Multi-scale finite element analyses on the thermal conductive behaviors of 3D braided composites

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Abstract

The thermal conductive behaviors of 3D braided composites along in-plane and out-of-plane directions were characterized and analyzed by multi-scale finite element analyses (FEA) and also validated by experimental. Micro-scale representative volume element (RVE) was used to calculate the thermal conductivities of braiding yarns, and the meso-scale RVE and full-scale braided model were developed to research the thermal conductive behaviors of the whole braided composites. The differences of the two models are also analyzed in this paper. Another attention of this paper was focused on revealing the thermal conductive structural effects of braided composites. It is found that the thermal conductivities along out-of-plane direction are larger than that of in-plane direction. The temperature distribution and heat flux transmission are mainly along fiber orientation direction. With the increment of temperature, the thermal conductivities of the braided composites are increased. As the existence of surface and corner regions, the thermal conductivities calculated from full-scale model are closer to experimental by comparison with meso-scale RVE. In addition, the temperatures in interior regions are slightly higher than those in surface and corner regions of the braided composites. This paper could make for further understanding the thermal conductive behaviors of braided composites.

Keywords

3-Dimensional braided composite; Thermal properties; Finite element analysis (FEA); Multi-scale

1 Introduction

Three-dimensional (3D) four-directional braided composites have received a great attention and widely used in many fields (such as aircraft and vehicle design) due to its integrated reinforced preform. The thermal conductive behavior is one of the important thermo-mechanical properties affecting the failure and destruction of composites under high temperature condition.

It is well known that the thermo-mechanical behaviors strongly depend on the thermal conductive properties [1-3]. Therefore, it is particularly important to accurately reveal the thermal conductive properties of materials. The research methods on the thermal conductivity of 3D rectangle braided composites have been widely studied on the geometrical structures at the unit-cell level in numerical simulations, such as finite element analysis (FEA). The basic idea is to select a periodical representative unit cell by applying appropriate periodical non-adiabatic temperature boundary conditions in finite element software. For example, Liu et al. [4] chose a factual micro-structural model of braided composites for improving the calculating precision of thermal property by finite element method. Jiang et al. [5] presented a modified finite element model to investigate the thermal conductivity and temperature distribution of 3D braided composites. Gou et al. [6] studied the temperature distribution in a representative volume element (RVE) of 3D four-directional braided composites with appropriate boundary conditions by the finite element method. Although this RVE method is simple and effective in calculating the thermal conductivity of braided composites, it ignored many other factors, e.g. the surface and corner regions which have an important effect on the overall thermal conductive behaviors of braided composites, because this scale RVE model only consider the interior regions of braided composites. Moreover, the heat flux transmitting path and the detailed temperature distribution in the braided composite could not be revealed from this kind of RVE model. Although some novel methods including the lattice Boltzmann method [7], artificial neural network [8] and Monte Carlo method [9], attempt to calculate the thermal conductivity from numerical calculation, they neglected the structural effects of composites, which couldn't show the temperature distribution or heat flux transferring either. Owing to the limit of calculation ability and mesh quality, very few studies can conduct the thermal conductive researches from the perspective of large scale models. In addition, the thermal conductive differences between the representative unit cell model and the actual braided composite model have never been compared.

Aiming at these problems, this paper presents its research on the thermal conductive behaviors of

braided composites both at meso-scale and full-scale structure level. The emphases in this paper were focused on uncovering the thermal conductive structural effects of braided composites, including temperature distribution and heat flux transmitting. The differences of the thermal conductivities of 3D rectangle braided composite along in-plane and out-of-plane directions were characterized and compared. The differences of the thermal conductive results of the braided composite obtained from the meso-scale RVE and full-scale model were also analyzed and discussed. The thermal conductive behaviors and structural effects of 3D braided composites are really revealed by this paper. Such an effort could also be extended to investigate the thermo-mechanical properties of the braided composite materials.

2 Experimental

2.1 Materials

Carbon fiber tows (T700SC-12K) provided by Toray Co., Japan and epoxy resin (JA-02C) from Jiafa Chemical Co., China, were used to prepare the braided composite specimens. Table 1 lists the basic thermo-physical parameters of the carbon fibers and the epoxy resin at room temperature. The 3D braided composite samples were prepared with epoxy resin impregnated into braided preform by using vacuum assistant resin transfer modeling (VARTM) process. 3D braided preforms shown in Fig.1 with a surface braiding angle of 30° were fabricated with a 4-step 1×1 braiding technique on the square braiding machine. The curing temperature was 90°C for 2 h, followed by 110°C for 1 h, and finally 130°C for 4 h. The samples were removed from the oven after cooling for 12h, then cut into the needed shape and size for testing. The tests were conducted in standard conditions at a room temperature of $25 \pm 2^\circ\text{C}$ and $65 \pm 2\%$ relative humidity to ensure its reliability.

