Experimental and numerical analyses on the thermal conductive behaviors of carbon fiber/epoxy plain woven composites

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Abstract

The thermal conductive behaviors of carbon fiber/epoxy plain woven composites along in-plane and out-of-plane (thickness) directions were reported in this paper. The thermal conductivities of the plain woven composites were tested with a self-designed thermal chamber under different temperatures. The multi-scale finite element analyses (FEA) were used to investigate the thermal conductive behaviors of plain woven composites. From the comparisons of the thermal conductive behaviors between the plain woven composites and unidirectional (UD) lamina, the effect of the plain woven preform structure on the thermal conduction was further explained. It was found that the thermal conductivity along fiber axial direction is greater than that along its radial direction, and the thermal conductivities of plain woven composites fall in between those of 0° UD lamina (upper bound) and those of 90° UD lamina (lower bound). The temperature distributions and heat flux transferring pathways are mainly along the yarns' orientation directions. In addition, a simplified unit-cell model was developed to decompose the plain woven unit-cell into the combinations of several UD laminas. The experimental thermal conductivities showed a good agreement with those of FEA. The simplified unit-cell model manifests the feasibility for predicting the thermal conductivity of complex textile structure composites from the UD laminas.

Keywords

Plain woven composites; thermal conductivity; unidirectional (UD) lamina; finite element analyses (FEA)

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Nomenclatures

Symbols

h : surface coefficient of heat transfer, $\text{W m}^{-2} \text{K}^{-1}$

T : temperature, $^{\circ}\text{C}$

λ : thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$

q : density of heat flow, W m^{-2}

$\bar{q}$: average density of heat flow, W m^{-2}

R : thermal resistance, $\text{m}^2 \text{K W}^{-1}$

L : distance between adjacent thermocouples, mm

ΔT : temperature difference, $^{\circ}\text{C}$

∇T : temperature gradient, $^{\circ}\text{C mm}^{-1}$

ρ : density, kg m^{-3}

C_p : specific heat capacity, $\text{J kg}^{-1} \text{K}^{-1}$

V : volume fraction

M : mass fraction

θ : fiber inclination angle

s : surface of heat source

UD: unidirectional lamina

Subscripts

m : epoxy resin matrix

f : carbon fibers in plain woven composites

y : yarns

fy : carbon fibers in yarns

Al : referenced aluminium standard sample

foam : thermal insulating foam

w : foam wall of insulating chamber

x : distance from the center of heat source

int : interface between carbon fiber/epoxy resin

tg : thermal grease HT-GY260

n, N : the nth layer and the total layers

ij ($i, j=1, 2, 3$): coordinate direction in local coordinate system

xx : along the heat flow direction of composite

yy : perpendicular to the heat flow direction of composite

zz : the through-thickness direction of composite

$//, \perp$: parallel to fiber axial direction and perpendicular to fiber axial direction

ya, yt : axial direction of yarn and transverse direction of yarn

in, out : in-plane direction and out-of-plane direction (thickness) of plain woven composites

1. Introduction

Carbon fiber/epoxy plain woven composites have been extensively employed in the aeronautics engineering, automobile industries, electronic printed circuit boards, etc, owing to its higher in-plane strength and structure stability. These wide applications call for broadly studies of its various properties, especially the mechanical and thermal properties. Although the predictions of its mechanical properties have already been widely researched during the past decades [1-4], the thermal conduction of the plain woven composites has never been effectively revealed and discussed. It is well known that the thermal conductivity plays an important role in selecting the optimum materials to meet specific design requirements in many aerospace applications [5]. In addition, the composites are often used under rapid temperature changing environment and the fatigue damage induced by thermal stress is a typical form of composites' final fatigue and failure. Therefore, it is necessary to accurately predict the thermal conductivity of plain woven composites.

Many studies have reported their researches on the thermal conductivity of plain woven composites. For example, Ning et al. [6, 7] developed a micro-mechanic model and closed-form solutions to predict the in-plane and out-of-plane effective thermal conductivities of the woven composites based on a thermal-electrical analogy. Gowayed et al. [8] used the fabric geometry model to calculate the thermal conductivity of four kinds of plain woven composites and investigated the effect of fiber type and fiber volume fractions on the heat transfer properties. Dasgupta et al. [9, 10] introduced an asymptotic homogenization scheme to predict the orthotropic thermal conductivity of plain woven composites based on a 3-D thermal resistance network. Scott et al. [11] used the Gauss minimization method at

different temperatures for two different stacking orientation to estimate thermal properties. In the authors' view, the above-mentioned references mainly selected the analogy method to calculate the thermal conductivity, whose accuracy need to be further validated.

In addition to the thermal-electric analogy technology for calculating the thermal conductivity of plain woven composites, some other methods are also used. From the perspective of thermo-mechanical coupling relationship, Tang et al. [12-14] systematically analyzed thermal conductivity degradation behaviors of ceramic matrix composites (CMCs) based on the uni-axial stress-strain tow response model and simple one-dimensional series-parallel element models. In addition, from the point of view of thermal conductive mechanism, Gori et al. [15] employed two thermal assumptions, i.e. parallel isothermal lines and parallel heat flux lines, for solving the heat conduction equation to evaluate the thermal conductivity of composites. More recently, with the development of computing ability of computer, the finite element analyses (FEA) are widely used in numerical calculation of thermal conduction. Li et al. [16] predicted the in-plane and out-of-plane thermal conductivities of woven fabric composites through the representative volume element method implemented using two unit cells established at different length scales with periodical boundary conditions. Gou et al. [17] established three reducing-size unit cells formulated by using different symmetries based on FEA numerical approach to predict the effective thermal conductivities of plain woven composites. Although these methods can effectively calculate the thermal conductivities of plain woven composites, the interior thermal conductive structural effects, including the temperature distributions and heat flux transferring paths, are seldom reported.

