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Virtual specimens for analyzing strain distributions in textile ceramic composites

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ABSTRACT

Methods are presented for calibrating the local elastic properties of tow-scale material domains in virtual specimens of textile composites. A model of the tow geometry is calibrated using 3D tomographic data via previously published methods. The local elasticity is defined to vary with the local tow orientation and fiber volume fraction within tows. The accuracy of the tow geometry is assessed by comparing the surface geometry of virtual specimens with an alternative data source, viz. topographical data obtained by digital image correlation. Calibration of the elastic constants is validated by comparing measured surface strain distributions with computed strain distributions. An approach is also presented for extending the model to the non-linear regime, by simulating the response of virtual specimens in which the bonds between abutting tows are broken and the resulting fracture surfaces are frictionless. The latter results yield a better match to the measured strain distributions.

1. Introduction

Fabricating and testing textile ceramic composites is expensive and time consuming. To minimize cost and delay, computational models (virtual tests) are desired to inform and, to a substantial degree, replace experiments [1–3]. Since experiments show that cracking patterns in a textile composite are spatially correlated with the positions of individual tows [4–9], a virtual test must include heterogeneous material information at least down to the scale of tows, i.e., represent the tows as separate entities. Furthermore, the representation of tows should include stochastic variations in the local fiber orientation and volume fraction, the fiber tow shape and size, and the tow position; these factors can influence local stresses and strains at the tow scale. In this work, we examine a material representation that includes these tow-scale characteristics. Furthermore, while homogenization is applied within each tow (i.e., discrete fibers are not represented), the material properties assigned within each tow may vary along the tow, because of variations in its orientation and cross-sectional geometry, and in the fiber packing density.

A method for generating stochastic virtual textile composites with tow-scale retention of material heterogeneity and implementing such virtual specimens in finite element (FE) models that predict local strains is presented in this article. The generating algorithm for the virtual specimens and a procedure for calibrating the local elastic properties of tows are validated by comparison with geometrical data and strain-field data acquired using digital image correlation (DIC).

The article continues a series that addresses the integration of experiments and theory to create a virtual test system for analyzing the behavior of textile ceramic composites under mechanical and thermal loads [3]. The series began with an article describing how X-ray micro-computed tomography (μCT) images can be used to quantify the statistics of the geometry of fiber tows within a woven composite [10]. (Similar results have also been obtained for composites with 2D twill weaves [11].) The second article described how that statistical information is used to calibrate a one-dimensional (1D) virtual specimen generator, which uses a Markov Chain algorithm to describe local deviations of tows from average or "deterministic" trends throughout the composite material [12]. The tow loci are generated as 1D elements in three-dimensional (3D) space. A third article presented the exploitation of the Markov Chain algorithm in a 3D virtual textile specimen generator, with 3D representations of tows with stochastic shapes and positions [13]. Virtual specimens with 3D tow representations

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are the starting point for the present study. Other articles in the series reported the analysis and replication of stochastic tow positioning for specimens of sub-component size (ca. 0.1 m × 0.1 m) [14] and the calibration of the thermoelastic properties of the tows within a textile ceramic composite [15].

Over the years, approaches to representing the geometry of woven composites have progressed from assuming simple shapes for tows, such as rectangular segments arranged at approximately the correct weave angle [16–18], to more complex shapes that estimate tow cross-sections and weave paths from imaged specimens [19,20]. A key feature these methods lack is the ability to model stochastic variations in the weave architecture as determined from an experimental source. Other methods of geometrical modeling include simulations of the processing of textile preforms, in which the compressive and shear deformation of individual tows is modeled [21,22]. Complications associated with this route include uncertainty about the loading conditions applied in weaving and in the subsequent handling of the fiber preform and the highly non-linear, generally unknown deformation response of bare fiber bundles to such loads [23–25].

In terms of mechanical modeling, many studies exist that show the accurate prediction of the spatially-averaged macroscopic properties of woven textiles using methods in which homogenization is applied at the laminate scale, i.e., individual tows are not represented [26,27]. Such approaches, however, may not be suitable for predicting strains at the local level. In woven fiber composites, experiments suggest that most failure mechanisms are associated with a length scale comparable to that of a single tow [4–7].