2.2 Experimental setup

All the testing works were conducted in a self-designed apparatus which has already been calibrated by standard aluminum specimen (6063-T4) with known thermal conductivity $200 \text{ W m}^{-1}\text{K}^{-1}$. The range of measuring errors was kept within 5%, which demonstrated the reliability of this apparatus. The apparatus shown in Fig.2 mainly consists of three parts, i.e. thermal insulation, temperature controlling system and signal acquisition system. An adiabatic chamber for measuring the thermal conductivity of the braided composite was composed of foam insulation boards and alumina fiber plates, which can

effectively prevent the heat from diffusing to outside air. The binding sites of foam insulation boards and alumina fiber plates were fixed with heat insulated adhesive sealing tape. The temperature controlling system could make the temperature of heat source stable with $\pm 1-6^{\circ}\text{C}$ deviation, which could provide a stable thermal gradient to the specimens. The signal acquisition system could record the temperature changes of thermocouples every one minute, which can effectively record the temperature change in the process of thermal conduction. It is assumed that when the temperature variation satisfied $\Delta T \leq 0.1^{\circ}\text{C}$, the status of thermal conductive equilibrium was achieved and then the experiment was finished.

2.3 Experimental method

In this paper, all the experimental methods were based on one dimensional Fourier's heat conduction law. Considering carbon fiber/epoxy resin composites have obvious anisotropic characteristics, the thermal conductive measurements along in-plane direction and out-of-plane directions were adopted different methods. Since the thermal conductive path along the in-plane direction is short, the modified transient hot wire technique [10, 11] was used. The hot wire method is a technique based on a linear heat source of infinite length and infinitesimal diameter and on the measurement of the linear heat source embedded in the test material. When an electric current of fixed intensity flows through the wire, the thermal conductivity can be derived from the resulting temperature change over a known time interval. As shown in Figs.2 (a) and 3 (a), the electrical resistance wire Cr20Ni80 with 0.6 mm diameter and $3.855\ \Omega$ resistance per meter was embedded in the axial yarn and located in the center of the rectangle braided preform. Although the temperature of resistance wire would fluctuate in a short time, it can be regarded as constant in the whole process of thermal conduction. The two ends of wire were connected with DC power source. The temperatures of resistance wire were controlled by a K-type thermocouple whose head was closely attached to resistance wire and end was connected with the temperature controlling system to make its temperatures not exceed the set values. Since the wire was embedded in the center of specimens, it can be assumed that the heat produced by wire was all used to heat the specimen and no loss occurred. The resistance wire was isotropic homogeneous material, therefore, the heat produced from different positions was assumed to be same. By applying the appropriate voltages

U on resistance wire, the thermal power Q , i.e. electrical power of resistance wire would be produced and the consequent thermal flow would transmit from resistance wire to the test specimens. By recording the corresponding temperature values of thermocouples, the thermal conductivity of braided composites along the in-plane direction K_{in} can be calculated by:

$$K_{in} = -Q / (A \cdot \nabla T) = -U / (R^2 \cdot A \cdot \nabla T) \quad (1)$$

where R is the resistance per meter of the resistance wire and ∇T is the temperature gradient which represents the velocity of thermal conduction. A is the thermal conductive area of composite specimens.

According to ASTM C 177-97 and the fact that the specimens of out-of-plane direction having long distance, the transient plane source [12] method was adopted in order to provide a uniform heat flux going through the specimens. As shown in Figs.2 (b) and 3 (b), the heating aluminum plate with the size 50×80×10 mm was placed in the bottom of the chamber. An aluminum bar with the same size as composite specimens and known thermal conductivity was placed on the top of specimens. The gap between aluminum bar and specimen bar was filled with epoxy adhesive to make them as whole with no interval existence. In view of good sealing of this self-made apparatus, it was assumed that the heat flow going through the composites specimens and aluminum bar were the same. Therefore, according to this assumption, the thermal conductivity of out-of-plane direction K_{out} could be calculated by the following:

$$K_{out} = k_{Al} \frac{A_{Al}(\nabla T)_{Al}}{A_C(\nabla T)_C} \quad (2)$$

where k_{Al} is the thermal conductivity of rectangle aluminum bar, A is the area perpendicular to the heat conduction direction. The subscript Al and C refer to aluminum bar and composite specimens, respectively.

It is well known that the main thermal conductive mechanism of polymer matrix composites (PMCs) is attributed to phonon vibration. However, the phonon vibration is greatly affected by the applied temperature. Therefore, it is necessary to measure the thermal conductivity of carbon fiber and resin matrix under different temperatures. This paper also used the transient plane source method to measure the thermal conductivity of carbon fiber and epoxy resin, just as our previous work [13]. As shown in

Fig.4, the five K-type thermocouples were embedded in epoxy resin bar before curing to measure its temperature changes. By the same way, thermocouples wrapped inside the three fiber bundles to measure the thermal conductivity of carbon fiber under different temperatures both along fiber axial and radial directions. Because that measuring the thermal conductivity of single carbon fiber was very difficult, it was assumed that the thermal conductivities of the three fiber bundles were the same as single carbon fiber.