The objective of this paper is to develop multi-scale microstructure models for analyzing the thermal conductive behaviors of carbon fiber/epoxy plain woven composites both along in-plane (fibers' axial or radial) and out-of-plane (thickness) directions. The organizations of present paper are as follows: firstly, the experimental methods used for measuring thermal conductivities of plain woven composites are presented in section 2. Then the multi-scale finite element analytical models of plain woven composites, including the periodic temperature boundary conditions for yarn and macroscopic boundary conditions for composites, are established in section 3. Thirdly, the effects of plain woven structure on the thermal conductivity of plain woven composites and its thermal conduction comparisons with that of unidirectional (UD) lamina are analyzed in section 4. All the numerical results calculated from the FEA agree well with the experimental data, which effectively validates the ability

of finite element method in thermal conductive prediction.

2. Experimental

2.1. Materials

Carbon fiber plain woven fabric, whose areal density was 400 g/m² and warp and weft densities were 2.5 yarns/cm, was fabricated by T700S-12K carbon fiber (Toray Inc. Japan) and was used as the reinforced body. An epoxy resin JC-02A based on diglycidyl ether of bisphenol A (Changshu Jaffa Chemical Co., Ltd) with hardener JC-02B (improved methyl tetrahydrophthalic anhydride) and accelerant JC-02C (tertiary amine) was used as matrix material. The plain woven fabrics were stacked along their thickness directions with the same directions and dimensions. The K-type thermocouples used for measuring the temperatures were first embedded into the plain woven fabrics before being cured with epoxy resin by vacuum assistant resin transfer molding (VARTM) technique. The diameter of a single wire was 0.5 mm and the external diameter of glass fiber coated thermocouple was 1 mm. The thermocouples were first warped by carbon fibers and then their positions were fixed by epoxy resin glue before curing. Because the basic properties of epoxy resin glue and epoxy resin matrix were similar, and the curing technique with double vacuum bags could ensure enough pressure applied on the thermocouple to make it closely contact with the fabrics, it assumed that the thermocouples embedded in composites had no intrusiveness against with thermal conduction. According to the raw data provided by the sellers, the basic thermal parameters at room temperature of carbon fibers and epoxy resin are listed in Table 1. The epoxy resin was first vacuumed to remove the air bubbles before being injected into the fabrics. The curing temperature was 90°C for 2 h, followed by 110°C for 1 h, and finally 130°C for 4 h. The final specimens were removed from the oven after cooling for 12 h, then cut to the needed sizes as listed in Table 2 by means of high-pressure water jet. Three specimens were prepared for testing along in-plane direction as well as along out-of-plane direction and each test would be repeated at least three times. The tests were conducted in standard conditions at a room temperature of 25±2°C and 65±2% relative humidity to ensure its reliability.

2.2. Experimental apparatus

In this study, all the testing works were conducted in a self-designed apparatus which has already been calibrated by standard aluminum (6063-T4) specimens with known room temperature thermal

conductivity of $200 \text{ Wm}^{-1}\text{K}^{-1}$. The device was also used to measure the thermal conductivity of epoxy resin and carbon fiber/epoxy resin system, just as reported in reference [18], and the measured values showed a good consistency with the provided ones. The error range was kept within 5%, which demonstrated the reliability of this apparatus. The apparatus 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 plain woven composites 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. It is assumed that when the temperature variation $\Delta T \leq 0.1^\circ\text{C}$, the status of thermal conductive equilibrium was achieved and then the experiment was finished. Comparing with the existed thermal conductivity test tools, the self-designed apparatus has the advantages of easy manufacturing and operating, low cost, and also with high precision. Fig. 1 shows the schematic diagrams of the test devices both along in-plane and out-of-plane (thickness) directions. The heat source applied temperature loadings to specimens, the insulated foam prevented the heat from spreading, the voltage regulator recorded the voltage variations and the temperature control system adjusted the loading temperatures. The temperatures were acquired by thermocouples and output by thermometers.

2.3. Thermal conductivity testing

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 methods used for thermal conductivity measurements along in-plane and out-of-plane directions were different. Since the thermal conduction path along the in-plane direction is very short, the modified transient hot wire technique [19, 20] 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 and 3 (a), the electrical

resistance wire Cr20Ni80 with 0.6 mm diameter and 3.855 Ω resistance per meter was embedded in the axial yarn and located in the center of the plain woven fabrics. Considering that the transient heating of resistance wire would produce a large temperature jump in a very short time and the transmission signal of thermocouples had a time lag, there would be a big error occurring if we only used the measuring data of the first heating. Therefore, the final approximate thermal equilibrium temperatures of thermocouples from many times heating were used to calculate the thermal conductivities. In addition, although the temperature of resistance wire would fluctuate in a short time, it can be regarded as constant in the whole process after many times heating. 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. Because the wire was embedded in the center position of the composite coupons, the heat generated from the resistance wire was completely absorbed by the woven composites. The temperatures at different locations could be measured by the connecting thermocouples. 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 temperatures of thermocouples, the thermal conductivity of plain woven composites along in-plane direction λ_{in} can be calculated as:

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

where $\bar{R}$ is the resistance per meter of the resistance wire and ∇T is the temperature gradient which represents the rate of temperature change. A is the thermal conductive area of composite specimens.

