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Comparison of two finite element homogenization prediction approaches for through thickness thermal conductivity of particle embedded textile composites

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ABSTRACT

A detailed three dimensional finite element model was developed to predict the through-thickness thermal conductivity of a textile composite structure consisting of a woven fabric and matrix in our previous work [1] in which conductive particles are randomly distributed in the matrix in the unit cell already containing the woven fabric and the effective thermal conductivity of this three-phase system is numerically evaluated. In this paper, results of this three-component system are compared with a two-component system in which the thermal conductivity of the matrix and particles is homogenized by a finite element approximation under the same thermal conditions. A parametric study of this comparison is conducted over different volume fractions and thermal conductivities of both textile fabric and loaded particles and its efficacy is discussed. Typically such composites could be coated with a conductive skin on the surface. Thus, the role of the skin and fiber conductivities in enhancing heat transfer is compared for this structure. The proposed approach of finite element homogenization of particle-matrix medium can be used to conduct a preliminary assessment of through-thickness thermal conductivity of such three-component composite systems with fabrics, particles and matrices with and without the presence of a skin layer.

1. Introduction

Textile composites continue to gain market share in fabrication of composite structures since the last decade [2–5]. Two dimensional woven fabrics [6,7] are commonly used in composite structures because of their light weight, low fabrication costs, ease of handling, high adaptability and tailorability. Different types of fibers, including carbon, glass, aramid and various polymer matrix materials have been used to create these heterogeneous composite laminates for different applications. Also, different woven architectures (e.g. weaving [8], braiding [9], knitting [10]) for textile fabrics can be employed to tailor the composite physical and mechanical properties. Over the last few decades, a number of predictive models have been proposed to assess effective properties of composites based on constituent materials and their properties.

Predictive models to find effective properties of a composite material range from very simple weighted average of the constituent material properties such as the rule of mixtures to very complicated formulations that account for spatial and orientation variation of the fibers in the system [11–14]. The effective properties have also been determined using numerical methods which can address the specifics of the geometry [15–19] and can be integrated with macroscopic analysis [20].

Effective properties determined from an analytic constitutive relationship can be readily used in stress, thermal or electrical analysis of the composite but no models that can accurately predict the effective thermal properties for particle embedded woven structures exist to the authors' knowledge. In this work, we will focus on through-thickness thermal conductivity prediction of woven fabric with particle loaded polymer matrix [21]. Currently there is no closed form equation that can accurately describe the effective through thickness thermal conductivity of the composite, given the thermal conductivity of the fibers, matrix and particles over a range of fiber and particle volume fractions. Our approach is to predict the effective thermal conductivity using very detailed

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finite element models of a unit cell that represent the fiber configuration and geometry, covering a range of particle and fiber thermal conductivities and volume fractions. The results are compared with a simplified two-phase model (fiber and matrix) in which the mixture of particles and matrix are homogenized as one phase by using finite element approximation to find the homogenized matrix value to be used in the simplified two-phase model. Models with different volume fractions of fibers and particles over a range of thermal properties are compared in terms of the efficacy of the finite element homogenization approach. The role of a conductive skin as a coating on the surface is evaluated for the effective through-thickness thermal conductivity of the three-phase model. The results of the parametric study can be used to provide guidelines for material selection and design.

2. 3D geometric model of woven fabric

The effective through-thickness thermal conductivity of woven fabric is highly dependent on the constituent properties and the reinforcement architecture. The fabric geometry in microscopic detail will influence the effective properties of the composite. It is important to mesh the 3D geometric model to describe the fiber continuity and undulation without simplifying the architecture. Here Sheng and Hoa's approach [22] was adopted and weft and warp yarns were assumed to have elliptical cross sections as shown in Fig. 1.

The central path of the fiber crimp is taken to be a repetitive combination of elliptical segment *kJ* and rectilinear segment *JM* to simplify fiber spatial orientation. The undulated segment *kJ* of the yarn is described by an elliptical equation

$$\frac{(x-m)^2}{w^2}+\frac{(y-n)^2}{t^2}=\frac{1}{4}, \quad (J_{lx}\leqslant x\leqslant J_{rx}) \tag{1}$$

where m, n represent the central coordinates of the cross section of the yarn on the XY plane; J_{lx}, J_{rx} are the x coordinates of the two tangent points of woven yarns; w, t represent the major axis (width) and minor axis (thickness) of the fabric cross section, respectively. The rectilinear segment *JM* of the yarn between two elliptical segments is given by a linear equation

$$y=kx+d, \quad (J_{rx}\leqslant x\leqslant M_x) \tag{2}$$

where k is the slope of the rectilinear segment *JM*, d is a constant and M is the center point of the linear path.

