

The editors wish to thank all authors for their contribution and the reviewers for their valuable comments and recommendations. After the peer review process, 12 papers are finally presented in this book aiming to become a helpful and valuable reference in the field of mechanics for scientists as well as for engineers.

Magdeburg, October 2014 Holm Altenbach
Neubiberg Michael Brünig

Contributors

Adel Abdel-Wahab Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, UK

Holm Altenbach Lehrstuhl für Technische Mechanik, Institut für Mechanik, Fakultät für Maschinenbau, Otto-von-Guericke-Universität Magdeburg, Magdeburg, Germany

Daniel Brenner Institut für Mechanik und Statik, Universität der Bundeswehr München, Neubiberg, Germany

Michael Brünig Institut für Mechanik und Statik, Universität der Bundeswehr München, Neubiberg, Germany

Emrah Demirci Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, UK

Halina Egner Department of Mechanical Engineering, Institute of Applied Mechanics, Cracow University of Technology, Cracow, Poland

Artur Ganczarski Institute of Applied Mechanics, Cracow University of Technology, Kraków, Poland

Steffen Gerke Institut für Mechanik und Statik, Universität der Bundeswehr München, Neubiberg, Germany

Somnath Ghosh Departments of Civil and Mechanical Engineering, Johns Hopkins University, Baltimore, MD, USA

Anna Girchenko Lehrstuhl für Technische Mechanik, Institut für Mechanik, Fakultät für Maschinenbau, Otto-von-Guericke-Universität Magdeburg, Magdeburg, Germany

Kazutaka Ikenoya Department of Mechanical Science and Engineering, School of Engineering, Nagoya University, Nagoya, Japan

Guozheng Kang School of Mechanics and Engineering, Southwest Jiaotong University, Chengdu, People's Republic of China

Naoto Kasahara Department of Nuclear Engineering and Management, School of Engineering, The University of Tokyo, Tokyo, Japan

Shahriyar Keshavarz Departments of Civil and Mechanical Engineering, Johns Hopkins University, Baltimore, MD, USA

Zbigniew L. Kowalewski Institute of Fundamental Technological Research, Warsaw, Poland; Motor Transport Institute, Warsaw, Poland

Andreas Kutschke Lehrstuhl für Technische Mechanik, Institut für Mechanik, Fakultät für Maschinenbau, Otto-von-Guericke-Universität Magdeburg, Magdeburg, Germany

Simin Li Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, UK

Jan Maciejewski Warsaw University of Technology, Warsaw, Poland

Francesco Marotti de Sciarra Department of Structures for Engineering and Architecture, University of Naples Federico II, Napoli, Italy

Thomas J. Martin United Technologies Research Center, East Hartford, USA

Konstantin Naumenko Lehrstuhl für Technische Mechanik, Institut für Mechanik, Fakultät für Maschinenbau, Otto-von-Guericke-Universität Magdeburg, Magdeburg, Germany

Nobutada Ohno Department of Mechanical Science and Engineering, School of Engineering, Nagoya University, Nagoya, Japan

Maciej Oleksy Dephi, Kraków, Poland

Roman Petráš Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Brno, Czech Republic

Jaroslav Polák Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Brno, Czech Republic; CEITEC, Institute of Physics of Materials Academy of Sciences of the Czech Republic, Brno, Czech Republic

Maciej Ryś Department of Mechanical Engineering, Institute of Applied Mechanics, Cracow University of Technology, Cracow, Poland

Vadim V. Silberschmidt Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, UK

Błażej Skoczeń Department of Mechanical Engineering, Institute of Applied Mechanics, Cracow University of Technology, Cracow, Poland

Alexander Staroselsky United Technologies Research Center, East Hartford, USA

Tadeusz Szymczak Motor Transport Institute, Warsaw, Poland

George Weber Departments of Civil and Mechanical Engineering, Johns Hopkins University, Baltimore, MD, USA

Yilin Zhu School of Mechanics and Engineering, Southwest Jiaotong University, Chengdu, People's Republic of China

