Advanced Structured Materials

Volume 112

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Modeling High Temperature Materials Behavior for Structural Analysis

Part II. Solution Procedures and Structural Analysis Examples

Springer

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Preface

Many structural components operate at high temperature and mechanical loadings over a long period of time. Examples include components of power plants, chemical refineries and heat engines. Long-term strength analysis, design and life-time assessments require to take into account inelastic deformation and damage processes. The main subject of “modeling materials behavior at high temperature for structural analysis” is to develop methods for the analysis of inelastic processes in components, such as time-dependent changes of stress and strain states and damage evolution 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 more broad sense to “behavior of materials and structures at high temperature”. In the first part of the book Naumenko and Altenbach (2016) basic equations of continuum mechanics and constitutive models describing the mechanical behavior of structural materials under multi-axial stress states are introduced. This, second part is devoted to the application of structural mechanics models, such as beams, plates and shells, as well as the solution procedures of nonlinear initial-boundary value problems. These subjects have become traditional since the pioneering texts written in 1950s by Prager (1959) and 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 the simple constitutive models like the Norton-Bailey equation. The monographs of 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 books of Kraus (1980), Malinin (1981) and Boyle and Spence (1983), published in 1980s, introduce advanced constitutive models with internal state variables and apply numerical methods for the structural analysis.

The aim of modeling and simulation is to reflect basic features of inelastic behavior in structures including the development of inelastic deformations, relaxation and redistribution of stresses as well as the local reduction of material strength. A model should be able to account for material deterioration processes in order to predict long term structural behavior and to analyze critical failure zones. Structural analysis usually requires the following steps:

1. Assumptions must be made with regard to the geometry of the structure, types of loading and heating as well as kinematical constraints.
2. A suitable structural mechanics model must be applied based on the assumptions concerning kinematics of deformations, types of internal forces (moments) and related balance equations.
3. A reliable constitutive model must be formulated to reflect inelastic deformations and processes like hardening/recovery and damage.
4. A mathematical model of the structural behavior (initial-boundary value problem) must be formulated including the material independent equations, constitutive and evolution equations as well as initial and boundary conditions.
5. Numerical solution procedures to solve non-linear initial-boundary value problems must be developed.
6. The verification of the applied models must be performed including the structural mechanics model, the constitutive model, the mathematical model as well as the numerical methods and algorithms.

The first two steps are common within continuum mechanics and engineering mechanics. Here, mathematical models of idealized solids and structures are developed and investigated. Examples include the models of three-dimensional solids, beams, rods, plates and shells. The idealizations are related to the continuum hypothesis, cross section assumptions, etc. The above models were originally developed within the theory of linear elasticity, e.g. Hahn (1985); Timoshenko (1953). In creep mechanics they are applied together with constitutive and evolution equations describing idealized inelastic behavior, e.g. steady-state creep (Boyle and Spence, 1983; Hult, 1966; Kraus, 1980; Malinin, 1981; Odqvist, 1974). As mentioned in the first part (Naumenko and Altenbach, 2016), many structural materials exhibit non-classical phenomena such as different inelastic strain rates under tension and compression, stress state dependence of tertiary creep, damage induced anisotropy, etc. Consideration of such effects may require various extensions of available structural mechanics models. For example, the concept of the stress free (neutral) plane widely used in the theory of beams and plates becomes invalid if the material shows different creep rates under tension and compression. In this book we discuss the applicability of classical and refined models of beams, plates and shells to the inelastic analysis. Based on several examples we examine the accuracy of cross section assumptions for displacement and stress fields.

The mathematical model of an inelastic structure is the initial-boundary value problem (IBVP) which usually includes partial differential equations describing kinematics of deformation and balance of forces, ordinary differential equations describing inelastic processes as well as initial and boundary conditions. The numerical solution can be organized as follows, e.g. Boyle and Spence (1983). For given values of the inelastic strain tensor and internal state variables at a fixed time the boundary value problem (BVP) is solved. Here direct variational methods, e.g.

the Ritz method, the Galerkin method, the finite element method are usually applied. In addition, a time step procedure is required to integrate constitutive and evolution equations. In this book various methods are reviewed and discussed with respect to their efficiency and numerical accuracy.

In recent years the finite element method has become the widely accepted tool for structural analysis. The advantage of the finite element method is the possibility to model and analyze engineering structures with complex geometries, various types of loadings and boundary conditions. General purpose finite element codes like ABAQUS or ANSYS were developed to solve various problems in solid mechanics. In application to the inelastic analysis one should take into account that a general purpose constitutive equation which allows to reflect the whole set of creep and damage processes in structural materials over a wide range of loading and temperature conditions is not available at present. Therefore, a specific constitutive model with selected internal state variables, special types of stress and temperature functions as well as material constants identified from available experimental data should be incorporated into the commercial finite element code by writing a user-defined material subroutine. In this book the ABAQUS and ANSYS finite element codes are applied to the numerical analysis. In order to consider damage processes the user-defined subroutines are developed and implemented. The subroutines serve to utilize constitutive and evolution equations with damage state variables. In addition, they allow the postprocessing of damage, i.e. the creation of contour plots visualizing damage distributions.

