Mechanics of Advanced Composite Structures 13 (2026), Serial Number 27, 69 – 82

Semnan University

Mechanics of Advanced Composite Structures

Journal homepage: https://macs.semnan.ac.ir/

ISSN: 2423-7043

Research Article

Modeling and Experimental Validation of Carbon Fiber-Kevlar Honeycomb Core Sandwich Structure

Anil Kumar [a] *, Sapna Raghav [a], Jayant Pandurang Supale [a], Gajanan Shravan Datar [b]

[a] G. B. Pant DSEU Okhla-I Campus, New Delhi,110020, India

[b] Government College of Engineering and Research, Avasari, Pune- 412406, India

ARTICLE INFO

Article history:

Received: 2024-12-18

Revised: 2025-04-15

Accepted: 2025-06-27

Keywords:

Numerical modeling;

Composite sandwich;

Kevlar® Honeycomb;

Orthotropic properties;

Stiffness.

ABSTRACT

Composite sandwich structures are becoming more and more popular in the sports, automotive, and aerospace sectors because of their excellent strength-to-weight ratio. However, more research is required to fully understand their stiffness properties and the accuracy of predictive modeling. By simulating and examining two different sandwich structures made of Carbon fiber face sheets and Kevlar honeycomb core material represented as an equivalent solid, this study fills this gap. The Gibson and Ashby model has been adopted to find the equivalent orthotropic properties of the core because this model provides a balance between precision, computational efficiency, and suitability for honeycomb cores, guaranteeing accurate stiffness predictions and facilitating simple engineering design implementation. Experimental stiffness values of 529.74 N/mm and 479.98 N/mm for the two configurations are obtained by performing a "Three Point Bend Test" on the manufactured panels. With an accuracy deviation of about 0.84%, the numerical model predictions closely resemble the experimental findings, demonstrating the model's dependability in representing the material's static behavior. The sandwich structure demonstrates a stiffness of about 565 N/mm, suitable for high-load applications in aerospace and automotive sectors. Numerical modeling effectively validates the experimental results by accurately predicting the stiffness of Kevlar honeycomb core sandwich panels.

1. Introduction

A composite is a blend of materials with distinct properties, either physical, chemical, or both, widely employed in the production of different sports items, motorcycles, and aircraft. The composite exhibits significant potential for use in critical areas where strong resistance to impact and high load-bearing capacity are essential [28]. Typically formed by bonding two or more materials together, composites aim to enhance overall strength, with the individual components maintaining their separate identities within the final structure. Effectiveness hinges on the composite surpassing the properties of its constituent materials. These materials offer advantages like increased strength, thermal and electrical conductivity, and can achieve improved performance through compositing, interface adjustments, or dimensional effects. This forms the basis of composite research. Pre-shaped composite components, notably 'Carbon Fiber

*** Corresponding author.**

E-mail address: anil.kumar1@dseu.ac.in

Cite this article as:

KUMAR, A., Raghav, S., Supale, J. P. and Datar, G. S., 2026. Modeling and Experimental Validation of Carbon Fiber-Kevlar Honeycomb Core Sandwich Structure. *Mechanics of Advanced Composite Structures*, 13(1), pp. 69-82.

https://doi.org/10.22075/MACS.2025.36296.1782

Reinforced Plastic', offer strength and lightness while minimizing joints and heavy fasteners. Honeycomb materials contribute effective and lightweight internal structural components. CFRP, for instance, can be easily molded into specific shapes without additional machining, making it a preferred material for crafting diverse internal structures, potentially replacing traditional HPSA metals. Advanced composites stand out by surpassing the efficiency of their constituent materials. They result from structural design and optimization, often incorporating the latest advancements in individual materials. A composite sandwich panel is a structural material consisting of three layers: a lightweight core material sandwiched between two thin, stiff face sheets. The core material is typically made of foam, honeycomb, or balsa wood, while the face sheets are often composed of materials like fiberglass, carbon fiber, or aluminum. The primary components of composite sandwich panels are as follows:

(a). Facesheets – Positioned on both sides of the composite sandwich structure, these thin sheets, typically composed of Carbon, Glass, or Basalt Fibers, bear the bending stress of the structure. During loading, one facing skin experiences compression, while the other undergoes tension, akin to the flanges of an I-beam.

(b). Core – This pivotal component contributes to reducing the weight of the sandwich panel. The core's "low density" is crucial for minimizing sandwich weight, functioning similarly to the web of an I-beam. It resists shear stresses and enhances structural stiffness by keeping the facing skins apart.

(c). Adhesive – In a composite sandwich structure, the adhesive's purpose is to establish a robust bond between the material components. Epoxy is utilized for this purpose because it cures at relatively low temperatures, typically ranging from 20 to 90 degrees Celsius. Epoxies offer versatility as they can be used with various core materials due to their lack of solvents. They are available in multiple forms, including paste, films, powder, and solid adhesives, with most epoxies exhibiting shear strength of approximately 20-25 MPa. Depending on specific requirements, alternative adhesives like Polyurethanes, Polyester, and Vinyl Ester Resin may also be employed.

The demand for composite sandwich structures is driven by the critical need for materials that can withstand rigorous mechanical demands while simultaneously adhering to weight constraints. In aerospace applications, for instance, the lightweight nature of these structures contributes to fuel efficiency and overall performance. In the automotive industry, composite sandwich structures offer a compelling solution for achieving the desired balance between strength and weight, contributing to enhanced fuel economy and reduced environmental impact.

Moreover, these structures find extensive use in sports equipment and other applications where the combination of strength, stiffness, and low weight is crucial. The design and optimization of composite sandwich structures involve a sophisticated interplay of materials, geometric configurations, and manufacturing processes, making them a subject of intense research and development.

The mechanical characteristics of a composite sandwich panel depend upon various design factors, including fabrication method, face sheet, core, and adhesive usage [29]. The Finite Element Method (FEM) is a reliable tool for predicting the mechanical behavior of materials without experiments [1]. Analytical solutions are often unsuitable for typical engineering problems, prompting the development of numerical techniques like FEM to address governing equations. Over the past four decades, extensive research in numerical modeling has empowered engineers to conduct simulations that closely approximate real-world scenarios.