Contents

Creep Behavior Modeling of Polyoxymethylene (POM) Applying Rheological Models 1
Holm Altenbach, Anna Girchenko, Andreas Kutschke and Konstantin Naumenko

Experiments and Numerical Simulations on Stress-State-Dependence of Ductile Damage Criteria 17
Michael Brünig, Steffen Gerke and Daniel Brenner

Constitutive Modeling of Dissipative Phenomena in Austenitic Metastable Steels at Cryogenic Temperatures 35
Halina Egner, Błażej Skoczeń and Maciej Ryś

Modeling of Continuous Damage Deactivation Accompanying Low Cycle Fatigue of Al-2024 Under Complex Loading 49
Artur Ganczarski and Maciej Oleksy

Computational Multiscale Modeling of Nickel-Based Superalloys Containing Gamma-Gamma' Precipitates 67
Somnath Ghosh, Shahriyar Keshavarz and George Weber

Homogenized Elastic-Viscoplastic Behavior of Thick Perforated Plates with Pore Pressure 97
Kazutaka Ikenoya, Nobutada Ohno and Naoto Kasahara

Experimental and Numerical Investigations of the Effects Associated to Complex Loading Combinations 117
Zbigniew L. Kowalewski, Tadeusz Szymczak and Jan Maciejewski

Fracture of Cortical Bone Tissue 143
Simin Li, Adel Abdel-Wahab, Emrah Demirci
and Vadim V. Silberschmidt

A Nonlocal Model of Plasticity and Damage with Different Internal Lengths 171
Francesco Marotti de Sciarra

Hysteresis Loop Analysis in Cyclically Strained Materials 185
Jaroslav Polák and Roman Petráš

Creep, Plasticity and Fatigue of Single Crystal Superalloys: Physics-Based Life Prediction for Turbine Components in Severe Operating Environments 207
Alexander Staroselsky and Thomas J. Martin

Ratchetting of Snake Skin: Experiments and Viscoelastic-Plastic Constitutive Model 243
Yilin Zhu and Guozheng Kang

Creep Behavior Modeling of Polyoxymethylene (POM) Applying Rheological Models

Holm Altenbach, Anna Girchenko, Andreas Kutschke and Konstantin Naumenko

Abstract Polyoxymethylene (POM) is a semi-crystalline thermoplastic polymer with broad technical application. Microstructure after solidifying is strongly dependent on the thermodynamical conditions. As an outcome macroscopic observable time dependent behavior is complex and significantly non-linear. To describe creep behavior of POM a rheological model with five elements is utilized. Creep behavior of POM under monotonic loading and constant temperature conditions can be described in a satisfying manner according to experimental results. A three-dimensional generalization with a comparable backstress formulation will be given. Finally, influence of data scattering will be estimated applying statistical analysis.

Keywords Creep · Polyoxymethylene · Rheological models · Backstress

1 Introduction

POM is widely used in technical application especially for high performance engineering components, because compared to other widely used thermoplastics, e.g. Polyethylene and Polypropylene, POM posses higher stiffness, ultimate strength as well as better long term properties, see Bonnet (2014) among others. A reliable material model in the design process of high performance components is of essential use

H. Altenbach (✉) · A. Girchenko · A. Kutschke · K. Naumenko
Lehrstuhl für Technische Mechanik, Institut für Mechanik,
Fakultät für Maschinenbau, Otto-von-Guericke-Universität Magdeburg,
Universitätsplatz 2, 39106 Magdeburg, Germany
e-mail: holm.altenbach@ovgu.de

A. Girchenko
e-mail: anna.girchenko@ovgu.de

A. Kutschke
e-mail: andreas.kutschke@ovgu.de

K. Naumenko
e-mail: konstantin.aumenko@ovgu.de

H. Altenbach and M. Brünig (eds.), *Inelastic Behavior of Materials and Structures Under Monotonic and Cyclic Loading*, Advanced Structured Materials 57, DOI 10.1007/978-3-319-14660-7_1

to avoid or at least reduce expensive prototype tests during shape or construction optimization.