The K-type thermocouples marked by red circle in Figs.2, 3 and 4 connecting with thermometers were embedded into the specimens to record the temperature variation at every one minute until the temperature was stable. Each test was repeated at least three times both along in-plane and through-thickness directions.

3 Geometrical model

Geometrical models at different levels have been developed for characterizing the 3D textile composite structures. For example, Chou et al [14] treated the unit cell model as an assembly of inclined unidirectional laminates. Pandey et al [15] developed a representative volume elements for four-step braided composites. Wu [16] proposed a three-cell model based on the microstructure analysis of braided composites and Chen et al [17] employed the three types of unit cell to analyze the structural geometry of the preforms. Here we use multi-scale models shown in Fig.5 to study the thermal conductive properties of 3D braided composite. In this paper, the established steps of multi-scale models are as follows: firstly, carbon fibers whose cross section was round were embedded in resin matrix, which can form the micro-scale RVE. Then, according to microscopic observation and the works done by others [17, 18], the cross-section shape of braiding yarns in rectangle braided composites was regarded as regular hexagon. This paper didn't analyze and compare other cross-section shapes, e.g. circular, elliptical and octagon, because they were not suitable for our specimens and also the work of Gou [6] has already proved that the cross-section shapes of braiding yarn have no obvious effect on the thermal conductivity of rectangle braided composite. Based on the basic geometrical parameters of meso-scale RVE obtained from microscopic observation and experimental measurement, including interior braiding angle, pitch length, side length, fiber volume fraction in braiding yarn and yarn volume fraction, the meso-scale RVE was established. Then by Boolean operation, the whole interior yarns of braided preform were formed. The surface and corner

yarns of braided preform can be formed by spline connecting interior yarns. And finally the full-scale model of braided preform was formed. The basic comparisons between the selected multi-scale models are listed in Table 2.

The topological structure of 3D rectangle braided preform is determined by the braiding process, which is realized through the permutation of yarn carriers on a machine bed by row and column track movements in the X and Y direction, respectively, and the preform is fabricated in the Z direction. The total number of yarn in braided composite can be defined by the number of rows m and the number of columns n . As depicted in Fig.6, the full-scale 3D braided model is composed of three regions, i.e. interior, surface and corner, which can refer to Chen et al [17] for detailed discussions of region division. The trajectory of braided yarns in interior region is straight, but changes the directions in surface and corner regions.

Since the most parts of the 3D braided composite are the interior regions, the meso-scale RVE extracted from interior regions is presented to investigate the microstructure and parameters relationship of rectangle braided composites. Fig.7 shows the topological relationship of the main yarns in the parallelepiped unit cell. The interior braiding angle γ , the braiding angle α depicted in Fig.7 and the surface braiding angle θ shown in Fig.1 are used to describe the orientation of the braiding yarn. The relationship between them can be defined as

$$\tan \gamma = \sqrt{2} \tan \alpha = 12 / \pi \tan \theta \quad (3)$$

The relationships of structure parameters including the yarn volume fraction in meso unit cell V_y , the fiber volume fraction in meso unit cell V_f and the fiber volume fraction in braiding yarn V_{fy} are defined as following :

$$V_{fy} = V_f / V_y \quad (4)$$

$$V_y = \frac{4A(h / \cos \gamma)}{a^2 h} \quad (5)$$

where a and h refer to the side length and pitch length of meso unit cell, respectively. A is the area of the cross section of braiding yarn, which can be calculated by

$$A = \frac{3\sqrt{3}}{2} c^2 = \frac{n_f \cdot \pi d_f^2}{4V_{fy}} \quad (6)$$

where n_f and d_f represent the number and diameter of fibers in one braiding yarn, respectively.

When the yarns contact ideally with each other, the hexagonal cross-section side length c can determine the value of a

$$c = a / 4 \quad (7)$$

Table 3 gives the parameters of the braided samples and the microstructure of meso-scale RVE.

4 Finite element analyses

4.1 Governing equations and constitutive relationship

The finite element analyses of micro-scale and meso-scale RVE were run for steady-state conditions to obtain temperature and heat flux throughout the model. However, the full-scale model was based on transient thermal conductive analyses to obtain the relationship between temperature and heat flux distribution and conductive time. The governing equation used for steady-state conditions is described as:

$$k_{xx} \frac{\partial^2 T}{\partial x^2} + k_{yy} \frac{\partial^2 T}{\partial y^2} + k_{zz} \frac{\partial^2 T}{\partial z^2} + (k_{xy} + k_{yx}) \frac{\partial^2 T}{\partial x \partial y} + (k_{xz} + k_{zx}) \frac{\partial^2 T}{\partial x \partial z} + (k_{yz} + k_{zy}) \frac{\partial^2 T}{\partial y \partial z} = 0 \quad (8)$$

