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Predicting the effective properties of 3D needled carbon/carbon composites by a hierarchical scheme with a fiber-based representative unit cell

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ABSTRACT

This paper presents a fiber-based representative unit cell (fRUC) on the mesoscale to estimate the elastic constants of a three-dimensional (3D) needled carbon/carbon (C/C) composite through a hierarchical modeling scheme. The material variations due to needle-punching, including fiber dislocations, fiber distributions and matrix pockets, are precisely considered in the proposed fRUC model. A quarter-size mathematical model with a periodic boundary condition of a general mesh is established to perform the fRUC analysis by using interpolation functions. The predictive results from the fRUC are transitioned to a ply representative unit cell (pRUC) based on the developed analytical homogenization method. The proposed model agrees well with the experimental results, and the effects of microstructural parameters on the overall composite properties are discussed. The results allow great confidence in the reliable predictions of the effective properties and the damage and strength of 3D needled C/C composites.

1. Introduction

A novel multiply needled composite, with fibers deflected and reinforced in the thickness direction by the needling technique, demonstrated improved interlaminar properties and cost savings compared with its two-dimensional (2D) and multi-dimensional counterparts [1]. The needle fibers located through the stacked layers enable mechanical and thermophysical improvements, such as in the interlaminar shear strength, thermal conductivity and tribological properties of the composites [2]. This needled carbon preform has been widely applied to fabricate C/SiC and C/C composites by processes such as chemical vapor infiltration (CVI) or precursor infiltration pyrolysis (PIP) [3]. This kind of composite has been applied for thermal protection systems (TPS) of re-entry vehicles, rocket engine components, propulsion systems, advanced braking systems, etc. [4–6].

Needling is a kind of carbon fiber preform-forming technology with strong designability. Considerable experimental works on the mechanical and thermal performance of the resulting composites have been performed. These studies found many influential factors on composite performance, including preform density [7], fabric configurations [8], needling process parameters and temperature [9,10]. Needling can enhance the interlaminar properties of composites by the transfer of fibers through the thickness of the material, though further improvements are limited due to needling-induced damage of the fibers. Therefore, there often exists an optimal value of each influential factor, that is to say, the influence on material behavior is not a monotonous increase or decrease.

On the other hand, the flexibility offered by needled composites can make theoretical and numerical analyses challenging [11–13]. Additional material phases and the needling process complicate the mechanical responses by inducing local material variability. The first attempt to theoretically estimate the stiffness properties of needle-punched composites was carried out by Li et al. [14], who established a representative volume element (RVE) containing one needle fiber bundle. The elastic properties of individual layers were estimated by the mixture rule. Therefore, some factors such as the needle fiber distribution and in-plane fiber architectures could not be studied sufficiently. To consider the regularity of non-woven yarn crimp resulting from needling in three-dimensional (3D) needled composites, Xu et al. [13] applied the concept of 'modified lamina modeling'. A triangular block was used to substitute the crimp yarn section, and the stiffness matrices of the divided three blocks were calculated based on the Halpin-Tsai formula. However, the needled fibers were omitted in the proposed model. Considering that the mechanical behaviors can be

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related to the composite microstructure, some micromechanical models for predicting the elastic properties of 3D needled composites have been reported. Xu et al. [15] presented hierarchical micromechanical modeling, in which a micromechanical RVE model consisting of hexagonal-packed fibers was established for the unidirectional fiber ply. Instead, a Mori-Tanaka-theory-based schema was used for the randomly distributed short-fiber layer; this was because of the high computational cost of the finite element analysis induced by the complex microstructural topology. Xie et al. [12] advanced the unit cell approach by choosing four typical RVEs to take into account the local geometrical characteristics of the non-woven cloth layer. However, the short-cut carbon fiber net layer was assumed to be a homogeneous isotropic material. Thus, this method does not make it possible to study local material variability of the short-fiber felt layer caused by the needling process.

The mechanical responses of a needled composite, including deformation and damage, depend on microscale states, such as the configuration and behavior of its constituents. A precise analysis of the mechanical properties of needled composites should extend to the microscale for the mechanisms of mechanical transitions from the micro- to macroscale to be explicitly understood. However, challenges remain when the analysis and predictions of stiffness and strength [16,17] focus on the overall behaviors from the micro- or mesoscale to the macroscale: (i) multilevel material systems characterized by fibers with a magnitude of 10 μm, as well as millimeter-sized lamina- and laminate-scale parts; (ii) large representative unit cell sizes for the consideration of laminate structural features and needling periodicity; and (iii) the complex microstructures attributed to the random redistribution of short fibers, unidirectional fiber misalignment and matrix pockets caused by the needling process.