Description of material response under mechanical loadings, temperature changes, etc., can be performed applying various approaches (Altenbach 2012). Two general main directions exist: the deductive approach (top-down modeling) and the inductive approach (bottom-up modeling). The first one is presented in monographs of Haupt (2002), Palmov (1998), among others, and as usual this approach is applied for materials with very complex behavior, see for example Altenbach et al. (2003), Vilchevskaya et al. (2014). The starting point are mathematical forms of constitutive equations, application of constitutive axioms, etc. The second approach is usual in most of engineering applications. Simple experimental observations are transferred in equations, which are generalized step by step. At each level correctness, for example, w.r.t. the second law of thermodynamics should be proved. The method of using rheological models is somehow a combination of both ways. Basic rheological elements, for which thermodynamical consistency is proved, see Krawietz (1986), Palmov (1998), are combined (series or parallel connections) in a bottom up way for description of complex behavior (Längler et al. 2014; Naumenko and Altenbach 2005; Naumenko et al. 2011; Naumenko and Gariboldi 2014).

2 POM—Microstructure and Macroscopic Behavior

After solidifying POM shows a significant microstructure, see Fig. 1, crystalline lamellae are radially arranged, separated by amorphous phase, and form so called spherulitic crystal volumes. Although some typical dimensions are indicated in the schematic sketch of Fig. 1. The resulting dimensions are strongly dependent on the

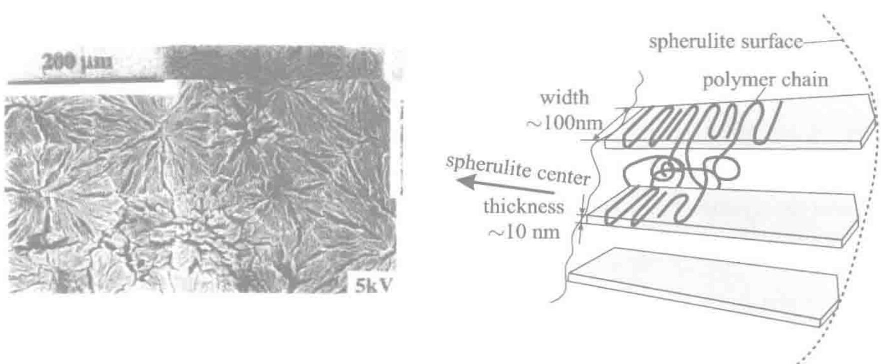


Fig. 1 Microstructure of partially crystalline polymers (SEM-pictures from Plummer and Kausch 1995, the schematic sketch after Katti and Schultz 1982)

conditions during solidification mainly cooling rate, shear rate and pressure, see Mileva et al. (2012).

This complex microstructure leads to a number of deformation mechanism under mechanical and thermal load, like formation, growth and coalescence of crazes, reorientation of broken crystalline lamellae, see Kim and Michler (1998). It is obvious that a description on the micro scale directly based on these mechanism resulting in an applicable material model is not only a challenging task but with the current state of computational methods as well as mechanical models is impossible.

Therefore, in this paper the phenomenological approach is utilized. To this end phenomena to describe have to be taken from experimental results like Fig. 2. A typical creep strain rate versus creep strain curve is shown with two main stages primary creep, reduction of creep rate to a minimum, and tertiary creep, increase of creep strain rate after minimum creep rate. During the first stage, usually addressed as hardening, several deformation mechanism may take place, e.g. polymer chain stretching and sliding in the amorphous phase and stress accumulation in bad, in the sense of deformation, orientated crystalline lamellae. Usually the tertiary creep stage is accompanied by damage and/or micro-mechanical changes and thus a consequently reduced area to withstand mechanical load. However, for this paper only the macroscopic test data was available, so a mechanism based material model can not be derived.

Nonetheless, a material model according to experimental results should reflect primary creep, a non-linear stress dependent minimum creep rate and tertiary creep.

