Thermal conductivity of biomimetic leaf composite

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Abstract
The venous morphology of a typical plant leaf affects its mechanical and thermal properties. Such a material could be considered as a fiber reinforced composite structure where the veins and the rest of the leaf are considered as two materials having highly contrast mechanical and thermal properties. The variegated venations found in nature is idealized into three principal fibers—the central mid-fiber corresponding to the mid-rib, straight parallel secondary fibers attached to the mid-fiber representing the secondary veins, and then another set of parallel fibers emanating from the secondary fibers mimicking the tertiary veins of a typical leaf. This paper addresses the in-plane thermal conductivity of such a composite by considering such a venous fiber morphology embedded in a matrix material. We have considered two cases, fibers having either higher or lower conductivity respect to the matrix. The tertiary fibers do not interconnect the secondary fibers in our present study. We carry out finite element based computational investigation of the thermal conductivity of these composites under uniaxial thermal gradients and study the effect of different fiber architectures. To this end, we use two broad types of architectures both having similar central main fiber but differing in either having only secondary fibers or additional tertiary fibers. The fiber and matrix volume fractions are kept constant and a comparative parametric study is carried out by varying the inclination of the secondary fibers. We find the heat conductivity in the direction of the main fiber (Y direction) increases significantly as the fiber angle of the secondary increases. Furthermore, for composite with metal fibers, the conductivity in the Y direction is further enhanced when composite is manufactured by having secondary fibers forming a closed cell structure. However, for composite with ceramic fibers, the conductivity of the composite in the Y direction is little affected by having secondary fibers closed. An opposite behavior is observed when considering conductivity of the composite in the X direction. The conductivity of the composite in the X direction is reduced with increase in the angle of the secondary fibers. Higher conductivity in the X direction is achieved for composite with no closed cells for composites with metal fibers. The results also indicate that for composites with the constant fiber volume fraction, morphology of tertiary fibers may not significantly alter material conductivities. In conclusion, introducing a leaf-mimicking topology in fiber architecture can provide significant additional degrees of tunability in design of these composite structures.

Keywords
Thermal conductivity, venous morphology, mechanical and thermal properties, composite structure, finite element

Introduction
The structure of the leaf can be tremendously variegated both in function and morphology. At the broadest structural scale, the venation typically consists of a main fiber (or a midrib), which holds the leaf in contact with the rest of the tree structure and the many secondary veins emanating from it which can further support tertiary veins attached to them as illustrated in Figure 1. Understanding the mechanical and thermal properties of leaf-like structures is an exciting area of
research due to the extreme variety in both function and morphology. Among a variety of morphological traits that distinguish leaves, the venation patterns can be both strikingly different while simultaneously preserving broad universality in their organization making them an important variable in explaining certain aspects of leaf variations. One of the most important functions of leaf is conversion of solar irradiation into chemical energy utilizing photosynthesis. Thus, harnessing sunlight is a chief function of a leaf. However, this can also become a source for unwanted heating of the leaf thereby causing mechanical damage or impeding the photosynthesis process. Several mechanisms exist to alleviate the thermal load on the leaf such as long-wave radiation, heat convection into the air and transpiration. These principal mechanisms of heat transfer depend on the venation pattern either directly through leaf hydraulics or indirectly in conjunction with overall leaf shapes in influencing the boundary layer for convection. In contrast, conduction is not typically considered an important component in thermal management of leaves. This is primarily because of the inherently poor thermal conductivity of organic leaf materials. However, considering the topical similarities between the hydraulics and heat transfer processes (e.g. Poiseuille’s and Fourier’s law), replacing the hydraulically optimized leaf venation with thermally conducting materials for a synthetic design offers an exciting new avenue of bio-inspired design.

To this end, we envision, from a material point of view, this veins-leaf morphology as a two-phase high contrast composite. Traditional composite materials have found widespread use for improving cost, weight, size, surface condition, strength, thermal and electrical conduction, etc. In this context, leaf-like biomimetic composites can serve an important template for thermal material design especially since by changing the arrangements of the fibers, the properties of the material can be tailored to meet the requirements of a specific application. In addition, leaf-like composite can be used in the design of various sensors by properly controlling temperature of various veins.

