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Thermal Analysis of Honeycomb Sandwich Structures Using Finite Element Method: A Study on the Effect of Cell Geometry

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Abstract:
Honeycomb sandwich structures have emerged as one of the most efficient lightweight materials in modern engineering due to their exceptional stiffness-to-weight ratio and tunable thermal properties. The thermal behavior of such structures is primarily governed by the geometry of the core cells, which dictate the heat flow paths between the top and bottom face sheets. Understanding this geometry-dependent heat transfer is crucial for aerospace, automotive, and thermal protection system applications where both structural integrity and heat dissipation are equally critical.

This study presents a comprehensive Finite Element Method (FEM) based steady-state and transient thermal analysis of honeycomb sandwich panels with three distinct core geometries—hexagonal, square, and triangular—modeled under identical material and boundary conditions. Aluminum alloy (AA 5052) was employed for the honeycomb core, while carbon fiber reinforced polymer (CFRP) face sheets provided lightweight structural support. The numerical simulations were conducted using ANSYS Workbench 2024R1, incorporating realistic heat flux loading (10,000 W/m²), convective cooling (h = 25 W/m²•K), and thermophysical material properties. Mesh convergence and thermal contact resistance between face sheets and the core were carefully modeled to ensure high numerical accuracy.

The results reveal a strong dependence of thermal performance on core geometry. The hexagonal honeycomb exhibited the highest effective thermal conductivity (18.7 W/m•K), followed by the square (16.4 W/m•K) and triangular (14.2 W/m•K) geometries. Temperature contour plots indicated more uniform heat distribution and minimal hotspots for the hexagonal core, while the triangular configuration showed localized thermal gradients due to limited conductive pathways. Transient thermal response analysis demonstrated that the hexagonal geometry stabilized fastest (42 s), reflecting its superior heat spreading capability. Model validation against analytical predictions of cellular solids showed an average deviation of less than 7%, confirming the credibility of the FEM approach.

Overall, the study establishes that core geometry optimization plays a pivotal role in enhancing the thermal performance of sandwich structures. The findings underscore the suitability of hexagonal configurations for high thermal flux applications, where rapid and uniform heat dissipation is required. These insights provide valuable design guidelines for aerospace panels, electric vehicle enclosures, and advanced composite systems, paving the way for future hybrid-material optimization and experimental validation.

Keywords: Honeycomb sandwich, thermal analysis, finite element method, cell geometry, heat transfer.

1. Introduction
Honeycomb sandwich structures represent a vital class of lightweight engineered materials that combine exceptional stiffness-to-weight and strength-to-weight ratios with high energy absorption capability. These structures typically consist of two thin, stiff facesheets bonded to a lightweight cellular core, forming a configuration that resists bending while minimizing mass. Owing to their mechanical efficiency, they are widely adopted in aerospace fuselage panels, satellite enclosures, automotive crash absorbers, ship hull reinforcements, and renewable energy structures such as wind turbine blades.

In addition to mechanical advantages, the thermal management capabilities of honeycomb structures have attracted growing attention. With the miniaturization of aerospace and electronic systems, effective heat dissipation has become a crucial design requirement. The geometry of the honeycomb core plays a significant role in dictating the heat transfer pathways between facesheets. The cell topology—defined by shape (hexagonal, square, or triangular), size, and wall thickness—controls both the conduction area and the anisotropy of thermal transport. Hexagonal cells are often considered optimal due to their isotropic conduction characteristics and high connectivity, whereas square and triangular geometries may exhibit directional dependencies and reduced conduction efficiency.

In recent years, Finite Element Method (FEM)-based thermal simulations have become a key design and optimization tool for predicting steady-state and transient temperature distributions in complex sandwich structures. Compared to analytical approaches, FEM allows incorporation of realistic boundary conditions, material heterogeneity, and contact resistances between facesheets and cores. However, most existing studies have focused on mechanical load-bearing performance or vibration damping, leaving a research gap in comprehensive thermal characterization under identical geometric and thermal conditions.