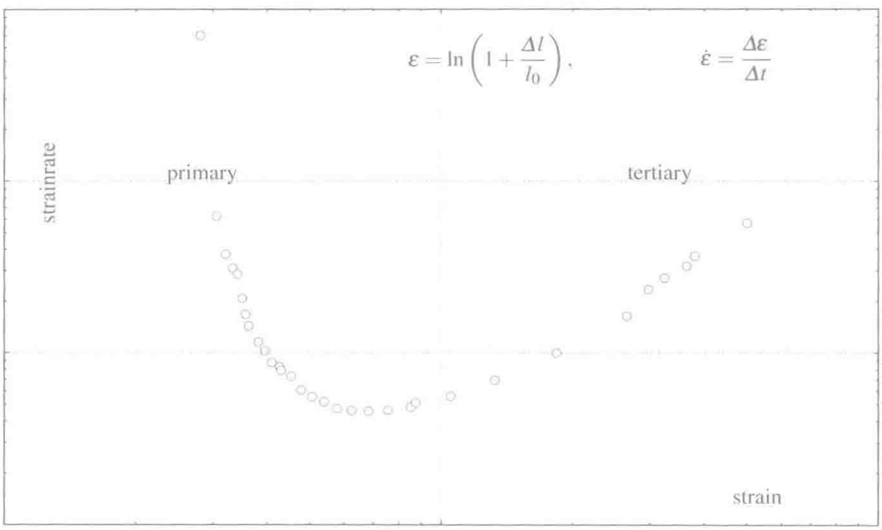


Fig. 2 Typical example of creep test data for POM, in this plot as well as the following axes of the diagram are normalized: strain rate $\dot{\varepsilon}^{cr}/\dot{\varepsilon}^{cr}_{min}$ and strain $\varepsilon^{cr}/\varepsilon^{cr}_{min}$, where $\dot{\varepsilon}^{cr}_{min}$ and ε^{cr}_{min} are minimum creep rate and the strain at minimum creep rate, respectively. $\Delta\varepsilon = \varepsilon_n - \varepsilon_{n-1}$, $\Delta t = t_n - t_{n-1}$ are the strain and time increment, n denotes the data point in experiment

3 One-Dimensional (1D) Material Model

The method of rheological modeling is widely used for describing viscoelastic and viscoplastic behavior of plastics. Basics are given in the pioneering monograph Reiner (1960). Later developments are given, for example, in Palmov (1998), Gisekus (1994). Starting point of any rheological models are the basic elements: elasticity, viscosity and plasticity. For creep behavior of POM it is sufficient to use springs (mechanical elastic elements) and dashpots (viscous or more general time dependent elements), Figs. 3 and 4. Both elements can be, as shown in the figures, utilized to show linear and non-linear response.

Let us develop a complex rheological model for creep behavior of POM. The Maxwell model (Fig. 5) does not fit the experimental data even in the simplest case of applied constant stress σ_0, where σ_0 is related to the initial cross section. Because with such an arrangement creep rate will be obviously constant if the applied stress is constant. Hardening will be incorporated into the model by arranging a spring parallel to the dashpot. In this case the spring will try to pull back the dashpot with increasing creep strain. Primary creep can be modeled with such an approach presented by two elements. But with this arrangement no minimum creep rate will be reached, refer Fig. 6. To reach a minimum creep rate a second dashpot in series to the last introduced spring is necessary and thus hardening and stress dependent minimum creep rate behavior can be described, Fig. 7.

To describe the tertiary creep stage we will only take geometric non linearity into account. On one hand this is a strong limitation in the sense of mechanism based phenomenological modeling and intuitively not realistic according to the briefly mentioned damage mechanism, but on the other hand no appropriate experimental data was accessible to differentiate between damage and geometric effects. Concluding from this we decided that there is no benefit from an additional damage equation of unknown influence whereas geometric effects have to be taken into account according to the conducted creep tests with constant initial load. Influence of the geometric non-linearity can be visualized as shown in Fig. 8.

