THE EFFECT OF PLY SCHEME ON THERMAL CONDUCTION OF FIBER REINFORCED POLYMER COMPOSITES

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ABSTRACT

The rapid increasing of heat load in aircraft and spacecraft has attracted more and more attention on highly conductive carbon fiber reinforced polymer composite. The anisotropic feature of fiber reinforced polymer composite caused great differences of heat dissipation along different in-plane directions. The reasonable ply scheme may greatly improve heat transfer efficiency. This paper investigated the heat transfer process of carbon fiber reinforced composite by finite element mode. The results showed that the composite with a ply scheme of [-45/+45/0] showed more uniform temperature field than unidirectional composite. Moreover, the dissipation process of PAN-based carbon fiber, pitch-based carbon fiber and their hybrid composite were compared. It was found that the addition of quasi-isotropic highly conductive layer on the surface was an efficient method to enhance thermal conductive property of unidirectional fiber reinforced polymer.

1 INTRODUCTION

Carbon fiber reinforced polymer composite as structural material possesses many advantages, such as excellent mechanical property, lightweight, designability, multifunctionality [1-5]. With the rapid increasing of heat load in airplane and satellite, thermal management of structural material has taken more and more attentions [6, 7]. PAN-based carbon fiber is one of the most widely used reinforcement. The poor thermal conductivity of PAN-based fiber composite restricts its application [8]. Enhancing the thermal conductivity of traditional carbon fiber reinforced polymer composite has become the key for thermal management in the field of aeronautics and astronautics.

Y. A. Kim *et al* applied 7 wt% CNTs to establish heat transfer path between carbon fibers to improve the thermal conductivity of final composite from 250 W/mK to 393W/mK [9]. D.D.L. Chung e*t al*, investigated the effect of pressure and thermal conductive filler on through-thickness thermal conductivity of fiber reinforced polymer. It was found that enhancing curing pressure from 0.1 MPa to 2 MPa, the through-thickness thermal conductivity would increase 60% [10]. Robitaille *et al*, designed a simulative model to predict in-plane and through-thickness thermal conductivity. The results suggested that the enormous influence of ply structure on thermal conductivity [11].

Ply scheme as an important structural design influences enormously the anisotropy of fiber reinforced polymer including anisotropic thermal conductivity. In this research, the effect of ply scheme on thermal conduction property of fiber reinforced polymer composite was investigated by characterizing in-plane temperature distribution by both experiment and simulation. A hybrid structure was developed to improve thermal conduction property of PAN-based fiber reinforced polymer composite.

2 EXPERIMENTS

2.1 MATERIAL PROPERTIES

Carbon fiber XN-90-60S was produced by Nippon Graphite Fiber Corporation, with axial thermal conductivity 500W/mK and radial thermal conductivity 10 W/mK (hardly to be measured and influenced the thermal conductivity) [12, 13]. Epoxy resin AG80 was produced by Shanghai Research Institute of Synthetic Resins. Al_2O_3 disk was used as heat source with diameter and thickness of 20 mm and 1.26 mm, respectively. This ceramic disk has thermal conductivity of 27.5 W/mK, density of 3.6 g/cm^3, specific heat capacity of 0.6 J/gK. The built-in resistor had resistance of 9.6 Ω.

2.2 PREPARATION OFCARBON FIBER REINFORCED POLYMER LAMINATES

Carbon fiber prepreg was prepared using solvent dip process. Prepreg was laid up in the stacking-sequence of $[0]_9$ and [-45/+45/0].The assembly was placed in autoclave and cured with the schedule of 45 ℃/1h +90 ℃/1h +115 ℃/0.5MPa/1h +150 ℃/0.5MPa/1h +177 ℃/0.5MPa/3h. The thickness of final laminates with stacking-sequence of $[0]_9$ and [-45/+45/0] were 1.26 mm and 0.42 mm, respectively.

2.3 CHARACTERIZATION OF TEMPERATURE FIELD IN COMPOSITE LAMINATE

Central area of composite laminate was polished. Heat source was bonded on laminate surface at the central area firmly by thermal adhesive to avoid contact thermal resistance between heat source and laminate. K-type thermocouples were set on the laminate surface, the locations of which were shown in figure 1 and 2. The number represented the sequence of K-type thermocouples, and the round area at the center represented heat source. Heat source was applied with 0.51 A current to generate 5 W heat power. The temperature was recorded by Data logging devices. Experiment was conducted at ambient temperature (295K), and convection coefficient between laminates and environment was measured to be about 10 W/m^2K.