The accurate modeling and assembly of face sheets and regular hexagon honeycomb cores are crucial for Finite Element Analysis (FEA) in Ansys Software. While face sheet materials with low thickness, such as carbon and glass, have readily available elastic properties in Ansys, the honeycomb core, with its greater height and orthogonal properties, requires calculation of all nine in-plane and out-of-plane properties for the development of an equivalent solid. Increasing the thickness of the core in sandwich structures leads to higher stiffness, which in turn affects both compressive strength and modulus [2]. The use of numerically derived orthotropic properties, obtained via the Strain energy-based homogenization technique, enables the development of an equivalent solid model for honeycomb cores. This enhances the efficiency of simulations using the 3PBT approach [3-5]. The most effective analytical models for assessing the orthotropic properties of a honeycomb core are found to be the modified "Gibson and Ashby model" [6]. Various research indicates that the two most influential core material properties are the shear moduli (Gxz and Gyz) [7-8]. 3PBT has been observed in the numerical analysis, verified experimentally to explore various mechanical properties of composite sandwich beams [9-11]. Formulas have been formulated to calculate the effective elastic properties of hexagonal honeycomb structures. Among these, the "Gibson and Ashby model" stands out as a particularly valuable model for conducting such analyses and assessments [12]. Foo et al. extensively presented test results for the linear elastic mechanical properties of Nomex facesheet and core structures in their study. They utilized the fundamental mechanical characteristics of Nomex paper in the Finite Element Method (FEM) and evaluated the properties of Nomex honeycomb structures [13]. Roy et al. carried out FEA on sandwich panels with a Nomex honeycomb core, highlighting the significance of taking orthotropic properties into account in numerical models. This study builds on their findings by using comparable techniques to examine Kevlar honeycomb cores, which have unique mechanical properties [14]. In the same way, Herranen et al. showed that the stiffness of double-thickness Kevlar honeycomb cores is more affected by the properties of the core material than by the thickness of the core, which is a crucial factor in this investigation [15]. Ijaz et al. chose to replace the hexagonal core with a simple equivalent volume for FEA, determining the effective elastic orthotropic modulus properties of the equivalent polypropylene honeycomb core. Their research involved Finite Element Analysis using 3PBT and 4PBT on a sandwich panel with the equivalent core and Glass Fiber (GFRP) face sheets, exploring mechanical properties [16]. Hussain et al. investigated a sandwich composite comprising glass fiber face sheets and an aluminum honeycomb core using 3PBT. They examined both the static and fatigue behavior of the sandwich composite, concluding that FEA is suitable for validating experimental results and determining various properties of sandwich structures by varying parameters [17]. Yuan et al. introduced an equivalent modeling method for a sandwich structure with a honeycomb core, representing honeycomb panels with 'shell elements' and modeling the honeycomb core using orthogonal anisotropic solid components. Displacement errors under common static load cases were less than 3.12% compared to accurate models, validating the equivalent method [18]. It has been noted that utilizing a combination of CFRP facesheets and a Kevlar honeycomb core in a sandwich panel could be a fitting choice for the construction of aircraft floor panels [19]. Seemann and Krause conducted a detailed numerical analysis of honeycomb cores, incorporating accurate core cell wall geometry at a mesoscale level. Their study involved experimental determination of stress-strain curves for a Nomex honeycomb core, comparing simulated curves with experimental data and suggesting best-fit material properties for future applications [20]. The composite sandwich panel, constructed with a Kevlar Honeycomb core and CFRP facesheet, exhibited outstanding stiffness performance [21]. Narasimhan and Zeleniakiene analyzed the stiffness of a sandwich panel with a paper honeycomb core and CFRP facings. Their numerical model considered different thickness conditions for the face sheets, allowing exploration of strength and stiffness properties at varying thicknesses [22]. According to Rupani et al., modeling honeycomb sandwiches with actual cell arrangements is challenging and time-consuming. However, they suggest that modeling the sandwich structure as an equivalent homogeneous structure can yield more accurate results [23]. FEM can be successfully adopted for numerical modeling of composite sandwich panels [24]. The use of FEM is shown to be a practical choice for investigating diverse sandwich structures. Notably, there is a limited amount of research dedicated to modeling and analyzing sandwich panels with a Kevlar honeycomb core.

It has been observed that the energy absorption in nanocomposites increases with nanosilica (up to 0.2%) and nanoclay (up to 0.4%), with conical structures performing better than cylindrical ones [31]. It has been found that in hybrid composites, elastomer hardness plays a crucial role, with the best impact resistance achieved using hard outer layers and a soft middle layer, leading to enhanced energy absorption, reduced projectile velocity, and improved damage resistance under high-velocity impact [32].

The literature review highlights that the majority of research is based on Aluminum, Foam, Glass, and Nomex Honeycomb cores, and there is a notable scarcity of data and studies on the various orthotropic properties of Kevlar Honeycomb cores. Therefore, it is proposed to select the Kevlar honeycomb as a core material. The 'Gibson and Ashby' model is suitable for determining the effective elastic properties of the honeycomb core. The model has received extensive industrial validation because it accurately depicts anisotropic behavior and takes into consideration important deformation mechanisms like cell wall bending and buckling. In contrast to empirical models' computational homogenization or purely numerical FEA approaches, the Gibson and Ashby model is the recommended option for analyzing stiffness in lightweight honeycomb structures used in automotive and aerospace applications because it balances accuracy and computational efficiency. To assess the mechanical behavior of a panel, 3PBT can be conducted using FEM and the results can be corroborated through analytical or experimental verification. Since the three-point bending test efficiently assesses both flexural rigidity and core shear response under controlled loading. Also, it is best suited for figuring out how stiff composite sandwich panels are. It provides information about the distribution of load between the face sheets and the core by simulating actual bending situations. It is also a commonly used technique in structural and aerospace applications where bending resistance is crucial because it makes precise measurements of flexural stiffness possible.

This study tests the hypothesis that the stiffness of Kevlar honeycomb core sandwich panels can be accurately predicted using numerical modeling, with validation through experimental testing. By comparing numerical and experimental stiffness values, the research aims to establish the reliability of the computational approach in capturing the static behavior of these composite structures.

The objective of this research is to create a numerical model for a sandwich panel, featuring CFRP face sheets and a regular hexagonal Kevlar honeycomb core with double thickness, treated as an equivalent solid.

To achieve this, the Gibson and Ashby model formulae will be applied to determine the orthotropic properties of the core, enabling its conversion into an equivalent solid. Subsequently, a three-point bending test will be conducted on the sandwich panel using Ansys, adhering to the ASTM C393 standard, to calculate equivalent stiffness. Experimental testing will involve fabricating a composite sandwich and conducting a 3PBT, with deflection values determined analytically. The obtained stiffness from the FEM will be compared with the analytical and experimental results. Successful alignment of values across different analyses will validate the model, making it suitable for numerically modeling different sandwich panels.

2. Methodology

2.1. Material for Facesheet

Metallic or fiber-reinforced polymer (FRP) can be used as the honeycomb composite's Facesheet. Fiber serves as reinforcement, while the polymer serves as a matrix in the fiber-reinforced polymer composite. Fibers can be arranged in a variety of ways inside the polymer. It is divided into two categories: continuous and fiber, which can be in the form of unidirectional, woven, knitted, or stitched multi-axial fabric. The Fiber arrangement in discontinuous form can be a random orientation of fibers. Because of its remarkable strength-to-weight ratio, high stiffness, and superior fatigue resistance, CFRP (Carbon Fiber Reinforced Polymer) was selected for the facesheets. This makes it a perfect choice for applications in sports, automotive, and aerospace. These sectors place a premium on lightweight constructions without sacrificing structural soundness.

