Preface

Many engineering structures are subjected to high temperature environment and mechanical loadings over a long period of time. Examples include components of power plants, chemical refineries, and heat engines. Design procedures and residual life assessments for pipework systems, rotors, turbine blades, etc., require to take into account inelastic deformation and damage processes. The aim of "modeling materials behavior at high temperature for structural analysis" is the development of methods to simulate and analyze time-dependent changes of stress and strain states in engineering structures up to the critical stage of rupture.

The scope of this book is related to the fields "creep mechanics" (Betten 2008; Hyde et al. 2013; Naumenko and Altenbach 2007; Odqvist 1981), "continuum creep and damage mechanics" (Hayhurst 2001; Murakami 2012), "mechanics of high-temperature plasticity" (Ilschner 1973) or in a broader sense to "behavior of materials and structures at high temperature." The objectives are the formulation of constitutive equations describing the mechanical behavior of structural materials under multi-axial stress states; the application of structural mechanics models of beams, plates, shells, and three-dimensional solids; and the utilization of solution procedures of nonlinear initial-boundary value problems. They have become traditional since the pioneering texts written in the 1950s by Prager (1959) and in the 1960s by Odqvist and Hult (1962), Hult (1966), and Rabotnov (1969), among others. These classical books provide a first collection of solutions to plasticity and creep problems for elementary structures such as rods, beams, and circular plates based on simple constitutive models like the Norton-Bailey equation. The results illustrate the basic features of inelastic behavior of materials and structures: time-dependent deformations, relaxation and redistribution of stresses, and creep buckling. Furthermore, the introduction of internal or hidden state variables to characterize processes accompanying inelastic deformation has been established. The monographs by Penny and Mariott (1995) (first edition in 1971) and Viswanathan (1989) concentrate on robust methods and empirical relationships, which are useful for the design procedures. The monographs by Kraus (1980), Malinin (1981), and Boyle and Spence (1983), published in the 1980s introduce new constitutive models with hardening/recovery and damage variables and initiate the use of advanced numerical methods for structural analysis. The monographs published by Lemaitre and Chaboche (1990) (3rd French edition Lemaitre et al. 2009) and Skrzypek and Ganczarski (1998) in 1990s designate the framework of continuum thermodynamics to derive constitutive models, present the advanced techniques for testing materials under multi-axial non-proportional loading conditions, and overview the developments of continuum damage mechanics. Recent monographs (Besson et al. 2009; Kassner and Pérez-Prado 2004; Yagi et al. 2004; François et al. 2012a, b) and collections of papers (Altenbach and Kruch 2013; Altenbach and Brünig 2015; Altenbach et al. 2015) present constitutive models at different length scales, and provide new methods of homogenization and localization with interlinks to materials science and physics.

Creep problems in materials and structures are widely discussed at various conferences and in scientific papers. The International Union of Theoretical and Applied Mechanics (IUTAM) organizes once in every ten years the symposium "Creep in Structures": 1960—Stanford (Hoff 1962), 1970—Gothenburg (Hult 1972), 1980—Leicester (Ponter and Hayhurst 1981), 1990—Cracow (Zyczkowski 1991), and 2000—Nagoya (Murakami and Ohno 2001). The aim of these symposia was to establish new and fundamental topics on creep and bring together scientists and engineers from fundamental research and applications. The proceedings show developments in modeling and understanding creep phenomena starting from the physical and microstructural aspects of creep and creep-damage up to the structural design procedures. The IUTAM symposium "Advanced Materials Modelling for Structures," held in Paris during April 23–27, 2012, was a continuation and a new version of the previous IUTAM symposia "Creep in Structures" with a focus on new materials and on generalized and unified models of inelastic deformation (Altenbach and Kruch 2013). Materials science foundations of high-temperature plasticity including deformation and damage mechanisms, materials design for high-temperature applications, experimental data on creep and plasticity as well as constitutive models are discussed in International Conferences of Creep and Fracture of Engineering Materials and Structures (CREEP), first organized in 1981 and held from 1981 to 1993 in Swansea on a triennial basis. Since 1993 this conference has been held in London (1995), Irvine (1997), Tsukuba (1999), Swansea (2001), Pittsburgh (2005), Bad Berneck (2008), Kyoto (2012), and Toulouse (2015). The European Creep Collaborative Committee (ECCC) organized the International Conference on Creep and Fracture in High Temperature Components: 2005 in London, 2009 in Zurich, and 2014 in Rome.

During the past decade many advances and new results in the field of high-temperature inelasticity were presented at conference proceedings and in scientific papers. Examples include: the interlinks with materials science in formulation of constitutive equations to consider different deformation and damage mechanisms over a wide range of stresses and temperature; the application of tensor-valued state variables to account for stress state effects and deformation/damage-induced anisotropy; the assessment of models for beams, plates, and shells in structural analysis considering inelastic deformation and damage; the development and verification of material subroutines for use in general-purpose finite element codes; the application of the finite element method to the inelastic analysis of engineering structures under complex thermo-mechanical loading profiles; the consideration of processing conditions, such as welding or induction bending of pipes, and their influence on the subsequent behavior in structures.

