

Investigation of mechanical properties of aluminum 3003 core honeycomb sandwich structures reinforced with carbon, nylon fibers face sheet and polyurethane foam filler

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Abstract

Lightweight sandwich-based structures are progressively used in the aerospace industries and automotive industries, such as bumper and marine sectors, like rubbing nails in boats, mainly for their high strength-to-weight ratios. Among these, honeycomb cores made of Aluminum 3003 offer excellent stiffness and energy absorption. Enhancing their mechanical performance through reinforcement and optimized filler materials is the predominant focus. This study focuses investigating the mechanical behavior of the Aluminum 3003 honeycomb sandwich structures filled with polyurethane foam reinforced with carbon and nylon fibers. The objective is to improve key mechanical properties, including compressive, tensile, impact, and flexural strength under three-point bending tests by introducing a low-density filler within the honeycomb core. Core, face sheets, and filler materials are selected for optimal energy absorption. Experimental and numerical analyses are conducted to compare performance, with an emphasis on achieving enhanced mechanical properties through filler integration. The findings hold potential for advancing lightweight, high-performance energy-absorbing structures in automotive and marine design. The incorporation of polyurethane (PU) foam significantly enhanced the mechanical performance of the sandwich structures. Compared with the corresponding unfilled configurations, the PU-filled sandwich panels exhibited improvements of 9% in tensile strength, 33% in compressive strength, 28% in flexural strength, and 34% in impact resistance, depending on the face-sheet configuration. The results indicate a significant improvement in mechanical properties, especially with carbon fiber reinforcement. Nylon fibers also showed performance gains, particularly in energy absorption. The reinforced foam acted synergistically with the honeycomb to delay failure and improve stiffness.

Keywords: Aluminum 3003, Honeycomb sandwich structure, Polyurethane foam, Carbon fiber reinforcement, Nylon fiber reinforcement, Mechanical properties, Energy absorption

1. Introduction

The demand for lightweight materials, especially in the fields of automobile and aerospace, has surged in recent days, focusing on reducing fuel consumption and enhancing overall vehicle efficiency. The Industry has adopted composite materials instead of metallic materials and alloys due to the better stiffness-to-weight ratio. Aluminum honeycomb sandwich panels, originating from the aerospace industries, are preferably suitable for lightweight applications, mainly for the characteristics of superior strength-to-weight ratio. This one key approach provides a replacement of traditional heavier steel-like materials with advanced composite materials offering low density with high strength and stiffness [1, 4].

The changes in the materials further shifted to sandwich structures, especially in aluminum honeycomb panels [2], which are renowned for the better ratio of strength-to-weight and excellent energy absorbing capabilities, preferable for protective applications like automotive bumpers and shields. Automotive bumpers, designs are focused on absorbing the impact energy during the front collision and protecting various internal parts of the vehicle, including the engine and radiator in vehicles or hulls in boats. The traditional materials during the early periods are primarily steel-based, which offers substantial impact strength by resistance and on the other hand, the vehicle weight increases significantly [3]. Presently, industry demands lightweight materials which have superior strength without compromising the fuel consumption and vehicle performance. Aluminum honeycomb sandwich panel's standout from the composite material for their exceptional mechanical properties due to their distinctive geometry and structural interplay with core and face sheets like a sandwich [5]. In these sandwich structures, the core typically has a lightweight material, such as honeycomb-patterned core which distributes the forces efficiently during the addition of weight. The honeycomb core is bonded with outer face or skin sheets, which provide better rigidity and resistance to deformation [6]. These structures' mechanical properties are inherently linked to the materials and geometry of the core, as well as the face sheet, and by adding filler materials inside the core structure improves the properties. Furthermore, these fillers occupy within the honeycomb cells, resulting in additional resistance to the impact and compressive forces. The filler materials chosen, preferably of lower density with high impact resistance, result in better energy absorption with persevering the core structures' light-weight advantages [7].

The performance of the sandwich panel will be enhanced further if the face sheet is made up of carbon fiber reinforcement and the Aluminium alloy as a core material [11]. In order to predict the performance and validation, both the experimental and numerical analyses are planned to be carried out in this project. Mechanical properties can be further improved by introducing different filler materials in cap of the core material of the sandwich structures [12]. [13] Choices of material, core cell size, and density of the material are some of the vital parameters that affect the mechanical behavior and properties of the sandwich structure [14]. The variations in the cell size result in an increase in the results related to the energy absorbing capacity. [15] Aluminium alloy is preferably used in the transport industry due to its low weight and high-energy absorbability capabilities. [16] Mechanical performance of the honeycomb sandwich plate can also be enhanced by varying the honeycomb web thickness variation and individual cell size variation [17, 18]. Both the experimental models and finite element models are carried out to predict and validate the behavior of the sandwich structure with different loading conditions. [19] Improvement in the energy absorption under impact loading conditions if the bumper beam system is filled with filler material [20]. Carbon fiber has high-strength and lightweight characteristics and along with the aluminum alloy, it can be used as a protective shielding for the bumpers.