In spite of this promising avenue of design, to the best knowledge of the authors, no prior work on this subject has been done although mechanical analogs have been investigated in some earlier work. In this paper, we examine the effect of different vein topologies on the thermal conductivity of the biomimetic leaf composite using finite element (FE)-based computational investigation on 3D models. The computational models are used to carry out extensive parametric studies on the effect of fiber architecture and their angular configuration. We use two broad geometrical classes of fiber organization—one with only secondary fibers and the other including tertiary fibers. Within each class, we vary the fiber topologies while keeping the volume fraction of fibers and matrix phases constant for comparisons.

Computational model

Computational analysis is carried out using a commercially available FE software ABAQUS® (Dassault Systemes). The leaf veins and the surrounding matrix are alternatively selected as metal and ceramic to compare the conductivities of two sets of material combinations. The thermal conductivity of the metallic material is taken as 401 \( \text{W/(mK)} \) (close to copper) and that of ceramic is taken as 25 \( \text{W/(mK)} \) (close to aluminum oxide). Thus these two materials provide us with two high contrast phases of the composite.

Heat conductivity calculation

There are several ways in which effective conductivity can be calculated for composites. In this paper, we use a simple method, which can be directly used with a commercial FE software. The effective Heat conductivity of the whole structure, \( k \) can be related to the heat flux and thermal gradient using Fourier’s Law, which is expressed as

\[
q'' = -k \nabla T
\]
where $q''$ is the heat flux vector and $T$ is the temperature field inside the structure. For the purpose of our calculations, we choose a square domain of side $L = 100\text{cm}$ and orient the $y$-axis in the direction of the main fiber, Figure 2. In order to compute heat conductivity in either directions, we set temperature boundary conditions on opposite sides, whereas the lateral sides are assumed to be insulated. This setup for $Y$-direction conductivity calculation is depicted in Figure 2, where the temperatures on the top and bottom boundaries are fixed at $T_1 = 500\ K$, $T_2 = 400\ K$ while the remaining boundaries are assumed to be insulated. Same temperatures are set for the $X$-direction calculation but the temperature and insulating boundaries are now exchanged. Assuming a uniform temperature gradient, the heat equation can be simplified as

$$q'' = -k \frac{T_2 - T_1}{L} \tag{2}$$

Since $L = 100\text{cm}$ and $T_2 - T_1 = -100$ for either directions, equation (2) can be used to directly calculate the effective conductivity using the following equation

$$q'' = k \tag{3}$$

Therefore, by simply calculating the heat flux under the applied boundary conditions, we can directly determine the effective conductivity of the composite.

In order to make sure our numerical simulations result in a reliable data, conductivity of multilayer composite was evaluated in the direction normal to the layers using the same methodologies as those used for evaluating conductivity in the leaf composites. Our numerical simulation results were in agreement with those obtained from the classical conductivity evaluation of multilayer composite, equation (4).

$$\frac{1}{k_{\text{eff}}} = \frac{V_1}{k_1} + \frac{V_2}{k_2} \tag{4}$$

where $V_1$ and $V_2$ are the volume fraction of each layer in the composite and $k_1$ and $k_2$ are conductivity of each layer and $k_{\text{eff}}$ is the composite conductivity.

We also considered the effect of mesh size on the evaluated thermal conductivities. There was a little change on the evaluated leaf composite thermal conductivities for element size less than 3 mm. We used element size of 1.5 mm in all simulations.

**Results and discussions**

In this section, we use our computational model to compute the effective thermal conductivity of biomimetic leaf-like composite structures. Two broad types of leaf structures are considered. The first type is leaf composites with only secondary fibers. In this broad class, we consider four types of fiber architecture. For the

![Figure 2. Imposed boundary conditions in the X and Y directions of biomimetic leaf composite material and multilayer verification model.](image)
second class of composites, we introduce tertiary fibers and consider six different architectures. In both cases, we study the evolution of material thermal properties with different fiber angles and compare the results. For these fully 3D models, we keep the diameter of the main fiber constant at 1.4 cm and the total leaf-like composite dimensions at 100 cm × 100 cm × 1 cm. The fiber volume fraction for all simulations is kept constant at 30%. This research aims at understanding the effects of fiber morphologies on the composite thermal conductivities. No exhaustive efforts are made to understand the effects of fiber volume fraction on the thermal properties of these composites.

