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Structural benchmark creep and creep damage testing for finite element analysis with material tension–compression asymmetry and symmetry

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ABSTRACT

A generalized constitutive model for describing the creep deformation and creep damage development in initially isotropic materials with characteristics dependent on the kind of the stress state has been implemented into the finite element analysis. This paper presents a number of benchmark creep damage tests and reference solutions to verify the finite element results taking into account the material tension–compression asymmetry and symmetry. The numerical results based on the ABAQUS finite element code in which a user subroutine CREEP is incorporated have been compared in the benchmark tests with the numerical results obtained by other authors or by other methods.

1. Introduction

Analysis of the creep deformation and creep damage growth as well as the lifetime estimation are necessary for many structures used in aerospace, chemical, nuclear, mechanical and civil engineering at a high temperature and under severe operational and accidental conditions [1–5]. In this regard, the appropriate constitutive models of continuum damage mechanics and applicable numerical tools need to be used. Unfortunately, up to now, a creep continuum damage faculty has not been included in general purpose commercial software packages, such as ADINA, ANSYS or ABAQUS based on the finite element (FE) method. Therefore, a user defined material subroutine should be written and implemented into the commercial FE code. In the following, it is necessary to check that those subroutine is written and incorporated in FE code correctly as well as to estimate the accuracy of the numerical results with respect to the space and time discretization, e.g., finite element type, meshing, time step size, time step checking conditions. For this purpose, a number of the benchmark tests together with the reference solutions are required.

The concept of benchmarks is becoming increasingly important in computational structural mechanics [6]. Several structural benchmark problems with analysis of creep and creep damage are considered in [7–9] by assuming the material tension–compression symmetry.

Attention in the structural creep damage analysis is given not only to the material tension–compression symmetry, but also to the particular cases of the material tension–compression asymmetry in the tertiary phase of creep described by the Leckie–Hayhurst constitutive model [10]. Herein, the material tension–compression symmetry has been accepted in the primary and secondary stages of creep, as well as, much smaller damage growth intensity in the tertiary phase in compression compared with tension (or no damage in compression) has been considered [11–15]. The results of using the Leckie–Hayhurst model in the structural benchmark creep damage testing are discussed in [7]. However, unfortunately, creep and creep damage in the thin-walled structures is not considered in the analysis.

Different behavior in tension and compression is a significant feature of the creep deformation and creep damage development for many initially isotropic polycrystalline materials [16–22]. In this regard, creep curves obtained from uniaxial tests under tensile and compressive loading types for one and the same absolute value of constant stress, and at the same temperature are essentially different and depend on the sign of the stress. This difference can be very large in the tertiary creep state due to the different creep damage growth in tension and compression. Actually, the appearance, growth and coalescence of microscopic cavities and wedge microcracks under uniaxial tension take place along grain boundaries which are perpendicular to the axis of tensile loading while the same phenomena under uniaxial compression occur at the grain boundary faces located parallel to the axis of compressive loading.

In fact, the effect of the kind of the stress state on the creep deformation and creep damage growth is more complicated

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phenomenon for many initially isotropic polycrystalline materials, and it can not be identified using only material characteristics in tension and compression [23]. For example, the creep curves up to creep rupture for an aluminum alloy AK4-1T at the temperature of $T = 473$ K [24,25] under uniaxial tension, uniaxial compression, and pure shear realized under pure torsion conditions are shown in Fig. 1 by circles. It is seen that the behavior in the secondary stage of the creep curves for tension and compression is different by a factor of about two, while the corresponding creep rupture times are different by a factor of about three (Figs. 1(a) and (b)). It is interesting also to note that the creep data under pure torsion (Fig. 1(c)) cannot be predicted using the constitutive models which are coupled with the experimental data under tension and compression [23].Thus, it is necessary to take into account the effect of shear stress under pure torsion conditions on the creep deformation and creep damage growth in initially isotropic materials under consideration as an independent phenomenon. Furthermore, it is necessary to use the results of three series of the basic experiments (uniaxial tension, uniaxial compression and pure torsion) to describe the creep deformation of an aluminum alloy AK4-1T at 473 K up to creep rupture. Therefore, a number of constitutive models coupled with three series of the basic experiments (uniaxial tension, uniaxial compression and pure torsion) have been developed [18,20,23–35] in order to reproduce the effect of the kind of the stress state on creep and creep damage. Using one of the above mentioned models in the following, the creep deformation of an aluminum alloy AK4-1T up to creep rupture has been broadly discussed [29–35]. In this way, the formulation and solution of numerous one- and two-dimensional initial/boundary value problems related to creep with and without damage in structures made from the aluminum alloy AK4-1T at 473 K have been considered, and the constitutive models under discussion have been incorporated in-house developed software packages [26,28,36,37]. Furthermore, the constitutive model proposed to describe the creep deformation of an aluminum alloy AK4-1T at 473 K up to creep rupture has been implemented in commercial ABAQUS code [35]. In order to estimate the accuracy of the obtained numerical results, a number of the benchmark tests with an aluminum alloy AK4-1T at 473 K together with the reference solutions are required.