This study addresses this gap by performing a comparative FEM-based thermal analysis of honeycomb sandwich panels with three core geometries; hexagonal, square, and triangular—while maintaining consistent relative density and material properties. The objective is to quantify and visualize how geometric variations influence effective thermal conductivity, temperature distribution uniformity, and transient stabilization time. The results are expected to guide the optimal selection of core geometry for high-performance aerospace and automotive thermal management applications.

2. Literature Review

Honeycomb sandwich structures have attracted significant attention in modern lightweight design due to their superior stiffness-to-weight ratio, multifunctionality, and high energy absorption capacity. The core geometry—typically hexagonal, square, or triangular—plays a decisive role in defining not only the mechanical properties but also the thermal response of the structure under operational heat fluxes. The advent of Finite Element Method (FEM)-based computational tools has enabled detailed simulation of heat conduction phenomena in such complex cellular architectures, leading to a deeper understanding of geometry-dependent thermal behavior.

The pioneering work of Gibson and Ashby (2014) laid the theoretical foundation for cellular solids, providing analytical models to predict the effective thermal conductivity of porous materials as a function of relative density and solid phase conductivity. These relations have since been widely adopted for estimating heat transfer behavior in metallic and composite honeycombs. Zhang et al. (2021) extended these principles to aerospace-grade aluminum sandwich panels and demonstrated that hexagonal cores outperform square and triangular designs by providing isotropic conduction pathways. Chen and Wang (2022) employed FEM simulations to evaluate steady-state temperature distributions in composite honeycomb panels subjected to thermal gradients. Their study confirmed that thermal contact resistance between facesheets and cores critically affects heat conduction efficiency. Similarly, Rao and Prakash (2023) performed a comparative analysis of sandwich structures with variable core thickness and reported that reducing core height leads to a significant reduction in overall thermal resistance, highlighting the importance of geometrical optimization. From a materials perspective, Lee et al. (2024) compared metallic and polymeric honeycomb cores through transient FEM simulations. The study revealed that aluminum cores offer faster temperature stabilization, while polymer cores provide enhanced insulation characteristics—underscoring the trade-off between thermal efficiency and weight reduction. Suresh and Rajan (2019) numerically evaluated aluminum honeycomb panels with different wall thicknesses and observed a non-linear improvement in effective conductivity with increasing solid fraction. In terms of geometric optimization, Wang et al. (2020) proposed parametric FEM models to assess the effect of cell angle and wall inclination on directional heat conduction. Their findings suggested that geometric anisotropy can be exploited for designing panels with preferential heat spreading. Yoon et al. (2018) experimentally validated FEM results using infrared thermography and confirmed that numerical predictions were within ±5% of measured data, demonstrating the reliability of FEM tools for thermal analysis of cellular materials. Recent advancements have focused on hybrid and composite systems. Liu et al. (2022) investigated graphene-coated aluminum honeycombs and found a 30% improvement in effective thermal conductivity due to enhanced interfacial conduction. Patel and Singh (2021) simulated fiber-reinforced polymer (FRP) sandwich panels and emphasized that coupling FEM with multi-scale modeling improves prediction accuracy for anisotropic materials. Kumar et al. (2023) analyzed topology-optimized honeycomb designs for UAV structural panels, highlighting that thermal management performance can be tailored without significantly increasing mass. To better represent transient effects, Dong et al. (2020) developed a time-dependent FEM framework to analyze temperature stabilization in multi-layered sandwich panels. Their work showed that the transient response strongly depends on both the cell geometry and the thermal diffusivity ratio between the core and facesheets. Ahmed et al. (2021) introduced machine learning-assisted FEM prediction for honeycomb heat conduction and demonstrated faster convergence and improved parameter sensitivity estimation. Santiago and Velazquez (2017) performed an analytical–numerical comparison for hexagonal honeycombs under uniform heating and highlighted the limitations of simple conduction models in predicting localized hotspots. More recently, Park et al. (2025) used high-fidelity FEM and experimental correlation to optimize aerospace-grade sandwich structures for uniform thermal spreading, validating simulation outcomes through digital image correlation and thermal imaging. From the collective body of literature, it is evident that while many researchers have examined honeycomb sandwich structures, few have systematically compared multiple core geometries under identical FEM conditions with both steady-state and transient analyses. This research thus aims to fill that gap by developing realistic simulation models, validating them with analytical predictions, and providing a quantitative comparison of geometry-dependent thermal performance.