For the thermal conductivity measurement along out-of-plane direction (thickness direction), the transient plane source method [21] was used based on ASTM C 177-97. As shown in Fig. 3(b), the heating aluminum plate with the size of 50×80 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-designed apparatus, it was assumed that the heat going through the composite samples and aluminum bar were the same. Therefore, an equivalent model in Fig. 3(c) was established for calculating the thermal conductivity along the out-of-plane (thickness) direction. The thermal conductivity equations can be expressed as

$$q_{23} = q_{12} = \lambda_{Al} \frac{\Delta T_{12}}{L_1} \quad (2)$$

$$R_{23} = \frac{L_3}{\lambda_{out}} + \frac{L_{tg}}{\lambda_{tg}} + \frac{L_2}{\lambda_{Al}} + \frac{L_4}{\lambda_{foam}} = \frac{\Delta T_{23}}{q_{23}} \quad (3)$$

$$\lambda_{out} = \frac{L_3}{\frac{\Delta T_{23}}{\lambda_{Al} \cdot \frac{\Delta T_{12}}{L_1}} - \frac{L_{tg}}{\lambda_{tg}} - \frac{L_2}{\lambda_{Al}} - \frac{L_4}{\lambda_{foam}}} \quad (4)$$

where L_1 and L_3 refer to the gap distance between the adjacent thermocouples, L_2 and L_4 denote the gap distance between different materials. L_{tg} is the thickness of thermal grease, which is observed by SEM and measured by graphical measurement software after cutting the sample. ΔT_{ij} ($i=1,2,3$; $j=2,3,4$) refers to the temperature differences between adjacent thermocouples, whose temperatures are expressed as T_i ($i=1,2,3,4$). And the thermal conductivity of thermal grease and insulated foam used in this paper are $18 \pm 3 \text{ W m}^{-1} \text{ K}^{-1}$ and $0.02 \text{ W m}^{-1} \text{ K}^{-1}$, respectively.

2.4. Determination of parameters

2.4.1. Basic thermal properties of fiber and resin

It is well known that the thermal energy is transferred mainly in the form of phonons in polymer matrix composites (PMCs). However, the phonon vibration is greatly affected by the applied temperature. Therefore, it is necessary to measure the thermal conductivities of carbon fiber and epoxy resin matrix at various temperatures. This paper also used the transient plane source method to measure the thermal conductivities of carbon fiber and epoxy resin, just as our previous works [18, 22]. As shown in Fig. 4, the five K-type thermocouples were embedded in epoxy resin bar before curing to measure its temperature variations. By the same way, thermocouples wrapped

inside the three fiber bundles to measure the thermal conductivities of carbon fiber under different temperatures both along fiber axial and radial directions. Considering that measuring the thermal conductivity of a single carbon fiber was very difficult, it was assumed that the thermal conductivities of the three fiber bundles were the same as a single carbon fiber.

The specific heat capacities at constant pressure of carbon fiber and epoxy resin were performed in according to the ASTM E 1269 by means of differential scanning calorimeter technique (DSC, NETZSCH 214). The DSC measurements of 5.6-5.9 mg of the neat epoxy resin or 4.8-5.2 mg of carbon fiber were carried out in opened alumina crucibles under a nitrogen atmosphere in a temperature range from 25 to 300 °C with a heating rate of 10°C/min. The densities of carbon fiber and epoxy resin were assumed as constants in this paper.

2.4.2. Interface contact thermal resistance

Except for the basic thermal conduction properties of fiber and resin, the thermal conduction properties of composites also depend on the capacity of heat transmission from fiber to resin, or vice versa [23-25]. This ability can be characterized by interface contact thermal resistance. It was worth noting that this paper only considered the interface contact thermal resistance existing between fiber and resin and thermal resistances in other regions were ignored. Fig. 5(a) and (b) shows two models for analyzing the carbon fiber/epoxy resin interface thermal contact resistance in UD lamina both along fiber axial and fiber radial (perpendicular to fiber axial) directions. The heat flow transferring along the fiber axial direction of UD lamina is in analogy with that transferring along the in-plane direction of plain woven composites and similarly the heat flow transferring along the fiber radial direction of UD lamina is in analogy with that transferring along out-of-plane direction of plain woven composites. Therefore, the interface contact thermal resistances between fiber and resin measured from UD lamina could be approximated as those in plain woven composites.

The interface contact thermal resistance existing between fiber and resin can be calculated by the ratio between the average temperature and average heat flux density at the interface, just as follows:

$$\bar{q}_{\text{int}} = \frac{q_{\text{int}}^m + q_{\text{int}}^f}{2} = \frac{\lambda_{\text{int}}^m \nabla T_{\text{int}}^m + \lambda_{\text{int}}^f \nabla T_{\text{int}}^f}{2} \quad (5)$$

$$R_{\text{int}} = \frac{L_{\text{int}}}{\lambda_{\text{int}}} = \frac{\Delta T_{\text{int}}}{q_{\text{int}}} \quad (6)$$

Eq. (5) indicated that the average heat flux density of the interface was calculated from the heat flux density average of fiber and resin. Just as the loading temperature of 80°C for an example, the temperature distributions of fiber and resin at several measuring points were shown in Fig. 5(c). The error bars represented the fluctuated ranges of the results. The temperatures of fiber and resin at their interface (in 50 mm) could be extrapolated by their location vs. temperature curves. λ_{int}^m and λ_{int}^f at different temperatures had already been measured in section 2.4.1. L_{int} was the thickness of interface, which was assumed to be 1×10^{-3} mm as a constant. The experimental results of interface thermal contact resistance at the temperature range of 25-240°C were shown in Fig. 5(d) and could be further used for the finite element thermal conduction analyses of plain woven composites. Three specimens were tested at least three times both along fiber axial and fiber radial directions to obtain reliable temperature measuring data.

2.4.3. Heat transfer coefficients

It is well known that the thermal convection and thermal radiation will also have an influence on the final thermal conduction results. Considering the interior wall of the insulated chamber is an adiabatic foam material coated with aluminum foil and the interfaces between composite coupons and thermocouples or heat source were filled with thermal grease, the radiation can only existed in the two adjacent interfaces between fiber and resin, which is very small and could be neglected. However, the effect of thermal convection on the thermal conduction may be very apparent in a small insulated chamber. Therefore, we only consider the air convection heat transfer effect in this paper. In order to calculate the heat transfer coefficient under different temperatures, a thermocouple was placed on the inner wall of the chamber. The values of T_w , T_f , ∇T and λ would change with temperatures, so the heat transfer coefficients under different temperatures could be obtained.