The coordinates of the tangent point J connecting elliptical segment and linear segment can be written as

$$J\left(m+E, n-t\sqrt{\frac{1}{4}-\frac{E^2}{w^2}}\right) \tag{3}$$

Thus the slope of the segment *JM* is determined by the two points J, M as

$$k_{JM}=\frac{M_y-J_y}{M_x-J_x} \tag{4}$$

Also from the elliptical Eq. (1), the slope of the tangent line at the point J can be expressed as:

$$k_{JM}=\left.\frac{dy}{dx}\right|_{x=m+T}=\frac{Em/w^2}{\sqrt{\frac{1}{4}-\frac{E^2}{w^2}}} \tag{5}$$

By combining Eqs. (4) and (5), the distance E and the slope of the segment *JM* can be calculated. An arbitrary distance $t_d = w/10$ is designated as the distance from the yarn to the bottom and top surface of the model.

The three dimensional geometry of the reinforcing fabric for a woven fabric composite can be fully described by the previously defined geometric parameters and the spatial orientation of the yarn. In this paper, the fiber volume fraction is varied by changing the cross sectional area of the yarns and the thickness b of the cell while maintaining the ratio $w/t = 2$, and the unit cell width and length equal to a. With the above general approach, 3D finite element model of the geometric arrangement shown in Fig. 2 can be generated for further analysis. This approach also makes it easier to study other geometric parameters of the yarns and their influence on the effective composite property.

A set of 3D fabric models were developed and meshed using ANSYS software as the tool of Finite Element Analysis with formulated macros scripted using Mechanical APDL. The element type used for the geometry mesh is SOLID70 which is a 3-D thermal solid element which has eight nodes with a single degree of freedom-- the temperature at each node. The curved shape for the yarn undulation was approximated by piecewise line segments for the ease of line generation, hence there is a small gap of width equal to $w/40$ to avoid yarn geometric intervene at the nearest region.

The ANSYS finite element software solves the steady state heat diffusion equation to evaluate the temperature field in the whole domain. Each element is assigned a thermal conductivity value of the fiber, matrix or particle. The boundary conditions prescribed are insulated along the four sides of the unit cell and constant temperature along the top and the bottom face (T_1 and T_2 respectively). Once the temperature field is evaluated, the heat flow q, which should be the same over the top and bottom face is calculated by integrating the heat flux across each element on the face. Then the effective through-thickness thermal conductivity can be calculated using Fourier's law as follows,

$$q=-k_{eff}A(T_1-T_2)/b \tag{6}$$

In which q is the calculated heat transfer rate over the entire surface area (A) across the unit cell thickness b; T_1 and T_2 are the temperature imposed as boundary conditions on the top and the bottom surface of the unit cell. Eq. (6) allows one to calculate the effective through-thickness thermal conductivity k_{eff}.

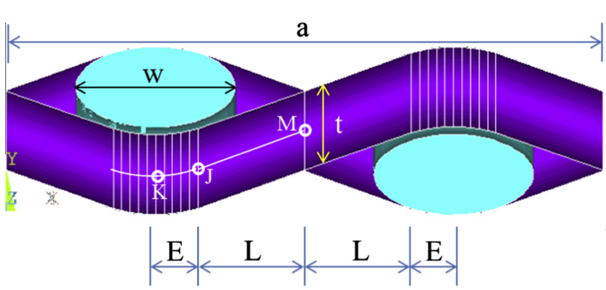

Fig. 1. Interlaced yarns in the woven fabric composite with geometric characteristic parameters.

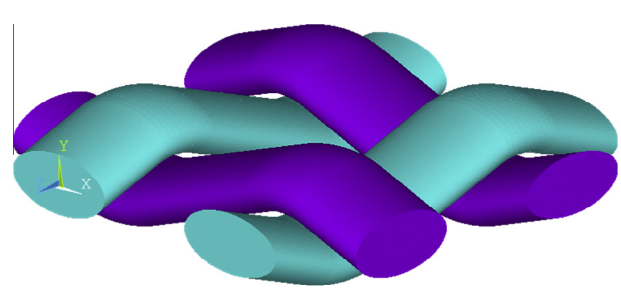

Fig. 2. Schematic of the three dimensional woven fabric.