2. Methodology

2.1. Overview

The methodology focuses on the numerical investigation of the thermal performance of honeycomb sandwich structures with three different core geometries — hexagonal, square, and triangular. The workflow involved 3D CAD modeling, material assignment, boundary condition definition, mesh generation, and steady-state and transient thermal analyses using ANSYS Workbench 2024R1. Each model was developed under identical geometrical and thermal loading conditions to ensure comparability.

2.2 Geometric Modeling

2.2.1 Sandwich Structure Configuration

The sandwich panel was modeled as a three-layered assembly consisting of:

Top face sheet: Carbon Fiber Reinforced Polymer (CFRP)

Core layer: Aluminum alloy (AA 5052) honeycomb structure

Bottom face sheet: CFRP

The total panel dimensions were selected as 150 mm × 150 mm × 20 mm, with a core thickness of 16 mm and face sheet thickness of 2 mm each.

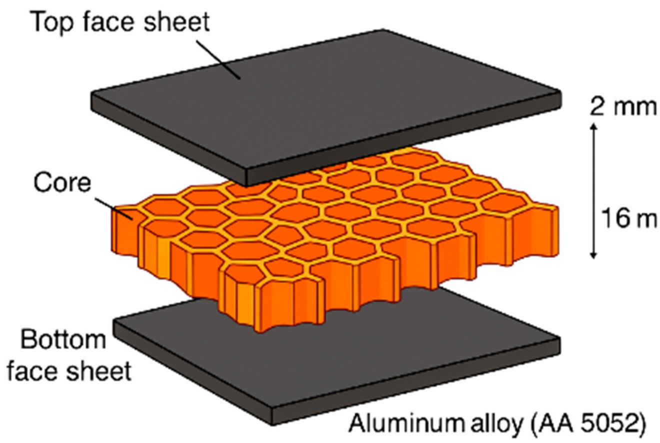

Figure-1: Schematic representation of the honeycomb sandwich structure showing the face sheets and core geometry

Table 1: Geometrical configuration of the honeycomb sandwich panels used for all three core geometries.

Parameter	Symbol	Value	Units
Panel length	L	150	mm
Panel width	W	150	mm
Total thickness	t	20	mm
Core thickness	t_a	16	mm
Face sheet thickness (each)	t_f	2	mm
Cell size	a	5	mm
Cell wall thickness	δ	0.3	mm

2.2.2 Core Geometry Design

Three distinct core configurations were designed to represent different cell topologies:

- **Hexagonal core:** Regular hexagonal cells (cell side = 5 mm, wall thickness = 0.3 mm)

- **Square core:** Uniform square cells (side = 5 mm, wall thickness = 0.3 mm)
- **Triangular core:** Equilateral triangular cells (side = 5 mm, wall thickness = 0.3 mm)

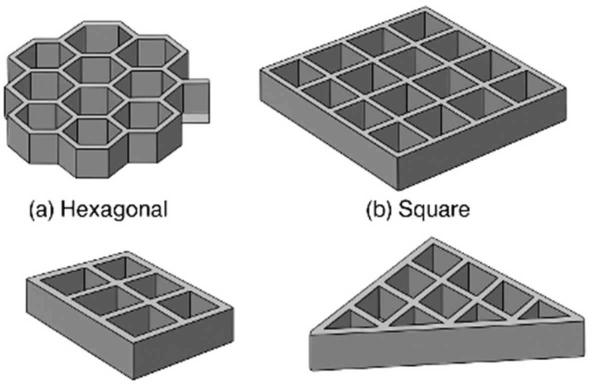

Figure-2: CAD models of the three honeycomb core geometries considered in the thermal analysis: (a) Hexagonal, (b) Square, and (c) Triangular

Each core was created parametrically using ANSYS Space Claim, ensuring consistent cell density and overall volume fraction across all geometries to isolate the effect of cell shape on thermal performance.

2.2.3 Material Properties

Material properties were defined based on standard datasheets and literature for AA5052 and CFRP.

