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A micromechanical creep model for stress analysis of non-reinforced regions of short fiber composites using imaginary fiber technique

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ABSTRACT

Stress behavior in short fiber composites under axial tensile stress is predicted based on well-behaved displacement rates in the steady state creep using imaginary fiber technique. This analysis is performed without using shear-lag model and other complex theories in non-reinforced regions of the short fiber composites. Direct analytical method (DAM) is presented to obtain the composite creep strain rate and stress behavior. Because of many applications of silicon carbide fiber SiC/Al6061 composites, stress analysis of this composite is done. Good agreements are found between the obtained present analytical and finite element method (FEM) results. Some important applications of the present comprehensive method are in the fields of the safe composite design and control of creeping composites in order to prevent the creep rupture. Also, present method is simple and accurate, unlike costly, difficult and time-consuming experimental methods.

1. Introduction

Stress analysis of the short fiber composites is important and necessary for composite design and optimization in the steady state creep. For preventing creep rupture, this phenomenon should be analyzed and controlled. Various researches were carried out about the creep analysis of the fibrous composites.

Here, available analytical, numerical and experimental researches are reviewed for providing extended vision in order to analyze the creep phenomenon.

Some analytical methods are based on shear-lag model for analysis of the fibrous composites (Cox, 1952; Lauke and Schultrich, 1983; Nairn, 1997; Beyerlein and Landis, 1999; Nairn and Mendels, 2001; Carlsson and Lindstrom, 2005; Gao and Li, 2005; Mondali et al., 2013; Monfared, 2015). For example, an efficient model was one-dimensionally presented in order to analyze stress transfer in the unidirectional long or the short fiber composites by Cox (1952), which is known as the shear lag model.

Also, various studies have been done based on imaginary fiber technique for analyzing the short fiber composites (Roscoe, 1969; Weng and Sun, 1979; Hsueh, 1990, 1992, 1995; Nayfeh and Abdelrahman, 1998; Jiang et al., 2005; Mondali et al., 2009). For example, one of the most effective researches has been carried out by Weng and Sun (1979). They used from fictitious fiber technique for studying the effects of the fiber length on elastic moduli of randomly-oriented chopped-fiber composites. This technique is similar to the imaginary fiber technique for analyzing the short fiber composites. The mentioned solution method based on fictitious fiber technique (Weng and Sun, 1979) is similar to Hsueh's elastic solution, known as the imaginary fiber technique, which its details are available (Hsueh, 1990, 1992, 1995). The application

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of the fictitious and imaginary fiber techniques is very important to analyze the matrix located at the top of the fiber. Also, this technique can help to the analysis of a complete composite. In this paper, one of the important applications of the fictitious and imaginary fiber techniques is presented. With considering the fictitious and imaginary fiber technique, we can simply solve and analyze the short fiber composites because the matrix (located at the top of the fiber) is divided into the two regions of the matrix and imaginary fiber. Also by dividing to two sections, more boundary conditions are applied for analyzing the short fiber composites. So, more exact results are obtained using this technique.

Moreover, different mathematical approaches have been proposed for creep analyzing instead of the mentioned approaches (Madgwick et al., 2001; Ohno et al., 2002; Zhang, 2003; Li and Li, 2012; Monfared et al., 2012, 2013a, 2013b; Monfared and Mondali, 2014).

Other different mathematical methods have been used for analyzing the steady state creep of the short fiber composites such as techniques based on Fourier analysis (Madgwick et al., 2001), variational method (Ohno et al., 2002), parametric study based on shear model (Zhang, 2003), mapping, logarithmic functions (MF) and dimensionless parameter (DP) techniques (Monfared et al., 2012), complex variable method (Monfared et al., 2013a), rigorous Eshelby inclusion theory (Li and Li, 2012), and quasi shear-lag model with semi-analytical approaches (Monfared and Mondali, 2014).

