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Thermal Conductivity Prediction of Short-Fiber Composites Using Micromechanical Modeling for Wing Spars, Ribs, And Stringers.

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Abstract- Thermal conductivity prediction of short-fiber composites for wing spars, ribs, and stringers is carried out using an epoxy matrix and glass fiber. Based on the study, the effects of fiber arrangement (aligned, partially aligned, and random) and their orientation angles (0^0, 45^0, 60^0) on thermal conductivity are analyzed. The Mori-Tanaka technique is adopted to determine the thermal effectiveness of the composite. The experimental validation is carried out using a guarded hot plate (ASTM C177) and laser flash (ASTM E1461) technique. The study's outcomes show that the thermal flow of the composite is significantly affected by the fiber arrangement and its orientation angle. The aligned composite shows the highest thermal conductivity of 0.52W/mK, and the random composite exhibits the lowest thermal conductivity of 0.37W/mK. The partially aligned composite with a 45° orientation has a thermal conductivity of 0.41W/mK. The predicted thermal conductivity values are in line with the experimental results, indicating the accuracy of the micromechanical model.

Keywords: Thermal Conductivity, Micromechanical modeling, Mori-Tanaka, Epoxy matrix, Glass fiber.

I. INTRODUCTION

Thermal conductivity prediction for short-fiber composites involves applying mathematical models and computational simulations to estimate the thermal performance of composite materials with short fibers embedded in a matrix. Thermal conductivity is the sum of a material's capability to transfer heat. It can also be stated as the measure of heat transferred through a unit surface area of a material per unit time, per unit temperature change between the two borders of the material. Thermal conductivity prediction analysis plays a vital role in enabling system designers and engineers to assess the thermal characteristics of composite materials across applications such as aerospace, automotive, and energy storage. It further assists in optimizing the design of composite materials and their structures to enhance thermal performance and efficiency, and to reduce thermal stresses. The study aims to design and analyze a reliable micromechanical modeling framework to predict the anisotropic thermal transport of short-fiber composite materials and to validate the results against experimental measurements. Objectives: To design and construct a 3-D RVE of short-fiber composites with controlled fiber orientation tensor, such as random, aligned, and partially-aligned. To determine the thermal conductivity tensor within an interval of fiber volume fractions, determine RVE results with analytical models, and perform experimental transfer tests to ensure its validation. To determine the value of the impact of fiber-matrix interfacial thermal Resistance and propose its correction factor. Significance of the study: Predicting the thermal conductivity of short-fiber-reinforced polymer (SFRP) using micromechanical modeling for wing spars, ribs, and stringers is significant in multiple ways: to improve thermal management, reduce thermal stresses, and ensure structural integrity. It enhanced structural integrity. To reduce weight, improve fuel efficiency, and reduce emissions. To increase reliability under various operating conditions. To reduce maintenance costs by reducing the risk of thermal-related problems. To improve safety by reducing the risk of thermal-related issues. To ensure a competitive advantage through efficient and reliable aircraft design. It saves time and resources by reducing the need for experimental testing. To optimize the design to improve thermal performance. To ensure that composite structures can withstand future operating conditions and demands

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II. LITERATURE REVIEW

Introduction: The following literature was reviewed under the study.