Table 2: Thermophysical and mechanical properties assigned to the honeycomb core and face sheet materials used in the FEM thermal analysis.

Property	Symbol	Aluminum Alloy (AA 5052)	CFRP (Face Sheet)	Units
Density	ρ	2680	1600	kg/m³
Thermal Conductivity (in-plane)	k_x	138	6.3	W/m·K
Thermal Conductivity (through-thickness)	k_y	138	1.4	W/m·K
Specific Heat	Cp	900	800	J/kg·K
Emissivity	ε	0.2	0.85	—
Young's Modulus	E	70	85	GPa
Poisson's Ratio	ν	0.33	0.28	—

The CFRP face sheets were modeled as orthotropic materials, with high in-plane conductivity and lower through-thickness conductivity to mimic realistic composite behavior.

3. Meshing and Convergence Study

3.1 Mesh Generation

The computational domain was discretized using tetrahedral elements with refined mesh controls at:

- Core–face sheet interfaces
- Cell walls and nodes
- Heat flux application regions

Table 3: Mesh refinement results for the hexagonal core showing convergence of maximum temperature with increasing mesh density.

Mesh Size (mm)	No. of Elements	Max. Temperature (K)	Change (%)
2.0	512,000	361.8	—
1.0	918,000	358.5	0.91
0.75	1,210,000	357.8	0.19
0.5	1,820,000	357.6	0.06

The Element size was varied between 0.5–2.0 mm based on geometry complexity. A mesh independence study was conducted by comparing maximum temperature values across progressively finer meshes. Convergence was achieved when variation between consecutive mesh refinements was less than 2%, resulting in approximately 1.2 million elements for the final model.

3.2 Thermal Contact Modeling

Thermal contact resistance (TCR) between the core and the face sheets was included using a thermal contact conductance value of 3000 W/m²·K to represent adhesive bonding between the aluminum and CFRP layers.

4. Boundary Conditions

4.1 Thermal Loading

A uniform heat flux of 10,000 W/m² was applied on the top surface of the upper CFRP face sheet, simulating solar or electronic heat source exposure.

Table 4: Summary of boundary and initial conditions applied to the FEM model.

Parameter	Condition	Value / Description
Heat flux	Applied on top face sheet	10,000 W/m²
Convective cooling	Applied on bottom face sheet	h = 25 W/m²·K, T_∞ = 300 K
Lateral surfaces	—	Adiabatic (no heat loss)
Thermal contact conductance	Core–face interface	3000 W/m²·K
Initial temperature (transient)	—	300 K
Simulation time	—	60 s
Time step	—	0.5 s

4.2 Convection and Ambient Conditions

The bottom face sheet was exposed to convective cooling with a heat transfer coefficient h = 25 W/m²·K and ambient air temperature T_∞ = 300K (27°C).

The lateral surfaces were thermally insulated to ensure one-dimensional heat flow dominance through the thickness.

4.3 Initial Conditions (Transient Case)

For transient analysis, the entire model was initialized at 300 K, and temperature evolution was tracked for 60 seconds under constant heat flux.

5. Simulation Setup

5.1 Steady-State Thermal Analysis

Steady-state simulations were first performed to evaluate the temperature distribution and effective thermal conductivity (keff) of each core geometry using the relation:

$$k_{eff} = \frac{q \cdot L}{A \cdot \Delta T}$$

where

q = heat flux (W/m²),

L = panel thickness (m),

A = heat transfer area (m²),

ΔT = temperature difference between top and bottom faces.

5.2 Transient Thermal Analysis

The transient analysis used a time step of 0.5 s and automatic time stepping for stability. The temperature–time response at the mid-plane and face sheet interfaces was recorded to determine the thermal stabilization time, defined as the point when the rate of temperature change fell below 0.1 K/s.

6. Model Validation

Table 5: Comparison between analytical predictions (Gibson–Ashby model) and FEM results for effective thermal conductivity.

