Composite Structures 126 (2015) 62–71

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Multiscale model of woven ceramic matrix composites considering manufacturing induced damage

Luke Borkowski *, Aditi Chattopadhyay

School for Engineering of Matter, Transport and Energy, Arizona State University, P.O. Box 876106, Tempe, AZ 85287-6106, United States

ARTICLE INFO

Article history:
Available online 12 February 2015

Keywords:
Ceramic matrix composites
Progressive damage
Micromechanics
Multiscale modeling
Woven composites
Manufacturing-related damage

ABSTRACT

Multiscale models play an important role in capturing the nonlinear response of woven carbon fiber reinforced ceramic matrix composites. In plain weave carbon fiber/silicon carbide (C/SiC) composites, for example, when microcracks form in the as-produced parts due to the mismatch in thermal properties between constituents, a multiscale thermoelastic framework can be used to capture the initial damage state of these composites. In this paper, a micromechanics-based multiscale model coupled with a thermoelastic progressive damage model is developed to simulate the elastic and damage behavior of a plain weave C/SiC composite system under thermal and mechanical loading conditions. The multiscale model is able to accurately predict composite behavior and serves as a valuable tool in investigating the physics of damage initiation and progression, in addition to the evolution of effective composite elastic moduli caused by temperature change and damage. The matrix damage initiation and progression is investigated at various length scales and the effects are demonstrated on the global composite behavior.

1. Introduction

The extreme stiffness, strength, and toughness, as well as nonbrittle failure of advanced ceramic matrix composites (CMCs) make them an ideal choice over monolithic ceramics for many aerospace applications, such as hot engine components [11,22,6,8,12,2,9]. Ceramic matrix composites also offer oxidation and creep resistance, as well as thermal shock stability at elevated temperatures. However, under extreme loading and environmental conditions, the structural reliability of these composites remains a critical issue because a damage event will compromise the integrity of the composite structure, resulting in ultimate failure. Damage in CMCs can initiate at the fiber, matrix, tow, or weave levels. The widespread use of CMCs in critical aerospace components such as turbine blades and thermal barriers, therefore, necessitates development of physics-based models that accurately account for constitutive linear elastic and nonlinear behavior at the pertinent length scales of these materials. Multiscale models can link constitutive model parameters and behavior at the micro- and mesoscale to damage evolution at the macroscale, thus further extending our understanding of damage initiation and propagation in heterogeneous material systems. Traditional analysis methods for composites account for only macroscopic or structural level responses, rendering them inadequate in capturing the complex multiscale phenomena governing composite behavior. Multiscale physics-based models, on the other hand, are well suited for structural analysis because they can effectively determine stress, strain, stiffness, damage, and various state variables at multiple length scales. These models also enable information transfer between scales using appropriate localization and homogenization techniques.

In this work, a recently developed multiscale modeling technique is further extended to incorporate manufacturing-related, temperature-dependent damage behavior as a function of thermal and mechanical loading and nonuniform void distribution in CMCs. The Multiscale Generalized Method of Cells (MS-GMC), developed by Liu et al. [16] extends the Generalized Method of Cells (GMC) theory [23,1] to include additional length scales beyond the micro- and global scales, therefore allowing for the analysis of woven or braided composites. Hence, the number of length scales under investigation is not limited by the analysis technique, but rather can be determined by the physically relevant length scale dependent phenomena that must be captured in the analysis. For example, in the case of a woven composite, as shown in Fig. 1, the relevant length scales may include: (i) constituent level (microscale), (ii) tow level (mesoscale), (iii) weave level (macroscale), and (iv) structural level. Fig. 1 also demonstrates the relevant features at each length scale taken into consideration in the multiscale

* Corresponding author.
E-mail addresses: Luke.Borkowski@asu.edu (L. Borkowski), aditi@asu.edu (A. Chattopadhyay).

http://dx.doi.org/10.1016/j.compstruct.2015.02.015
0263-8223/

analysis, including the void structure within the inter- and intratow matrix.

The MS-GMC framework used in this work has previously been demonstrated effective for predicting the linear elastic and nonlinear behavior of different types of composites (e.g., polymer and ceramic matrix composites with woven and braided architectures) in a highly computationally efficient manner [16,17,18]. This framework is further extended to include the following important manufacturing related phenomena in CMCs: (i) thermal residual stress and damage state following manufacturing; (ii) interaction between nonuniform void distributions and stress and damage fields; and (iii) global nonlinear behavior due to multiscale damage and release of thermal residual stresses.