**Biomimetic leaf composite with only secondary fibers**

In this case, we consider a composite with 46 secondary fibers. The diameter of main fiber is kept constant for all of simulations, as shown in Figure 3. We denote the angle between secondary fiber and matrix boundary by \( \theta \), as shown in Figure 3. Note that these secondary fibers may be connected to each other through transverse auxiliary fibers parallel to the mid rib resulting in close-cell architecture as shown in Figure 3. Within this broad class of fiber geometry, four distinct geometrical organizations are studied as shown in Figure 4, which differ from each other in the number of closed cells thus formed through these auxiliary fibers. Note that, as the angle of the secondary fibers is changed, or newer auxiliary fibers are introduced, the diameter of the secondary fibers is adjusted to keep the fiber volume fraction constant at 30%.

We first investigate the variation of conductivities with changing angle of the secondary fibers for a composite with metallic fibers and ceramic matrix.

Figure 5(a) shows the variation of Y-direction conductivity \( (k_Y) \) with angle \( \theta \). It is clear that increasing angle leads to an increase in the overall thermal conductivity of the composite for all architectures within this class of geometry. This can be explained by observing the change in the geometry of the composite with increasing angle as seen in Figures 3 and 4. As more and more fibers begin to orient themselves towards the direction of temperature gradient, the amount of heat flux also increases due to the higher conductivity of the metallic fibers. This phenomenon is observed across the different fiber architectures and thus an increase in fiber angle leads to a universal gain in thermal conductivity with increasing angle. Furthermore, for this type of composites with metallic fibers, the thermal conductivity of the composites is enhanced by having closed cell secondary fibers, Figures 4 and 5(a). Surprisingly, this monotonic increase in thermal conductivity with increase in fiber angle is also found when the materials are switched as shown in Figure 5(b), which shows the variation of \( k_Y \) with increasing \( \theta \) for a ceramic fiber and metal matrix composite. This somewhat counterintuitive result can be explained by first noting that, in this type of composite, the matrix material is now the primary conductor of heat with the ceramic fibers acting as thermal barriers for heat flow. Thus when the fibers are completely transverse to the temperature gradient \((\theta = 0^\circ)\), they are more effective in thermal impedance than when they are fully aligned with the temperature gradient, which provides conducting channels for thermal transport. Thus, as the angles of the fibers increase, the thermal conductivity steadily improves due to decreasing effectiveness of the ceramic fiber thermal barriers and also increased exposed volume of metallic matrix at the sides of the fibers as seen in Figures 3 and 4. Thus highest heat conductivity is observed at the highest angles of fibers at \( \theta = 50^\circ \). Note that since the volume fraction of the fibers is kept constant at 30%, the overall conductivity of the composite is now much higher than the previous case. Unlike the previous case, here the difference in \( k_Y \) between the various cell architectures is minimal. This is because in this case the effective conductivity is mostly affected by the matrix with volume fraction of 70%. Thus, the arrangement of fibers has little contribution, Figure 5(b).

Figure 5(c) shows the variation of effective heat conductivity in X direction \( (k_X) \) with \( \theta \) for the metallic fiber and ceramic matrix composite. The results show that \( k_X \) decreased with increase in \( \theta \). This is clearly opposite to the trend in \( k_Y \). This decrease is attributed to the fact that since heat conduction occurs primarily through the fibers, with the matrix acting as a barrier to heat flow. Figure 4 shows that for the extreme case of \( \theta = 0^\circ \), the fibers traverse the entire span of the composite providing conducting channel for the heat flow from one end.
Figure 4. ABAQUS model with $\theta = 50$. (a) Without closed cell, (b) one closed cell model, (c) two closed cells model, and (d) three closed cells model.