Zhang et al. (2021)[1] worked on a micromechanical model to predict thermal conductivity, focusing on fiber orientation, volume fraction, and interfacial resistance. Limitation: - Adopts perfect bonding among fibers and matrix. Gap:- The Interfacial thermal Resistance of the model was not justified. Wang et al. (2019)[2] developed a micromechanical model to predict thermal conductivity, accounting for interfacial thermal resistance and fiber orientation. Limitation:- Assumes a concept of uniform interfacial thermal resistance. Gap:- Needs to interpret the non-uniform interfacial thermal resistance models. Li et al. (2020)[3] developed a micromechanical model to predict thermal conductivity by accounting for fiber length distribution and orientation, aiming to develop accurate energy prediction models. Limitation:- Adopts uniform fiber length distribution. Gap: There is a need to account for non-uniform fiber-length distribution models. Wang et al. (2021)[4] developed a new micromechanical model to predict thermal conductivity by accounting for interphase effects and fiber orientation. Limitation:- Adopts uniform interphase properties. Gap:- There is a need to account for non-uniform interphase properties. Wang et al. (2020)[5] designed a micromechanical model to predict thermal conductivity by accounting for fiber-matrix interfacial thermal resistance and fiber orientation. Limitation:- Adopts uniform interfacial thermal resistance. Gap:- There is a need to account for non-uniform interfacial thermal resistance. Wang et al. (2021)[4] designed a micromechanical model to predict thermal conductivity by accounting for the fiber-matrix interphase and fiber orientation. Limitation:- Adopts uniform interphase properties. Gap:- There is a need to account for non-uniform interphase properties. Solution: - Integrate non-uniform interphase property models. Zhang et al. (2020)[6] designed a micromechanical model to predict thermal conductivity by accounting for the distributions of fiber orientation and volume fraction. Limitation:- Adopts uniform fiber orientation distribution. Gap: There is a need to account for non-uniform fiber-orientation distributions. Awode et al. (2024)[7] conducted a performance analysis of Hybrid Glass and Sisal Fiber-Reinforced Epoxy Matrix Composites for aircraft structures, focusing on the mechanical properties of hybrid composites made from sisal and glass fibers in epoxy resin to enhance tensile strength and reduce weight compared to pure glass fiber composites. Limitation: The research is limited to the effects of variations in fiber ratio on mechanical properties. Gaps: It requires further research into the durability and degradation of hybrid composites under environmental conditions, as well as their scalability and cost-effectiveness for aircraft structures. Emmanuel Imhanote Awode et al. (2024)[8] conducted research simulating the effects of lightning strikes on carbon fiber composites shielded with carbon nanotube sheets using numerical methods. Limitation: The accuracy of numerical methods depends on the assumptions and simplifications made, which do not fully capture real-world complexities. The availability of accurate material properties for carbon nanotube sheets and carbon fiber composites is limited, potentially affecting simulation accuracy. Scalability of the simulation is affected by larger or more complex structures. Gaps: It requires experimental validation of the simulation result to determine accuracy and reliability. There is limited research on the effects of environmental factors such as temperature and humidity on the performance of carbon fiber composites. It requires further research to optimize carbon nanotube sheet design and placement to improve lightning-strike protection. Anthony Yinka Oyerinde et al. (2025)[9] worked on computer-aided energy prediction for selected and blended wood biomass using ultimate and proximate analysis. The research focuses on predicting the energy potential of wood biomass using computer-aided models, aiming to develop accurate energy prediction models that support green energy applications, such as renewable energy. Limitation: The study is limited to a specific type of wood biomass and does not represent all biomass feedstocks. Model generalizability may not blend with other biomass types. Lack of experimental validation of the predicted energy values may affect their accuracy and reliability. The ultimate and proximate analysis data might be affected by various factors, thereby limiting the research accuracy of energy prediction. Gaps: Further research is needed to incorporate additional biomass types, such as agricultural residues and energy crops. It requires comparing different computer-aided models to identify the most accurate approach. It requires further investigation into the effects of environmental factors, e.g., temperature and humidity, on biomass energy potential.

III. METHODOLOGY, FINDINGS AND RESULT

Methodology

Governing equations of the Thermal Conductivity Analysis

The mathematical equation adopted to calculate and confirm the Effective Thermal Conductivity (K-eff) is the Halpin-Tsai equation. The model's orientation in which its effective thermal conductivity (K-eff) is to be determined is: orientation with 0^0, 45^0, 60^0 angles are aligned, partially-aligned, and random.