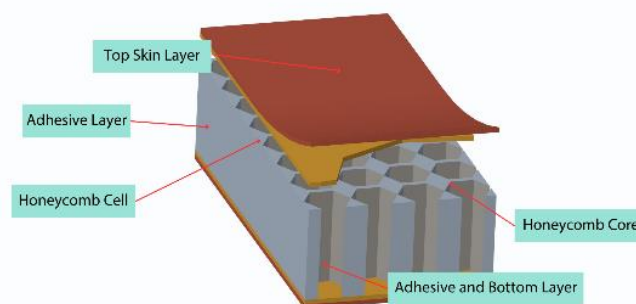
The current work aims at the enrichment of the mechanical properties of the honeycomb sandwich panels or structures by incorporating the filler materials into the core made of aluminum material with a honeycomb pattern, with the face sheets made up of carbon fibers [8]. The study investigates the behavior of the modified structures under the focused mechanical-based testing conditions, tensile testing, compression testing, flexural testing or three-point bending testing, and impact testing. These experimental test results are again attempted to improve the panel properties by adding nylon fiber along with carbon fiber at a suitable proportion. The study aims in extent to which the filler materials in the sandwich panel enhance the energy absorption characteristics by comparing the experimental with numerical results, thus offering insight into how modified hybrid

panels' face sheet better protects the vehicles during the collision [9]. This work not only advances the understanding of composite material applications in vehicle design but also contributes to more economical, high-performance solutions for future lightweight transportation systems [10].

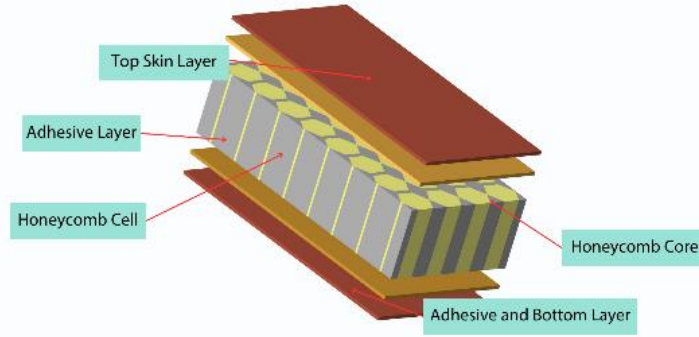
Although numerous studies have investigated aluminum honeycomb sandwich structures, most have focused either on foam-filled cores or on single-fiber composite face sheets. Comparatively fewer studies have examined the combined influence of polyurethane foam filling and hybrid carbon–nylon fiber face sheets under identical fabrication and testing conditions. Furthermore, limited attention has been given to correlating experimental mechanical behaviour with finite element analysis and microscopic failure characterization within a single investigation. The present work addresses these limitations by systematically comparing carbon fiber and carbon–nylon hybrid face sheet configurations bonded to Aluminum 3003 honeycomb cores, both with and without polyurethane foam reinforcement. In addition to evaluating tensile, compressive, flexural, and impact performance, the study combines numerical simulation and microscopic failure analysis to explain the mechanisms responsible for the observed improvements. This integrated approach provides a more comprehensive understanding of the structural behaviour of lightweight sandwich composites for transportation and energy-absorbing applications.

2. Materials and Methods

The experimental work has been segmented into two major categories. In the first segment, the unidirectional carbon fiber fabrics are used in the top and bottom layers of the composite face sheets as a reinforcement constituent. Epoxy resin (LY556) with hardener is used as the additive material [21]. Aluminum 3003 grade is taken for the study as a core material with honeycomb cell configuration (cell size=12 mm) of core thickness of 10 mm is used for the manufacturing of the composite sandwich plate or panel [22] as shown in Fig.1. Polyurethane (PU) is selected as filler material for the study due to less dense, capabilities to enhance the structure's mechanical based properties such as strength, stiffness and energy absorption capabilities. Similar panels are prepared with PU foam as filler to testify to the impact of fillers on core strength [23]. The contribution of polyurethane foam extends beyond simply filling the honeycomb cells. The closed-cell foam provides continuous support to the thin aluminum cell walls, reducing the likelihood of premature local buckling under mechanical loading. The foam also enhances stress transfer between the honeycomb core and composite face sheets while restricting localized deformation within the core. Consequently, crack initiation is delayed, damage propagation becomes more gradual, and the overall stiffness and energy absorption capability of the sandwich structure are significantly improved. These strengthening mechanisms explain the superior performance observed in the PU-filled specimens.



(a) Sandwich panel without filler



(b) Sandwich panel with PU foam filler material
Figure 1. Composite sandwich panels

In the second stage of the experiment, carbon fiber with nylon fiber has been used as a reinforcing constituent of the hybrid face sheet (top & bottom), with the same aluminum hexagonal comb (cell size=12mm) as the core material. Similar panels are prepared with Polyurethane (PU) foam as filler to assess the impact of fillers on core strength [24].