"Carbon Fiber Reinforced Plastic (CFRP)" has been chosen as the facesheet material with a thickness of 0.4 mm and 0.6 mm for the design and analysis of the composite sandwich panel. It is responsible for bearing the bending stress. Carbon fibers have a high tensile strength while being lightweight and stable. Carbon crystals are linked in a chain to form an extremely strong material that is 5 times stiffer and stronger than steel [30]. Carbon fibers have a relatively small diameter, ranging from 5 to 10 microns. Carbon Fiber production and usage have increased in recent years as a result of its superior mechanical qualities.

Many applications favour carbon Fiber because it outperforms many other Fiber materials. It is mostly utilized in high-end items to replace Fiber-glass, wood, or alloys because it's lighter, stiffer, and more fatigue resistant. Carbon Fiber, for example, can lower vehicle weight and, as a result, fuel consumption. Table 1 shows the different elastic properties of CFRP.

Table 1. Properties of CFRP

PROPERTY	VALUE
E_X, E_Y (GPa)	61.34
E_Z (GPa)	6.90
V_{XY}	0.04
V_{XZ}, V_{YZ}	0.30
G_{XY} (GPA)	195
G_{YZ}, G_{XZ} (GPA)	2.7

2.2. Material for Core

In the realm of sandwich structures, four commonly employed core types include corrugated, honeycomb, balsa wood and foams. A pivotal feature sought in a core for composite sandwich structures is low density, aiming to reduce overall weight. Core attributes such as density, shear modulus, and shear strength are vital considerations. Honeycomb cores can be fabricated from aluminum, impregnated glass, or Kevlar. Each core material exhibits distinct properties under varying conditions.

Because of its lower density, superior energy absorption capacity, high impact resistance, and durability, Kevlar honeycomb was chosen as the core material. Kevlar offers superior resistance to crack propagation when compared to other core materials like Aluminum or Nomex, which is essential in applications that are subject to impact and dynamic loads. The Kevlar honeycomb, with a cell size of 3.2 mm and 4.8 mm and with a height of 10 mm and 8 mm, respectively, has been adopted for this research work. A balance between structural performance and weight optimization led to the selection of cell sizes of 3.2 mm and 4.8 mm. These measurements are in line with industry standards for honeycomb core sizes in automotive and aerospace applications. Higher density and better stiffness are offered by the smaller cell size (3.2 mm), while weight reduction and adequate mechanical strength are provided by the larger cell size (4.8 mm). As Kevlar is not integrated into ANSYS software's Engineering Data Sources, determining the nine elastic constants of the Kevlar honeycomb core is necessary for its inclusion. The geometry and axes of the regular hexagonal double-wall thickness honeycomb core have been shown in Figures 1 and 2.

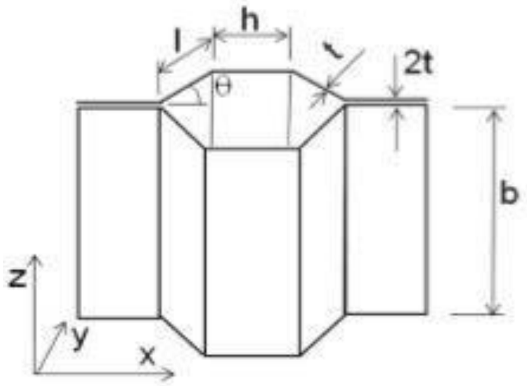

Fig. 1. Geometry of honeycomb cell [25]

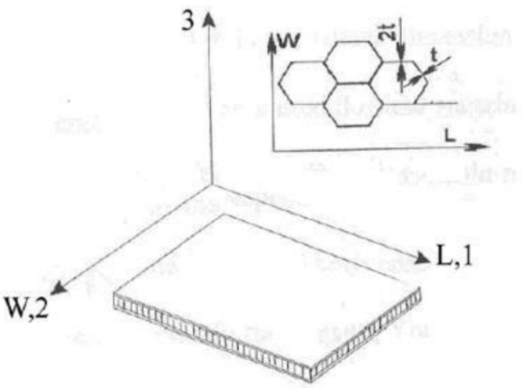

Fig. 2. Honeycomb axis system

In this study, the Kevlar honeycomb core is characterized by specific dimensions, outlined as follows:

- Wall Thickness core (t) = 0.07 mm.
- Honeycomb cell size (h) = Honeycomb side length (l), with an angle θ = 30°.

Table 2 presents the various properties of the bare honeycomb core, as supplied by Plascore Ltd.

Table 2. Kevlar® Honeycomb Core [26]

Cell Size (mm)	Comp. Strength (MPa)	Shear Strength, L Direction (MPa)	Shear Modulus, W Direction (MPa)
3.2	2.85	1.62	110
4.8	2.21	1.59	100

2.2.1. Orthotropic Values (Kevlar Honeycomb Core)

The updated Gibson and Ashby model has been employed to identify various properties of a core because it offers a proven analytical framework for forecasting the mechanical behavior of porous and cellular materials. The Gibson and Ashby model enables a more straightforward and effective estimation of mechanical properties than FEA, which necessitates intricate numerical simulations and substantial computational resources. Homogenization techniques are more complicated and less useful for initial design and analysis because they usually require numerical calculations and detailed microstructural information, even though they can also be used to estimate effective material properties. Tables 3 and 4 display the different values of in-plane and out-of-plane properties for two Kevlar honeycomb cores.

Table 3. Properties for cell size of 3.2 mm

S. N.	Property	Height (10 mm)
1	G_S (GPa)	6
2	E_s (GPa)	15.6
3	E_x, E_y (MPa)	0.287
4	V_{xy}	0.999
5	G_{xy} (MPa)	0.013
6	E_z (MPa)	480.48
7	V_{xz} & V_{yz}	0
8	G_{xz} (MPa)	70
9	G_{yz} (MPa)	108

Table 4. Properties for cell size of 4.8 mm

S. N.	Property	Height (8 mm)
1	G_S (GPa)	7
2	E_s (GPa)	18.2
3	E_x E_y (MPa)	0.142

4	V_{xy}	0.999
5	G_{xy} (MPa)	0.006
6	E_z (MPa)	420.42
7	V_{xz} & V_{yz}	0
8	G_{xz} (MPa)	60
9	G_{yz} (MPa)	96

2.3. Material for Adhesive

In the context of this research, sandwich panels have been constructed using epoxy resin. They are characterized by their low-temperature curing range of 20°C to 90°C. An advantageous feature of epoxy lies in its versatility, as it can be employed with any type of core material owing to the absence of solvents. Epoxy formulations are available in various forms, and their shear strength ranges around 20–25 MPa. Since epoxies cure at low temperatures and offer better resistance to environmental deterioration than polyurethanes or polyester resins, they are perfect for bonding Kevlar honeycomb cores in high-performance applications.