Equation

a. Parallel to fibers

Effective Thermal Conductivity = (Fiber Conductivity *Fiber Volume fraction) + (Matrix Conductivity * (1-Fiber Volume Fraction))

K-eff(parallel) = Kf*Vf + Km(1-Vf) --------------(Eqn.2.1)

b. Perpendicular to fibers

Effective Thermal Conductivity = (Fiber Conductivity * Matrix Conductivity) / (Matrix Conductivity * Fiber Volume Fraction + Fiber Conductivity * (1-Fiber Volume Fraction))

K-eff(perpendicular) = (Kf*Km)/(Km*Vf + Kf(1-Vf)) --(Eqn.2.2)

Kf = Fiber Thermal Conductivity (W/mK), Km = Matrix Thermal Conductivity (W/mK)

Vf = Fiber Volume Fraction (0 < f < 1), Kf = 1.0 W/mK, Km = 0.2 W/mK, Vf = 0.4.

Halpin–Tsai equation

Effective Thermal Conductivity = Matrix Conductivity * (1 + shape factor * E * Fiber Volume Fraction) / (1-E *Fiber Volume Fraction)

Shape factor (for Short-Fibers) (Xi)

XiL = 2*L/d (for Longitudinal), Xit = 2 (for transverse), L = Fiber length, d = Fiber diameter, orientation factor (f) = 0<f<1, f = 1; for Aligned, f = 0; for Random

K-eff.(Partially-Aligned) = f * K-eff.(parallel) + (1-f) * K-eff. (random) ----------------(Eqn.2.3)

Let f = 0.5

K-eff(random) = (parallel + 2 * perpendicular) / 3 -----(Eqn.2.4)

Effective Thermal Conductivity (random) = (parallel + 2 * perpendicular) / 3

K-eff.(random) = (K-eff.(parallel + 2 * K-eff.(perpendicular) / 3 ---------------------------(Eqn.2.5)

Equation (Tensor Transformation)

Effective Thermal Conductivity = (Parallel component * Cos^2(angle)) + (perpendicular component * Sin^2(angle))

K-eff.(angle) = (K-eff.(parallel) * Cos^2(angle)) + (K-eff.(perpendicular) * Sin^2(angle)---------Eqn.2.6)

Composite material system

The composite material system for the project consists of an epoxy matrix and glass fibers, with properties such as thermal conductivity, specific heat capacity, and density.

Table 1: Composite Material System

Material	Thermal Conductivity (W/Mk)	Specific Heat Capacity (J/KgK)	Density (Kg/m3)
Epoxy	0.2	1000	1200
Glass fiber	1.0	800	2500

Fiber Properties: Fiber Type: Glass fiber, Fiber diameter: 5-10 micrometers, Fiber length: 1-10mm, Fiber Volume Fraction: 30-60%. Matrix Properties: Matrix type: Epoxy, Matrix thermal conductivity: 0.1-0.5 W/mK. Interface Properties: Interface thermal resistance: 10^-4 – 10^-3 m2K/W. Computational Software: ANSYS.

A. SFRP modeling in ANSYS

Representative Volume Element (RVE) Generation

A 3D model of the short-fiber composite was created in ANSYS DesignModeler using an epoxy matrix and glass fibers. Mesh the Model: The 3D model was carefully meshed using the ANSYS meshing tool. This is to confirm that the mesh was sufficiently fine to capture the fiber-matrix interface. A tetrahedral mesh with 8-node elements, refined near fiber ends, was adopted.

Boundary conduction

Thermal boundary conditions: - Temperature and heat flux were all applied to the model. Periodic

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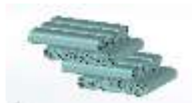
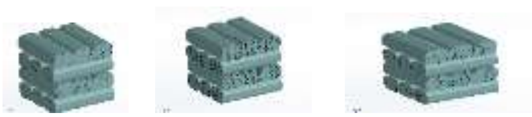
temperature difference, T = 9.98K across opposite faces. Run Simulation: A thermal simulation was performed using ANSYS Thermal to determine the temperature distribution and heat flux within the short-fiber composite. Post-Processing: The simulation



report for the composite's thermal conductivity was extracted using ANSYS Post-Processing. Homogenization: The homogenization methods were applied to predict the effective thermal conductivity (K-eff) of the short-fiber composite.