From these points of view, a fiber-based representative unit cell (fRUC) is presented in this paper, which can consider the local fiber-scale configurations to promote understanding of the microstructure performance. Additionally, a hierarchical scheme is adopted to study the profound effects of the microstructure behaviors on the overall macroscale composite structure. The paper is structured as follows. In Section 2, the microstructural characteristics of the 3D needled C/C composite are presented for the later detailed modeling on the fiber-scale. In Section 3, the hierarchical modeling scheme is illustrated from the fiber-scale through the ply-scale to the laminate-scale. Meanwhile, the boundary conditions for a quarter-size model are deduced to alleviate the high computational costs. Also, an analytical homogenization method is used for the transition from the fiber- to ply-scale. In Section 4, modeling validations and experimental verifications are presented. Further, parametric studies on the effect of microstructural parameters on the overall composite are accomplished. Finally, the paper ends with the concluding remarks in Section 5.

2. Microstructural characteristics of needled C/C composites

The needled C/C composites were manufactured by the CVI of needled preforms. During the process, the carbon fiber preform is infiltrated by a hydrocarbon gas, followed by deposition of a pyrolytic carbon matrix on the fiber surfaces and in the spaces between them. The preform is processed by the step-by-step layering of non-woven fiber cloth ply and short-cut fiber felt, followed by needling of the stacked composite. Schematic diagrams of the needling process and preform structure unit cell are shown in Fig. 1.

As shown in Fig. 2, the typical microstructures in cross-sections of the composite were examined by microscopy. The overall microstructure of the composite can be seen in Fig. 2(a), which presents a laminate structure with a repeated sequence of non-woven fiber plies separated by layers of felt. Fig. 2(b) shows a top view of the continuous fiber ply, which reveals that the needling process disturbs the in-plane continuous fibers and also induces matrix-rich zones in the composite. The microstructure shown in Fig. 2(c) is a side view of the needling position, where short fibers are deflected in the thickness direction due to the needle-punch. Therefore, needling regions should be considered in more detail in the analysis model. The microstructural morphology of the short-cut fiber felt with needling regions is less affected than the continuous fibers, as can been seen in Fig. 2(d).

3. Hierarchical modeling scheme

The mechanical properties of needled C/C composites are dependent on the reinforcement architecture [12] that has a much smaller scale than the final composite structure. Therefore, a multiscale strategy is used to evaluate the overall homogenous elastic performance of needled C/C composites, and to study the effects of the small-scale structures—especially in critical regions affected by

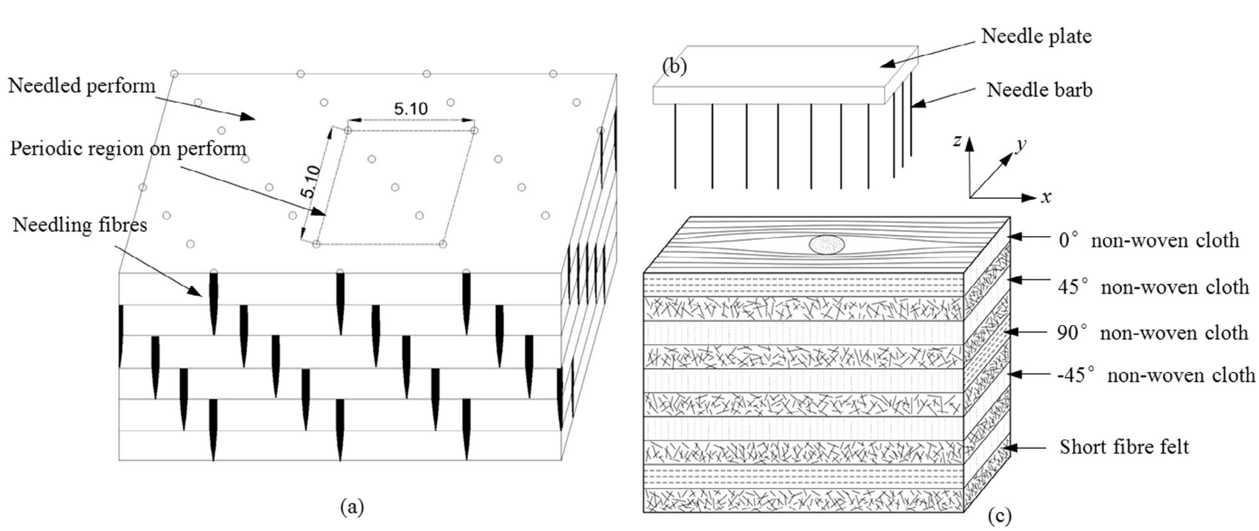

Fig. 1. Schematic diagram of 3D needling of the preform: (a) distribution of needling regions on the preform and the repeated unit cell region; (b) needle plate and barbs; and (c) a laminate domain close to a needle yarn with deflected continuous in-plane fibers.