2.4. Mechanics of a Composite Sandwich Panel

The stiffness of such panels can be derived as per the Gibson and Ashby model. A composite sandwich panel having span length ‘l’ has been considered. Figure 3 shows that a concentrated load (P) has been applied at the center of the panel. The different notations used for the different design parameters of the sandwich structure and the properties of the constituent material are as follows:

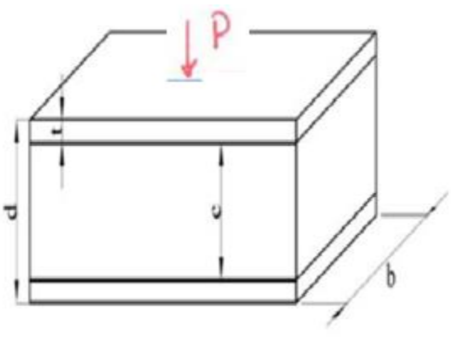

Fig. 3. Sandwich panel with concentrated load

- ρ_f, E_f, σ_{yf} - Density, Modulus of Elasticity, and Normal stress of facesheet.
- ρ_c, E_c, G_c, σ_{yc} - Density, Modulus of Elasticity, Shear Modulus, and Normal stress of core.
- ρ_s, E_s, σ_{ys}- Density, Modulus of Elasticity, and Normal stress of original solid core material. (Typically $E_c \ll E_f$ Sandwich panel
- t- Face-sheet thickness
- c- Core thickness
- b- Width of the panel
- P- Concentrated load
- δ –Deflection in the sandwich panel
- δ_b- Bending deflection
- δ_s - Shear deflection (of core)
- d- Total thickness of sandwich panel.

After the solution,

- Finally , $\delta = \delta_b + \delta_s$ and $G_c \ll E_f$
- l- Span Length of *But as* $G_c \ll E_f$

Therefore, the core shear deflections are highly significant. Also,

- *Bending stiffness (Same Face-sheets)*

$$D = \frac{E(d^3 - c^3)b}{12} \quad (1)$$

- *Panel shear rigidity*

$$U = \frac{G(d+c)^2 b}{4c} \quad (2)$$

- *Sandwich Panel deformation*

$$\delta = \frac{PL^3}{48D} + \frac{PL}{4U} \quad (3)$$

2.5. Numerical Modeling

For the finite element analysis, a sandwich panel has been selected, featuring specific dimensions such as a honeycomb core cell size of 3.2 mm, facesheet thickness of 0.4 mm, honeycomb core height of 10 mm, panel width of 45 mm, and length of 200 mm.

Ensuring precision in the 3PBT conducted in ANSYS on this sandwich panel requires the creation of an accurate model. The modeling procedure incorporates the utilization of design modules tailored for composite sandwich panels and ANSYS Composite Prep-Post (ACP).

To streamline the modeling process, an alternative approach has been employed in which the solid core is attributed the orthotropic properties of the cell wall material, offering a more simplified representation. Because so many elements are needed, directly modeling the honeycomb cell geometry in ANSYS is computationally costly. Rather, the study uses a strain-energy homogenization-based equivalent solid model, which lowers computational complexity without sacrificing accuracy. A crucial component of this study is numerical modeling because while ANSYS offers elastic properties for thin face sheets like carbon fiber, it necessitates special computations for honeycomb cores with orthotropic behavior. Figure 4 represents the Equivalent core in the solid form of a honeycomb structure.

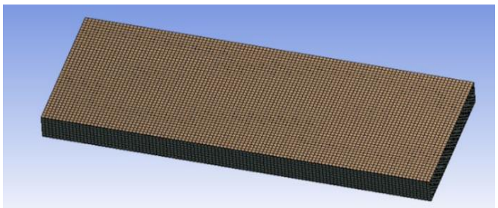

Fig. 4. Equivalent Core

2.6. Meshing

The modeling process employs Ansys software, where the face sheets are modeled orthotropically using Ansys Composite Prep-Post, while the homogenized core is created in Ansys Design Modeler. In this method, the core is represented by replacing honeycomb cells with a solid core mimicking the honeycomb structure at a macroscopic level. The solid core is given the same orthotropic properties as the original honeycomb core. Meshing of the core involves SOLID 186 elements, which are higher-order 3D 20-node solid elements capable of handling plasticity, large deflection, and large strain. Meanwhile, the face sheets are meshed using SHELL 181 elements, 3D four-node elements with six degrees of freedom at each node. The contact between the face sheet and the core is considered bonded, treating them as an integrated unit, and configured using a penalty method formulation in the FEA approach. The penalty method was selected because of its computational efficiency, which reduces cost and convergence time by avoiding iterative updates of Lagrange multipliers, as opposed to the augmented Lagrange and pure Lagrange multiplier methods. Additionally, it prevents divergence in nonlinear contact problems by permitting tiny interpenetrations, which improves numerical stability. Additionally, because the majority of commercial finite element solvers offer reliable automatic tuning, they offer ease of implementation. Given the trade-offs between accuracy, stability, and computational feasibility, it is the best option because previous research has confirmed its efficacy for composite sandwich structures. This contact setup provides translations along the x, y, and z axes, as well as rotations about the three axes. Table 5 shows the mesh statistics.

Table 5. Mesh Statistics

	No. of Elements	Element Size (mm)	Nodes	Element Quality	Jacobian Ratio
Upper F/S	4662	1.8	4816	.978- .999	1-1.03
Core	37832	1.8	168661	.991	1
Lower F/S	4662	1.8	4816	.981-.999	1-1.03

2.7. Simulation Methodology

After the sandwich panel modeling and material properties definition are finished, the panel is imported into the static structure module of Ansys. The study assumes that the primary cause of sandwich panel failure will be core shearing. Due to its dominance in sandwich structures, especially those with honeycomb cores, which have a low shear modulus, core shear failure was thought to be the main failure mode. Additionally, under bending and transverse loads, core shear failure usually occurs before face sheet delamination or buckling. Knowing core shear resistance is essential for structural integrity because of its industry relevance in aerospace and automotive applications. The analysis entails using a flat support and a flat loading bar, both with a width of 25 mm. A gradually increasing load is applied to the panel at a rate of 16.5 N/s until failure occurs. ASTM C393/C393M (Standard Test Method for Flexural Properties of Sandwich Constructions) and other experimental testing standards, as well as industry practices, are in line with the selected load application rate. These standards generally suggest loading rates that minimize dynamic effects and guarantee quasi-static conditions. Failure is determined by the shear stress in the homogenized core reaching the shear strength in the L direction, with the load at this point termed the "ultimate load." To simulate rollers, the centerline's five degrees of freedom are constrained, except for rotation about the y-axis. Figure 5 depicts the final assembled model of a composite sandwich panel with an equivalent honeycomb core.