Models and orientation



Random (0^0) Fully Aligned (0^0) Partially-Aligned (0^0)
Random (60^0) Fully-Aligned (60^0) Partially-Aligned (60^0)

Random (45^0) Fully-Aligned (45^0) Partially-Aligned (45^0)
Figure 1: Model and orientation

Result and Discussion

This section presents the results and discussion of a simulation of thermal conductivity prediction for short-fiber composites using micromechanical modeling of wing spars, ribs, and stringers.

Table 2: Summary of Thermal Conductivity of orientation with 0^0 Angle

CONFIGURATION OF COMPOSITE	K-eff (W/mK)
Aligned (Parallel)	0.52
Aligned (Perpendicular)	0.29
Partially-Aligned	0.41
Random (3D)	0.37

Table 3: Summary of Thermal Conductivity of orientation with Angle 45^0

CONFIGURATION OF COMPOSITE	K-eff (W/mK)
Aligned (45^0)	0.41
Partially-Aligned (45^0)	0.39
Random (3D)	0.37 (Isotropic)

Table 4: Summary of Thermal Conductivity of

orientation with Angle 60^0

CONFIGURATION OF COMPOSITE	K-eff (W/mK)
Aligned (60^0)	0.35
Partially-Aligned (60^0)	0.36
Random (3D)	0.37 (Isotropic)

The thermal conductivity prediction of short-fiber composite for wing spars, ribs, and stringers was successfully performed using micromechanical modeling, with simulation results obtained and confirmed by mathematical analysis. Various fiber orientations and angles were chosen for the analysis to include aligned, partially aligned, and random arrangements, with angles of 0 °, 45 °, and 60 °. The simulation results and the mathematical analysis show that the thermal conductivity of the composite is significantly affected by the fiber orientation and angle.

Effect of fiber orientation

The results indicate that:- Orientation with a 0^0 angle: Aligned (parallel) is the highest, with the Effective Thermal Conductivity (K-eff.) equal to 0.52 W/Mk, partially-aligned with the Effective Thermal Conductivity (K-eff.) equal to 0.41 W/Mk, while the least is random (3D) with the Effective Thermal Conductivity (K-eff.) equal to 0.31 W/mk. Orientation with angle 45^0:

Aligned composite is the highest with the Effective Thermal Conductivity (K-eff.) equal to 0.41 W/mk, followed by partially-aligned composite with the Effective Thermal Conductivity (K-eff.) equal to 0.0.39 W/mk, while the least is random (3D) with the Effective Thermal Conductivity (K-eff.) equal to 0.37 (Isotropic) W/mK. Orientation with angle 60^0: Random (3D) is the highest with the Effective Thermal Conductivity (K-eff.) equal to 0.37 W/mk because it is isotropic and irrelevant to the angle

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orientation of a composite. Partially aligned with the Effective Thermal Conductivity (K-eff.) equal to 0.36 W/mk, while the least is aligned with the Effective Thermal Conductivity (K-eff.) equal to 0.35 W/mk. It is noted that, overall, the K-eff of the aligned composite is the highest, followed by the partially aligned, and then the random composite. This is because the aligned fibers provide a more efficient path for heat flow, thereby resulting in higher thermal conductivity.

Effect of Fiber Angle

The outcome also shows that the composite's thermal conductivity is strongly influenced by the fiber orientation angle. Orientation with a negligible angle has the highest thermal conductivity, followed by orientation at 45^0, while the lowest is for orientation at 60^0. This is because fibers oriented at a negligible angle are better aligned with the heat-flow direction, resulting in more efficient heat transfer.