The objective of this book is to review some of the classical and recently proposed approaches to modeling of high-temperature inelasticity of materials for structural analysis as well as to extend the collection of available solutions of inelastic problems by new, more sophisticated examples.

In Chap. 1 we discuss the basic features of the inelastic behavior of materials and structures and present an overview of various experimental and theoretical approaches to modeling of inelastic behavior. Typical material responses for various loading paths are presented and classified. Microstructural features and microstructural changes in the course of inelastic deformation at high temperature are discussed. Furthermore, the state of the art on material modeling and structural analysis in the inelastic range at high temperature is presented.

Chapter 2 gives a short introduction to the basics of Continuum Mechanics in one dimension. Here we consider a rod subjected to uniaxial stress state to illustrate the main ideas of continuum mechanics in a simple, transparent manner. Motion, deformation, conservation of mass, balance of momentum, balance of energy, entropy inequality, and the dissipation inequality are introduced and some consequences for material modeling are presented.

Chapter 3 collects elementary constitutive models that describe material behavior under uniaxial stress state. Constitutive equations for elasto-plasticity as well as evolution equations to characterize hardening, softening, aging, and damage processes are presented.

Chapter 4 gives an introduction to the basics of three-dimensional Continuum Mechanics. Equations describing kinematics motion, deformation as well as balance laws are now extended to the three-dimensional case. The consequences for material modeling are discussed.

Chapter 5 is devoted to constitutive modeling of materials subjected to multi-axial stress states. To analyze material behavior under complex thermo-mechanical loading a combined model for thermo(visco)elasto-plasticity considering hardening, softening, damage, and other processes is required. The idea of this chapter is to introduce basic ingredients, useful for the formulation of such unified material models. They include heat transfer modeling, modeling of elasto-plastic deformations, hardening and softening rules as well as aging and damage evolution equations. To formulate a constitutive model for a multi-axial stress state several assumptions must be introduced. Appropriate stress and deformation measures must be considered to capture complex local loadings. Constitutive and evolution equations must be defined such that invariance requirements with respect to the choice of reference frame, laws of continuum thermodynamics, and other principles are fulfilled. To specialize the constitutive equation, results of basic tests of the material behavior, such as tensile test, creep test, relaxation test, etc., should be systematically analyzed. On the other hand, basic features of materials microstructure in the reference state and after a course of inelastic deformation process should be established. Microstructural analysis and appropriate assumptions with regard to symmetries of microstructure would essentially reduce the identification effort. Different types of material symmetries and appropriate forms of constitutive laws are discussed.

Chapter 6 deals with the application of constitutive models to the description of inelastic behavior of several structural materials. Basic approaches to calibrate constitutive models against experimental data of high-temperature material behavior are discussed. Constitutive models of isotropic high-temperature plasticity of several alloys including identified response functions and material parameters are introduced. Two examples of initially anisotropic materials including a forged aluminum alloy and a multi-pass weld metal are presented.

Appendices A and B are a summary of the direct tensor notation and basic tensor operations used throughout the text. This notation has the advantage of a clear, compact, and coordinate free representation of constitutive models and initial-boundary value problems. The theory of anisotropic tensor functions and invariants is discussed in detail. Approaches to derive basic sets of functionally independent invariants for vectors and second rank tensors for the given symmetry group is presented. The invariants are found as integrals of a generic partial differential equation (basic equation for invariants).

Several chapters of this book have grown out of our lectures and lecture notes on fundamentals of continuum mechanics, mechanics of materials, and finite element modeling for graduate level students and Ph.D. students held at the Martin-Luther-Universität Halle-Wittenberg, Otto-von-Guericke-Universität Magdeburg, Fraunhofer Institut für Werkstoffmechanik, Politechnico Milano, Nagoya University, Politechnika Lubelska and National Technical University "Kharkiv Polytechnical Institute." Many results presented originate from scientific and academic exchange projects. We wish to acknowledge financial support from the German Research Foundation (DFG), German Academic Exchange Service (DAAD), the State Saxony-Anhalt, and European Commission (ERASMUS). This book is partly based on the *Habilitation* thesis of the first author (Naumenko 2006) and the book *Modeling of Creep for Structural Analysis* (Naumenko and Altenbach 2007). The extensions are made with regard to the description of the inelastic behavior in a unified manner to include creep, rate-dependent plasticity, hardening/recovery, softening, aging, and damage. New examples are included to illustrate structural behavior under complex, thermo-mechanical loadings.

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Konstantin Naumenko
Holm Altenbach

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Naumenko, K.; Altenbach, H.

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