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A displacement based model to determine the steady state creep strain rate of short fiber composites

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A R T I C L E I N F O

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A B S T R A C T

A novel analytical method is developed for predicting steady state creep of short fiber composites using shear-lag theory, imaginary fiber technique and polynomial displacement functions. Also, this method employs equilibrium and constitutive equations. Polynomial displacement method (PDM) is a new insight for analysis of plasticity and elasticity problems which can be used as a simple, exact and general method. PDM is more accurate than the available methods. Important novelties of the PDM are determination of unknowns such as shear stresses and displacement rates on top of the fiber analytically. In this paper, all unknowns are obtained by well-behaved polynomial displacement functions. These functions satisfy incompressibility and boundary conditions. In spite of the previous researches, strain rates and stresses are analytically obtained by PDM without non-analytical assumptions. Also, suitable agreements are found among present analytical method, numerical (FEM) and available published results.
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1. Introduction

Short fiber composites (SFC) are growing in aircraft and aerospace industries, automotive and other applications due to many their advantages. One of the dangerous phenomena is creep phenomenon which may happen for composites. Therefore, this phenomenon should be precisely analyzed for preventing dangerous and unpleasant events. Many investigations have been carried out to determine the creep behaviors of the fibrous composites.

Some analytical researches are based on the shear-lag model fundamentally [1–13]. For example, one dimensional shear lag model originally was presented by Cox [1], which is a robust and strong method for the stress transfer analysis of the unidirectional fibrous composites. In recent years, Mondali et al. [12] presented an analytical model for predicting the steady state creep behavior of the short fiber composites using shear-lag theory and imaginary fiber technique. In which, creep behavior of the matrix was also obtained by a creep exponential law. In addition, some researchers have analyzed the short fiber composites using imaginary fiber technique elastically [14–18]. Also, a number of researches have been performed regarding the creep of the fibrous composites and their applications with various insights analytically [19–24]. Various researchers have used different approaches instead of the shear-lag theory for solving problems such as Eshelby's thought experiment with a formulation based on the Schapery model [19] and variational method [21]. For instance, Monfared et al. [22] recently presented the steady state creep strain rate of the short fiber composites without using the shear-lag theory. They obtained some important unknowns in the second stage creep of the short fiber composites utilizing mapping function and dimensionless parameter techniques.

Numerical attempts have been done for analyzing the creep problems by various investigators. Numerical methods have helped to researchers for analyzing the problems [25–33]. FEM study on the second stage creep behavior of the metal matrix composite has been carried out with assuming the fiber–matrix debonding parameter in the modeling by Mondali et al. [31]. At which, correct simulation and time consuming are some difficulties of FEM. Moreover, one of the important sections of Ref. [33] is prediction of partial creep debonding at the interface in the steady state creep of the short fiber composites under tensile axial stress.

With attention to some difficulties of the experimental methods, they have been also helpful for predicting the creep behavior approximately [34–48]. For example, the steady state creep behavior of 6061 aluminum alloy and SiC/Al6061 composite has been investigated experimentally and analytically by Morimoto et al. [35]. In which, occurrence of non-aligned fibers and creation of micro-cracks in the creeping composite are some

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difficulties during the experimental process. For instance, the creep behavior of the TiC-particulate-reinforced Ti alloy composite has been studied at temperatures from 500 to 650 °C and applied stresses from 230 to 430 MPa [36]. Up till now, numerous constitutive models have been presented to address viscoplastic behaviors of materials [49,50].

According to the mentioned previous researches, a simple, exact and straightforward method should be analytically presented to predict the creep behavior of the short fiber composites without using non-analytical assumptions. In this regard, present analytical method (PDM) easily determines all unknowns without using non-analytical assumptions unlike the available researches. For example, the matrix shear stresses and displacement rates on top of the fiber in the short fiber composite have not been obtained analytically, while present analytical method (PDM) can strongly determine the mentioned unknowns theoretically. The mentioned method can be used for the creep stress–strain analysis of the nano-composites, composite design and the other applied sciences because of high performance in determination of all parameters. Most researchers have determined the mentioned unknowns using some weak and non-analytical assumptions. However, present method PDM determines all unknowns without using non-analytical assumptions with high accuracy theoretically.

Considering above discussions and difficulties of FEM and experimental methods, a simple and exact analytical method PDM is presented for predicting the steady state creep behavior of the short fiber composites based on shear-lag theory, imaginary fiber technique and polynomial displacement method (PDM), as well as, equilibrium and constitutive equations, incompressibility and boundary conditions are also used.

