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Two-scale micromechanical modeling of the time dependent relaxation modulus of plain weave polymer matrix composites

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ABSTRACT

In this study, a micromechanical model is presented for prediction of the time dependent relaxation modulus of plain weave polymer matrix composites. This model is based upon the analysis of the representative volume element (RVE) of composites. The RVE models are firstly created on two scales consisting of the fiber bundle modeling (fiber-scale) followed by a weave fabric modeling (bundle-scale). The material properties of fiber and matrix are described by linear elastic law and viscoelastic constitutive law respectively. The generalized Maxwell rheological model is used to describe the viscoelastic behavior of matrix. A time dependent strain energy model is then proposed for evaluating the relaxation modulus of composites. Stress relaxation experiments are conducted for plain weave T300 carbon fabric reinforced 5105 AXSON epoxy resin composites with different fiber volume fractions. Predictions are compared with experimentally measured response to verify the proposed model. In addition, a series of numerical simulations are performed to examine the influences of the loading time and fiber volume fraction on the relaxation behavior of composites.

1. Introduction

The utilization of polymeric woven composites in various fields of application has progressed significantly over past decades. Due to viscoelastic nature of polymer matrix [1], time-dependent behavior, characterized as stress relaxation and strain creep of polymer composites, has become a major concern in load bearing polymer composite structures. During past three decades, in order to understand and design the mechanical behavior of composites, considerable research has been carried out to the development of theories for the modeling of composites. A common method is micromechanical approach, which provides overall behavior of the composites through an analytical or finite element analysis of a representative volume element (RVE) [2–4]. The advantage of this approach is not only in obtaining global properties of the composite but also mechanical behaviors can be related to the composite microstructure.

A majority of micromechanical models for predicting the elastic properties of woven composites have been reported in the literature [5–9]. In comparison, the studies for viscoelastic properties of polymeric woven composites are slightly limited and insufficient. Seifert et al. [10] presented the finite element based micromechanics model to obtain the viscoelastic properties of a glass fabric composite at elevated temperatures. Govindarajan et al. [11] utilized the elastic–viscoelastic principle to predict the creep behavior of graphite/epoxy woven composites. They determined the matrix response by fitting predictions to the measured creep compliance and characterized the creep compliance of the composites. Shrotriya and Sottos [12,13] used elastic–viscoelastic correspondence principle and two-dimensional finite element analysis to predict the viscoelastic response of a woven composite from fabric, fiber and matrix properties. Computation results and experimental data indicated that the relaxation modulus of the composite is dependent not only on the relaxation of the matrix but also on the woven fabric bundles. Pan et al. [14] presented a mechanistic model for quantifying the time-dependent creep of woven carbon fiber composites, assuming that the carbon fibers remain elastic and the matrix is linear viscoelastic. Predictions of this model were compared with experimental values for both stitched and unstitched woven composites. Zhu et al. [15] presented a 3-D viscoelastic model of a woven fabric used in circuit boards with accurate geometry characterization. Close correlation of analytical results with the experimental data available suggested that the creep compliance of the composite depends on the relaxation of matrix and the time dependent deformations of the fiber bundles as well. Sawanta and Muliana [16] introduced a

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numerical algorithm based on implicit stress integration solutions for nonlinear thermo-mechanical viscoelastic analysis of orthotropic composite materials and structures that follow thermo-rheological complex behavior. Pavan et al. [17] proposed a model to combine continuous damage with viscoelasticity. In this work, a hardening law associated with the damage process was identified from the experimental data and further used to derive the rate type constitutive equations.

It can be concluded that the studies for viscoelastic properties of polymeric woven composites are still insufficient and most of the published studies have focused on the creep behavior of composites. Besides the creep behavior, stress relaxation is also a fundamental characteristic for describing the long-term mechanical performance of the polymeric composites. Knowledge of the relaxation behavior of composites enables us to predict the dimensional stability of load-bearing structures and the retention of clamping force for bolts fastened to composites [18].

Thus, this study proposes a detailed two-scale micromechanical model for predicting stress relaxation modulus of plain weave polymer matrix composites. The RVE models are created on two scales consisting of the fiber bundle modeling (fiber-scale) followed by a weave fabric modeling (bundle-scale). The material properties of fiber and matrix are described by linear elastic model and generalized Maxwell rheological model, respectively. It should be noted that the generalized Maxwell model is primarily used for describing the stress relaxation behavior of polymers. The creep behavior and temperature dependence of polymers cannot be rationally represented by this model. However, considering the presented study is focused on the stress relaxation modulus of composites, the generalized Maxwell model is adopted to identify the viscoelastic behavior of polymer matrix. A time dependent strain energy model is proposed for evaluating the relaxation modulus of composites. The proposed micromechanical model is applied on a plain weave T300 carbon fabric reinforced 5105 AXSON epoxy resin composite. Stress relaxation experiments are conducted for specimens with different fiber volume fractions in a time period of 4 h. Predictions are compared with experimentally measured response to illustrate and assess the predictive capability of the proposed model. Finally, a series of numerical simulations are performed to examine the relaxation behavior of the composites in detail.

