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An anisotropic hyperelastic constitutive model for thermoplastic woven composite prepregs

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ABSTRACT

A hyperelastic constitutive model is developed to characterize the anisotropic and large deformation behavior of woven thermoplastic composite prepregs during thermo-forming process. In the model, a strain energy function representing the material behavior of melting prepreg is additively decomposed into three parts nominally representing the energy contributions from the matrix, fiber and their interaction, respectively. The proposed constitutive model is demonstrated on a balanced 2 × 2 twill glass/PP prepreg. The specific forms of the strain energy functions are determined by fitting uni-axial tensile and bias extension tests of the prepregs at melting temperature. The developed model is then applied to simulation of a benchmark double dome thermo-forming, demonstrating that it is highly suitable for predicting the large deformation behavior of woven prepregs during thermo-forming process. The effects of matrix on forming simulation results are also investigated.

1. Introduction

Their high specific strength, high specific stiffness and outstanding design ability make woven fabric composites important materials when weight reduction is a major trend [1]. Although the widespread use of fabric composites, the commonly used forming technologies, such as LCM processes (Liquid Composite Moulding), have disadvantages as high operation complexity, low efficiency and high cost [2–4]. Prepreg thermo-stamping is a potential alternative to the LCM processes to provide a solution for overcoming the primary obstacle [5,6]. Prepregs are semi-products where the matrix, which can be thermoplastic or thermoset, is already integrated into the continuous fiber woven reinforcement. Compared with LCM process or thermoset prepreg forming, thermo-stamping FRTP (fiber reinforced thermoplastic plastic) prepreg is a fast manufacturing process for the omission of a long polymerization stage [7]. In the thermo-stamping process, woven fabric-reinforced thermoplastic prepregs, which have been heated above their melting temperature, can be stamped to a shape and cooled back to a rigid solid. The duration of thermo-stamping process can be within 1 min, which contain forming and consolidation phase. Moreover thermoplastic materials are more easily recyclable than thermoset materials.

Nevertheless, prepreg thermo-stamping is a thermal-mechanical coupled process which involves complex phenomenon such as anisotropic material behavior, heat transfer, viscosity and large deformation. Though thermo-forming of prepregs has recently attracted increasing interests, relatively fewer reports on the simulations of thermo-forming behavior of woven composite prepregs exist comparing to the extensive literature available on forming process. Numerical simulations of thermo-stamping could provide a powerful tool for tool design and process optimization. One of the main challenges in numerical simulation is the development of appropriate constitutive models that can accurately predict the anisotropic behavior of FRTP textile prepregs resulting from complex reorientation, redistribution of yarn fibers and interaction between fibers and matrix [4].

Due to the multi-scale nature of woven composites, three families of modeling approaches have been developed to describe the thermo-forming of prepregs: kinematical, discrete and continuous approaches. The kinematic approach based on the pin-jointed net idealization [8] is simple and computationally very efficient. But it cannot provide the stresses and deformations necessary to the prediction of incomplete forming, buckling and wrinkling. Discrete approach is an alternative approach for numerical simulation of

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woven composites forming [9–13]. Nevertheless, the computational effort in these approaches is significant for forming processes of complex fiber architectures.

Conversely to discrete approaches, in continuous models, woven fabric prepregs are considered as homogenized continuum which can be discretized by shell elements in standard finite element method. O'Bradaigh and Pipes [14,15] presented a mixed penalty finite element approach for the analysis of composite sheet-forming by treating composite laminates as a transversely isotropic Newtonian fluid with fiber of inextensibility. De Luca et al. [16] investigated thermo-forming of a fiber-reinforced composite sheet by using shell elements for each ply which was assumed as a thermo-viscous matrix with elastic fiber reinforcements. Specialized viscous-friction and contact constraints were used to characterize the shearing between each ply. Boisse et al. [17–20] developed a numerical approach for thermo-forming of multi-layer thermoplastic prepregs in which each ply was modeled by semi-discrete shell elements with tension, in-plane shear and bending Stiffness. However, semi-discrete elements do not consider the complex nonlinear tensile behavior of the prepreg and therefore cannot predict shear angle and wrinkles accurately in the stamping simulation of composite forming [19,20].

A viscoelastic model based on a phenomenological framework which uses a particular Helmholtz free-energy function that allows modeling of composite sheets with two arbitrary families of fibers was proposed [21–23]. Yet, the Helmholtz free-energy function does not incorporating interactions between individual fibers and matrix material. Peng et al. [24] developed an anisotropic hyperelastic constitutive model for woven fabrics accounting for the fiber-fiber interaction with the change of angle between weft and warp yarns. Their simulation results showed good accordance with experimental data of double dome forming. This paper aims to develop a simple hyperelastic constitutive model to characterize the anisotropic nonlinear material behavior of FRTP prepregs under large deformation during thermo-stamping. The strain energy for the model stores in matrix, fibers and fiber–fiber-matrix shear interaction. By decoupling the fiber extension energy with in-plane shearing energy, the material characterization of textile fabric prepreg is greatly facilitated. The material parameters can be conveniently obtained from two simple tests, namely, uni-axial tensile and shearing tests at the melting temperature. The proposed constitutive model is demonstrated on a balanced 2 × 2 twill weave fabric prepreg.