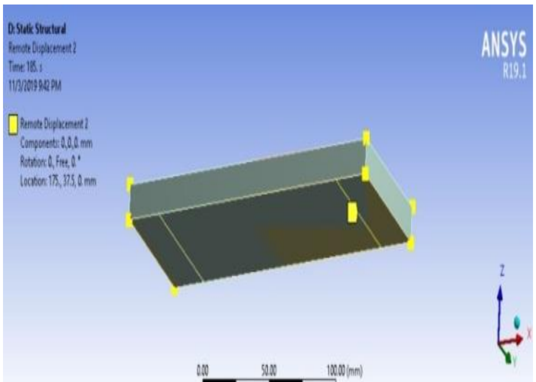

Fig. 5. Assembled model

3. Results

3.1. FEA Results for Sandwich Structure

Since stiffness directly affects the panel's structural integrity and load-bearing capacity, it is a crucial parameter in the study of failure mechanisms of composite sandwich panels composed of epoxy carbon face sheets and Kevlar honeycomb core. So, for the following reasons, stiffness has been calculated for this research work:

- *Failure Prediction and Control of Deformation:* In general, higher stiffness results in lower deflections under load, preventing excessive bending that may cause early failure modes such as delamination, face sheet buckling, or core shear.
- *Core Shear and Face Sheet Buckling:* The way a sandwich structure withstands shear forces is influenced by the stiffness distribution between the face sheets and core. Before the face sheets can support their full load, the core may fail in shear if it is overly pliable (low stiffness). Failure before the core absorbs a substantial amount of energy may result from local or global buckling of the face sheets caused by inadequate panel stiffness.
- *Delamination Resistance:* Concentration of stress at the interface may cause delamination between the shell and the core. Hardness affects the distribution and transfer of these stresses, which in turn affects the probability of delamination.
- *Energy Absorption and Impact Resistance:* The ability of sandwich panels to absorb energy is influenced by stiffness. Impact loads are effectively dispersed throughout the structure with a well-optimized stiffness, minimizing localized damage and improving overall impact resistance.

Two sandwich panels having a core with a cell size of 3.2 mm and 4.8 mm, CFRP facesheets of thickness 0.4 mm and 0.6 mm, and core heights of 10 mm and 8 mm, respectively, have been selected randomly for the finite element analysis. The FEA results are shown below for the panels having a core cell size of 3.2 mm and 4.8 mm, respectively.

Figure 6 displays the finite element simulation results of a 3PBT. The simulation setup consists of a rectangular composite beam with boundary conditions applied at both ends to simulate simple supports. A concentrated force of 1484 N is applied at the center of the beam, as indicated by the red-highlighted loading zone.

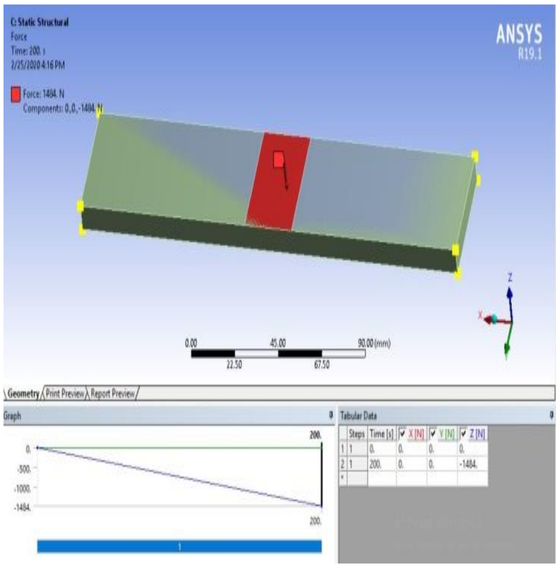

Fig. 6. Three-Point bending test simulation of a composite sandwich structure in ansys r19.1 with core cell size 3.2 mm

The color gradient on the beam represents the deformation and stress distribution, with the red region indicating the highest stress concentration at the loading point. The graphical results below show a linear force-deflection response, characteristic of elastic bending behavior.

This analysis provides insights into the structural behavior of the composite sandwich panel under flexural loading, which is critical for assessing its strength, stiffness, and failure mechanisms. It is depicted that the ultimate load attained during the 3PBT is 1484 N. This ultimate load is reached at the juncture where the core experiences failure due to core shear.

Figure 7 shows the FEA results of a 3PBT simulation. The Z-axis directional deformation is captured by the simulation, and the displacement magnitude is indicated by the color gradient. At both ends of the beam, the red areas represent the maximum displacement of 0.0471. The blue area at the center indicates the minimum displacement of 2.628mm, which is caused by the applied force and occurs in the negative Z-direction. With the sandwich panel's upper face experiencing compression and its lower face experiencing tension, the structure displays a distinctive bending deformation. A gradient of displacement values is represented by intermediate colors in the scale bar at the bottom, which measures the deformation throughout the structure. This simulation helps evaluate stiffness, strength, and failure mechanisms in engineering applications by offering important insight into the flexural behavior of the composite sandwich panel under loading.

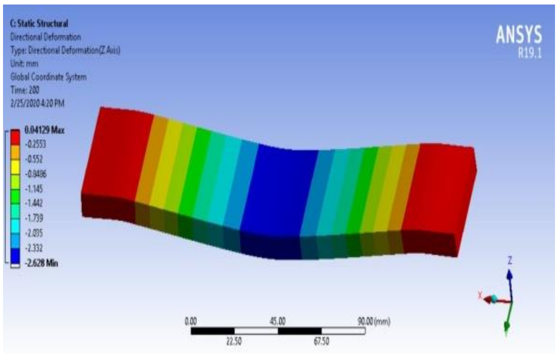

Fig. 7. 3PBT test simulation – directional deformation analysis for core cell size 3.2 mm

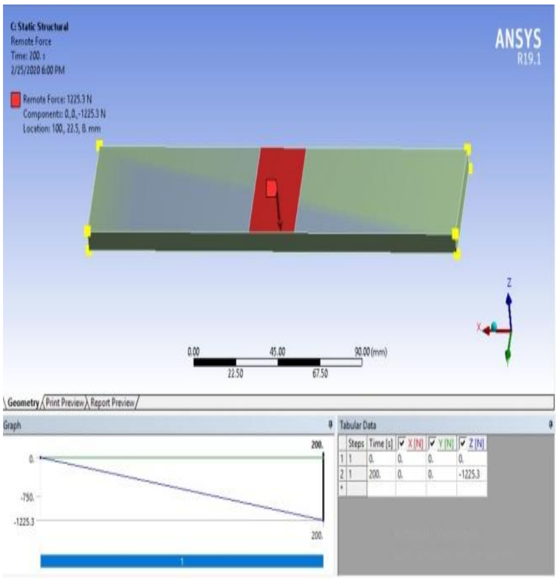

Fig. 8. FEA simulation under remote force with core cell size 4.8 mm

Figure 8 shows that when the panel is subjected to a remote force of 1225.3 N at a specific location (X = 100 mm, Z = 8). The model appears to be a static structural analysis (5 mm). While the red-highlighted area indicates the load application point, the boundary conditions (possibly fixed supports) are applied at the panel ends (yellow markers). The graph at the bottom left shows that the force remains constant over time at 1225.3 N. As the tabular data confirms the force values in the Z-direction (-1225.3 N), a downward force is applied. The color gradient of the panel shows the distribution of stress or deformation, with the red zone indicating the area where stress is concentrated the most.

This type of simulation is useful for determining the strength, deformation, and stress distribution of composite sandwich structures under various loading conditions.