And the governing equation for transient thermal conduction is:

$$k_{xx} \frac{\partial^2 T}{\partial x^2} + k_{yy} \frac{\partial^2 T}{\partial y^2} + k_{zz} \frac{\partial^2 T}{\partial z^2} + (k_{xy} + k_{yx}) \frac{\partial^2 T}{\partial x \partial y} + (k_{xz} + k_{zx}) \frac{\partial^2 T}{\partial x \partial z} + (k_{yz} + k_{zy}) \frac{\partial^2 T}{\partial y \partial z} = C_p \rho \frac{\partial T}{\partial t} \quad (9)$$

where T is the temperature, k_{xx} , etc. are thermal conductivity, which can be seen as transversely isotropic for carbon fiber and isotropic for resin matrix. C_p and ρ are the specific heat and density, respectively. The constitutive relationships used in FEA both in steady-state and transient analyses are the same as Fourier's law and can be defined as:

$$q = -k \nabla T \quad (10)$$

where q , k and ∇T are heat flux density, thermal conductivity and temperature gradient, respectively.

4.2 Boundary conditions

According to different thermal conductive modes in FEA, different boundary conditions were used.

Micro-scale model and meso-scale model are based on the RVE, the periodical boundary conditions (PBCs) should be applied in the model to obtain a reasonable temperature and heat flux distribution. The periodical displacement boundary conditions proposed by Xia et al [19] and further developed by Li et al [20], which inspired a positive and beneficial enlightenment to incorporate PBCs in a finite element method by using linear multi-point constraint. Fig.8 shows the location and numbering used for the faces, edges, and vertices of the RVE to apply PBCs. By setting the point A as a datum mark to be fixed, the corner points A' , B and D as the master nodes, the equations for establishing PBCs are summarized in the following:

• Faces

$$T^{\xi'} - T^{\xi} - T^D = 0, \quad T^{\eta'} - T^{\eta} - T^B = 0, \quad T^{\zeta'} - T^{\zeta} - T^{A'} = 0 \quad (11)$$

• Edges

$$\begin{aligned} T^{C'D'} - T^{CD} - T^{A'} &= 0, \quad T^{C'D'} - T^{A'B'} - T^D = 0, \quad T^{A'B'} - T^{AB} - T^{A'} = 0 \\ T^{C'C} - T^{DD'} - T^B &= 0, \quad T^{C'C} - T^{BB'} - T^D = 0, \quad T^{BB'} - T^{AA'} - T^B = 0 \\ T^{BC} - T^{AD} - T^B &= 0, \quad T^{B'C'} - T^{BC} - T^{A'} = 0, \quad T^{B'C'} - T^{A'D'} - T^B = 0 \end{aligned} \quad (12)$$

• Vertices

$$T^C - T^D - T^B = 0, T^D - T^{D'} - T^{A'} = 0, T^{B'} - T^{A'} - T^B = 0, T^{C'} - T^C - T^{A'} = 0 \quad (13)$$

It should be noted that the above PBCs merely applied to the nodes coordinates consistent between the master and slave faces. However, in the actual meso-scale meshing, some nodes in master face versus the nodes in slave face inconsistent, for example, a master node M corresponding to slave node M' is not in the position of grid node but fall within a certain unit. Therefore, the general PBCs should be used to process these inconsistent nodes. As shown in Fig.8 (b), the position of a slave node M' in $\Delta S_1 S_2 S_3$ can be defined by the following equation:

$$M' = S_1 + x'(S_2 - S_1) + y'(S_3 - S_1) \quad (14)$$

where the coefficient x' and y' should meet the constraint equations:

$$x' \geq 0, y' \geq 0, x' + y' \leq 1 \quad (15)$$

The general PBCs have better adaptability for applying boundary conditions to RVE, and also have the same effects as PBCs [21]. The present general temperature boundary condition has been justified by

applying thermal gradient to opposite nodes both in micro-scale and meso-scale RVE, whose error was controlled in $\pm 5\%$.

Fig.9 shows the boundary conditions for full-scale braided composite model, which were the same as experimental loading form. As for in-plane direction, the thermal gradient was directly applied on resistance wire to provide heat flux for surround specimen. Others surfaces were all set to adiabatic surface. The thermal gradient along the out-of-plane direction was applied on the bottom surface of specimens to provide heat flux for going through along its axial direction.