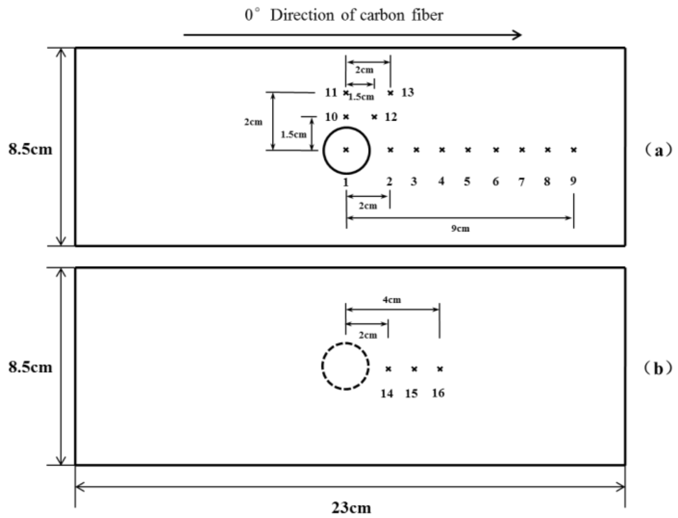

Figure 1: Location of thermocouples in [0 °]$_9$ laminate: (a) front surface and (b) back surface.

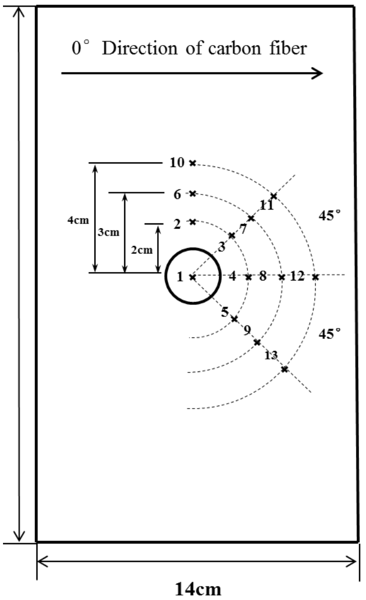

Figure 2: Location of thermocouples in [-45/+45/0] laminate.

Thermal conductivity of carbon fiber composite in the direction parallel and perpendicular to carbon fiber was measured by Netzscz LFA447. The sample specific heat was measured at nitrogen atmosphere by DSC (Mettler Toledo). The density was measured by ME104 Balance (Mettler Toledo) based on Archimedes law.

3 SIMULATION METHOD

The heat transfer simulation was conducted by Abaqus finite element package. Assumptions of FEM simulation was as follow. (1) Carbon fiber composite was simplified as homogeneous material. (2) Contact thermal resistance between heat source and laminate was negligible. (3) Thermal expansion and thermal stress was not taken into account. (4) The porosity of unidirectional CFRP was assumed to be zero.

Representative volume elements were designed according to real size of laminates and heat source. Thermal conductivity, specific heat capacity and density of composite were assigned to RVEs. The initial temperature of RVEs was set as 295 K, the same with environment temperature. Convection coefficient between laminates and environment was set as 10 W/m^{2}K. The power of heat source was set as 5 W. RVEs were meshed into DC3D6 grids. When the rate of grids with Tri-Face Corner Angle less than 5 ° was under 0.01%, and eccentric geometric factor of all grids was under 0.2, the simulative result were reliable. The temperature of RVEs was recorded until temperature of the whole RVEs reached balance when temperature change rate was less than 10^{-3} K/s.

4 RESULTS AND DISCUSSION

Table 1 lists the properties of XN-90-60S carbon fiber reinforced composite. Fig. 3 shows the temperature variation with time for unidirectional composite. It was found that simulative results agreed well with experimental values. At first 150 s, the temperature enhanced rapidly with time. Then the temperature slowly increased till temperature balance at about 500 s. By comparing the temperature gradient in Fig. 3(a) and (c), the temperature gradient in the parallel direction to carbon fiber was close to 10 K/m, which was less than the perpendicular direction of 1000 K/m. Therefore, heat conduction in the parallel direction was much faster than perpendicular direction. The same phenomenon was revealed in Fig. 4. According to Fig. 3(e), the temperature difference between top and bottom surfaces was less than 1 K which meant rapid thermal conduction through thickness direction.

Thermal conductivity (W/mK)		Specific heat	Density
parallel	perpendicular	(J/gK)	(g/cm^3)
373	0.92	0.78	1.80

Table 1: characterization of XN-90-60S carbon fiber reinforced polymer.