The material system analyzed in this article is a carbon fiber reinforced, silicon carbide matrix (C/SiC), plain weave composite. The triply periodic plain weave repeating unit cell (RUC) analyzed using the MS-GMC framework is assumed to be representative of the entire periodic composite structure. For the analysis, the weave is discretized into several sub-volume cells, as seen in Fig. 2. In this figure, the through-thickness discretization utilized by MS-GMC to represent the woven tow architecture is evident; the four cells in the thickness direction are composed of either matrix subcells (red) or tow subcells (white with black lines representing tow fiber direction). The specific CMC under investigation is manufactured through densification of the carbon fiber preform via a chemical vapor infiltration (CVI) process, which follows the coating of the carbon fibers with a pyrolytic carbon (PyC) interphase, also performed via CVI [12]. Since the carbon fibers are susceptible to corrosion at elevated temperatures, the PyC interphase offers increased corrosion resistance while also serving as a toughing mechanism through crack deflection, fiber/matrix debonding, and fiber pullout [14]. Due to the manufacturing process and insufficient infiltration (i.e., canning) of the matrix material, voids are distributed in the composite nonuniformly [29]. Using the MS-GMC multiscale modeling scheme, the effects of void localization, volume fraction, and shape on the nonlinear damage-driven macroscopic CMC response were previously investigated in a deterministic and stochastic framework by Liu and Arnold [17] and Liu and Arnold [18], respectively. It was concluded that void physical parameters, especially shape and localization, greatly influence the elastic and damage characteristics of a CMC. The nonuniform shape and size of voids in the composite microstructure is considered in the analyses presented in this article and described in further detail in Section 2.1.

The innovative aspect of this research lies in the inclusion of manufacturing process effects within the multiscale analysis on the as-produced state and nonlinear mechanical behavior of the

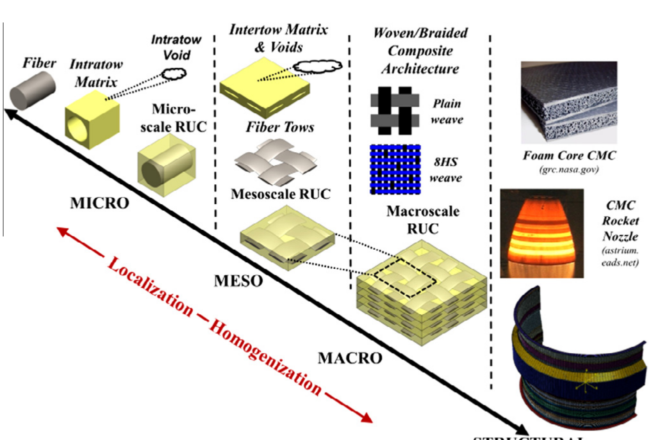

Fig. 1. Concurrent multiscale model analysis framework.

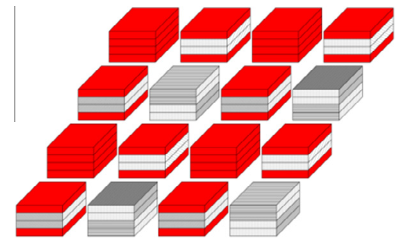

Fig. 2. Plain weave RUC with localized void structure.

composite under mechanical and thermal loading conditions and in the presence of nonuniform and multiscale void structure. The CVI process, which is typically isothermal and isobaric and is carried out at a temperature between 900 °C and 1100 °C [21], is examined. As the specimen cools to room temperature following CVI, the mismatch in the temperature-dependent coefficients of thermal expansion (CTEs) between the carbon fiber and silicon carbide matrix, as presented in Figs. 3 and 4, respectively, causes thermal residual stresses to develop in the composite. Specifically, large residual stresses develop between the plies of the laminated composite and at the fiber/matrix interface during the cool-down phase following manufacturing. The residual stresses, in turn, cause microcracks to form in the inter- and intratow matrix. Because of the heterogeneity and architecture of the woven composite material system, the manufacturing-induced damage is distributed nonuniformly within the composite. Accounting for the presence, distribution, and severity of such damage in the

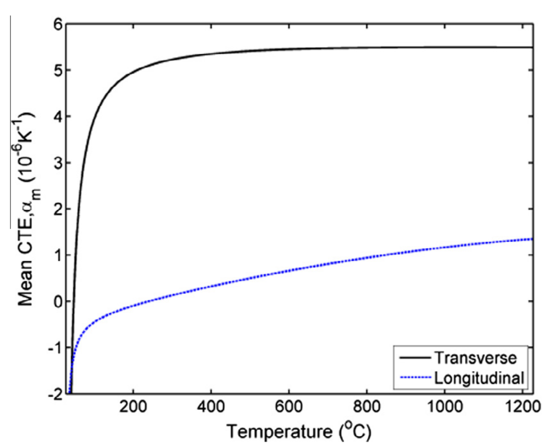

Fig. 3. Carbon fiber CTE vs. temperature [26].

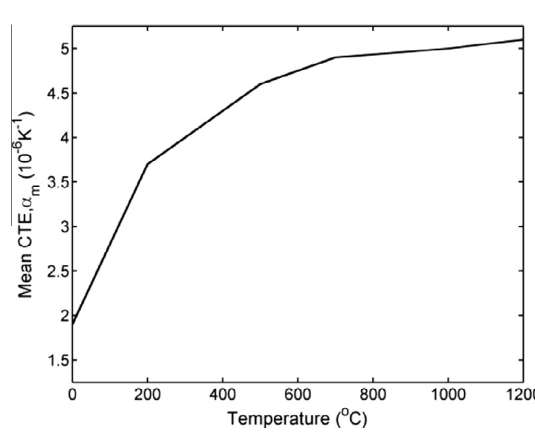

Fig. 4. Matrix CTE vs. temperature [7].