A number of numerical studies have been done using finite element method (Dragon and Nix, 1990; Biner, 1994; Kolluru and Pollock, 1998; Ismar et al., 2000; Kim et al., 2008). Numerical approaches are of interest to many researchers because sometimes these methods are generally simpler than the analytical and experimental methods for analyzing creep in the composites. 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 (1994). For example, finite element method has been employed for investigating the continuum aspects of the creep behavior of the unidirectional discontinuous composites loaded parallel and transverse to the fiber axis by Kolluru and Pollock (1998).

The experimental methods are of interest to many material researchers and engineers such as experimental methods for obtaining creep behavior of the materials and composites (Morimoto et al., 1988; Nagarajan et al., 1999; Cseh et al., 1999; Girard et al., 2014; Vöse et al., 2014). For example, steady state creep behavior of the metal matrix composites has been experimentally determined under various temperatures and stresses along with its effect on interfacial sliding (Morimoto et al., 1988; Nagarajan et al., 1999; Cseh et al., 1999).

Each of the three mentioned methods (analytical, numerical and experimental) has various advantages and disadvantages for analyzing the creep of the fibrous composites. Combination of these methods simultaneously would be ideal for analyzing the creep problems. According to the available researches, prediction of the creep strain rate and stress behaviors can be beneficial for analyzing the creep behavior of the short fiber composites in the non-reinforced regions. Therefore, a comprehensive study on the creep behavior of the short fiber composites is essential in the non-reinforced regions.

According to the presented literature reviews and available researches, this study presents a method in order for better analyzing the creep phenomenon in the non-reinforced regions of the short fiber composites. Here, short fiber has linear elastic behavior (similar to the rigid fiber) while the matrix behavior is described by a creep exponential law. Interface bonding between the fiber and matrix is considered to be perfect without any slipping. Suitable and considerable compatibilities are seen between the obtained present analytical method and FEM results.

The main objective of this study is to predict the composite creep strain rate and stress behavior in the creeping short fiber composites in the non-reinforced regions under axial tensile loading. In this way, constitutive and equilibrium equations, incompressibility condition, imaginary fiber technique, well-behaved displacement rates, geometric relations and comprehensive boundary conditions are used for predicting composite creep strain rate and stress behavior.

This analysis is done without using shear-lag model and other complex theories. In which, the imaginary fiber and matrix have the same material properties in the non-reinforced regions and they creep simultaneously. Direct analytical method is presented for predicting the creep behavior. One of the insights of the present work is in application of the imaginary fiber technique for the strain rate and stress analysis of the non-reinforced regions in the creeping short fiber composites. Due to numerous applications of silicon carbide fiber SiC/Al6061 composites, stress analysis of this composite is carried out.

Unlike the present work, most of the available works are about analysis of the reinforced regions of the creeping composites. One of the important applications of the present work is in design of the short fiber composites based on stress and strain rate behaviors. Also, composite creep strain rate is analytically predicted, unlike expensive, difficult and time-consuming experimental method.

2. Definition of the problem

2.1. Composite model presentation

A micromechanical and cylindrical unit cell model is employed as a representative of the short fiber composites in the present research shown in Fig. 1 (e,g., Weng and Sun, 1979; Morimoto et al., 1988; Dragon and Nix, 1990).

A cylindrical short fiber (whisker) with radius a and length $2l$ is embedded at the center of a cylinder as the matrix with radius b and length $2l'$. Present research analyzes the creep behavior in the non-reinforced region II in the unit cell. The fiber aspect ratio and volume fraction are introduced by $s = l/a$ and $f = V_f/V_{unit\ cell}$ respectively. In which, V_f and $V_{unit\ cell}$ are respectively volumes of the fiber and unit cell. The unit cell geometric parameter is described by $k = (l'/b)/(l/a) = l'a/lb$. An applied tensile axial stress $\sigma_0 = \sigma_{app}$ is applied on the end faces of the unit