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Rate dependent plastic deformation analysis of creeping short fiber composites using the virtual fiber method in the non-reinforced regions

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ABSTRACT

In this research paper, analysis of time-dependent plastic deformation in non-reinforced regions of creeping short fiber composites is carried out under axial tensile stress using the virtual fiber method. As an important application of the present method, shuttles and spaceships, turbine blades and discs are usually subjected to the creep effects. So, analysis of the creep phenomenon is necessary and important in various industries. The nature of the stress distributions is investigated using the equilibrium and constitutive equations, compatibility relations, and incompressibility condition with various boundary conditions, and geometric relations. Analytical and finite element methods are used to predict the stress distributions in the steady state creep of the short fiber composites. Also, the creep analysis (nodal solution) is done by FEM to predict the possible creep rupture, in which, debonding at the interface of the matrix and fiber may happen due to the maximum tensile axial stress values at the interface. In addition to similarities of the present method and experimental results [34], a good agreement of the stress distributions between the present analytical solutions and the FEM results is found. As a result, the short fiber composites with large non-reinforced regions in the axial direction are proper because it increases the factor of safety for design.

1. Introduction

Creep may occur in a short fiber composite that is subjected to high temperature and/or mechanical loads. Therefore, considering creep in predicting the structural response of short fiber composites is important and essential in providing realistic response characteristics to designers in making critical decisions. Recently, the high-temperature creep behavior of the short fiber composites has been an important topic for various industries because these reinforced materials have a high performance and proper potential for using in structural applications at elevated temperatures. Because of increasing the application of the short fiber composite, these composites are significant to understand and predict their creep characteristics and deformation mechanisms. It is well known that the short fiber composites present better creep resistance than the related non-reinforced matrix alloy.

A variety of studies on the creep analysis of fibrous composites exist. Analytical approaches are often based on a shear-lag model for analyzing fibrous composites [1–8]. For example, Cox [1] proposed a stress transfer mechanism in the unidirectional long or short fiber composites, which is known as the shear lag model. A novel analytical method was presented to predict the steady state creep of the short fiber composites using shear-lag theory and polynomial displacement functions [8].

Various researchers analyzed short fiber composites using a virtual fiber technique [9–15]. Using the virtual platelets method, Hsueh [11] studied bonding effects at the ends, Young's modulus, and the aspect ratio of the platelet on stress transfer. Mondali et al. [15] proposed a method to predict creep behavior and stress distribution in short fiber composites using shear-lag model and virtual fiber technique in which the 2nd stage creep behavior of the matrix was determined by an exponential law. Other mathematical methods [16–24] can be used for analyzing the steady state creep of the short fiber composites. These include Fourier analysis

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[16], shear-lag model [17], electrical equivalent circuit [18], mapping, logarithmic functions (MF) and dimensionless parameter (DP) techniques [19], complex variable method [20], direct method [21], atomic properties [22], quasi shear lag model with semi-analytical approach [23], and direct analytical method (DAM) [24]. Monfared [24] presented a micromechanical model for obtaining the radial displacement rate at the outer surface ($\dot{u}_b$) and composite creep strain rate ($\dot{\epsilon}_c$) for creeping fibrous composites by DAM. In which, the constitutive and equilibrium equations, incompressibility condition, suitable displacement rates, geometric relations, and comprehensive boundary conditions were used for creep analysis of the short fiber composites.

Numerical approaches are of interest to many researchers because numerical methods are generally simpler and computationally more efficient than analytical and experimental methods for analyzing creep in the short fiber composites. Numerous numerical studies have been conducted using finite element method [25–32]. Role of the interface characteristics and material parameters in the creep behavior of discontinuous ductile fiber-reinforced brittle matrix composite systems have been numerically studied by Biner [26]. Kolluru and Pollock [27] used the FEM to study the continuum aspects of the creep behavior of the unidirectional discontinuous composites loaded parallel and transverse to the fiber axis. Recently, the FEM has been employed to analyze heterogeneous deformation at a micro-structural level [31].

Experimental methods are of interest because they can be used to validate analytical and numerical methods to study the creep behavior of composites [33–40]. For instance, second stage creep behavior of the metal matrix composites subjected to various temperature and mechanical loads has been experimentally predicted [33,34]. Compression creep behavior of fibrous composites has been predicted under different temperatures and different strain rates [35]. Also, high-temperature creep behaviors of 7075 and 2124 aluminum alloys have been predicted under uniaxial tensile loads [40], in which, constitutive models for explaining the high-temperature creep behavior have been developed using continuum damage mechanics [40]. As a different research work, global error control of the time-propagation for the Schrödinger equation with a time-dependent Hamiltonian has been presented for efficient and accurate solution of time-dependent equations [45].