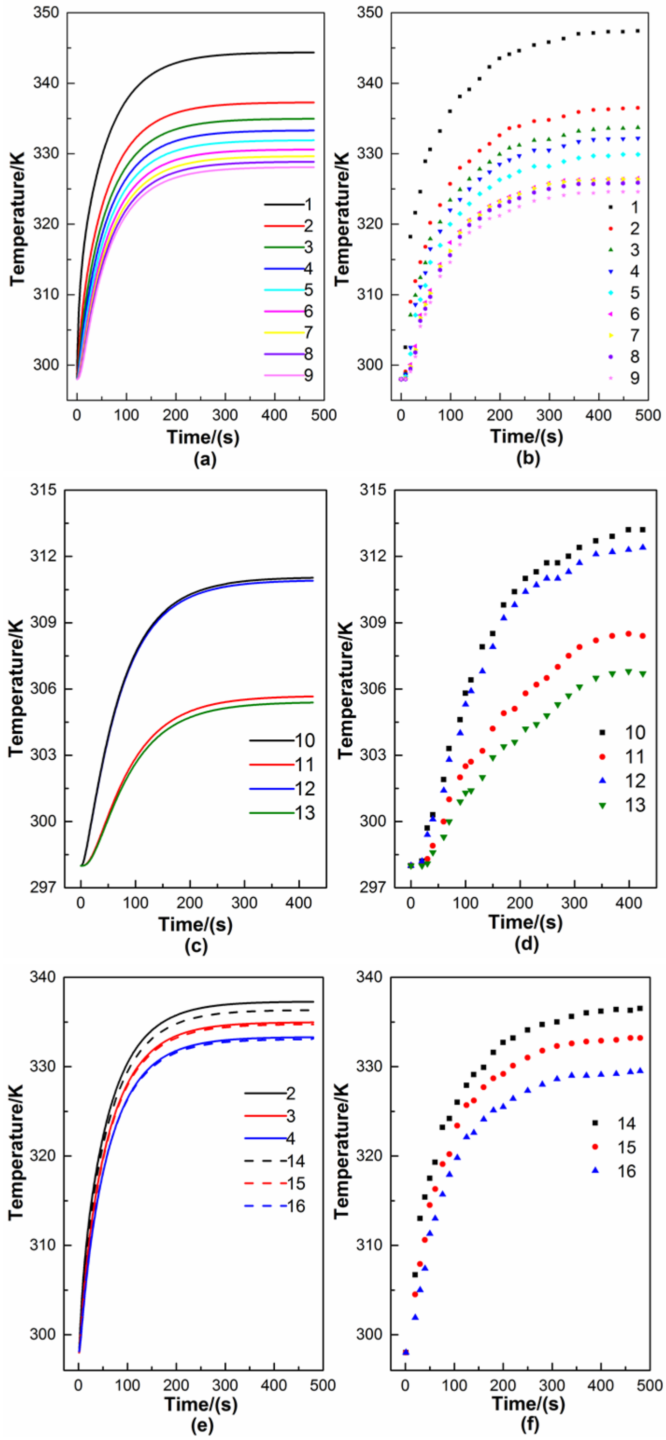

Figure 3: The variation of temperature versus time in the different locations of unidirectional composite: (a), (c), (e) simulative results and (b), (d), (f) experimental results.

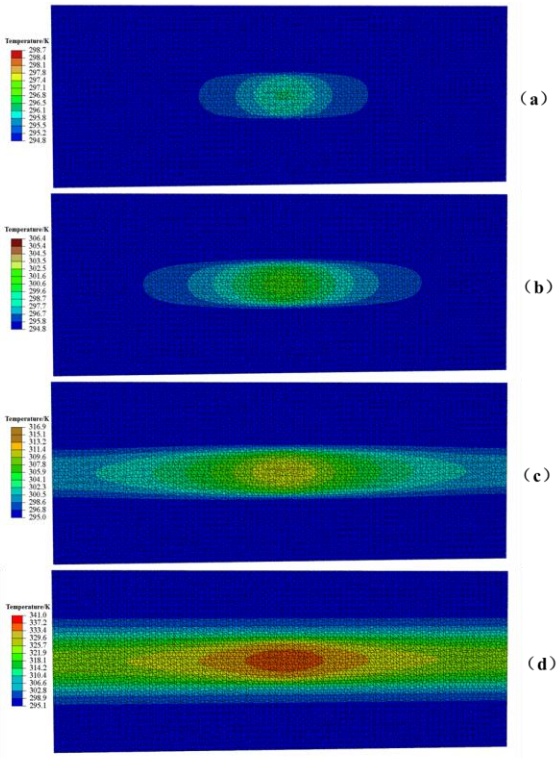

Figure 4: The heat conduction process of unidirectional composite; (a)~(d) 1 s, 5 s, 20 s, 300 s.