4.3 Finite element modeling

In this paper, the finite element analyses were operated on commercial available finite element software package ABAQUS/Standard (ver. 6.12) under the environment of operation system LINUX. The micro-scale RVE was directly built in ABAQUS. However, the complicated geometry models including meso-scale and full-scale RVE were established based on the geometric parameters calculated above by CAE (computer-aided engineering) software CATIA (ver. V5-R17). In order to obtain a good quality of mesh and also ensure the yarns and matrix share the same nodes in their contact interface, the powerful finite element meshing software HyperMesh (ver. 12.0) was used to mesh the microstructure models. The step was that the elements of resin were firstly created by tetramesh method, and the nodes of resin in the interface contact area were projected onto yarns, the elements of yarns were then meshed based on the projected nodes by tetramesh method. According to their microstructures, different scale models have different meshing schemes. As shown in Fig.10, the four-node linear tetrahedral elements (DC3D4) were used to mesh the meso-scale RVE, because of the irregularity of the resin part. As for more complicate full-scale 3-D model, each component was meshed with different types of elements. As shown in Fig.11, the elements of yarns were hexahedral (DC3D8) and epoxy was tetrahedral (DC3D10), considering the irregular curves and corners in resin structure. Because of that the results of thermal conduction were greatly influenced by the mesh sizes and mesh quality, this paper attempted different mesh sizes in HyperMesh and verified the mesh quality in the mesh module of ABAQUS with the purpose of reducing the number of warning grid as well as obtaining suitable total number of mesh. The present mesh size of meso-scale RVE and full-scale RVE were set as approximately 0.5 and 0.2mm, respectively, as a result of reducing computational cost and ensuring the computation quality. The number of elements for micro-scale RVE, meso-scale RVE and

full-scale model was 15607, 56452 and 468625, respectively. Accordingly, the number of nodes for these models was 34973, 107523 and 902638, respectively.

It is well known that the contact property existed at the interface between the fiber and matrix is an important factor influencing the final thermal conductive results. Although some studies[22-25] have done a few works to investigate the interface contact thermal properties both from experimental and numerical methods, the results were either overly-simplify or not suitable for the materials this paper used. This paper didn't focus its attention on the interface thermal contact property of carbon fiber and resin matrix. Therefore, considering the thermal contact resistance with no pressure between fibers and resin [26], the value of interface contact thermal conductivity was assumed to be about $1.5 \times 10^5 \text{ W m}^{-1} \text{ K}^{-1}$ and wouldn't change with temperature. The contact behaviors defined in FEA between yarns and resin matrix were defined as 'surface-to-surface' contact. The effects of convection and radiation were not considered, considering the good sealing and thermal insulation of the tested apparatuses having already been verified by standard test specimens.

5 Results and discussion

5.1 Micro-scale RVE

The micro-scale RVE established based on the fiber volume fraction in braiding yarn V_{fy} , which is 60% in this paper, can be regarded as unidirectional (UD) fiber reinforced composites. The thermal conductivity behaviors of this scale model were analyzed based on the thermal conductive properties of fibers and resin. It has been experimental validated above that both the thermal conductivities of carbon fibers and resin matrix are temperature-dependent. From the results shown in Fig.12, it can be found that the thermal conductivity of carbon fibers and resin matrix is a linear function of temperature. It turned out that the thermal conductivity of fiber axial direction is nearly five times more than that of its radial direction. Therefore, we just plotted the thermal conductivity vs. temperature curve along its axial direction.

For micro-scale RVE containing one fiber and four 1/4 fibers, the periodic temperature boundary conditions were applied to maintain the temperatures of corresponding nodes on the parallel faces consistent. By applying thermal gradients in the three local coordinate directions (11, 22 and 33),

respectively, the temperature and heat flux distribution shown in Fig.13 can be easily achieved, and thermal conductivities of braided yarns can be further calculated. Due to the heat flux applied in main direction ii ($i=1, 2, 3$) hardly stretch to other shear directions ij ($i, j=1, 2, 3, i \neq j$), the thermal conductivities k_{ij} ($i, j=1, 2, 3, i \neq j$) are close to zero.

In order to validate the accuracy of micro-scale RVE, several analytical models suitable for (unidirectional) UD fiber reinforced composite materials were used to calculate the thermal conductivities of the braiding yarns. The equations of these analytical models are listed below:

$$k_{ya} = k_{f11}V_{fy} + k_m(1 - V_{fy}) \quad (16)$$

$$k_{yt} = \frac{k_{f\perp}k_m}{k_mV_{fy} + k_{f\perp}(1 - V_{fy})} \quad (17)$$

$$k_{yt} = \frac{k_m(1 - V_{fy}) + k_{f\perp}(1 + V_{fy})}{k_{f\perp}(1 - V_{fy}) + k_m(1 + V_{fy})} \quad (18)$$

$$k_{yt} = k_m \left[\frac{\sqrt{(1 - V_{fy})^2 \left(\frac{k_{f\perp}}{k_m} - 1 \right)^2 + 4 \frac{k_{f\perp}}{k_m} - (1 - V_{fy}) \left(\frac{k_{f\perp}}{k_m} - 1 \right)}}{2} \right]^2 \quad (19)$$

where k is the thermal conductivity, V_{fy} is fiber volume fraction in braiding yarn. The subscripts f11, f $\perp$, ya, yt represent the direction of parallel to fiber axial, perpendicular to fiber axial, parallel to yarn axial and perpendicular to yarn axial, respectively. k_m is the thermal conductivity of resin matrix.