2. A simple hyperelastic model for thermoplastic prepregs with fiber-fiber-matrix interaction

In real prepreg thermo-stamping process strains up to 50% are occurring. For this purpose large deformations have to be considered. During forming, portion of the energy exerted on textile prepreg will be dissipated due to viscosity of thermoplastic matrix. Nevertheless, in hyperelastic approaches, the energy required to deform prepregs can be approximately treated as the strain energy of the corresponding deformations during forming unless the unloading process is considered [24]. Moreover, according to the thermoplastic composite prepregs bias-extension experimental results [25], the change of temperature gives weak influence to the inter-ply shear behavior of prepregs when the forming temperature is above the melting temperature. Consequently, the matrix is weak and only modifies the in-plane shear stiffness of prepregs. Meanwhile, analysis on bias-tensile strain-rate [25] shows that the influence of forming speed can be neglected.

The forming process must be performed at a temperature close to or higher than the melt temperature of the resin in order to render the textile prepreg deformation possible. Therefore, in the development of the constitutive model, the fibers are assumed to be extensible and uniformly distributed in the ground substance. Perfect bonding between fibers and matrix is assumed [26]. The matrix is assumed to be initially isotropic and hyperelastic [27,28]. Based on the composite material characterization approaches proposed by Peng et al. [24,26,29], we develop a nonlinear anisotropic constitutive model with fiber-fiber-matrix interaction for thermoplastic composite prepregs.

Assume **F** to be the deformation gradient tensor. For materials like fiber-reinforced composite with two families of fibers, the strain energy function W can be defined as a scalar function of the right Cauchy-Green deformation tensor $\mathbf{C}=\mathbf{F}^T\mathbf{F}$ and the original fiber directional $\mathbf{a}_0$ and $\mathbf{b}_0$, i.e., $W=W(\mathbf{C},\mathbf{a}_0,\mathbf{b}_0)$. The elastic response of the textile prepreg (for a single layer) is assumed to originate from the resistance of the matrix, fibers, and their interactions. Accordingly, the strain energy function W can be divided into three parts, namely

$$W = W(\mathbf{C},\mathbf{a}_0,\mathbf{b}_0) = W^M + W^F + W_{ab}^{FFM} \tag{1}$$

where nominally W^M is the strain energy contribution from the ground substance, W^F is the contribution from fiber stretches and W_{ab}^{FFM} is the strain energy caused by fiber-fiber-matrix interactions.

Alternatively, the strain energy function could be expressed in terms of principle invariants of **C** namely

$$W(\mathbf{C},\mathbf{a}_0,\mathbf{b}_0) = W\left(I_1, I_2, I_3, I_4^a, I_4^b, I_5^a, I_5^b, I_6, I_7\right) \tag{2}$$

where the invariants are given by

$$\begin{aligned}
&I_1 = \mathrm{tr}\mathbf{C}, \quad I_2 = \frac{1}{2}\left[(\mathrm{tr}\mathbf{C})^2 - \mathrm{tr}\mathbf{C}^2\right], \quad I_3 = \det\mathbf{C},\\
&I_4^a = \mathbf{a}_0\cdot\mathbf{C}\cdot\mathbf{a}_0 = (\lambda_F^a)^2, \quad I_4^b = \mathbf{b}_0\cdot\mathbf{C}\cdot\mathbf{b}_0 = \left(\lambda_F^b\right)^2,\\
&I_5^a = \mathbf{a}_0\cdot\mathbf{C}^2\cdot\mathbf{a}_0, \quad I_5^b = \mathbf{b}_0\cdot\mathbf{C}^2\cdot\mathbf{b}_0,\\
&I_6 = \mathbf{a}_0\cdot\mathbf{C}\cdot\mathbf{b}_0, \quad I_7 = \mathbf{a}_0\cdot\mathbf{C}^2\cdot\mathbf{b}_0
\end{aligned} \tag{3}$$

where λ_F is the fiber stretch.

The ground substance in prepregs is modeled as a hyperelastic material. Here, for simplicity, we use the well-developed incompressible Mooney-Rivlin model:

$$W^M = \frac{c_1}{2}(I_1 - 3) + \frac{c_2}{2}(I_2 - 3) \tag{4}$$

where the units for material parameters c_1,c_2 are MPa.

The fiber part of the strain energy function originates from the fiber elongation, which is assumed to be governed by an exponential function as

$$\begin{aligned}
W^F = &\frac{k_1}{2k_2}\left\{\exp\left[k_2(I_4^a - 1)^2\right] - 1\right\}\\
&+ \frac{k_1}{2k_2}\left\{\exp\left[k_2\left(I_4^b - 1\right)^2\right] - 1\right\}
\end{aligned} \tag{5}$$

where the unit for material parameter k_1 is MPa. k_2 is a dimensionless parameter.

Here we assume that the fibers do not contribute to the total strain energy when they are under contraction ($\lambda_F<1$), since the fibers are generally crimped and buckle readily and thus have negligible compression stiffness [21].