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Model for prediction of simultaneous time-dependent damage evolution in multiple plies of multidirectional polymer composite laminates and its influence on creep

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ABSTRACT

A model to predict time-dependent evolution of simultaneous transverse cracking developed in multiple plies during creep loading and its effects on creep of multidirectional polymer matrix composite laminates is presented. The stress states in the intact regions of the plies are determined using the lamination theory during an incremental change in time. The stored elastic energy, determined using this stress state, is compared with a critical stored elastic energy value for damage to determine if a ply would fracture after the increment. If fracture is predicted, variational analysis is used to determine the perturbation in ply stresses due to cracking. This procedure is repeated to determine the crack evolution and creep strain. Model predictions compared well with experimental results for a $[\pm\theta_m/90_n]_s$ laminate.

1. Introduction

Degradation of modulus (creep) and strength with time (creep rupture) due to viscoselasticity of the polymer matrix is a major concern in utilizing polymer matrix composites (PMC) in structural applications. Additional contribution to this degradation comes from various damage modes such as transverse cracking (matrix microcracking), vertical cracking, i.e. edge cracks due to out-of-plane normal stress [1], and delamination. These damage modes occur within and between the plies of a laminate and are influenced by the laminate stacking sequence [2]. Damage evolution in PMCs can be time-dependent (TDD) or time-independent (TID). TDD primarily develops in conjunction with creep deformation while TID typically develops under manufacturing process and transient quasi-static loading. Both TID and TDD influence creep of polymer composites.

Dillard et al. [3,4] were the first researchers who highlighted the influence of TDD on creep. Moore and Dillard [5] experimentally recorded the increase in transverse crack density in [90] plies of cross-ply laminates with time at room temperature at the stress levels greater than FPF (First Ply Failure) stress. Raghavan and Meshi [2] showed experimentally that the FPF stress was also time-dependent and the creep of cross-ply laminates increased with the increase in transverse crack density. Nguyen and Gamby [6] experimentally explained the loading rate dependence of FPF and cracking in cross-ply laminates with a linear viscoelastic behavior of the undamaged material and a load-rate dependent critical energy criterion. Birur et al. [1] experimentally studied the evolution of various damage modes with time in multidirectional polymer composite laminates subjected to a constant load and showed that the sequence of the damage modes varied with stacking sequence, stress, and temperature. They observed that the different damage modes influenced one another and the creep rupture time. These studies established that polymer composite laminates develop TDD and both polymer matrix viscoelasticity and TDD influence the creep and creep rupture of PMCs.

Previous research (both experimental and modeling) on time-independent damage evolution and their effect on modulus of composite laminates is extensive and a good review can be found in Refs. [7,8]. However, published studies on modeling time-dependent damage evolution and its influence on creep and creep rupture of multidirectional PMCs are limited. The various modeling approaches that have been used in the past to model the

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effect of time-independent damage on modulus degradation of a multidirectional PMC laminate during quasi-static testing are mainly, 1) Ply discounting methods, 2) Continuum damage mechanics (CDM) models and, 3) Elastic analysis based models. Ply discounting models reduce the modulus of the cracked ply near zero value and use it within the framework of lamination theory to determine the modulus of the laminate (many studies cited in Refs. [9,10]). Despite its simplicity, this method artificially changes the laminate stacking sequence and material properties. Continuum damage mechanics (CDM) models replace the damaged ply with an equivalent undamaged ply and experimentally relate the modulus degradation to a damage parameter, which in turn is related to applied stress/strain [11–15]. Elastic analysis based models determine the change in ply stresses or strains due to damage and use the new stress/strain state to determine the modulus of the laminate with damage. Elastic analysis based models are either analytical or numerical. Analytical models were mainly developed based on shear lag analysis [16–19] or variational analysis [20–24]. Analytical modeling of cracking in off-axis plies in multidirectional laminates requires three dimensional stress state analyses [18,22,24]. More complexity is involved in the analysis when simultaneous cracking in multiple plies occurs. Numerical models mostly involve finite element analysis [25–27]. Some studies have also combined different modeling approaches such as CDM with micromechanics [12–14], CDM with shear lag analysis [16,17], CDM with fracture mechanics [15], CDM with finite element analysis [11], and variational analysis with fracture mechanics [28]. The same modeling approaches can be adopted along an appropriate model framework and damage criterion for prediction of TDD evolution in multidirectional PMC laminates.