For numerical implementation it is necessary to express creep rate in terms of actual stress, the stress active in the current configuration of any time t. This can be obtained by assuming incompressible material during inelastic deformation which means that there is no change of volume during the deformation process. In the case of incompressibility geometric considerations will lead to an equation where initial

Fig. 3 Elastic rheological element

$\sigma = E\varepsilon$ -linear elastic response
$\sigma = \Phi(\varepsilon)$-nonlinear elastic response

Fig. 4 Viscose rheological element

$\sigma = \eta\dot{\varepsilon}$ -linear viscose response
$\sigma = \Psi(\dot{\varepsilon})$-nonlinear viscose response

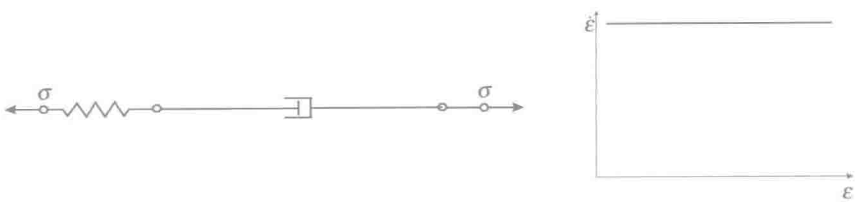


Fig. 5 Maxwell element

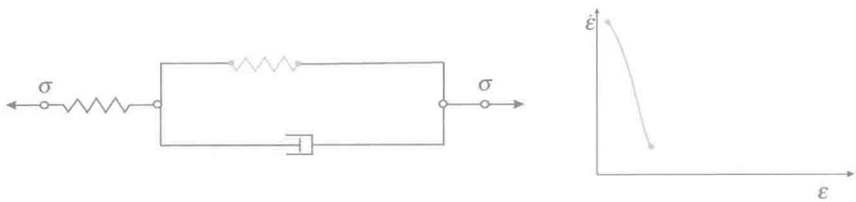


Fig. 6 Influence of the second elastic element

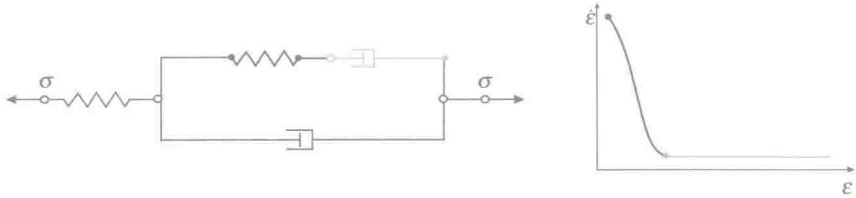


Fig. 7 Influence of the second viscose rheological element

stress and actual stress are linked by cross section shrinkage, among others derived in Besseling and Giessen (1994).

Finally one can write in the one-dimensional case

$$\sigma_{\text{Cauchy}} = \frac{f}{A} = \frac{f}{A_0}(1+\varepsilon) = P(1+\varepsilon),$$

where l_0 is the initial length, $\Delta l = l - l_0$ is the current change of length, f is the normal force to A_0, A respectively,

$$\varepsilon = \ln(1 + \frac{\Delta l}{l_0})$$

is the Hencky strain. With this formulation it is clear that a constant initial stress as argument of a viscosity function will lead to increasing strain rates with increasing creep strain.

With these basic remarks it is possible to analyze the following proposed rheological model for creep behavior of POM. The arrangement of our model is

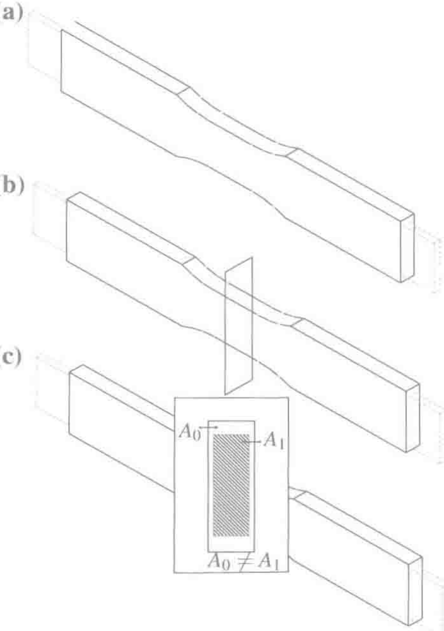


Fig. 8 Visualization of the geometrical non-linearity. **a** Undeformed and deformed state, **b** orthogonal cross-section under consideration, **c** significant cross-section reduction: A_0—reference cross-section, A_1—current cross-section (indicate to distinguish between engineering and true stresses)