The results in Table 4 indicate that the parallel model in equation 16 is close to the actual experimental value of yarns' axial direction, but the series model in equation 17 only give the low limit value of thermal conductivity along yarns' radial direction, and Charles model [27] in equation 18 only give the upper limit value, and Pilling model [28] in equation 19 is closer to the actual experimental thermal conductivity of yarns' radial direction. The results of thermal conductivity between periodic RVE and analytical models show a good consistency with the differences less than 3%. Therefore, the thermal conductivities of braiding yarns at any temperature can be calculated by this micro-scale RVE model with results shown in Fig.14. It can be found that both the nodes' temperatures and heat flux density in 11 direction (fiber axial direction) are higher than those in 22 and 33 directions, and the heat flux mainly concentrated in the fibers' regions. Therefore, the thermal conductivity of braiding yarns in

axial direction is larger than that in transverse direction.

5.2 Meso-scale RVE

Based on the thermal conductive results of braiding yarns calculated from the micro-scale RVE, the thermal conductivity of meso-scale RVE can be further calculated by applying general PBCs to it. As analyzed in section 3, the meso-scale RVE was composed of matrix impregnated yarns and approximately represents the entire braided composites. By means of applying temperature gradients on the master nodes A' , B and D after pre-set the temperature of point A as zero, respectively, the temperature fields shown in Fig.15 and heat flux distributions in Fig.16 in the three directions (xx , yy and zz) of global coordinate system can be obtained by FEA. The distributions of temperatures in Fig.15 are not very continuous and smooth, because the applied general PBCs have some inconsistent temperature nodes. Owing to the three reasons that the braiding axial direction is more inclined to yarns' axial direction, the braiding transverse direction is more inclined to yarns' transverse direction, and the thermal conductivity of yarns' axial direction is greatly higher than that of its transverse direction. The temperatures along zz direction (braiding axial direction) are much higher than those along xx and yy directions.

By extracting the temperatures and heat flux density of the following four nodes A , A' , B and D , the thermal conductivities matrix $[K_{xx}, K_{xy}, K_{xz}; K_{yx}, K_{yy}, K_{yz}; K_{zx}, K_{zy}, K_{zz}]$ can be easily calculated. The calculation results show that 3-D four-directional braided composites are apparent transversely thermal isotropic materials with K_{xx} nearly equal to K_{yy} . Due to the heat flux densities are very small in the shear directions ($i, j = x, y, z, i \neq j$), the thermal conductivities $K_{ij} (i, j = x, y, z, i \neq j)$ are close to zero. Fig.16 demonstrates that heat flux is mainly concentrated in the yarns. As the example of thermal conduction in xx direction, the heat flux in x direction is much larger than that in y and z directions, which can also be seen from other directions. These phenomena further explain why the thermal conductivities of shear directions are almost zero. The detailed discussions about the comparison of thermal conductivity of braided composite calculated from meso-scale RVE and experimental are listed in section 5.4.

5.3 Full-scale 3D braided model

Fig.17 shows that the temperature and heat flux distributions in cross-section A and B of full-scale model. It is obvious that both the temperature and heat flux present irregular distributions which are guided by the yarns orientation. They don't manifest the circular-distributed trend which centered as the heating resistance wire, but present a special shape just similar as that shown in Fig.18. As an evidence to verify this phenomenon, Fig.18 shows the experimental average temperature values of thermocouples and their isothermal line distributions (red lines) from several tests. The blue lines represent the orientation of braiding yarns in the in-plane direction of 3D braided composites. Because the straight and continuous yarns are easier to induce heat flux transmitting than the buckling and discontinuous yarns, it can be found that temperatures were not uniform distributions at the cross-section of braided composite, which shows that the temperatures along yarns' axial direction are higher than those of other regions. The temperature or heat flux started from the center heat source and then released to yarns and resins. Both the experimental and FEA results indicate that the temperature and heat flux give priority selections to the directions of yarns' orientation. This can be explained that the thermal conductivity of braided yarns is much higher than that of epoxy resin, and yarns provide a convenient channel more benefit for the heat flow transmission. Fig.19 explains the question that how the temperature and heat flux transmitted in the numerous yarns. By extracting the nodes' temperatures of a single yarn to plot its temperatures' curve in the xy coordinate plane, it can be found that temperatures of the yarns near the center hot source are higher than those away from hot source. In Fig.19 (c), the curve with red hollow circle represents its temperatures' distribution in xy coordinate plane, the curve with red solid circle indicates the position of the braiding yarn in xy coordinate plane, the curve with blue solid circle demonstrates its temperatures' distribution on the x coordinate axial, and the curve with green solid circle denotes its temperatures' distribution on the y coordinate axial. The heat flux transferring path of a single yarn begins from the position closest to the heat source, then to transmit along the direction of yarn's orientation, and finally to the location most far away from the heat source.

The heat transmitting in the thickness direction of braided composite is different from its radial direction described above. Fig.20 shows the temperature distributions in different cross-sectional positions of full-scale braided model. At the same height of cross-sectional position, the temperature of yarns is higher than that of resin matrix. As for the temperatures at the three braided region, it depends on the movement trajectories of yarns in braided composites. When the yarns run into the surface or

angle regions, the temperatures in these regions are higher than interior regions just as (1-3-5). On the contrary, if the yarns travel to the interior regions, higher temperatures will also come to these places, such as (2-4-6). Considering that interior regions occupy larger volume in braided composites and straight yarn arrangement is more advantageous to the heat conduction, the temperatures in interior regions are a bit higher than surface and corner regions.