Figure 5. Thermal conductivity of leaf-like composites with different fiber arrangements. (a) Y direction conductivity, fiber as copper, matrix as ceramic; (b) Y direction conductivity, fiber as ceramic, matrix as copper; (c) X direction conductivity, fiber as copper, matrix as ceramic; (d) X direction conductivity, fiber as ceramic, matrix as copper.
to another, thereby resulting in high $k_X$. As the angle increases, the diameter of secondary fibers decreases to maintain a constant volume fraction of constituents since the length of fibers increase. Thus, increasing the angle would have a net negative implication on the conductivity of the composite as confirmed in Figure 5(c). Furthermore, ceramic matrix provides greater thermal barrier to the heat flow in the X direction. The results also show that the thermal conductivity of the composite is adversely affected by increasing the number of closed cells at a given secondary fiber angle. The auxiliary fibers have no appreciable effect on the heat transfer in the X direction. However, their introduction results in a decrease in the secondary fiber diameter, which are the main mechanism of heat transfer in the X direction. The detail of Fiber dimensions are provided in Table 1.

This decreasing trend in $k_X$ is also mirrored when the phases of the composite are switched resulting in a ceramic fiber, metal matrix composite. This trend also originates from the changing geometry of the composite with the angle. Since the ceramic fibers act as thermal barriers their effectiveness decreases at lower angles as they are relatively sparse. However, as the angle increases, they begin to bunch together thereby providing more effective resistance to heat transfer thereby lowering the thermal conductivity. Interestingly, in this case, the presence of the closed cell has little effect on the conductivity of the composite in the X direction, Figure 5(b) and (d).

In summary, we find that $k_Y$ improves with increasing fiber angles and presence of closed cell for composites with metal fiber and ceramic matrix. This is also true for composites with metal matrix and ceramic fibers. In contrast, the conductivity of the composites in the X direction for all composites is reduced with increase in fiber angles.

**Biomimetic leaf composite with tertiary fibers**

In this section, we considered the effect of tertiary fibers on the thermal conductivities of the leaf composite. The diameter of fibers has been kept constant at 1.4 cm and the overall dimensions of the composite remains the same as in the previous simulations. The fiber angle varies from 0 to up to 40° in order to prevent interactions between tertiary fibers at high angles. Overall, for this set of simulations, the model with open cells discussed in previous section (Figure 5(a)) was used as the basic structure, but tertiary fibers were added to the secondary fibers, as shown in Figure 6. To keep the

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<th>Table 1. Fiber dimensions used in Figures 4(a) to (d) to keep fiber volume fraction at 30%.</th>
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<td>Fiber type</td>
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Figure 6. Model with tertiary fibers.
volume fraction constant, the number of secondary fibers has been decreased from 46 to 30. The radius of tertiary fibers was set to match with that of secondary fibers, which was equal to 7 mm. The length of tertiary fibers was 20 mm. The size of mid fiber and overall dimensions were same as those in the previous section. A total of five types of tertiary fiber architectures are considered in this section as shown in Figure 7. These five types are (1) 14 tertiary fibers 20-mm long on one side of each secondary fiber, (2) 7 tertiary fibers 20-mm long alternating on both sides of each secondary fiber, (3) this tertiary fiber arrangements can be considered as set of two secondary fibers with the tertiary fiber pattern shown in Figure 7(c) and (d). Each secondary fiber had 7 tertiary fibers with length of 20 mm on both side at the same location. This pattern was repeated on the second secondary fiber in the set. However, tertiary fibers were shifted upward to prevent its interference with the tertiary fibers on the first secondary fiber. This set of secondary fibers were repeated through the structure of the composite and is called A and B repetition. The fourth- and fifth-tertiary fiber arrangements were the same as pattern (1) and (2) but with twice number of fibers of shorter length. This pattern was used to identify the effects of the number of tertiary fibers and fiber length on the thermal conductivities of the composite.

Figure 7. (a) First kind of tertiary fiber model, (b) second kind of tertiary fiber model, (c) third kind of tertiary fiber model, (d) fourth kind of tertiary fiber model, and (e) fifth kind of tertiary fiber model.