Figure 9 shows the static structural simulation of a composite sandwich panel with a core cell size of 4.2 mm. The directional deformation of the Z-axis under an applied load is the main focus of this analysis. This deformation distribution is indicated by the red-to-blue color gradient. The greatest positive deformation (outward displacement) is seen in red areas. Maximum negative deformation (inward displacement) is seen in blue regions. According to the scale on the left, the maximum deformation is 0.002715 mm, and the minimum deformation is -2.623 mm. Under loading, the sandwich panel exhibits a typical flexural response by bending downward in the middle. Boundary conditions that limit movement are indicated by the fixed or constrained ends (highlighted in red).

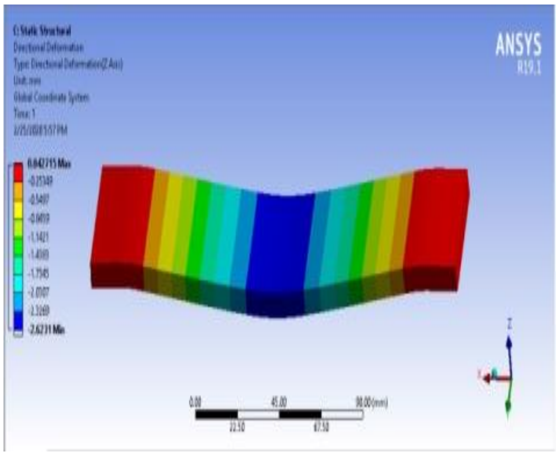

Fig. 9. 3PBT test simulation – directional deformation analysis for core cell size 4.8 mm

After detecting the load and deflection using ANSYS, the equivalent stiffness of the sandwich panel can be computed as:

Stiffness of panel 1=564.688 N/mm.

Stiffness of panel 2=467.137 N/mm.

3.2. Fabrication Process

To experimentally validate the numerical model, two composite sandwich panels, having the same configuration as employed for numerical analysis, have been fabricated using the "Vacuum-Assisted Hand Layup Method." During fabrication, stringent quality control procedures were used to guarantee consistency and dependability in the experimental results. Prior to use, the CFRP face sheets and Kevlar honeycomb cores were examined for flaws and obtained from approved vendors. Consistent curing time, temperature, pressure, and resin application were maintained through the use of a standardized fabrication process. Uniform bonding between the face sheets and the core was guaranteed by vacuum-assisted resin infusion. Using digital calipers, the dimensional accuracy was confirmed; deviations greater than ±0.1 mm were either discarded or reprocessed.

The fabrication process starts with the surface preparation of the steel substrate. Following surface preparation, the mold setting process is executed. A vacuum is employed to aid resin flow through a fiber layup contained within a mold tool, protected by a vacuum bag. Finally, a wax coating is applied to achieve a highly polished surface. Figure 10 illustrates the process of applying epoxy to the face sheet and positioning the honeycomb core on it. Composite manufacturers often blend epoxy resins with carbon fiber because these materials work well together. Epoxy is uniquely effective in adhering to carbon fiber.

Fig. 10. (a) Carbon fiber facesheet with epoxy, (b) Bonding of core and facesheet

It is followed by the application of a bonding agent to the carbon fiber; the Kevlar honeycomb core is placed in the middle of the surface as shown in Figure 10.

Afterward, the core surface is overlaid with a second layer of carbon fiber face sheet, and the entire specimen is wrapped with blue perforated film and a peel ply, as shown in Figure 11. To control resin bleed, a commonly used approach is to employ a perforated release film. The size and layout of the perforations can be adjusted to achieve the desired level of resin flow.

Fig. 11. Perforated film and peel ply

Afterward, the setup is enclosed by sealing it with a breather cloth, and a vacuum bag is introduced, with all sides carefully sealed. The breather facilitates the even distribution of vacuum pressure across the entire surface of the laminate. The laminate is shielded within a sealed covering, which could be either an airtight mold or an airtight bag, depending on the situation. Following that, the vacuum pump was activated, creating suction to remove air from the bag, as depicted in Figure 12.

Fig. 12. Final setup for panel fabrication

Subsequently, the arrangement was left to undergo the curing process. Once cured, the edges of the sandwich structures were cleansed. The same fabrication procedure was followed for the preparation of two different types of composite sandwich panels.

3.3. Three Point Bending Test (3PBT)

In accordance with ASTM C393 (27), the 3PBT is employed to assess various mechanical properties such as load, deformation, and stiffness in the sandwich structure of the sandwich using the Universal Testing Machine (UTM-D2-SERVO), which has a capacity of 500 KN. Because of its simplicity and efficiency in determining flexural properties, the Three Point Bending Test has been opted for over alternative techniques like the Four Point Bending Test or Shear Tests. By causing a greater concentration of stress at the loading point than four-point bending, 3PBT makes it possible to evaluate material failure characteristics more directly. Shear tests are also helpful for assessing shear characteristics, but they don't offer a thorough understanding of the flexural response, which was the main objective of our investigation. 3PBT was therefore judged to be the best approach for our study. Two specimens for each configuration have been tested using 3PBT, and the values of the load and deformation have been calculated. Figure 13, shown below, gives a look at the 3PBT testing setup.

Fig. 13. 3PBT setup

Following the testing, it was observed that the specimens failed due to the core crushing, attributed to face wrinkling and core shear. The typical force-displacement curve of the panel in the 3PBT is illustrated in Figure 14. The point of peak load (at point B) divides the curve into two stages: the initial stage indicates linear elastic deformation of the sandwich panel from point O to point B during the pre-buckling phase. The relationship between displacement and load exhibits linear growth, and the sandwich's stiffness is determined by the slope of this straight line. The second stage, post-buckling, commences from point B and extends to the endpoint. The CFRP face sheets and the Kevlar honeycomb core share the applied load in an elastic manner during the pre-buckling stage. Following peak load, the core experiences progressive densification, which causes a gradual load drop rather than an abrupt failure. This phase is known as the post-buckling stage. As opposed to aluminum cores, which break brittlely, and Nomex cores, which have a lower shear strength, the Kevlar honeycomb core shows high energy absorption because of progressive crushing. Research backs up this behavior, demonstrating Kevlar's greater impact resistance, which makes it perfect for protective automotive and aerospace applications.

The graph shown in Figure 14 reveals a rapid decrease in force after reaching the peak load, followed by a broad platform zone. During this stage, the overall bearing capacity of the sandwich panel declines rapidly as both the core and panel components collectively subside. This phase is characterized by significant energy absorption.