5.4 Comparisons

In this paper, the calculation methods of thermal conductivity were based on Fourier heat conduction law. As for the thermal conductivity calculation in FEA, the face nodes' number average method was used to obtain the ratio of nodes average heat flux density and nodes average thermal gradient, which can refer to the works of Siddiqui [29].

Table 5 and Fig.21 show the thermal conductivity comparative results calculated from experimental, meso-scale RVE and full-scale braided model, respectively. The thermal conductivities of full-scale model were calculated by the ratio of the average heat flux density to thermal gradient. The numerical results from the meso-scale RVE and full-scale braided model have a good agreement with experimental. However, the simulated results of full-scale model are closer to the experimental, because the surface and corner regions are also considered in full-scale model. Because the travelling paths of yarns in interior regions are straighter than those in surface and corner regions, and straight yarns are more benefit for heat flux transferring, the temperatures in surface and corner regions are a little lower than the those in interior regions. Owing to the existence of surface and corner regions, the whole thermal conductive ability of braided composites will be reduced. Meso-scale RVE didn't consider about the effects of surface and corner yarns, therefore, its thermal conductivity will be a little lower than that of full-scale model. The 3D rectangle braided composites are transversely isotropic in terms of thermal conductivity. Both the in-plane and out-of-plane thermal conductivities are increased with the increment of temperature. Due to the yarns are continuous along out-of-plane direction and discontinuous along in-plane direction, the thermal conductivities along out-of-plane direction are higher than those along in-plane direction. The temperature distribution and heat flux transmitting path are mainly along the orientation direction of braiding yarns. The guiding significance of this paper is that if the results require accurate and reliable, the full-scale model should be adopted, and if considering the calculation time and cost, the meso-scale model can be prioritized.

6 Conclusions

The thermal conductive behaviors of 3D braided composite were numerically characterized at micro-scale representative volume element (RVE) and meso-scale RVE models level, as well as full-scale model. The numerical results were validated with the experimental results. It was found that:

- (1) Meso-scale model can effectively compute the thermal conductivities of 3D four-directional braided composites. However, the calculated results are slightly larger than the experimental values and full-scale numerical values.
- (2) The thermal conductivities calculated from the full-scale model are closer to experimental values. In addition, it can well illustrate the temperature field distributions and heat flow transmitting pathway in braided composites, which shows that both the temperature and heat flux transmitting along fiber's orientation direction. The temperatures in the interior regions are slightly higher than in the surface and corner regions of 3D braided composite.
- (3) The 3D four-directional braided composites are typical transversely thermal isotropic materials. Furthermore, the thermal conductivity increases with the increment of temperature. And the thermal conductivity of 3D braided composite along the out-of-plane direction is larger than that along the in-plane direction.
- (4) The guiding significance of this paper is that if the results require accurate and reliable, the full-scale model should be adopted, and if considering the calculation time and cost, the meso-scale model can be prioritized.

Acknowledgement

The authors acknowledge the financial supports from the Chang Jiang Scholars Program and National Science Foundation of China (Grant Number 11272087, 11572085). The financial supports from Foundation for the Fok Ying-Tong Education Foundation (Grant No. 141070), Shu-Guang project (Grant No. 14SG31) supported by Shanghai Municipal Education Commission and Shanghai Education Development Foundation, the Fundamental Research Funds for the Central Universities of China and DHU Distinguished Young Professor Program are also gratefully acknowledged.

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Table 1

Thermo-physical properties of carbon fiber and epoxy resin at room temperature (25°C).

Materials	Density (g cm ⁻³)	Thermal conductivity		Specific heat capacity (J kg ⁻¹ K ⁻¹)
		(W m ⁻¹ K ⁻¹)		
		$k_{\parallel}$	$k_{\perp}$	
Carbon fiber (T700SC)	1.8	12.85	1.45	750
Epoxy resin (JC-02A)	1.3	0.18	0.18	1200

Table 2

Basic comparisons among the three scale models

Method	Features	Functions	Advantages
Micro-scale RVE	Periodic unit cell in braiding yarn, including one fiber and 1/4 fibers	Thermal conductivity calculation of braided yarn	Accuracy, effectiveness, compared with other methods
Meso-scale RVE	Periodic interior unit cell extracted from interior regions.	Thermal conductivity calculation of braided composites	Timesaving, effectiveness, convenience, but no structure effects
Full-scale model	Entire braided composite, including Interior, surface and corner regions	Thermal conductivity calculation of braided composites, structure effects	Time-consuming but can show temperature distribution and heat flux transmitting path

Table 3

Geometric parameters of 3D rectangle braided composites calculating from meso-scale RVE.