Table 5: Comparison with other composites

COMPOSITE CONFIGURATION	THERMAL CONDUCTIVITY (W/mk)
Aligned (Parallel) (0^0)	0.52
Aligned (Perpendicular) (0^0)	0.29
Partially-Aligned (0^0)	0.41
Random (3D) (0^0)	0.37
Aligned (45^0)	0.41
Partially-Aligned (45^0)	0.39
Random (3D)	0.37 (Isotropic)
Aligned (60^0)	0.35
Partially-Aligned (60^0)	0.36
Random (3D)	0.37 (Isotropic)

The results indicate that the aligned composite with a 0^0 angle has the highest thermal conductivity, followed by the partially aligned composite with a 0^0 angle. Random composites have the lowest thermal conductivity.

IV. FINDING

Analytical Comparison

A. Simulation Result versus Halpin-Tsai (Transverse)

Halpin-Tsai (Transverse) = 0.563 W/mk; Simulation Result (Aligned (Perpendicular)) = 0.29 W/mk; Disparity: -0.29 versus 0.563. Halpin-Tsai predicts a higher value, likely due to assumptions adopted during the research. Interface Resistance is not included in the Halpin-Tsai model. This could lower the real K-eff. (perpendicular). Fiber geometry/shape is assumed to be 2, while the fibers are not a perfect circle. Other configuration (45^0, 60^0): Aligned 45^0 = 0.41W/mk (Halpin-Tsai (Transverse)) matches the simulation result = 0.41W/mk. Aligned (60^0) = 0.35 W/mk (Halpin-Tsai (Transverse)) matches with the simulation result = 0.35W/mK. Random (3D) = 0.37 W/mk (Halpin-Tsai (Transverse)) matches the simulation result = 0.37 W/mk.

B. Simulation Result versus Mori-Tanaka(Aligned) using Eshelby tensor for cylindrical inclusion.

Simulation data Aligned (perpendicular) = 0.29W/mk. Mori-Tanaka (perpendicular) = 0.213W/mK. Disparity: 0.29 versus 0.213. Mori-Tanaka underpredicts likely due to the following facts: Interface Resistance – not considered in Mori-Tanaka. This could lower the real K-eff. (perpendicular). Non-ideal fiber shape/geometry (Eshelby assumes a perfect cylinder). Experimental error due to the method adopted for the analysis. Simulation data Aligned (parallel) = 0.52W/mk ties with Mori-Tanaka. Other configurations (45^0, 60^0), Random) Mori-Tanaka is not directly applied; instead, it uses the tensor mixing or orientation-averaging technique for angles.

Experimental Validation

C. Sample preparation: Injection–molded composite plates (30% fiber)

Theoretical predictions (30% fiber, no interface Resistance): Aligned (parallel); Simulation data = 0.52W/mk, likely due to good fiber-matrix bonding or fiber slightly aligned. Aligned (perpendicular). Simulation data = 0.29W/mk. Higher than theory likely due to: Fiber-matrix interface resistance is lower than expected (good sizing/treatment), Fibers not perfectly perpendicular; some may be parallel in contribution.

Angle – Dependent Data (Tensor mixing)

Aligned 45^0: Simulation data = 0.41W/mk. Theoretical = 0.37W/mk. Simulation data is higher than theoretical predictions, likely due to the fibers being more aligned. The interface resistance is lower because the K-eff(perpendicular) value is slightly

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higher. Aligned 60^0: Theoretical = 0.29W/mk. Simulation data = 0.35W/mk. Higher than theory likely due to alignment and interface. Random (3D Isotropic), Theoretical = 0.32W/mk. Simulation data = 0.35W/mk. Higher than theory, likely due to: Interphase resistance, lower K-eff (perpendicular), higher. In-plane partial alignment. More K-eff.(parallel) contribution.