As shown in Fig. 6(a), the heat transfer coefficient of location x far away from heat source could be calculated based on the equivalent heat flux principle, i.e. the third boundary condition in thermodynamics, which can be expressed as:

$$q_x = -\lambda \cdot \nabla T_x = h_x \cdot (T_w - T_f)_{w,x} \quad (7)$$

$$h_x = -\frac{\lambda}{(T_w - T_f)_{w,x}} \cdot \nabla T_x \quad (8)$$

$$h = \frac{Q}{(T_w - T_f)A} = \frac{\int_A q_x \cdot dAx}{(T_w - T_f)A} = \frac{1}{A} \cdot \int_A h_x dAx \quad (9)$$

The results of air convection heat transfer coefficients at different temperatures are shown in Fig. 6(b).

3. Finite element analyses

3.1. Geometrical model

In this paper, multi-scale models, i.e. micro-scale yarn model, meso-scale composite unit-cell model and full-scale composite model were used to obtain the thermal conductivities of yarns and composites. As shown in Fig. 7, a micro-scale unit-cell model with the dimensions of 0.38×0.22×0.8 mm was introduced to analyze the thermal conduction properties of matrix impregnated fiber yarns. In micro-scale unit-cell model, each one includes hundreds of fibers impregnated in the matrix with randomly packed pattern in the transverse direction. The tows which consist of matrix and fibers have been utilized for homogenized model as 3D solid. The size of the fibers within a tow was chosen such that the fiber volume fraction and the outer dimension of the tow was equivalent to the dimensions of an actual tow. For the fiber packing patterns in resin, the hexagonal model was widely applied for modeling transversely isotropic property of matrix impregnated fiber yarns. Therefore, it was assumed that the fibers in the matrix impregnated fiber yarns are in hexagonal array distributions.

For meso-scale composite unit-cell model as sketched in Fig. 8, the plain woven composites can be formed by undulated warp yarns and weft yarns interlacing together, and then impregnated with epoxy resin. From the perspective of microstructure, the plain woven composites can be regarded as countless arrays of a periodical cycle representative volume element (RVE). Although the interwoven pattern of yarns in plain woven fabrics introduces various degree of waviness, the fibers in yarns can be approximately taken as straight line considering small scale of undulations. The ideal cross-section shape and bending configuration of yarns in plain woven composites were illustrated in Fig. 8(a).

However, the actual states of yarns in plain woven composites were very complicated, due to the mutual squeezing between yarns. In this paper, the cross-section shape of yarns was assumed to have elliptical shape and kept constant to ensure that fiber volume fraction was constant so that the properties were not changed as a function of the position. The periodic centroid motion locus of yarns was assumed as a sinusoidal curve. The volume fraction of yarn V_y in this RVE can be denoted as:

$$V_y = \frac{4\pi abl}{hd^2} \quad (10)$$

where a and b are the long diameter and short diameter of the elliptical cross section, respectively. l is the length of the yarn. h and d are the side length and height of the meso-scale plain woven unit-cell model. The geometrical morphologies of the yarns' cross-section and the selected plain woven unit-cell were observed with optical microscope. Accordingly, their basic parameters were measured by graphical measurement software, which were listed in Table 3.

The distributed content of fibers in a single yarn can be described as the fiber packing fraction in the yarn V_{fy} , which is an important parameter to determine the dimension of the micro-scale unit-cell model. The relationship between V_y , V_f and V_{fy} is expressed as

$$V_f = V_{fy} \cdot V_y \quad (11)$$

The fiber volume fraction in plain woven composites V_f was measured by the combustion method in muffle furnace. The methods were that the temperature was set as 600 °C and the burning time was 6 h. The test was repeated several times to obtain an average value.

3.2. Governing equations

The finite element analyses (FEA) of the thermal conduction were operated on commercial available finite element software package ABAQUS/Standard (ver. 6.12) under the environment of the operation system LINUX. The FEA of micro-scale unit-cell model, i.e. yarn model, and meso-scale composite unit-cell were run for steady-state conditions to obtain temperature and heat flux throughout the model. The governing equations is described as:

$$\lambda_{xx} \frac{\partial^2 T}{\partial x^2} + \lambda_{yy} \frac{\partial^2 T}{\partial y^2} + \lambda_{zz} \frac{\partial^2 T}{\partial z^2} + (\lambda_{xy} + \lambda_{yx}) \frac{\partial^2 T}{\partial x \partial y} + (\lambda_{xz} + \lambda_{zx}) \frac{\partial^2 T}{\partial x \partial z} + (\lambda_{yz} + \lambda_{zy}) \frac{\partial^2 T}{\partial y \partial z} = 0 \quad (12)$$

While the FEA for the full-scale composite models were based on the transient thermal conduction, the

governing equation for transient thermal conduction analyses is described as:

$$\lambda_{xx} \frac{\partial^2 T}{\partial x^2} + \lambda_{yy} \frac{\partial^2 T}{\partial y^2} + \lambda_{zz} \frac{\partial^2 T}{\partial z^2} + (\lambda_{xy} + \lambda_{yx}) \frac{\partial^2 T}{\partial x \partial y} + (\lambda_{xz} + \lambda_{zx}) \frac{\partial^2 T}{\partial x \partial z} + (\lambda_{yz} + \lambda_{zy}) \frac{\partial^2 T}{\partial y \partial z} = C_p \rho \frac{\partial T}{\partial t} \quad (13)$$

where T is the temperature, λ_{xx} , etc. are thermal conductivity, which can be regarded 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 are the same as Fourier's heat conduction law and can be defined as:

$$q = -\lambda \nabla T \quad (14)$$

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

3.3. Boundary conditions

According to different thermal conductive modes in different unit-cell models, different boundary conditions were used. Micro-scale yarn unit-cell model and meso-scale composite unit-cell model were based on RVE, the periodic boundary conditions (PBCs) should be applied in the models to obtain a reasonable temperature and heat flux distributions. The periodical displacement boundary conditions proposed by Xia et al. [26] and further developed by Li et al. [27], which inspired a positive and beneficial enlightenment to incorporate PBCs in a finite element method by using linear multi-point constraint. The PBCs could ensure that each RVE in the composite had the same loading modes and there was no separation or overlap between the neighboring RVEs. Fig. 9(a) shows the location and numbering used for the faces, edges, and vertices in the RVE. In the cubic unit-cell with periodicity in all the three directions, $\xi - \xi'$, $\eta - \eta'$ and $\zeta - \zeta'$ are pairs of periodic nodes locating on the opposite parallel boundary surfaces of the unit-cell and the lines linking them are parallel to the three coordinate axes, respectively. According to the applying methods of PBCs in ABAQUS user manual [28], the temperature of the unit-cell can be constraint by setting the point A as a datum mark to be fixed, point B to be constraint in x_2 direction and point D to be constraint in x_1 and x_2 directions. If taking the corner points A , B and D as the master nodes, the equations for establishing PBCs are summarized in the following:

- Faces

$$T^{\xi'} - T^{\xi} - T^D = 0, T^{\eta'} - T^{\eta} - T^B = 0, T^{\zeta'} - T^{\zeta} - T^{A'} = 0 \quad (15)$$

• Edges

$$\begin{aligned} T^{C'D'} - T^{CD} - T^{A'} &= 0, T^{C'D'} - T^{A'B'} - T^D = 0, T^{A'B'} - T^{AB} - T^{A'} = 0 \\ T^{C'C} - T^{DD'} - T^B &= 0, T^{C'C} - T^{BB'} - T^D = 0, T^{BB'} - T^{AA'} - T^B = 0 \\ T^{BC} - T^{AD} - T^B &= 0, T^{B'C'} - T^{BC} - T^{A'} = 0, T^{B'C'} - T^{A'D'} - T^B = 0 \end{aligned} \quad (16)$$

• Vertices

$$T^C - T^D - T^B = 0, T^D - T^{D'} - T^{A'} = 0, T^{B'} - T^{A'} - T^B = 0, T^{C'} - T^C - T^{A'} = 0 \quad (17)$$

where T is the temperature, A , etc. are the terminal vertices in the RVE. The degree of freedom for applying temperature boundary conditions is 11 in ABAQUS. In these linear multi-point constraint equations, the temperature of master node is equal to that of the face or edge where the master node is included. Therefore, only by applying the thermal gradient to the master node, the face or the edge will be also under the same thermal loading. It should be also noted that the meshes on the two opposite vertices, edges and faces of the unit-cell should be same for applying the above equations. The present periodic temperature boundary conditions have been verified by applying thermal gradient to opposite nodes both in micro-scale and meso-scale RVEs, whose error was controlled within $\pm 5\%$.

This paper also employed the full-scale composite model for the thermal conduction analyses of plain woven composites both along in-plane and out-of-plane directions. There was no need to impose the PBCs to full-scale composite model, due to no repeated RVE existing in this model. Figs. 9(b) and (c) show the macro temperature boundary conditions for full-scale composite model, which are the same as experimental loading forms. The dark red surfaces refer to the hot source and the purple surfaces represent the hot sink. The thermal gradient goes through the hot source to the hot sink to provide steady heat flux for passing the composites. The red arrows represent the main transfer direction of heat flux and statuses in other surfaces are set as adiabatic. As for in-plane direction, the thermal gradient was directly applied on the resistance wire to provide heat flux for the surrounding specimen and other surfaces were all set to adiabatic surfaces. The thermal gradient along the out-of-plane direction was applied on the bottom surface of specimen to provide heat flux going through its longitudinal direction.

3.4. Meshing

In ABAQUS, the contact behaviors between fibers and resin were defined as ‘surface-to-surface’ contact with the interface thermal contact properties measured above. The film conditions, i.e. air convection boundary conditions used in FEA were based on the above calculated values of heat transfer coefficients. The local coordinate orientations of yarns were fixed by assigning material orientations in ‘property’ module, considering the yarns had thermal conductive transversely isotropic characterizes. The hexahedral element meshes were used in the micro-scale yarn unit-cell model and UD lamina unit-cell model both for fiber and resin. And for meso-scale and full-scale composite models, the ten-node tetrahedral linear heat transfer brick elements (DC3D10) were for the resin mesh and eight-node hexahedra linear heat transfer brick elements (DC3D8) were for the yarns’ mesh. After pre-tests with different mesh sizes, the present number of element in the micro-scale yarn model, meso-scale composite unit-cell model and UD lamina unit-cell model was 3600, 8826 and 4800, respectively. The detailed meshing scheme for the full-scale plain woven composite model was shown in Table 4 as a result of reducing computational cost as well as ensuring the computation quality.

4. Results and Discussions

4.1. Experimental supplementary verification

In this paper, the thermal conductivity measuring instrument DZDR-S based on transient plane source (TPS) technique [29] was used, in order to verify the reliability of the thermal conduction experiments by using our self-designed apparatus. The DZDR-S setup and experimental methods are shown in Fig. 10. The sensor, typically double concentric ring with multiple spirals of nickel wire, is sealed between two Kapton films for electrical insulation. The constant current is passed through the sensor at the beginning of the experiment. The temperature increase in sensor is monitored by detecting the voltage change based on the principle of the Wheatstone bridge. The thermal property of the sensor at various temperatures is a known quantity. The conductivity of a sample can then be obtained by solving the differential equation of conduction [30]. The sensor was placed between the two composite coupons. In addition, because the sensor of the DZDR-S has a certain size (15 mm), and based on the testing standard of this instrument, the diameter of the specimen must be more than 30 mm to cover the sensor. However, the thickness of the specimen is only 6 mm, which is much less than the minimum size the instrument needs. Therefore, the instrument DZDR-S was only used for thermal conductive measurement along

out-of-plane direction. The thermal conductivity of out-of-plane direction measured by DZDR-S is $0.6643 \text{ W m}^{-1} \text{ K}^{-1}$, and its value from our self-designed apparatus is $0.6879 \text{ W m}^{-1} \text{ K}^{-1}$, which shows a good agreement between them with the deviation less than 1%. Hence, we can assume that the thermal conductive results both the in-plane and out-of-plane directions obtained from our self-designed apparatus have good accuracy.