Braiding parameters of braided composites		Structural parameters of meso-scale RVE					
Dimensions (mm)	$\theta(^{\circ})$	a (mm)	h (mm)	c (mm)	V_y (%)	V_f (%)	V_{fy} (%)
13×13×28.8	30	2.6	3.6	0.475	30.56	51	60

Table 4

Thermal conductivities of the braiding yarns at room temperature (25°C).

Model	Axial thermal conductivity	Transverse thermal conductivity
	$k_{ya} = k_{11}$ (W m ⁻¹ K ⁻¹)	$k_{yt} = k_{22} = k_{33}$ (W m ⁻¹ K ⁻¹)
Parallel model	6.582	—
Series model	—	0.375
Charles model [27]	—	0.518
Pilling model [28]	—	0.471
Periodic RVE model	6.843	0.493

Table 5

Thermal conductivity results of 3D four-directional braided composites under different methods.

Direction	Experimental (W m ⁻¹ K ⁻¹)	Meso-scale RVE (W m ⁻¹ K ⁻¹)	Full-scale model (W m ⁻¹ K ⁻¹)
In-plane ($K_{in} = K_{xx} = K_{yy}$)	5.35-6.57	7.397	6.049
Out-of-plane ($K_{out} = K_{zz}$)	7.92-8.4	9.193	7.931

Fig.1. Specimen of 3D rectangle braided composites: (a) photograph from top view; (b) sketch diagram. (Notes: the angle 30° refers to the surface braiding angle θ)

Fig.2. Schematic diagram of thermal conductivity measuring apparatus: (a) in-plane; (b) out-of-plane.

Fig.3. Thermal conductivity measurement of 3D rectangle braided composite: (a) in-plane direction; (b) out-of-plane (thickness) direction. (Notes: the red points refer to the position of thermocouples.)

Fig.4. Specimens for thermal conductive experiment of carbon fiber and epoxy resin: (a) photograph of epoxy resin bar; (b) photograph of carbon fiber/epoxy resin system; (c) schematic diagram of measurement along fiber axial direction; (d) schematic diagram of measurement perpendicular to fiber axial (along fiber radial) direction.

Fig.5. Schematic diagram of multi-scale models of 3D rectangle braided composite: (a) full-scale braided model; (b) meso-scale RVE; (c) braided yarn; (d) micro-scale RVE.

Fig.6. Interior, surface and corner regions distribution in 3D braided composites: (a) interior regions; (b) surface regions; (c) corner regions.

Fig.7. Topological relationship of the main yarns in meso-scale unit cell: (a) central axes of yarns in space; (b) yarn configuration of the solid unit cell.

Fig.8. Application of general periodic temperature boundary conditions by master and slave nodes technique for micro-scale and meso-scale RVE: (a) representative unit cell; (b) position relationship between point and triangle. (Notes: ξ , η and ζ refer to the nodes on the surfaces.)

Fig.9. Boundary conditions used for full-scale braided composite model: (a) in-plane direction; (b) out-of-plane direction. (Notes: the directions of red arrows represent the directions of thermal gradient.)

Fig.10. Mesh schemes of fiber, resin and composite in meso-scale RVE. (Notes: the number in the upper left corner represents the grid number.)

Fig.11. Mesh schemes of preform, resin and composite in full-scale composite model. (Notes: [A] and [B] represent the middle cross-section of the xy plane and the xz plane, respectively.)

(a)

(b)

Fig.12. Thermal conductivity vs. temperature curves of carbon fiber and epoxy resin: (a) thermal conductivity of carbon fiber along its axial direction; (b) thermal conductivity of epoxy resin.

Fig.13. Temperature and heat flux fields in three local coordinate directions of the micro-scale RVE.

Fig.14. Thermal conductivity vs. temperature curves of the micro-scale RVE in three local coordinate directions.

Fig.15. Temperature distribution in meso-scale RVE: (a) in-plane xx and yy directions; (b) out-of-plane zz direction.

Fig.16. Heat flux distribution in meso-scale RVE by applying the thermal gradient in xx direction.

Fig.17. Temperature and heat flux distributions of full-scale 3D braided composite model.

Fig.18. Experimental results of the temperature distributions of 3D braided composites along the in-plane direction. (Notes: the red lines represent the isothermal lines, the blue lines denote the inclined direction of braided yarns.)

Fig.19.The temperature distribution diagram in xy coordinate plane of a single braiding yarn extracted from the braided composites: (a) the selected yarn in 3D braided composite; (b) the selected nodes in braided yarn; (c) the temperature distribution diagram of the braiding yarn. (Notes: the curve with red hollow circle represents its temperatures' distribution in xy coordinate plane, the curve with red solid circle indicates the position of the braiding yarn in xy coordinate plane, the curve with blue solid circle demonstrates its temperatures' distribution on the x coordinate axial, and the curve with green solid circle denotes its temperatures' distribution on the y coordinate axial.)

Fig.20. Temperature distribution of full-scale braided model at different length location in out-of-plane direction.

Fig.21. Comparison of thermal conductivity vs. temperature curves of 3D braided composites