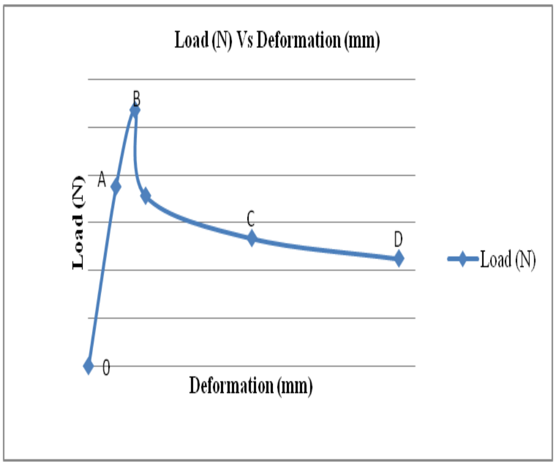

Fig. 14. Three-Point bend test curve of the sandwich panel

Also, from this test, the load and deformation have been calculated, and ultimately, the equivalent stiffness from the average of the results of two specimens has been calculated as shown in Table 6.

Table 6. Load and Deflection for Specimens

Specimen	P (N)	δ (mm)	Stiffness (N/mm)
1 (cell 3.2 mm)	1474	2.587	571.76
2 (cell 3.2 mm)	1482	2.613	567.16
Average	1478	2.60	569.46
1 (cell 4.8 mm)	1215.56	2.579	471.71
2 (cell 4.8 mm)	1222.75	2.612	468.13
Average	1219.15	2.595	469.80

3.4. Analytical Analysis

As mentioned above in the mechanics of the sandwich panel section, the different values of deflection have been calculated using the ultimate load values obtained in the numerical analysis section, as shown in Table 7.

Table 7. Stiffness using analytical analysis

Specimen	P (N)	δ *(mm)*	Stiffness (N/mm)
1 (cell 3.2 mm)	1474	2.78	530
2 (cell 3.2 mm)	1482	2.80	529.28
Average	1478	2.79	529.74
1 (cell 4.8 mm)	1215.56	2.53	480.46
2 (cell 4.8 mm)	1222.75	2.55	479.50
Average	1219.15	2.54	479.9

3.5. Validation of Results

To assess the credibility of the numerical model, the results from various types of analyses need to be compared. Thus, Table 8 is compiled to present distinct stiffness values obtained from three different types of analyses.

Table 8. Comparison of Results from Three Analyses

Type of Analysis	Stiffness (N/mm) With a cell size of 3.2 mm	Stiffness (N/mm) With a cell size of 4.8 mm
FE Analysis	564.688	467.137
Exp. Analysis	569.46	469.80
Analytical Analysis	529.74	479.98
Error % (FE and Exp. Analysis)	0.84%	0 .56%
Error % (FE and Analytical Analysis)	6.19%	2.74%

The comparative analysis presented in Table 7 indicates a consistent agreement among the three types of analyses. This confirms the adoption of the Gibson and Ashby model for determining the orthotropic properties of the honeycomb core. The conversion of the honeycomb core into a solid equivalent and the verification of the sandwich panel model have been effectively accomplished through both experimental and analytical approaches. Furthermore, the reliability of the provided numerical model for assessing composite sandwich panel structures has been verified. Differences in stiffness values, especially lower FEA predictions for the 3.2 mm core, are caused by idealized boundary conditions, variability of material properties, and loading/fixture constraints. FEA makes the assumption that there is perfect bonding, but experimental flaws, Test configurations introduce small misalignments that affect stiffness measurements, and manufacturer data used in FEA may differ slightly from actual material properties. Notwithstanding small variations, FEA trends and experiments agree well, demonstrating the accuracy of this method for forecasting mechanical behavior. This model and its associated modeling procedures can be extended for testing sandwich panels with cores composed of alternative materials such as Nomex or Glass honeycomb cores.

4. Conclusions

In this research, a composite sandwich panel comprising CFRP as outer layers and a Kevlar core, structured in a regular hexagon pattern, was modeled as an equivalent solid. The Kevlar Honeycomb core's orthotropic properties were determined using the Gibson and Ashby model. The sandwich panel's ultimate load and deformation were assessed using a 3-point bending test (3PBT) in ANSYS, following ASTM C393 standards.

Additionally, a physical composite sandwich specimen was fabricated and subjected to a 3PBT for experimental analysis. The stiffness of this specimen was also calculated analytically according to ASTM C393 standards.

The experimental values of 569.46 N/mm and 469.80 N/mm, respectively, are closely matched by the FEA results, which indicate stiffness of 564.688 N/mm for a 3.2 mm cell size and 467.137 N/mm for a 4.8 mm cell size. There is good agreement between the numerical and experimental methods, as evidenced by the small percentage error between FEA and experimental analysis, which is 0.84% for 3.2 mm and 0.56% for 4.8 mm. At 6.19% for 3.2 mm and 2.74 % for 4.8 mm, the error between FEA and Analytical Analysis is marginally higher. This could be because the analytical model was simplified. With only slight variations brought on by idealized boundary conditions and material assumptions in the simulations, the results show that FEA offers a trustworthy approximation of stiffness overall.

Whereas real-world variables like adhesive imperfections and fiber waviness result in localized variations, FEA assumes homogeneous bonding between CFRP face sheets and the Kevlar core. Idealized boundary conditions in simulations are not the same as experimental setups, where load distribution is impacted by misalignments and fixture compliance. Additionally, under high-impact or fatigue loading, other mechanisms such as debonding or face-sheet wrinkling may predominate even though core shearing is thought to be the main failure mode.

To gain a better understanding of failure mechanisms, future research could concentrate on dynamic impact simulations and progressive damage modeling. Strengthening the structure would require examining different core materials, bonding methods, and fatigue behavior under cyclic loading. Predictive models based on machine learning may also be integrated to enhance design optimization and numerical simulations.

Nomenclature

CRFP	Carbon fiber reinforcement fiber
GFRP	Glass fiber reinforcement
3PBT	Three point bend test
FEA	Finite element analysis
MPa	Mega pascal
ρ_c, ρ_s	Density of core and core solid material
Gs	Shear modulus of solid material
Es	Young's modulus of solid material
$E_{x,y,z}$	In and out young's modulus of core
Vxy	In plane poission's ratio of core
Vxz,yz	Out plane position's ratio of core
Gxy	In plane shear modulus of core
Gxz,yz	Out of plane shear moduli of core

Acknowledgments

We express our gratitude to Dr. Sonu Singh (IIT Delhi) for his invaluable assistance in conducting various mechanical tests.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

References

[1] Kalpak, S., Nagesh, S. & Manoj, D., 2017. A comparative study of hot rolled section (HRS) and cold formed section under combined bending and shear using ANSYS.16. International Journal of Scientific Research and Development, 5(2), pp.1399–1403.

[2] Arbaoui, J., Schmitt, Y. & Royer, F., 2014. Effect of core thickness and intermediate layers on mechanical properties of polypropylene honeycomb multi-layer sandwich structures. Archives of Metallurgy and Materials, 59(1), pp.11–16. doi:10.2478/amm-2014-0002.

[3] Khan, M.A. et al., 2017. Experimental and numerical analysis of flexural and impact behaviour of glass/pp sandwich panel for automotive structural applications. Advanced Composite Materials. doi:10.1080/09243046.2017.1396199.

[4] Ijaz, H. et al., 2017. Finite element analysis of bend test of sandwich structures using strain energy based homogenization method. Advances in Materials Science and Engineering, p.8670207. doi:10.1155/2017/8670207.