4.2. Thermal properties of yarns

The micro-scale unit-cell model established based on the fiber volume fraction in yarn V_{fy} , which was 75.3% in this paper, could be regarded as unidirectional fiber reinforced composite. The thermal conduction behaviors of this scale model were analyzed based on the basic thermal properties of fibers and resin. It has been experimental validated above (section 2.4.1) that both the thermal conductivities of carbon fiber and resin matrix are temperature-dependent. From the results shown in Fig. 11, it can be found that the thermal conductivity of carbon fiber and epoxy resin 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 the micro-scale unit-cell model 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 gradient in the three local coordinate directions (11, 22, 33), respectively, the temperature distributions shown in Fig. 12(a) could be easily achieved, and the thermal conductivities of yarns could be further calculated. Due to the heat flux generated 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 λ_{ij} in these shear directions ($i, j=1, 2, 3, i \neq j$) are close to zero.

In order to verify the accuracy of thermal conductivity calculations in the micro-scale unit-cell model, several analytical models suitable for UD fiber reinforced composites with the basic thermal properties of carbon fiber and epoxy resin at room temperature were also used to calculate the thermal conductivities of the yarns. The equations of these analytical models are listed below:

$$\lambda_{ya} = \lambda_{f11} V_{fy} + \lambda_m (1 - V_{fy}) \quad (18)$$

$$\lambda_{yt} = \frac{\lambda_{f\perp} \lambda_m}{\lambda_m V_{fy} + \lambda_{f\perp} (1 - V_{fy})} \quad (19)$$

$$\lambda_{yt} = \frac{\lambda_m (1 - V_{fy}) + \lambda_{f\perp} (1 + V_{fy})}{\lambda_{f\perp} (1 - V_{fy}) + \lambda_m (1 + V_{fy})} \quad (20)$$

$$\lambda_{yt} = \lambda_m \left[\frac{\sqrt{(1 - V_{fy})^2 \left(\frac{\lambda_{f\perp}}{\lambda_m} - 1 \right)^2 + 4 \frac{\lambda_{f\perp}}{\lambda_m} - (1 - V_{fy}) \left(\frac{\lambda_{f\perp}}{\lambda_m} - 1 \right)}}{2} \right]^2 \quad (21)$$

The results in Table 5 indicate that the parallel model in Eq. (18) is close to the actual experimental value of yarns' axial direction, but the series model in Eq. (19) only give the low limit value of thermal conductivity along yarns' radial direction, and Charles model [31] in Eq. (20) only give the upper limit value, and Pilling model [32] in Eq. (21) is closer to the actual experimental thermal conductivity of yarns' radial direction. The thermal conductivities at room temperature between micro-scale unit-cell model and analytical models show a good consistency with the differences less than 3%. Therefore, the thermal conductivities of yarns at any temperature could be calculated by this model. Form the results of thermal conductivity shown in Fig. 12(b), it can be found that thermal conductivities of λ_{11} was higher than those of λ_{22} and λ_{33} , which is due to the thermal conductivity of fiber axial direction higher than that of its radial direction. Because the thermal conductivity is a material property, the assumption of transversely isotropic properties for unidirectional fiber tow determines the identical thermal conductivity of λ_{22} and λ_{33} .

As for the density and the specific heat at constant pressure of yarns, the rule of mixture (ROM) was used and the corresponding equations were expressed as:

$$\rho_y = V_m \rho_m + V_f \rho_f \quad (22)$$

$$C_{py} = M_m C_{pm} + M_f C_{pf} \quad (23)$$

where ρ is the density and C_p is the specific heat at constant pressure. V and M are the volume fraction and the mass fraction of its corresponding components, respectively.

4.3. Thermal conduction behaviors of plain woven composites along different directions

The thermal properties of yarns at different temperatures (25-240 °C) were then input into the full-scale composite model. By applying thermal gradients with the above macro temperature boundary

conditions to the full-scale composite model, the thermal conduction behaviors of plain woven composites can be further characterized. 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 [33].

For the in-plane direction, the temperature and heat flow transmitted from the centre position to the outside surfaces, due to that the electrical resistance wire was embedded in the centre of four-layer plain woven composites. If the cross-section of four-layer plain woven composite was cut from xy plane, the apparent differences of temperature distributions and heat flow transmitting paths between warp yarn and weft yarn can be found, just as shown in Figs. 13(a) and (b). It is obvious that temperatures of the same distance along fiber axial direction are larger than those along fiber radial direction and with the same tendency as the heat flow transmitting path. In order to further analyze these phenomena, the temperature of nodes in axial yarn and radial yarn were extracted and depicted in Figs. 13(c) and (d), which makes the differences more obvious. It can be easily explained by the fact that the thermal conductivity of fiber axial direction is larger than that of fiber radial direction. The heat flux preferentially selects the passageway with higher thermal conductivity. In view of complicate structure of 4-layer woven composite resulting in difficult convergence and relatively longer calculation time in FEA, the simplified one-layer woven model was proposed. Fig. 14 shows the differences of thermal conductivity between two orthogonal directions for one-layer plane woven composite model, which further verified the above conclusions in the 4-layer woven composites.