Figure 8. Thermal conductivity of composites with different tertiary fiber models. (0 ter: without tertiary fibers model; 1 ter: first kind of tertiary fiber model; 2 ter: second kind of tertiary fiber model; 3 ter: third kind of tertiary fiber model; 4 ter: fourth kind of tertiary fiber model; 5 ter: fifth kind of tertiary fiber model.) (a) Y direction conductivity, fiber as copper, matrix as ceramic; (b) Y direction conductivity, fiber as ceramic, matrix as copper; (c) X direction conductivity, fiber as copper, matrix as ceramic; (d) X direction conductivity, fiber as ceramic, matrix as copper.
Figure 8(a) shows the conductivity ($k_Y$) of the composites with various tertiary fibers and secondary fiber angles, $\theta$. The results show that for composites with metal fiber and ceramic matrix, the thermal conductivity in the Y direction is enhanced with the introduction of tertiary fibers. However, the results do not clearly demonstrate that tertiary fiber patterns themselves significantly affect the thermal conductivity of the composite in the Y direction. The results may indicate that numerous tertiary fibers have more pronounced effect on the thermal conductivity of the composite in the Y direction. A similar conclusion may not be possible for conductivity of these composites in the X direction. The results suggest that introducing tertiary fiber reduces the volume fraction of the secondary fibers, which are the main mechanism of heat transfer in the X direction for composite with metal fibers and ceramic matrix. This may reduce the overall conductivity of the composite in the X direction, Figure 8(c). For composites with ceramic fibers and copper matrix, both secondary and tertiary fibers introduce thermal barriers in the X direction thus reducing thermal conductivity in the X direction with increase in the secondary fiber angle, Figure 8(d).

In order to understand the effects of tertiary fibers on the overall thermal conductivity of these class of composites, temperature distribution along Y directions for several composites with different fiber architectures were evaluated. Figure 9(a) and (b) shows temperature distribution for composites with 0° secondary fibers and composite with 0° secondary fibers but having also the fifth-type tertiary fiber as well. The results show for these class of composites, temperature distribution is uniform in the X direction and the tertiary fibers have little effect on the temperature distribution. Temperature distributions in composites with 50° secondary fibers with and without tertiary fibers are shown in Figure 9(c) and (d). The results show

![Figure 9](image.png)

**Figure 9.** Temperature distribution in composites with secondary fibers and with or without tertiary fibers. In all composites, fiber as copper, matrix as ceramic. (a) Basic model with 0° secondary fibers; (b) composites with 0° secondary fibers and fifth-type tertiary fibers; (c) composites with 50° secondary fibers; (d) composites with 50° secondary fibers and fifth-type tertiary fibers.
the temperature distribution along X direction for these composites is not uniform and it follows the secondary fibers. These secondary fibers provide a channeling mechanism for transferring heat in the Y direction. Here again the tertiary fibers seem to have little effect on the overall temperature distribution in the composites.

**Conclusion**

In this paper, we study the thermal conductivity behavior of lamina-like biomimetic leaf composites in two orthogonal directions. The composite is envisioned from a naturally occurring leaf by idealizing the veins as fibers and the rest of the leaf as matrix material. Two materials with highly contrasted thermal conductivities were selected as fiber and matrix to study the overall thermal conductivities of these class of composites. The principal parameters investigated to this end are the role of materials combination, vein geometrical organization, and their numbers in affecting the thermal behavior. Using FE analysis, effective heat conductivity is calculated which reveal a pronounced effect of the angle and organization of secondary fibers in influencing the overall thermal conductivity in both directions. Surprisingly, thermal conductivity in the direction of the main fiber (equivalent to the mid-rib of a leaf) was found to increase substantially with increasing angle of the secondary fibers for either combination of the high contrast phases, whereas the opposite was true in the other direction. More interestingly, we discover that this general trend holds even when tertiary fibers are introduced proving the dominant role of the secondary fibers in governing the thermal conductivity behavior of this type of composites. Although the tertiary fibers failed to alter the overall trend dictated by the geometry of the secondary fibers, their role was nevertheless subtle and sufficient to distinguish the overall behavior of the two classes of composites (secondary fibers only and with tertiary fibers). It was also found that the secondary fibers provided a channeling mechanism to transfer heat in the Y direction. This resulted in non-uniform temperature distribution in the X direction. The presence of the tertiary fibers did not alter this temperature pattern in both directions. In conclusion, this current thermal investigation of this novel biomimetic composite structure opens up an important new avenue for the conception and design of more advanced two phase ceramic and metal matrix biomimetic composite systems.

**Declaration of Conflicting Interests**

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