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Multiscale modeling of viscoelastic behaviors of textile composites

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ABSTRACT

Mechanics of Structure Genome (MSG) is extended to provide a new two-step homogenization approach to predict the viscoelastic behaviors of textile composites. The first homogenization step (micro-homogenization) deals with determining the viscoelastic properties of yarns from fibers (assumed to be linear elastic) and matrix (assumed to be linear viscoelastic) using the MSG solid model. In the second homogenization step (macro-homogenization), the viscoelastic behaviors of textile composites are computed from the homogenized yarns and matrix properties using the MSG plate model. Representative volume element (RVE) analysis using a commercial finite element package at micro-scale is conducted to verify the accuracy of MSG micro-homogenization. The viscoelastic behaviors of textile composites at macro-scale using the MSG plate model are validated using experimental data. All the results are in good agreements. The proposed approach is applied to several commonly used woven composites to study the effects of different weave patterns on the viscoelastic behaviors.

1. Introduction

Textile Composites have been widely used in many engineering fields due to their excellent mechanical performance and low manufacturing costs. However, because of the complex microstructures, it is much more challenging to accurately predict the material behaviors of textile composites. Mechanics of Structure Genome (MSG) (Yu, 2016) has recently extended to provide a two-step approach to compute effective elastic properties of textile composites (Liu, Rouf, Peng, & Yu, 2017; Rouf, Liu, & Yu, 2018), which has been proved to be an accurate and efficient way to predict the elastic behaviors of textile composites. However, because of the inherent viscoelastic behavior of polymers (Hashin, 1966), the long-term behaviors of textile composites should also be considered.

For unidirectional fiber reinforced composites, analytical approaches have been proposed using the correspondence principle (Hashin, 1965; 1966), but more general results have been obtained using numerical methods (Brinson & Knauss, 1992; Muliana & Haj-Ali, 2005; Tang & Felicelli, 2015). However, there are not many models available for predicting the viscoelastic properties of textile composites. The main difference is that both yarns and matrix in textile composites exhibit viscoelastic behaviors while only the matrix is considered to be viscoelastic in unidirectional fiber reinforced composites. Models using the classical lamination theory (CLT) have been proposed to study the viscoelastic properties of plain woven composites, and the laminar properties are computed using different micromechanical approaches such as the combined model

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(Upadhyaya & Upadhyay, 2011) and self-consistent model (Shrotriya & Sottos, 2005). There are two main limitations in these approaches. First, assumptions are used to describe the geometry of textile composites, which means that the models are limited to the specific assumed weave patterns. Second, ad hoc assumptions are used in describing the local stress and strain state that affect the accuracy of the predictions. To overcome the above limitations, numerical approaches such as three dimensional (3D) representative volume element (RVE) analysis based on the finite element analysis (FEA) has been used to study the viscoelastic problems in textile composites (El Mourid, Ganesan, & Lévesque, 2013; Kwok & Pellegrino, 2016). Usually, there are no ad hoc assumptions in numerical approaches, which means the viscoelastic behaviors of different weave patterns can be studied using a same approach. Thanks to the finite element mesh, complex yarn geometries such as yarn cross-sections and undulations can be captured. However, due to the complex microstructures in textile composites, large number of elements are often required to capture the geometric shapes of yarns, which will increase the computational costs. In addition, anisotropic viscoelastic materials are not available in most FEA software, and additional efforts are needed to define the properties through user-defined functions, such as Abaqus user-defined material subroutine (UMAT) (Barbero, 2013).

The above limitations have been addressed by using MSG, which was recently discovered as a unified approach for multiscale constitutive modeling of heterogeneous structures and materials (Yu, 2016). Since a finite element mesh is used to discretize the analysis domain, MSG can handle any textile composites with arbitrary microstructures. Being a semi-analytical approach, MSG greatly reduces the computing time and maintains accuracy as 3D RVE analysis without the complexity of applying the right boundary conditions. In addition, MSG unifies micromechanics and structural mechanics, which has the possibility to predict structural properties in terms of microstructures without unnecessary scale separation assumptions. MSG-based structural modeling has been demonstrated to be an efficient and accurate approach to model various engineering structures with complex geometry made of anisotropic materials (Liu & Yu, 2016; Peng, Goodsell, Pipes, & Yu, 2016). The ability of constructing stiffness matrix of structural components using MSG plate and beam models provides another solution to handle complex boundary conditions (BCs). For example, for thin textile composites that have one dimension much smaller than the other two dimensions, MSG plate model can be used to predict the plate stiffness matrix which satisfies the in-plane periodic boundary conditions (PBCs) and tractions free BCs on the top and bottom surfaces (Rouf, Liu, & Yu, 2018).

In this paper, MSG solid and plate models are extended to handle linear viscoelastic behaviors of constituent materials. The viscoelastic behaviors of textile composites in this paper are represented in terms of the stress relaxation modulus and the time-dependent plate stiffness matrix. A plain woven fabric is used as an example to demonstrate the accuracy of the proposed model. At the micro-scale, viscoelastic homogenization is performed using the MSG solid model, and the results are compared with those from the RVE analysis. At the macro-scale, the effective viscoelastic properties of yarns along with the viscoelastic properties of matrix are used as inputs to perform the MSG plate modeling. The results of the plate model are compared with experimental data in the literature. At last, the proposed approach is applied for two-dimensional (2D) woven (plain and twill) and 3D orthogonal woven examples to study the effects of different weave patterns on the viscoelastic behaviors.

2. MSG multiscale viscoelastic model of textile composites

2.1. Linear viscoelastic theory

The constitutive equation for the linear viscoelastic material can be expressed in the time domain in Eq. (1).

$$\boldsymbol{\sigma}(t) = \int_{-\infty}^{t} \mathbf{C}(t-\tau) : \frac{d\boldsymbol{\epsilon}}{d\tau} d\tau \tag{1}$$

A Prony series can be used to represent the relaxation modulus over a wide range of time scale. For an isotropic material, the Young's modulus can be represented in terms of the Prony series as:

$$E(t) = E_\infty + \sum_{i=1}^{n} E_i e^{-t/\rho_i} \tag{2}$$

where E_∞ is the long-term modulus, E_i are the Prony coefficients, and ρ_i are the relaxation times. Each exponential term is used to represent the variation of the relaxation modulus over a chosen time period, and the number of terms included in the Prony series depends upon the time range of interest for the problem that is considered. For general anisotropic material properties, the relaxation modulus tensor can be expressed in a similar way using the Prony series as:

$$C_{ijkl} = C_{ijkl,\infty} + \sum_{m=1}^{n} C_{ijkl,m} e^{-t/\rho_m} \tag{3}$$

2.2. MSG-based solid model

According to MSG, a homogenized model can be formulated by minimizing the information loss between the original heterogeneous body and the homogenized body. The information can be the transient strain energy for a linear viscoelastic