shown in Fig. 9 and is similar to the one in Fig. 7 but contains an additional dashpot parallel to our hardening spring. The additional introduced dashpot was found to be necessary to describe the hardening behavior accurately.

In what follows we present a straight forward derivation of our model to obtain a formulation in which the creep rate is only dependent on known quantities. Henceforth, we assume that the

- engineering stress is constant: $\sigma_0 = \text{const}$
- and creep strain can be presented as

$$\dot{\varepsilon}^{\text{cr}} = f\left[(\sigma_0 - \beta_0)\left(1 + \varepsilon^{\text{cr}}\right)\right],$$

where σ_0 is the applied stress and β_0 is the backstress

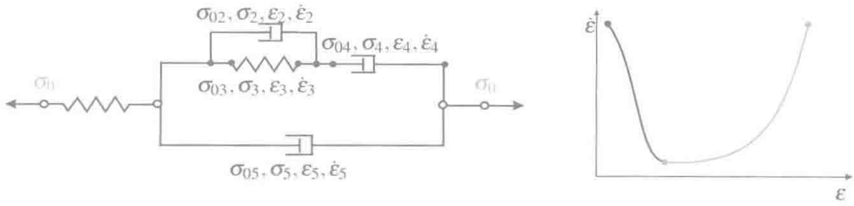


Fig. 9 Proposed four-element rheological model

Here and later the index 0 is related to quantities of initial configuration. It is now necessary to provide a proper formulation for the backstress β_0 as well as to define response functions.

- the creep strain ε^{cr} is equal to the nonlinear strain part of the rheological arrangement

$$\varepsilon^{cr} = \varepsilon_5 \tag{1}$$

  that leads consequently to

$$\dot{\varepsilon}^{cr} = \dot{\varepsilon_5} \tag{2}$$

- for the strain rate of the dashpot the following stress response function was chosen

$$\dot{\varepsilon}_5 = A \sinh(B\sigma_5), \tag{3}$$

  where A and B are constants that need to be calibrated and σ_5 is the active Cauchy stress in the dashpot
- σ_5 has to be replaced in terms of the known σ_0
- considering nonlinear geometric effects we know the relation for the 1D case

$$\sigma_5 = \sigma_{05}(1 + \varepsilon_5), \tag{4}$$

  where σ_{05} is the initial stress and ε_5 is the strain of the dashpot (for sake of simplicity we assume volume constant deformation for all rheological elements)
- the sum of the stresses in the two branches is equal to σ_0, i.e.

$$\sigma_0 = \sigma_{05} + \beta_0, \tag{5}$$

  where β_0 is the stress in the branch with the spring and the two dashpots and will be termed as backstress
- the expression $\sigma_{05} = \sigma_0 - \beta_0$ derived from (5) inserted in the statement (4) yields to

$$\sigma_5 = (\sigma_0 - \beta_0)(1 + \varepsilon_5) \tag{6}$$

- the remaining task is to find an expression for β_0
- similar to statement (5) β_0 can be represented as

$$\beta_0 = \sigma_{02} + \sigma_{03}, \tag{7}$$

  where σ_{02} is the initial stress load of the spring and σ_{03} the initial stress load of the dashpot
- referring to the relation (4) the initial stress loads σ_{02} and σ_{03} can be expressed in terms of the active Cauchy stress

$$\sigma_{02} = \frac{\sigma_2}{1 + \varepsilon_2} \quad \text{and} \quad \sigma_{03} = \frac{\sigma_3}{1 + \varepsilon_3} \tag{8}$$