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Uncertainty quantification in multiscale simulation of woven fiber composites

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Abstract

Woven fiber composites have been increasingly employed as light-weight materials in aerospace, construction, and transportation industries due to their superior properties. These materials possess a hierarchical structure that necessitates the use of multiscale simulations in their modeling. To account for the inherent uncertainty in materials, such simulations must be integrated with statistical uncertainty quantification (UQ) and propagation (UP) methods. However, limited advancement has been made in this regard due to the significant computational costs and complexities in modeling spatially correlated structural variations coupled at different scales. In this work, a non-intrusive approach is proposed for multiscale UQ and UP to address these limitations. We introduce the top-down sampling method that allows to model non-stationary and continuous (but not differentiable) spatial variations of uncertainty sources by creating nested random fields (RFs) where the hyperparameters of an ensemble of RFs is characterized by yet another RF. We employ multi-response Gaussian RFs in top-down sampling and leverage statistical techniques (such as metamodeling and dimensionality reduction) to address the considerable computational costs of multiscale simulations. We apply our approach to quantify the uncertainty in a cured woven composite due to spatial variations of yarn angle, fiber volume fraction, and fiber misalignment angle. Our results indicate that, even in linear analysis, the effect of uncertainty sources on the material's response could be significant.

Keywords: Uncertainty quantification and propagation; Multiscale simulations; Random fields; Spatial variations; Woven composites

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1. Introduction

It is widely accepted that materials are heterogeneous and possess a hierarchical structure where the coarse-scale behavior is greatly affected by the fine-scale details (i.e., the microstructure). Because the traditional one-scale continuum mechanics does not suffice to investigate the effect of microstructure on materials' properties,

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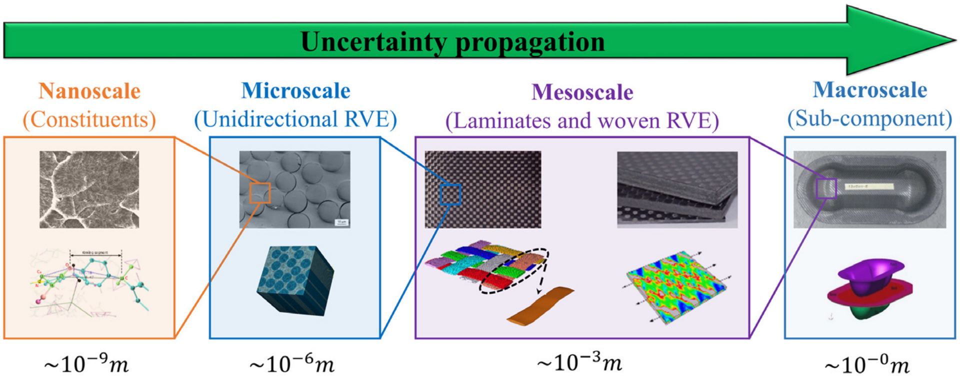

Fig. 1. (Color online) Schematic view of a four-scale woven fiber composite with polymer matrix: In computational modeling of this structure, each integration point at any scale is a realization of a structure at a finer scale. Due to the delicacy of materials at fine-scales, RVEs at lower scales may embody more uncertainty than those at higher scales. To quantify the uncertainty in a macroscopic quantity of interest, the relevant uncertainty sources at the lower scales should be identified for uncertainty propagation.

significant effort has been devoted to the development of multiscale computational models. These models have provided the means to study the effect of microstructure on many phenomena including damage evolution [1,2], fracture initiation [3], and strain localization [4].

Uncertainty is inevitably introduced in materials' behavior starting from the design and constituent selection stages, through the manufacturing processes, and finally during operation. For this reason, ever-growing research [5–7] is being conducted to rigorously couple computational models with statistical uncertainty quantification (UQ) and propagation (UP) methods to provide probabilistic predictions that are in line with the observed stochasticity in materials.

UQ and UP are actively pursued in various fields of science and engineering [6,8–23]. They are, however, seldom applied to multiscale simulations due to the significant computational costs and complexities. Our goal is to devise a non-intrusive UQ and UP approach that characterizes the uncertainties via random fields (RFs) and is applicable to multiscale simulations where multiple uncertainty sources (including spatial microstructural variations) arise from different length-scales. We are particularly interested in a non-intrusive approach because not only they are more general, but also *opening* multiscale computer models (i.e., changing the formulations) to directly introduce uncertainty sources into them requires considerable effort.

We take woven fiber composites as our motivating example. Such materials have been increasingly used in aerospace, construction, and transportation industries due to their superior properties including high strength-to-weight ratio, non-corrosive behavior [24], enhanced dimensional stability [25], and high impact resistance [26]. Woven fiber composites possess, as illustrated in Fig. 1, a hierarchical structure that spans multiple length-scales. *Macroscale* is at the highest length-scale where the overall mechanical performance under some loading conditions is evaluated and characteristics such as fiber and yarn (aka tow or bundle) volume fractions, effective properties, and part geometry are of interest. The individual yarns and their architecture (i.e., their dimension and relative spatial arrangement, see Fig. 2(a) and (b)) in the laminates are modeled in the *mesoscale*. The fibers (and their relative position within the yarns) and the matrix belong to the *microscale*. Finally, the constituent properties and the interaction between them (e.g., the interphase) are modeled in the *nanoscale*.

Multiple uncertainty sources that must be considered in the computational models are introduced at each of these length-scales [24]. For instance, during the preforming process, the high pressure and flow of the resin or draping change the *local architecture* of the fibers [27], see Fig. 2(c). Additionally, processing variations and material imperfections cause the *fiber volume fraction* to spatially vary over the part; especially along the yarn path where there is compact contact [28,29]. These macroscopic uncertainties are manifestations of a multitude of uncertainty sources that exist at the finer scales where, due to the delicacy of materials, the number and dimensionality of the uncertainty sources increase [10]. Moving down the scale ladder in Fig. 1, one can observe that the uncertainty sources are of different nature (e.g., morphological, geometrical, or property related), and spatially (within and across scales) correlated. These features render the UQ of a macroscopic quantity of interest extremely challenging. It is