2. Two-scale finite element modeling of RVE

The finite element modeling of RVE for the plain weave polymer matrix composites relied on a two-scale approach consisting of modeling the fiber bundles (fiber-scale) followed by a weave (bundle-scale) analysis. The weave has two constituents consisting of fiber bundles and pure polymer matrix pockets. Each fiber bundle consists of individual fibers with polymer matrix separating them. Therefore, a two-scale analysis procedure is as proposed: (a) RVE finite element model on fiber-scale is firstly built to obtain the relaxation modulus and the results are used for the bundles which are treated as a homogeneous transversely isotropic material. (b) Based on the obtained relaxation modulus of bundles, RVE finite element model on bundle-scale is then created to evaluate the relaxation modulus of the weave. In this study, finite element models on two scales are both produced using finite element software ANSYS [19].

2.1. Fiber-scale

The fiber bundle is assumed to be a unidirectional composite consisting of hexagonal packed fibers and surrounding matrix, as illustrated in Fig. 1(a). Geometrical model of fiber-scale RVE is

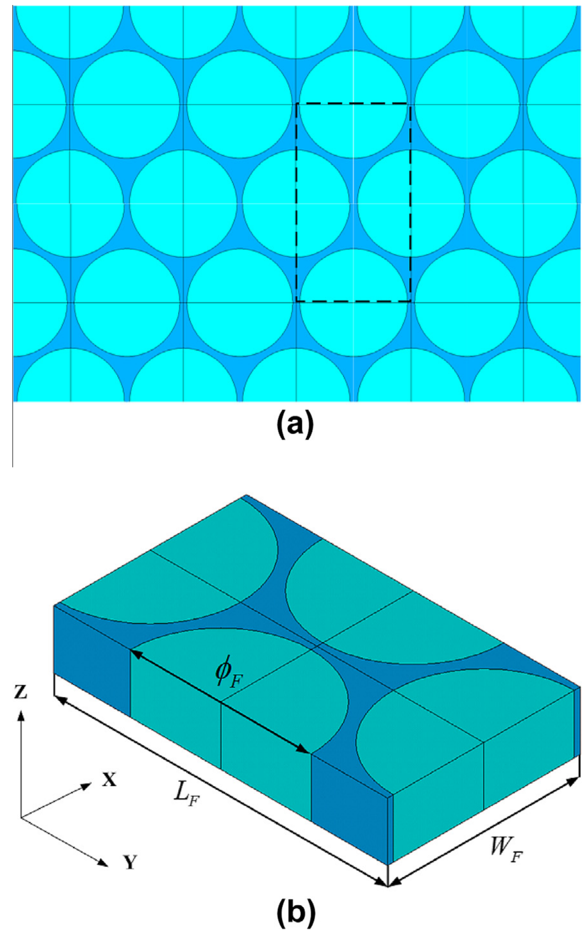

Fig. 1. Geometrical model of fiber-scale RVE (a) hexagonal packing for a fiber bundle (b) characteristic geometric parameters.

displayed in Fig. 1(b). Characteristic geometric parameters of the RVE model are: fiber diameter ϕ_F, length, width and height of the RVE L_F, W_F, and H_F, respectively.

Denote V_F^f to be the fiber volume fraction, following expression can be derived to evaluate V_F^f according to Fig. 1b

$$V_F^f = \frac{\pi \phi_F^2}{2L_F W_F} \tag{1}$$

The finite element model of the RVE is depicted in Fig. 2 where twenty-node prismatic solid element SOLID95 of ANSYS software is used.

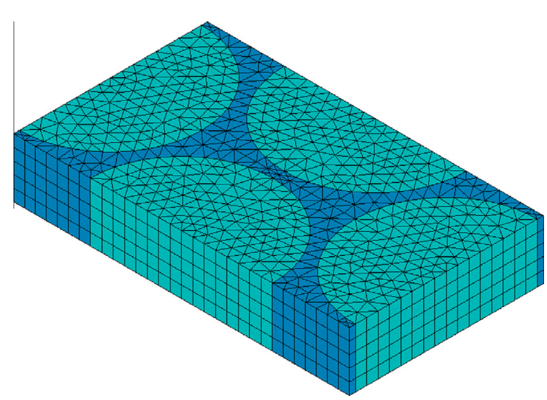

Fig. 2. Finite element model of fiber-scale RVE.