2. Constitutive modeling

A general form of the constitutive and damage evolution equations related to the creep deformation at small strains and creep damage growth in an initially isotropic material at the multiaxial stress state can be written as follows [16]:

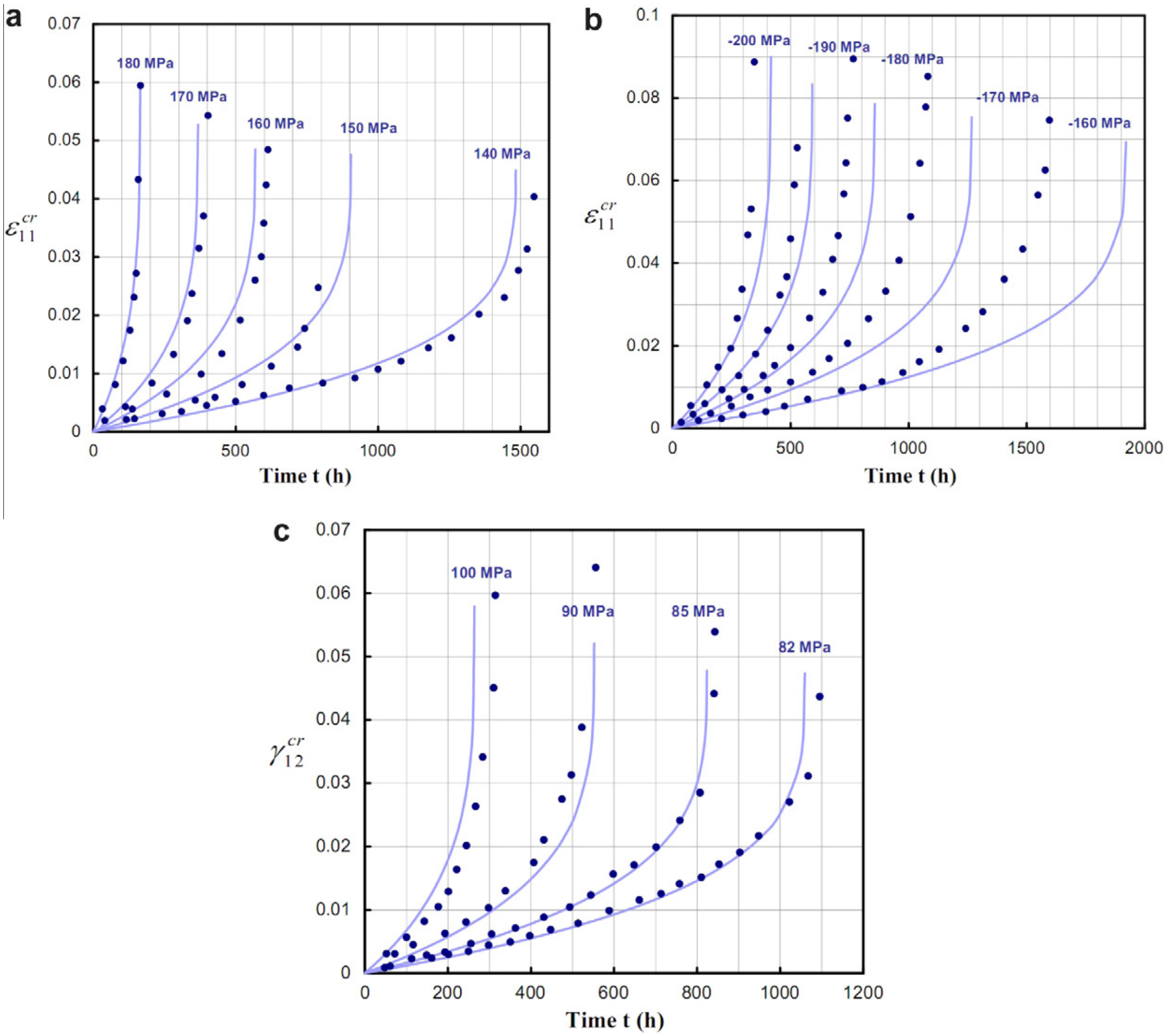

Fig. 1. Variation of the creep strain with time of an aluminum alloy AK4-1T at 473 K under uniaxial tension (a), uniaxial compression (b) and pure torsion (c). Experimental data are denoted by circles while solid lines are the analogous theoretical results.