PDM can analysis the creep behavior in all regions of the short fiber composites analytically. It should be mentioned that the present method PDM satisfies all equilibrium and constitutive equations, incompressibility and boundary conditions. In this work, behavior of the fiber is elastic unlike the creeping matrix behavior. One of the important advantages of PDM for the other researches is to analyze simultaneous creep behavior of both the fiber and matrix in the composites. PDM employs all the equilibrium and constitutive equations unlike the most previous available shear-lag based models. A perfect fiber/matrix interface is assumed and the steady state creep behavior of the matrix is described by a creep exponential law. The results obtained from the proposed analytical solution satisfy the equilibrium and constitutive creep equations. PDM decreases the number of calculations and also obtains independently all unknowns without using previous research results.

2. Material and method

2.1. Composite model

To analyze the steady state creep of short fiber composite, a cylindrical unit cell model is considered in accordance with the previous researches in order to model a short fiber (whisker) composite [14–18,31,35]. A unit cell is a representative for complete composite. For example, creep strain rate $\dot{\varepsilon}$ is the same for both the unit cell and complete composite ($\dot{\varepsilon}_{unit\ cell} = \dot{\varepsilon}_{complete\ composite} = \dot{\varepsilon}_c$). Moreover, general change of the length of the complete composite is calculated using change of the length of the unit cell (Fig. 1).

Volume fraction and aspect ratio of the fiber are $f = a^2l/b^2l'$ and $s = l/a$ respectively. Also, in this research, $k = l'a/lb$ is considered as a parameter related to the geometry of the unit cell. An applied axial stress σ_0 is uniformly applied on the end faces of the unit cell (at $z = \pm l'$). The cylindrical polar coordinate system (r, θ, z) used with the origin located at the center of the unit cell. Because of symmetry in the geometry, loading and boundary conditions, the analysis is performed only on half of the unit cell ($0 \leqslant z \leqslant l'$). Also, elastic deformations are small and are neglected compared with creep deformations and fibers behave elastically during the analysis. Steady state creep behavior of the matrix, which its properties are considered to be constant with temperature, is described by an exponential law as given in Eq. (1),

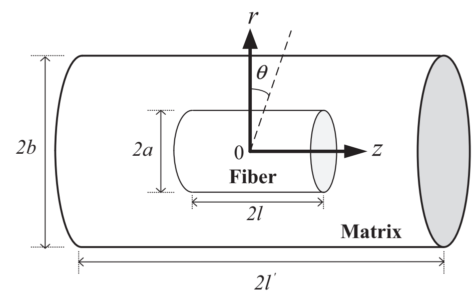

Fig. 1. Unit cell model.

$$\dot{\varepsilon}_e = A \exp\left(\frac{\sigma_e}{B}\right) \tag{1}$$

where σ_e and $\dot{\varepsilon}_e$ are equivalent stress and equivalent strain rate of the creeping matrix respectively. Creep exponential law is assumed for the creeping matrix. Exponential function behavior has a suitable compatibility with creep behavior. For example, general trend of the creeping matrix behavior is similar to the exponential function behavior mathematically.

2.2. Equilibrium equations and stress–displacement rate relations

The equilibrium equations for the mentioned problem with assumption of the cylindrical coordinates (r, θ, z) are obtained as the following [49,50],

$$\frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{rz}}{\partial r} + \frac{\tau_{rz}}{r} = 0 \tag{2a}$$

$$\frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{rz}}{\partial z} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \tag{2b}$$

The strain–displacement rate relations (geometric relations) are also given by Khan and Huang [50],

$$\dot{\varepsilon}_r = \frac{\partial \dot{u}}{\partial r} \tag{3a}$$

$$\dot{\varepsilon}_\theta = \frac{\dot{u}}{r} \tag{3b}$$

$$\dot{\varepsilon}_z = \frac{\partial \dot{w}}{\partial z} \tag{3c}$$

$$\dot{\gamma}_{rz} = \frac{\partial \dot{u}}{\partial z} + \frac{\partial \dot{w}}{\partial r} = 2\dot{\varepsilon}_{rz} \tag{3d}$$

The generalized constitutive equations for the creep small deformation of the matrix in r, θ and z directions are derived from reference [49] as the following,

$$\dot{\varepsilon}_r = \zeta[\sigma_r - \upsilon(\sigma_\theta + \sigma_z)] \tag{4a}$$

$$\dot{\varepsilon}_\theta = \zeta[\sigma_\theta - \upsilon(\sigma_r + \sigma_z)] \tag{4b}$$

$$\dot{\varepsilon}_z = \zeta[\sigma_z - \upsilon(\sigma_r + \sigma_\theta)] \tag{4c}$$

$$\dot{\gamma}_{rz} = 3\zeta\tau_{rz} \tag{4d}$$

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