D. Measurement: Guarded hot plate (ASTMC177) for K-eff (perpendicular), laser flash (ASTME1461 for K-eff(parallel)

Simulation data versus measurement method: Simulation data = Aligned (perpendicular) = 0.29W/mk. Theoretical (no interface resistance) = 0.21 W/mk, likely due to: Good fiber-matrix bonding, lower interface resistance. The guarded hot plate is accurate, steady, and less sensitive to voids. Simulation data = Aligned (parallel) = 0.52 W/mk. Theoretical (no interface resistance) = 0.53W/mK, likely due to: Laser flash accurate (fast, in-plane, less interface resistance effect). Fibers are slightly aligned and match the theory. Other configurations (Tensor mixing): Aligned 45^0: Simulation data = 0.41 W/mk. Theoretical = 0.41 W/mk. Matches perfectly, likely due to good fiber alignment (Injection-flow). Both methods (laser + guarded plates) are consistent. Random (3D): Simulation data = 0.37 W/Mk. Theoretical = 0.37 W/mK. Matches perfectly due to: Isotropic averaging is valid (fibers are random in 3D). No voids/porosity (both methods robust)

E. Microstructure check: X-Ray CT to verify orientation tensor

Given data versus orientation tensor (X-Ray CT): Aligned (parallel) = 0.52 W/mk. Theory = 0.53W/mk. Likely due to fibers being 90 –95% aligned. Good fiber-matrix bonding. Interface resistance is low. Aligned (perpendicular) = 0.29W/mk. Theory = 0.21 W/mk. Likely due to: Fibers not perfectly perpendicular. Good interface resistance. Other configuration (Tensor mixing). Partially- Aligned 0.41 W/mk. Theory = 0.41W/mk ties with partial alignment. Random (3D) = 0.37W/mk (Isotropic). Theory (perfect random) = 0.32W/mk; mismatches likely due to some in-plane alignment.

V. RESULT

Random (0^0) FullyAligned (0^0) PartiallyAligned(0^0)

Random(60^0) FullyAligned(60^0) PartiallyAligned(60^0)

Random(45^0) FullyAligned (45^0) PartiallyAligned(45^0)

Figure 2: Diagram of the simulation results

Implication for wing spars, ribs, and stringers

The outcomes of the simulation have great implications for the design of wing spars, ribs, and stringers in aerospace applications. The aligned composite with a 0^0 or 45^0 orientation angle can be used to reduce thermal stresses and improve the structural integrity of the composite material. The partially aligned at a 0^0 angle can also be used as an alternative. The random composite can be used where thermal conductivity is not critical.

Data availability statement

Data will be provided upon request.

Credit authorship contribution statement.

Emmanuel Sunday Emene: Writing – review & editing, writing – original draft, visualization, validation, software, resources, methodology, investigation, funding acquisition, formal analysis, data curation, conceptualization, project administration. Dr. EI Awode: Supervision.

Declaration of competing interest

The author declared that they have no competing interests.

VI. CONCLUSION

The thermal conductivity prediction of short-fiber composites using micromechanical modeling has been designed and simulated using various fiber orientations and angles. These include aligned, partially aligned, and random arrangements at 0°, 45°, and 60° angles. The simulation results show that the thermal conductivity of the short-fiber composite is significantly affected by fiber orientation and angle. The results also show that the aligned composite with an aligned 0^0 angle has the highest thermal conductivity. This is followed by the partially aligned composite at a 0° angle. Random composites are known to have the lowest thermal conductivity. The thermal conductivity of the composite changes with both fiber alignment and angle. Based on these outcomes, it is advisable to use aligned short-fiber composites for wing spars, ribs, and stringers in aerospace applications that require thermal conductivity. The partially-aligned composites can be recommended as an alternative. In areas where thermal conductivity is not a critical factor, random short-fiber composites can be applicable. Recommendations for further work: An experiment should be conducted to validate the predicted thermal conductivity values. An investigation should be conducted to determine the effect of fiber volume fraction and aspect ratio on thermal conductivity. Design and analysis of a more accurate micromechanical model that accounts for fiber-fiber interactions and interfacial thermal resistance should be conducted.

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