If failure mechanisms depend only on the average of the local strain field over a gauge length comparable to the tow width, predictions can be based on relatively coarse representations of tows. One such representation is provided by the Binary Model, which is constructed by embedding 1D tows, such as those generated by the stochastic Markov Chain algorithm [12], within 3D effective medium elements that fill out the external shape of a component. In the Binary Model, the 1D tow elements confer the axial stiffness of tows, while the effective elements confer the matrix-dominated contributions to global stiffness. When used in combination with gauge-averaging methods, the Binary Model can yield meaningful predictions of tow-scale variations in strains [7,28] and thence accurate predictions of failure in cases where ultimate failure follows in a quasi-brittle manner after the first local failure event occurs at the tow scale (e.g., rupture of a tow, kink failure of a tow in compression, or shear failure) [29,30]. However, the absence of 3D details of tow shapes renders the Binary Model incapable of tracking the full evolution of systems of interacting microcracks, such as trans-tow cracks, local delamination cracks between tows, and cracks in matrix domains. These complex microcracking systems govern failure in ceramic textile composites in high temperature and aggressive environments; their complete description is necessary for accurate life prediction [3].

The present article therefore addresses the construction of virtual specimens of textile composites based on 3D representations of tow geometry and the calibration of local elastic properties for individual tows within such virtual specimens. Calibration and most validation is restricted to the elastic regime. In the materials studied, which have non-smooth surfaces, elastic fields show strong, discontinuous variations that are correlated with the tow architecture. Simulations are extended into the early stages of the non-linear regime by considering the possibility that debonding occurs between pairs of orthogonal tows. This phenomenon can arise at relatively low applied strains. Simulations of matrix microcracking, which contributes to substantial nonlinearity at higher strains, is beyond the scope of this work.

Construction of virtual specimens begins with the output from the generator based on 3D tow representations that was described in previous work [13], which we will refer to here as the *3D Virtual Textile Specimen Generator*, or *3D Virtual Specimen Generator* in short. The output from the *3D Virtual Specimen Generator* comprises a list of points and connecting facets that define tow surfaces. Surface profiles for each tow are extracted from the 3D mesh and compared to data for real test specimens obtained via DIC, providing a check on the geometry of the virtual specimen. To prepare the model for use in commercially available FE software, the tow surfaces are divided into 3D computational elements and each element is assigned calibrated elastic constants, with material symmetries dictated by the local direction of the tow axis. The predictive capabilities of virtual tests that are based on the calibrated virtual specimens are assessed by comparing strain fields measured by DIC with those computed by the FE model.

2. Acquisition of experimental data

2.1. Subject material

The subject material is a three-layer angle interlock weave whose reinforcement consists of tows of T300-6k carbon fibers. The unit cell is comprised of four warp tows that undulate with staggered phases and twelve nominally straight weft tows. The fibers in the weave are first coated with very thin (<0.1 μm) pyrolytic carbon by chemical vapor infiltration (CVI). CVI is then used to deposit a low volume fraction of SiC matrix. The process results in thin (ca 1 μm) SiC coatings on the individual fibers and thicker (30–50 μm) SiC layers around the tows (Fig. 1). The result is a highly porous but rigidified composite. Such materials have practical use in heat exchangers where flow is turbulent and some leakage is tolerable or transpiration is required [31]. Additional details of the weaving and processing procedures are presented elsewhere [10,12,13].

This material provides a severe test case for validating the virtual test, because its visible surface follows the complex topography of the textile reinforcement, and the strain fields developed under load exhibit high levels of heterogeneity, with sharp discontinuities where tows overlap one another.

2.2. Mechanical test setup

Dog-bone-shaped tensile specimens were laser-machined from a larger composite panel in both warp and weft orientations (i.e. the tensile loading direction is aligned with the longitudinal axis of the warp and weft tows respectively). The gauge sections were 25.4 mm long and 12.5 mm wide. The ends of the specimens were infiltrated with epoxy and allowed to cure under load to achieve flat surfaces. Fiberglass tabs, each 0.8 mm thick, were bonded to the specimen ends, to facilitate uniform load transfer from the grips to the specimen. In preparation for topography and displacement mapping, one surface of each specimen was first coated with a thin layer of white water-soluble paint. A speckle pattern of black paint was then applied with an airbrush. Two specimens were tested in each orientation at room temperature at a nominal strain rate of $3 \times 10^{-5}\ s^{-1}$.

2.3. Topography and displacement mapping

Images for DIC were taken with a pair of digital cameras (Point Grey Research Grasshopper) with a resolution of 2448 pixels by 2048 pixels. Each camera used a Nikon ED AF Micro-Nikkor 70–180 mm lens with the focal length set to 180 mm. The cameras were oriented with a 24° angle between them, a configuration that