[5] Gornet, L., Marguet, S. & Marckmann, G., 2006. Finite element modeling of Nomex® honeycomb cores: Failure and effective elastic properties. International Journal of Computational Materials Science and Continuum Technology, 4(2), pp.63–74. DOI:10.3970/cmc.2006.004.063.

[6] Ijaz, H. et al., 2014. Strain energy based homogenization method to find the equivalent orthotropic properties of sandwich structures. Sindh University Research Journal (Science Series), 46(1), pp.93–98.

[7] Schwingshackl, C.W., Aglietti, G.S. & Cunningham, P.R., 2006. Determination of honeycomb material properties: Existing theories and an alternative dynamic approach. Journal of Aerospace Engineering, 19(3), pp.177–183.doi:10.1061/(ASCE)08931321(2006)19:3(177).

[8] Chamis, C., Aiello, R. & Murthy, P., 1988. Fiber composite sandwich thermostructural behavior: Computational simulation. Journal of Composite Technology and Research, 10, pp.93–99.

[9] Czechowski, L., Jankowski, J. & Kotełko, M., 2017. Experimental and numerical three-point bending test for sandwich beams. Journal of KONES Powertrain and Transport, 24(3), pp.53–62. doi:10.5604/01.3001.0010.3071.

[10] Hussain, M., Khan, R. & Abbas, N., 2019. Experimental and computational studies on honeycomb sandwich structures under static and fatigue bending load. Journal of King Saud University - Science, 31, pp.222–229. doi:10.1016/j.jksus.2018.05.012.

[11] Chauhan, S.S. & Bhaduri, S.C., 2020. Structural analysis of a four-bar linkage mechanism of prosthetic knee joint using finite element method. EVERGREEN – Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 7(2), pp.209–215.

[12] Çınar, O., Erdal, M. & Kayran, A., 2017. Accurate equivalent models of sandwich laminates with honeycomb core and composite face sheets via optimization involving modal behavior. Journal of Sandwich Structures & Materials, 19(2), pp.139–166. doi:10.1177/1099636215613934.

[13] Foo, C.C., Chai, G.B. & Seah, L.K., 2008. Mechanical properties of Nomex material and Nomex honeycomb structure. Composite Structures, 80(4), pp.588–594. doi:10.1016/j.compstruct.2006.07.010.

[14] Roy, R. et al., 2012. Finite element modeling of Nomex® honeycomb core carbon/epoxy composite sandwich panels. Advanced Science Letters, 15(1), pp.257–264. doi:10.1166/asl.2012.4164.

[15] Herranen, H. et al., 2012. Design and testing of sandwich structures with different core materials. Materials Science (Medžiagotyra), 18(1),pp.45–50. doi:10.5755/j01.ms.18.1.1340.

[16] Ijaz, H. et al., 2017. Finite element analysis of bend test of sandwich structures using strain

energy based homogenization method. Advances in Materials Science and Engineering. doi:10.1155/2017/8670207.

[17] Hussain, M., Khan, R. & Abbas, N., 2017. Experimental and computational studies on honeycomb sandwich structures under static and fatigue bending load. Journal of King Saud University - Science, 31(2), pp.222–229. doi:10.1016/j.jksus.2018.05.012.

[18] Yuan, J., Zhang, L. & Huo, Z., 2017. An equivalent modeling method for honeycomb sandwich structure based on orthogonal anisotropic solid element. International Journal of Aeronautical and Space Sciences, 21(4), pp.957–969. doi:10.1007/s42405-020-00259-6.

[19] Kumar, A. & Supale, J.P., 2023. Manufacturing and structural analysis of a composite sandwich panel used for aircraft flooring. Energy and Environment Focus, 7(2), pp.129–136. doi:10.1166/eef.2023.1276.

[20] Seemann, R. & Krause, D., 2017. Numerical modelling of Nomex honeycomb cores for detailed analyses of sandwich panel joints. *In* 11th World Congress on Computational Mechanics (WCCM XI).

[21] Kumar, A., Chanda, A.K. & Angra, S., 2020. Analysis of the effects of varying core thicknesses of Kevlar honeycomb sandwich structures under different regimes of testing. Materials Today: Proceedings, 21, pp.1615–1623. doi:10.1016/j.matpr.2019.11.2.

[22] Narasimhan, R.K. & Zeleniakiene, D., 2017. Modelling of honeycomb core sandwich panels with fiber reinforced plastic facesheets and analysing the mechanical properties. IOP Conference Series: Materials Science and Engineering, 111(1). doi:10.1088/1757-899X/111/1/012001.

[23] Rupani, S.V., Jani, S.S. & Acharya, G.D., 2017. Design, modelling and manufacturing aspects of honeycomb sandwich structures: A review. International Journal of Scientific Development and Research. doi:10.1712/ijsdr.17013.

[24] Kumar, A., Chanda, A.K. & Angra, S., 2021. Numerical modelling of a composite sandwich structure having non-metallic honeycomb core. EVERGREEN – Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, 8(4), pp.759–767. doi:10.5109/4742119.

[25] Gibson, L. & Ashby, M., 1997. Cellular solids: Structure and properties (Cambridge Solid State Science Series). Cambridge: Cambridge UniversityPress. doi:10.1017/CBO9781139878326.

[26] Plascore, 2019. Honeycomb Data Sheets. [online] Available at: https://www.plascore.com/download/datasheets/honeycomb_data_sheets/PLA_PK2_2019.pdf [Accessed January 2023].

[27] ASTM International, 2020. ASTM C393 / C393M-20. Standard test method for core shear properties of sandwich constructions by beam flexure. West Conshohocken, PA: ASTM International. Available at: www.astm.org.

[28] Kumar, A., Dev, K. & Dahiya, A., 2023. Fabrication and mechanical characterization of pomegranate peel powder mixed epoxy. EVERGREEN, 10(4), pp.2173–2179. doi:10.5109/7160892.

[29] Kumar, A., Chanda, A.K. & Angra, S., 2021. Optimization of stiffness properties of composite sandwich using hybrid taguchi-gra-pca. EVERGREEN, 8(2), pp.310–317. doi:10.5109/4480708.

[30] Gupta, M.K., Singhal, V. & Rajput, N.S., 2022. Applications and challenges of carbon-fibers reinforced composites: a review. EVERGREEN, 9(3), pp.682–693. doi:10.5109/4843099.

[31] Taghipoor, H. & Ghiaskar, A., 2024. Optimized enhanced energy absorption in polymer nanocomposites reinforced with nano-clay, nano-silica, and diethylenetriamine. Scientific Reports, 14. doi:10.1038/s41598-024-77960-z.

[32] Ghiaskar, A. & Nouri, M.D., 2023. Investigating fracture behavior and energy absorption of flexible hybrid biocomposites with soft–hard rubber/biofiller layers and fabric impregnated with matrix under high-velocity impact. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 45, p.585. doi:10.1007/s40430-023-04507-0.