The effect of ply scheme on thermal conduction of fiber reinforced composite was investigated by comparing temperature distribution of unidirectional laminate $[0]_9$ and [-45/+45/0], as shown in Fig. 5. It was found that the composite with a ply scheme of [-45/+45/0] showed more uniform temperature field than unidirectional composite. When the temperature reached equilibrium, the temperature of heat source area in unidirectional composite was measured to be at 341.0 K as shown in Fig. 5 (a). The [-45/+45/0] composite showed the highest temperature of 328.3 K as shown in Fig. 5 (b). This indicated that the heat dissipation of non-unidirectional composites was faster than unidirectional laminate. The simulation showed that heat conduction mainly occurred along the axial direction of carbon fiber in different plies, e.g. 0°, 45°, -45° for composite [-45/+45/0], as shown in Fig. 6.

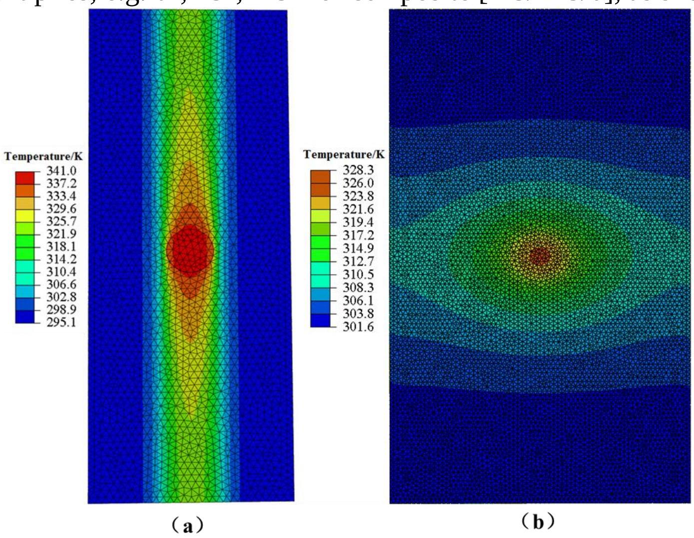

Figure 5: Temperature fields of (a) $[0]_9$; (b) [-45, +45, 0].

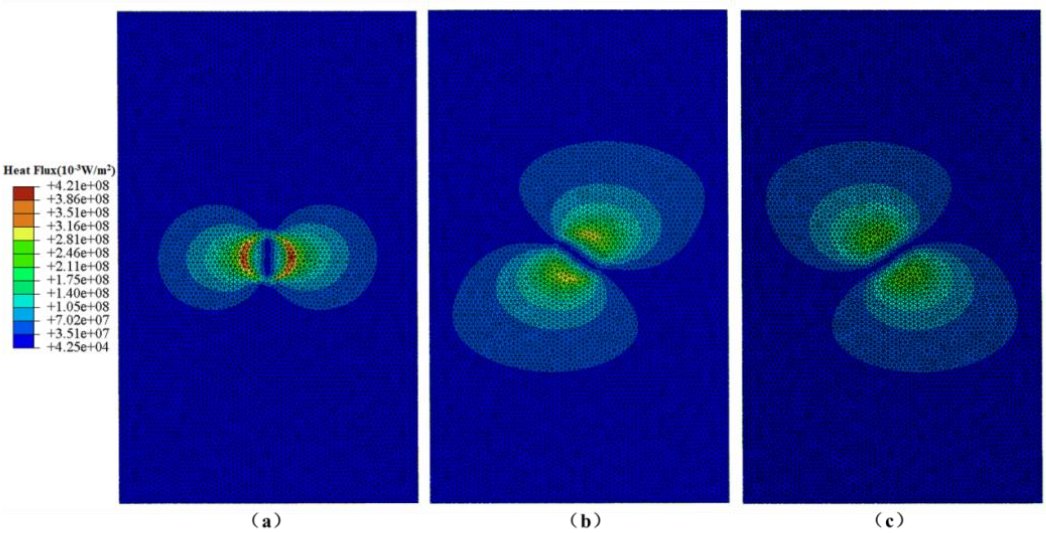

Figure 6: Heat flux of [-45, +45, 0] in three laminates, respectively.