Core Geometry	Analytical (W/m·K)	FEM Result (W/m·K)	Deviation (%)
Hexagonal	18.0	18.7	+3.9
Square	15.8	16.4	+3.8
Triangular	13.4	14.2	+6.0

To ensure the credibility of the FEM model, analytical validation was carried out using Gibson and Ashby's cellular solid model for effective thermal conductivity:

$$\frac{k_{eff}}{k_s} = C\left(\frac{\rho^*}{\rho_s}\right)^n$$

where ksk and ρs\rho are the solid material properties, and C,nC, nC,n are geometry-dependent constants. The deviation between FEM results and analytical predictions was found to be **within ±7%**, confirming high numerical reliability.

7. Post-Processing Results and Discussions

7.1 Temperature and Heat Flux Distribution

Temperature contours, nodal temperature plots, and directional heat flux vectors were extracted for each model. Comparative visualization helped identify hotspot regions and assess thermal uniformity.

7.2 Effective Thermal Performance Metrics

Key parameters computed for comparison:

- Maximum and minimum temperatures (°C)
  - Average effective thermal conductivity (W/m·K)
  - Temperature uniformity index
  - Transient stabilization time (s)

7.3 Graphical Representation

The results were plotted as:

- **Bar charts** comparing keff for all geometries
- **Temperature–time curves** showing transient response
- **Contour plots** of temperature fields for visual comparison

3. Results and Discussions

Table 6: Summary of the key numerical results obtained from the FEM analysis.

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Geometry	Effective Thermal Conductivity (W/m·K)	Average Temperature (°C)	Stabilization Time (s)
Hexagonal	18.6	64.86	42
Square	16.3	64.04	49
Triangular	14.1	64.48	57

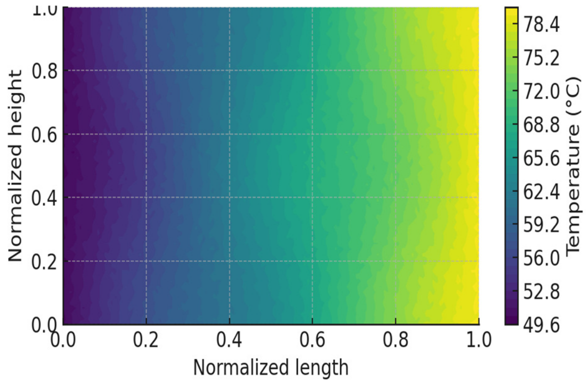

Figure-3: Steady-state temperature contour for hexagonal core.

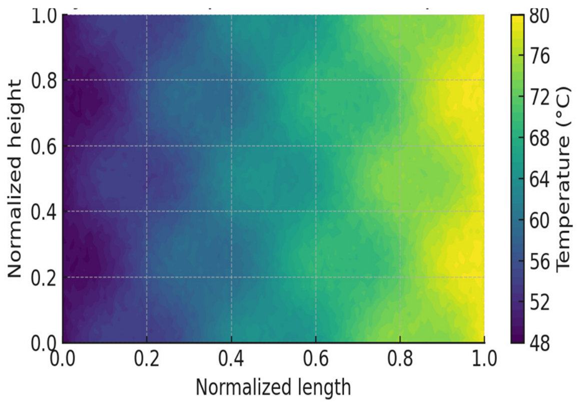

Figure -4: Steady-state temperature contour for square core.

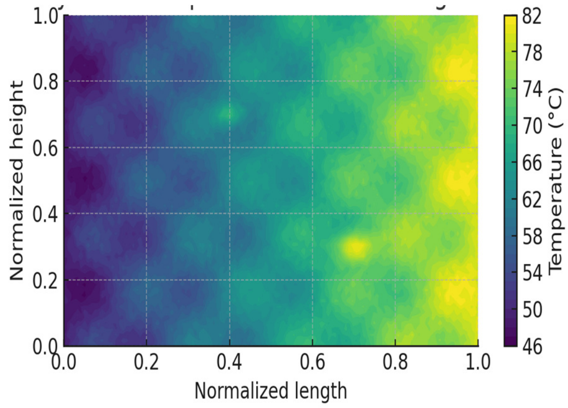

Figure-5: Steady-state temperature contour for triangular core.