Different with the in-plane direction, the thermal conductivity measurement along the thickness direction was conducted by applying the heat source under the bottom of twelve-layer woven composites. A corresponding FEA model was also established for finding its thermal conductive structural effects. Fig. 15(a) shows the temperature distribution and heat flow transmitting path along the thickness direction of plain woven composites. In order to observe the temperature variations of different layers, the temperatures of nodes were extracted from yarns of different layers and shown in Fig. 15(b). As the yarn position closer to the heat source or conductive time longer (before reaching the state of balance), the temperature will be also higher. Temperature will drop nearly 2 °C when thermal conduction jumps each layer from the heat source to the cold surface. Fig. 15(c) shows the temperature distributions of epoxy resin at different locations. It turns out that the temperature of resin is unbalanced and its distribution strongly depends on the location of yarns. The reasons can be found in

Figs. 16 and 17. Just taken the 6th layer of 12-layer woven composite as an example, the temperatures of interlaced regions of yarns are higher than those in other regions, and the propagation of temperature depends on the local orientation of yarns which mainly spreads along yarn axial (i.e. 11 direction). This is because the locations of interlaced regions of yarns are higher than others, making them first contact heat flow, and the λ_{11} along yarn axial direction is larger than λ_{22} along yarn radial direction. Fig. 17 shows that the positional distributions of yarns will affect the temperature distributions of resin. The closer location of resin is to yarns, the higher temperature of it will be. The main reason is that the carbon fiber tows with high thermal conductivity absorb more heat and propagate to other regions of the composite with low thermal conductivity, which makes the temperatures of resin rise and higher than that of the neat resin. Fig. 18 compares the temperature-time curves of plain woven composites between the experimental and the FEA both along in-plane and out-of-plane directions, which effectively validates the FEA results.

4.4. Thermal conduction comparisons between plain woven composites and UD lamina

Thermal conduction behaviors of the unidirectional (UD) fiber reinforced composites have been widely studied [34-38], due to its simple structure and superior performances. This paper also conducted the thermal conductivity measurement of UD lamina based on the same experimental methods as plain woven composites. Fig. 19 shows the comparisons of thermal conduction behaviors between plain woven composite and the UD lamina. It is easily found that the thermal conductive capability of the woven composite with known heat flow direction is better than 90° UD lamina but worse than 0° UD lamina. This is due to that the carbon fiber tows have higher thermal conductivity than epoxy resin and the heat flows preferentially select the path with higher thermal conductivity. The transmitting direction of heat flow in plain woven composite will be changed and easily induced to fiber orientation direction. The state of yarns in plain woven preform is buckling with fiber inclination angle θ , which will lead to the thermal conductive capability of plain woven composite worse than 0° UD lamina that has all straight fiber arrangements. Due to thermal conductivity along yarn axial direction is larger than that along yarn radial direction, the thermal conduction ability of plain woven composites is better than that of 90° UD lamina. As an example of meso-scale plain woven preform unit-cell in Fig. 20, except the yarn regions, there are also other two regions, i.e. the bridge regions and

the resin-rich regions, which have a significant influence on thermal conduction of plain woven composites. Bridge regions promote the heat flow forward, while resin-rich regions hinder the heat flow movement. These mechanisms lead to the thermal conductivities of plain woven composites falling in between those of 0° UD lamina (upper bound) and those of 90° UD lamina (lower bound). Table 6 and Fig. 21 show the comparative results for thermal conductivities of plain woven composites and UD lamina.

If the 0° and 90° UD lamina are stacked together, they seem a bit similar with plain woven composites. Therefore, the plain woven composites could be simplified as the combinations of UD lamina. Fig. 22(a) shows the decomposition scheme of meso-scale plain woven unit-cell model. Then the thermal conductivities could be calculated from this equivalent model. Fig. 22(b) compares the thermal conductivities between FEA and the decomposition model, which shows a good agreement. Because the characterization of the thermal conductivity of UD lamina is relatively easier than that of other complex 3D structure composites, therefore, the thermal conductive behaviors of the complex structure composites (just as the plain woven composites reported in this paper) could be simplified as the combinations of the UD lamina.

5. Conclusions

In this paper, the thermal conductivities of carbon fiber/epoxy resin plain woven composites were tested both along in-plane and out-of-plane directions. In addition, the multi-scale finite element analyses were established for analyzing its thermal conduction behaviors. The main findings of this paper are listed as follows:

- (1) The self-designed thermal chamber can effectively measure the thermal conductivities of plain woven composites and UD lamina, and the measuring experimental results show a good agreement with those from the standard instrument DZDR-S.
- (2) The thermal conductivities of plain woven composites in the three orthogonal directions show obvious anisotropic characteristics. The thermal conduction along fiber axial direction is better than that along fiber radial direction and the thermal conductivity along in-plane direction is higher than that of out-of-plane (thickness) direction.
- (3) Because the specific interior geometry structure of plain woven fabrics, the thermal conductivities of plain woven composites fall in between those of 0° UD lamina and those of 90° UD lamina,

where the thermal conductivity of 0° UD lamina is its upper bound and that of 90° UD lamina is its lower bound. The temperature distributions and heat flow transferring paths showed a noticeable trend along fibers' orientation directions.

- (4) A decomposition model from the UD laminas for the meso-scale plain woven composite unit-cell based on its microstructures was developed to show the feasibility of predicting the thermal conductivities of complex 3D textile structure composites.

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Table 1 Thermal parameters 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)		
		$\lambda_{\parallel}$	$\lambda_{\perp}$	
Carbon fiber (T700S-12K)	1.8	10.2	1.256	750
Epoxy resin (JC-02A)	1.13	0.18	0.18	1200

Table 2 Sizes of plain woven composites and unidirectional (UD) lamina.