The high cost and brittleness of pitch-based carbon fiber constrained its application. In order to combine the mechanical advantage of PAN-based fiber with highly conduction of pitch-based fiber, to hybrid a few layers of pitch-based fibers with PAN-based fibers had taken more and more attentions. We stimulated the dissipation processing of PAN-based carbon fiber reinforced composite (PAN-c), pitch-based carbon fiber reinforced composite (pitch-c) and hybrid composite (hybrid-c). PAN-c and pitch-c were unidirectional. For hybrid-c, the top three laminas were quasi-isotropic pitch-based carbon fiber reinforced composite and the rest laminas were unidirectional PAN-based carbon fiber reinforced composite. As shown in Fig. 7, the heat transfers along the axial direction of fiber in PAN-c and pitch-c. Because of high axial thermal conductivity of pitch-based fiber, the temperature distribution of pitch-c in axial direction is more uniform than PAN-c. However, hybrid-c shows the most uniform temperature distribution. The top three quasi-isotropic highly conductive layers make heat transferring rapidly in-plane. Moreover, heat source’s equilibrium temperature of hybrid-c was the lowest 317.3 K according to Fig. 8. Therefore, we concluded that the heat dissipation property of hybrid-c is the best. Further, adding quasi-isotropic pitch-based carbon fiber composite layer on the surface of unidirectional fiber reinforced composite was an efficient method to enhance thermal conductive property.

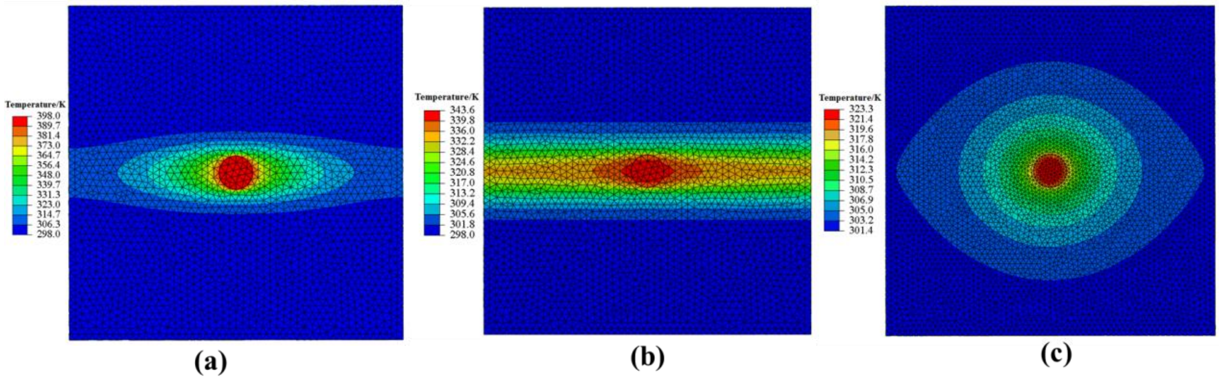

Figure 7: temperature fields of (a) PAN-c; (b) pitch-c; (c) hybrid-c.

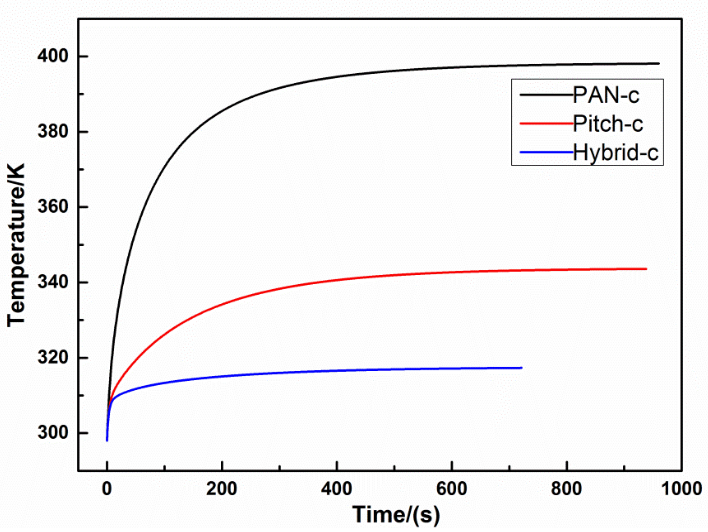

Figure 8: Temperatures of heat sources.

5 CONCLUSIONS

According to experiment and simulation, the heat conduction of fiber reinforced polymer in the parallel direction was much fast than perpendicular direction. Moreover, the temperature difference between top and bottom surfaces was not more than 1 K which meant rapid thermal conduction through thickness direction. By comparing temperature of heat source, the heat dissipation property of non-unidirectional composites was greater than unidirectional laminate. Further, a hybrid ply design was developed. Adding quasi-isotropic highly conductive layer on the surface of unidirectional fiber reinforced composite was an efficient method to enhance thermal conductive property.

ACKNOWLEDGEMENTS

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