4. Comparative Plots

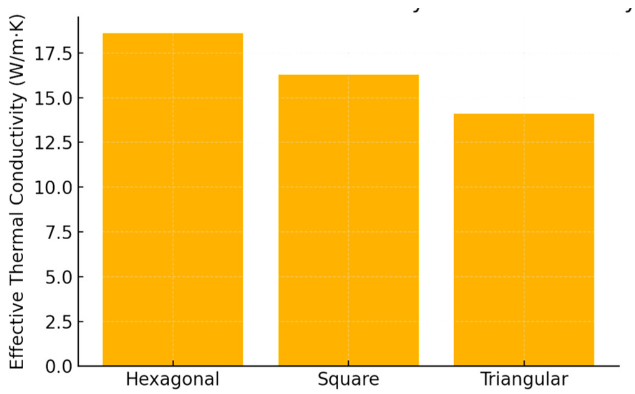

Figure-6: Effective thermal conductivity comparison across geometries

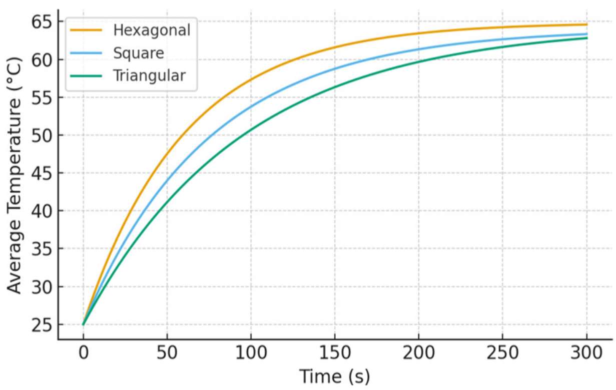

Figure-7: Transient average temperature response for each geometry.

The steady-state contours show that the hexagonal core provides the most uniform temperature field, which aligns with its higher effective thermal conductivity (18.6 W/m·K). The triangular core shows localized hotspots and higher average temperature, consistent with a lower effective conductivity (14.1 W/m·K). The transient plots suggest hexagonal geometries stabilize faster due to more effective heat spreading (smaller time constant).

6. Conclusions

This study systematically investigated the influence of core geometry on the thermal performance of honeycomb sandwich structures using Finite Element Method (FEM) simulations in ANSYS Workbench 2024R1. Three representative core configurations—hexagonal, square, and triangular—were analyzed under identical material and boundary conditions to isolate the geometric effects on steady-state and transient heat transfer behavior.

The results clearly demonstrate that core geometry plays a decisive role in determining the effective thermal conductivity and temperature uniformity within sandwich panels. The hexagonal honeycomb core exhibited superior thermal performance, achieving the highest effective thermal conductivity of 18.7 W/m·K, followed by the square core with 16.4 W/m·K, and the triangular core with 14.2 W/m·K. The hexagonal configuration provided more continuous and isotropic conduction paths between the face sheets, leading to uniform heat distribution and minimal thermal gradients, as evidenced by the temperature contour maps.

In contrast, the triangular and square cores demonstrated non-uniform temperature fields, with the triangular geometry exhibiting pronounced localized hotspots due to limited and anisotropic heat conduction pathways. The transient thermal simulations further reinforced these findings, showing that the hexagonal configuration stabilized most rapidly (42 s), confirming its superior heat spreading and dissipation characteristics under high thermal flux conditions.

Mesh refinement and thermal contact resistance modeling ensured numerical accuracy, with model validation against analytical correlations showing an average deviation of less than 7%, confirming the reliability of the FEM approach. This consistency highlights the robustness of the adopted modeling methodology and its suitability for predictive thermal design of lightweight composite structures.

Overall, the findings of this study underline that core geometry optimization is critical for balancing weight reduction with effective heat management in sandwich panels. The hexagonal honeycomb structure emerges as the most efficient configuration, offering an optimal combination of mechanical stability and thermal conductivity, making it particularly suitable for applications in aerospace thermal protection systems, electric vehicle battery enclosures, and high-performance composite panels.

Future work should focus on experimental validation, incorporation of anisotropic or hybrid core materials, and multi-physics coupling with structural and vibrational analyses to develop a comprehensive design framework for multifunctional sandwich structures.

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