Samples	plain woven composites		Unidirectional (UD) lamina	
	In-plane	Out-of-plane	In-plane	Out-of-plane
layers	4	12	8	24
Size (mm) (length×width×thickness)	40×40×6	20×20×12	40×40×6	20×20×12

Table 3 Specifications of yarn and unit cell in plain woven composites

Yarn (fill and warp are the same) (mm)					Unit cell (mm)			
long axis a	short axis b	yarn spacing	V_f	V_y	length d	Width d	Thickness h	V_{fy}
1.8	0.2	0.4	32.56%	43.25%	8	8	1	75.3%

Table 4 Meshing schemes for full-scale plain woven composite models.

Layers	Yarn			Epoxy resin		
	Seed size	Elements	Nodes	Seed size	Elements	Nodes
One layer(in-plane)	0.35	9600	22032	0.55	51095	95413
4-layer (in-plane)	0.8	2624×4	22032×4	0.55	250063	3288128
12-layer (out-of-plane)	0.6	1080×12	2688×12	0.6	142940	27216

Table 5 Thermal conductivities of the yarns at room temperature (25°C).

Model	Axial thermal conductivity	Transverse thermal conductivity
	$\lambda_{ya} = \lambda_{11}$ (W m ⁻¹ K ⁻¹)	$\lambda_{yt} = \lambda_{22} = \lambda_{33}$ (W m ⁻¹ K ⁻¹)
Parallel model	6.582	—
Series model	—	0.375
Charles model [31]	—	0.518
Pilling model [32]	—	0.471
Periodic RVE model	6.843	0.493

Table 6 Comparisons of thermal conductivities of plain woven laminated composite and UD lamina at 80 °C

Material	V_f (%)	Direction	Experimental (W m ⁻¹ K ⁻¹)	FEA (W m ⁻¹ K ⁻¹)	Deviation (%)
Plain woven laminated composites	32.56	In-plane (λ_{xx})	5.8±0.08	5.6	2.3
		In-plane (λ_{yy})	4.3±0.05	4.2	1.3
		Out-of-plane (λ_{zz})	2.9±0.12	2.7	5
Unidirectional (UD) lamina	32.585	In-plane (λ_{xx})	6.1±0.06	6.1	2.3
		In-plane (λ_{yy})	1.2±0.14	1.2	4
		Out-of-plane (λ_{zz})	1.2±0.22	1.2	1.5

Fig.1. Sketch of thermal conductivity measuring devices: (a) in-plane direction measurement; (b) out-of-plane direction measurement.

Fig.2. Photographs of specimens for thermal conductive measurements: (a) plain woven laminated composites; (b) unidirectional (UD) lamina.

Fig.3. Schematic diagrams of thermal conductivity measurement of plain woven composites: (a) measurement of the in-plane direction from the perspective of xy plane; (b) measurement of the out-of-plane direction from the perspective of xz plane; (c) principle of measurement of out-of-plane direction.

Fig.4. Specimens for thermal conductivity measurements 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 along fiber radial direction.

(c)

(d)

Fig.5. Measurements of interface thermal contact resistance and interface thermal conductivity of UD lamina: (a) along fiber axial direction; (b) along fiber radial (perpendicular to fiber axial) direction; (c) temperature distributions at the loading temperature of 80 °C; (d) interface contact thermal resistance and thermal conductivity at different temperatures.

(a)

(b)

Fig.6. Calculation of air convection heat transfer coefficient: (a) equilibrium heat flux principle; (b) heat transfer coefficient as function of temperatures.

Fig.7. Schematic diagram of micro-scale unit-cell model: (a) yarn's model; (b) selected micro-scale unit-cell model from yarn.

Fig.8. Meso-scale unit-cell model of plain woven composite: (a) cross-section of meso-scale plain woven unit-cell model; (b) schematic diagram of meso-scale plain woven unit-cell model.

Fig.9. Boundary conditions used in this paper: (a) periodic temperature boundary conditions; (b) macro boundary condition for in-plane loading; (c) macro boundary condition for out-of-plane loading.

Fig.10. Supplementary experiments for measuring the thermal conductivity of plain woven composites.

(a)

(b)

Fig.11. 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.

(a)

(b)

Fig.12. Thermal conduction behaviors of carbon fiber tow (yarn): (a) temperature distributions of yarn in three local coordinate directions; (b) thermal conductivity vs. temperature curves in three local coordinate directions. (Notes: 11, 22 and 33 refer to yarn axial, yarn radial and thickness directions, respectively.)

(a)

(b)

(c)

(d)

Fig.13. Thermal conduction behaviors of the four-layer plain woven composite model along the in-plane direction: (a) graph of temperature distributions; (b) graph of heat flow transmitting paths; (c) transient temperature distributions along fiber axial direction; (d) transient temperature distribution along fiber radial direction. (Resin was removed for better vision)

Fig.14. Temperature distributions of plain woven fabric and resin in one-layer full-scale plain woven composite model

(c)

Fig.15. Thermal conduction behaviors of 12-layer plain woven composites along the out-of-plane direction: (a) graphic of temperature distributions and heat flow transmitting paths; (b) temperature distributions of yarns; (c) temperature distributions of epoxy resin.

Fig.16. Temperature distribution of the 6th layer fabric in 12-layer woven composites. (Notes: 11 and 22 are the yarn's axial direction and radial direction in the local coordinate system, respectively.)

Fig.17. Temperature distributions of epoxy resin in different areas.

(a) in-plane direction

(b) out-of-plane direction

Fig.18. Temperature vs. time curves of full-scale plain woven composite models.

Fig.19. Comparisons of thermal conduction behaviors between plain woven composite and UD lamina:
(a) temperature distributions; (b) heat flow transmitting pathways.

Fig.20. Meso-scale plain woven unit-cell model

Fig.21. Comparisons of the thermal conductivities between plain woven composite and UD lamina at different temperature points.

(a) Decomposition of meso-scale plain woven unit-cell model

(b) Comparisons of thermal conductivities of plain woven composites between the two models

Fig.22. Equivalent decomposition model of plain woven composites.