Schapery [28] developed constitutive equations based on CDM for linear viscoelastic lamina within a laminate with time-dependent transverse cracks and Gamby and Delaumenie [29] have modeled the transverse crack growth rate in a [90] ply using Schapery's viscoelastic fracture criterion [30]. Guedes [31] developed a model working in a lamination theory framework to predict the creep rupture of multidirectional PMCs. His model used Schapery's non-linear viscoelastic constitutive equations [32,33] to determine the free energy of individual plies and compare it with an energy-based proposed failure criterion to predict the progressive failure of the laminas. Park et al. [34] and Treasurer et al. [35] developed constitutive equations based on CDM approach in PMC [$\pm\theta$] laminates. The former studied the effect of rate-dependence transverse cracking in stress–strain response and the latter investigated the stiffness loss due to creep. These studies did not focus on prediction of time-dependent damage growth in modeling. Ahci and Talreja [36] developed a thermodynamics based model along with finite element analysis for predicting the non-linear creep of woven polymer composites with pre-existing damage. Time-dependent damage evolution was not modeled in this study. Ogi et al. [37,38] developed a model based on shear lag analysis to predict the creep response of a laminate with cracks in [90] plies and used it to predict the creep of a cross-ply laminate with time-dependent transverse cracking [37] as well as the creep and recovery behavior of a quasi-isotropic laminate with pre-existing transverse cracks [38]. In both studies, experimental crack density was used and no appropriate model was developed to predict time-dependent crack growth. Akshantala and Brinson [39] developed a variational analysis based model to predict loading rate dependence of transverse cracking in [90] plies of cross-ply laminates during tensile testing. Evolution of crack density in a single ply ([90] plies) was considered in their model through prediction of its effect on the laminate modulus. However, this model was not extended and validated for creep. The authors [40] previously developed a model based on CDM working in a lamination theory model framework to predict the influence of time-dependent cracking on the creep compliance of $[\pm 45/90_2]_s$ laminates. In that study, a damaged ply was modeled using an equivalent undamaged ply with an apparent compliance, which was determined as a function of time-dependent transverse crack density. The time-dependent transverse crack densities in [90] and [±45] plies were experimentally recorded and input to the model to determine the increase in the apparent compliance of the laminate due to damage during creep.

In summary, modeling the time-independent transverse cracking [41], delamination induced from transverse cracking, and their effect on time-independent modulus of laminates has been studied in the past. There are also published research studies on experimental characterization of time-dependent evolution of damage in multidirectional polymer composite laminates. However, all the models published for time-dependent damage focused on transverse cracking in a single ply (mainly [90] plies) while simultaneous damage evolution in other plies has been experimentally observed [1]. To the knowledge of the authors, a model for predicting the evolution of concurrent damage in multiple plies with time, their interaction, and their effect on creep is not available in PMC laminates.

In this paper, a model based on a 3-D variational analysis combined with a lamination theory model framework and a time-dependent critical stored elastic energy (CSEE) damage criterion has been developed to predict the simultaneous evolution of both TID and TDD in multiple plies and their influence on creep of multidirectional PMC laminates. The core of this model is a three-dimensional variational analysis formulating the perturbations in the stress state of the plies when cracking occurs. It is also noted that the model employs a time-dependent damage criterion, which is essential for successful prediction of TDD in PMC laminates [42]. It has been found that fracture toughness of polymers and unidirectional polymer composites decreased with increase in creep time or decrease in loading rate [43]. Due the complexity involved in variational analysis of concurrent transverse cracking, vertical cracking, and delamination, the damage mode considered in this model was transverse cracking as the primary damage mode that continues to develop for a wide range of applied stress [7,8]. This model also attempts to address the knowledge gap in modeling the cracking interactions [41] when the cracked ply (e.g. [$-\theta$] in a $[\pm\theta_m/90_n]_s$ laminate) is sandwiched between two different cracking interfaces (e.g. [$-\theta$]/[$+\theta$] and [$-\theta$]/[90] interfaces) imposed by adjacent plies. Only the results on TDD and creep are presented. The details of the entire model can be found in Refs. [44,45].

2. Model

The stress state in the plies of PMCs depends on the curing process and loading history. The stress state can be further altered due to TID. During creep loading, the stress state of the plies would be additionally changed due to load transfer between the plies as well as TDD. A reliable creep model should be able to simulate the evolution of ply stress state, TID, and TDD for a given process and load history to predict the creep of a multidirectional PMC. The developed model in this study is comprehensive and considers the three zone of process and load history identified in Fig. 1. A block diagram of the model, consisting of four integrated modules, is shown in Fig. 2. The Process-Induced Residual Stress (PIRS) module predicts the process-induced residual stress for an imposed manufacturing and process history as a function of temperature (ΔT). The Quasi-Static Load (QSL) module predicts the stress states in plies as a function of stress ($\Delta\sigma$) for an imposed load profile with initial values input from the PIRS module. The Static Load (SL) module predicts the stress state as a function of time (Δt) for a