An important question in any structural analysis is that on reliability of the applied models, numerical methods and obtained results. The reliability assessment may require the following verification steps:

– *Verification of developed finite element subroutines.* To assess that the subroutines are correctly coded and implemented, results of finite element computations must be compared with reference solutions of benchmark problems. Several benchmark problems have been proposed in Becker et al (2002) based on an in-house finite element code. In this book several closed form and semi-analytical solutions of steady-state creep in elementary structures are presented. To extend these solutions to the primary and tertiary creep ranges the Ritz and the time step methods will be applied. The advantage of these problems is the possibility to obtain reference solutions without a finite element discretization. Furthermore, they allow to verify finite element subroutines over a wide range of finite element types including beam, shell and solid type elements.
– *Verification of applied numerical methods.* Here the problems of the suitable finite element type, the mesh density, the time step size and the time step control must be analyzed. They are of particular importance in creep damage related simulations. In this book these problems are discussed based on numerical tests and by comparison with reference solutions.
– *Verification of constitutive and structural mechanics models.* This step requires tests of model structural components and the corresponding numerical analysis by the use of the developed techniques. Examples of experimental studies on creep in structures include beams, transversely loaded plates (Boyle and Spence,

1983), thin-walled tubes under internal pressure (Koundy et al, 1997; Krieg, 1999), pressure vessels (Eggeler et al, 1994; Fessler and Hyde, 1994), circumferentially notched bars (Hayhurst, 1994).

In Chapt. 1 basics of inelastic structural analysis are introduced starting with elementary examples for bars and bar systems. Main features of inelastic structural responses including creep, relaxation, stress redistribution under various stress-controlled and displacement-controlled loading profiles are illustrated. Governing equations a for two-bar system are introduced and initial value problems for one-dimensional inelastic stress analysis are formulated. Closed-form solutions for a two-bar system under different types of material behavior are presented. Furthermore, examples for numerical time-step methods are introduced. They include one-step explicit and implicit time integration schemes.

Chapter 2 gives a summary of governing mechanical equations to describe inelastic behavior in three-dimensional solids. The set of equations includes material independent equations, constitutive and evolution equations, as well as the initial and boundary. The formulated initial-boundary value problem can be solved by numerical methods. Explicit and implicit time integration methods are presented to analyze three-dimensional solids. With time-step procedures, linearized boundary value problems should be solved within time and/or iteration steps. Variational formulations and direct variational methods are discussed in detail. In addition, time-scales methods are presented in order to formulate efficient solution procedures for components subjected to cyclic loadings.

Chapter 3 collects examples of inelastic structural analysis for beams. Both the classical Bernoulli-Euler beam theory and the first order shear deformation theory are introduced. Governing equations and variational formulations for inelastic analysis are presented. Closed-form solutions and approximate analytical solutions are derived for beams from materials that exhibit power law creep and stress regime dependent creep. Creep-damage constitutive models are applied to illustrate basic features of stress redistribution and damage evolution in beams. The reference solutions for various problems obtained by the Ritz method are applied to verify user-defined creep-damage material subroutines, implemented inside general purpose finite element codes.

Chapter 4 presents examples of inelastic structural analysis for plane stress and plane stress problems. Elementary structures including a pressurized thick cylinder, a rotating disc, and a plate with a circular hole are analyzed. Classical solutions with the power law creep constitutive equations as well as solutions with stress regime dependent inelastic behavior are presented.

Chapter 5 gives an overview of modeling approaches for plates and shells in the inelastic range and presents examples of inelastic analysis of thin-walled structures. Governing equations of the first order shear deformation theory of plates are discussed in detail. An emphasis is placed on the direct formulation of inelastic constitutive laws. For circular plates, numerical solutions of steady-state creep are presented. Advanced constitutive models with internal state variables, such as the damage parameter require the use of advanced plate theories to consider edge effects. An example of a rectangular plate with different types of boundary conditions is presented to illustrate edge effects. Finally, an example for a thin-walled pipe subjected to the internal pressure and the bending moment is discussed.

Several chapters of this book have grown out of our lectures and lecture notes on fundamentals of continuum mechanics, mechanics of materials and inelastic structural analysis for graduate level students and PhD students held at the Martin-Luther-Universität Halle-Wittenberg, Otto-von-Guericke-Universität Magdeburg, Fraunhofer Institut für Werkstoffmechanik (Halle/Saale), Politechnico Milano, Nagoya University, Politechnika Lubelska and National Technical University "Kharkiv Polytechnical Institute", among others. 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 partly includes structural analysis examples published in the monograph *Modeling of Creep for Structural Analysis* (Naumenko and Altenbach, 2007). Many additional examples of elementary structural analysis, which can be solved in a class by standard numerical methods, are introduced.

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