The review of the literature indicates that studies on creep behavior of non-reinforced regions in the short fiber composites are not available, although studies on the reinforced regions of the creeping short fiber composites have been carried out previously. Analysis of the non-reinforced regions is complex and intricate. The solution framework used for the analysis of the reinforced region I cannot predict the exact and correct creep behavior in the region II, because the creep analysis of the non-reinforced region II needs the high order and well-behaved displacement functions, extended boundary conditions, and new combination of the basic equations and relations without using the shear lag theory (due to the specific conditions of the non-reinforced region II). Therefore, the present study is undertaken to analyze creep behavior of the non-reinforced regions (region II: regions of A+B: the regions located at $0 \le r \le b, 0 \le z' \le l' - l$ or $0 \le r \le b, l \le z \le l'$) analytically and computationally (see Figs. 1, 2 and [13,23,25,33,34]). The major purpose of this study is to predict the steady-state creep behavior of short fiber composites in the non-reinforced regions. For achieving to this aim, constitutive and equilibrium equations, compatibility relations, incompressibility and boundary conditions, virtual fiber method and geometric relations are employed for predicting creep behavior. In the study, it is assumed that the short fiber behaves elastically, whilst the matrix behavior is expressed by a creep exponential law. Moreover, interfacial bond between the fiber and matrix is assumed to be perfect without slipping. Virtual fiber and matrix have similar material properties in the non-reinforced regions and they creep concurrently. Comparison of the obtained results between the present analytical and FEM results shows a good agreement. The study shows that the short fiber composites with large non-reinforced regions in the axial direction are suitable because it increases the factor of safety for design.

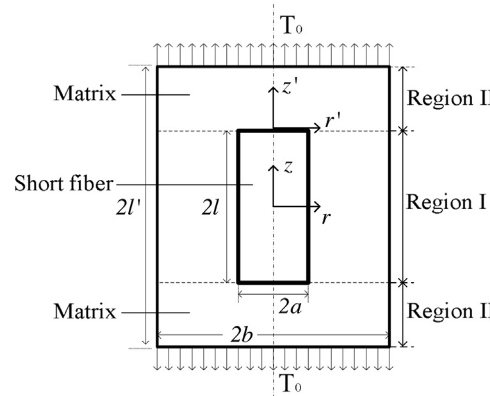

Fig. 1. Model of the representative unit cell in the axisymmetric model under tensile axial load T_0 for the region I (reinforced region: $0 \le r \le b, 0 \le z \le l$) and region II (non-reinforced region: $0 \le r \le b, 0 \le z' \le l' - l$ or $0 \le r \le b, l \le z \le l'$).

2. Theoretical formulation

2.1. Representative element

A cylindrical unit cell is generally assumed as a representative element of the short fiber composite, as shown in Fig. 1. Cylinders of the fiber and matrix are coaxial in the present model. Here, we study stress distributions in the non-reinforced region II of the unit cell. The fiber aspect ratio and volume fraction are defined by $s = l/a$ and $f = V_f/V$, respectively. At which, V_f and V are, respectively, volumes of the fiber and unit cell. The unit cell geometric parameter is expressed as $k = (l'/b)/(l/a) = l'a/lb$.

A tensile axial stress $T_0 = T_{app}$ is applied on the end faces of the unit cell uniformly (i.e., at $z = \pm l'$). Two cylindrical coordinate systems (r, θ, z) are normally used shown in Fig. 1. Only a region located in $0 \le z \le l'$, $0 \le r \le b$ is analyzed because of the symmetry in loading, geometry of the unit cell, and boundary conditions.

It is assumed that the elastic deformation of the fiber is negligible in comparison with the creep deformation of the matrix.

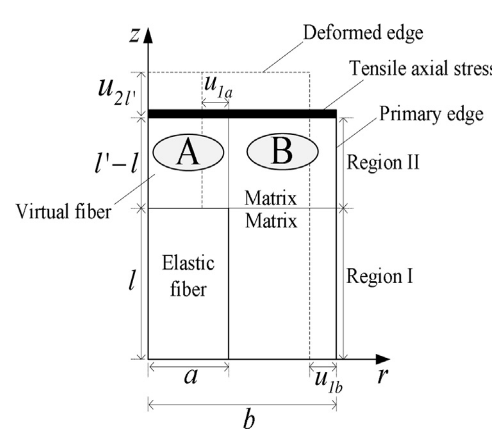

Fig. 2. Model of the virtual fiber with boundary displacements in the creeping unit cell.