Table 1. Mechanical properties of the fibers

Properties	Carbon fiber	Nylon 6 fiber
Tensile strength / MPa	4500	80
Tensile modulus / GPa	340	3
Bending strength / MPa	3500	105
Bending modulus / GPa	275	4
Compressive strength / MPa	650	120
Elastic modulus / MPa	340	3

The composite sandwich structure is made with carbon fiber as face sheets with aluminum honeycomb as core component that is 16 mm thick with epoxy adhesive as a binder. The vacuum infusion technique is used to create composite face sheets in the initial stage. A smooth infusion table is used to hold the dry carbon and nylon fabrics while the infusion components (vacuum bag) are prepared [25]. As the part was maintained in a vacuum, the resin was then allowed to permeate the whole fabric network. Following the infusion, the components are left to cure at room temperature for 48 hours before being post-cured. Test specimens are cut to the appropriate size using an EDM machine in accordance with applicable ASTM standards. Epoxy adhesive holds the face sheets and core materials together. Surfaces of composite face sheets were coated with adhesive, and aluminum cores were used to sandwich them together [26]. Adding nylon to the carbon fiber to prepare the face sheet offers combined benefits. Nylon offers good flexibility and impact resistance, while carbon fiber offers better strength and stiffness. Nylon and carbon fiber are combined to form the face sheet in a 3:1 ratio for the second segment using the same manufacturing process to enhance the durability of the structure and load-bearing capacity, and properties of the fibers are highlighted in Table 1. The hybrid composite face sheet was fabricated using a 3:1 carbon fiber-to-nylon fiber ratio to obtain a balanced combination of stiffness, strength, and impact resistance. Carbon fiber was selected as the primary reinforcement because of its high tensile strength and elastic modulus, enabling the laminate to sustain higher structural loads. Nylon fiber was incorporated in a smaller proportion to improve toughness, delay crack propagation, and enhance energy absorption without significantly reducing the overall stiffness of the laminate. The

incorporation of a limited proportion of ductile fibers into a carbon fiber laminate has been reported to improve energy absorption and delay crack propagation while maintaining the structural stiffness required for lightweight engineering applications [40]. The selection of a carbon-dominant hybrid configuration is consistent, which reported that asymmetric hybridization improves the balance between structural stiffness and impact performance by combining the high modulus of carbon fibers with the superior toughness of ductile reinforcing fibers [41]. In both segments, panels are prepared with both PU foam as filler and without filler [27]. The process flowchart of the study is indicated in the Fig.2. and the four specimens taken for the study are denotes as follows: CFS indicates Carbon Fiber Sandwich Structure (without any filler material), CNFS indicates Carbon & Nylon Fiber Sandwich Structure (without any filler material), CFWFS indicates Carbon Fiber with PU Filler Sandwich Structure, and CNFWFS indicates Carbon & Nylon with PU Filler Fiber Sandwich Structure.

For each sandwich configuration, two identical specimens were fabricated and tested under tensile, compression, flexural, and impact loading conditions. The reported mechanical properties represent the average of two independent measurements, and the corresponding standard deviations were calculated to assess the repeatability of the experimental results. Although the limited number of specimens does not allow for a comprehensive statistical analysis or rigorous interpretation of error-bar, both tests for each configuration exhibited consistent trends, indicating good experimental reproducibility.

Mechanical characterization was carried out in accordance with the relevant ASTM standards. Tensile tests were performed following ASTM D638 using a universal testing machine, while compression tests were conducted in accordance with ASTM D3410M. Flexural properties were evaluated using the three-point bending method specified in ASTM D790, and impact resistance was determined following ASTM D3029-95 using a pendulum impact testing machine. All experiments were conducted under identical laboratory conditions using the same testing equipment and procedures to ensure consistency and improve the reliability of the experimental observations.

The mechanical properties reported in this study were calculated using the measured load, displacement, specimen dimensions, and absorbed impact energy obtained during experimental testing. Table 2 indicated the equations, for evaluating the mechanical performance of the sandwich specimens.

Table 2. Equations for evaluating of the mechanical performance

Tensile Strength (MPa)	Compressive Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m²)
$\frac{P_{max}}{A}$	$\frac{P_{max}}{A}$	$\frac{3PL}{2bd^2}$	$\frac{E}{A}$

Where,

- P_{max} = Maximum load (N)
- A = Cross-sectional area of the specimen (mm²)
- P = Maximum applied load (N)
- L = Support span (mm)
- b = Specimen width (mm)
- d = Specimen thickness (mm)
- E = Absorbed impact energy (J)

The mechanical properties of the sandwich specimens were determined using standard engineering relationships based on the experimental load, specimen dimensions, and absorbed impact energy. Tensile and compressive strengths were calculated from the maximum load divided by the corresponding cross-sectional area, while flexural strength was determined using the three-point bending equation specified in ASTM D790. The impact energy was directly obtained from the pendulum impact tester and used to evaluate the energy absorption capability of each sandwich configuration. These calculation procedures ensured consistency in evaluating and comparing the mechanical performance of all the fabricated specimens.

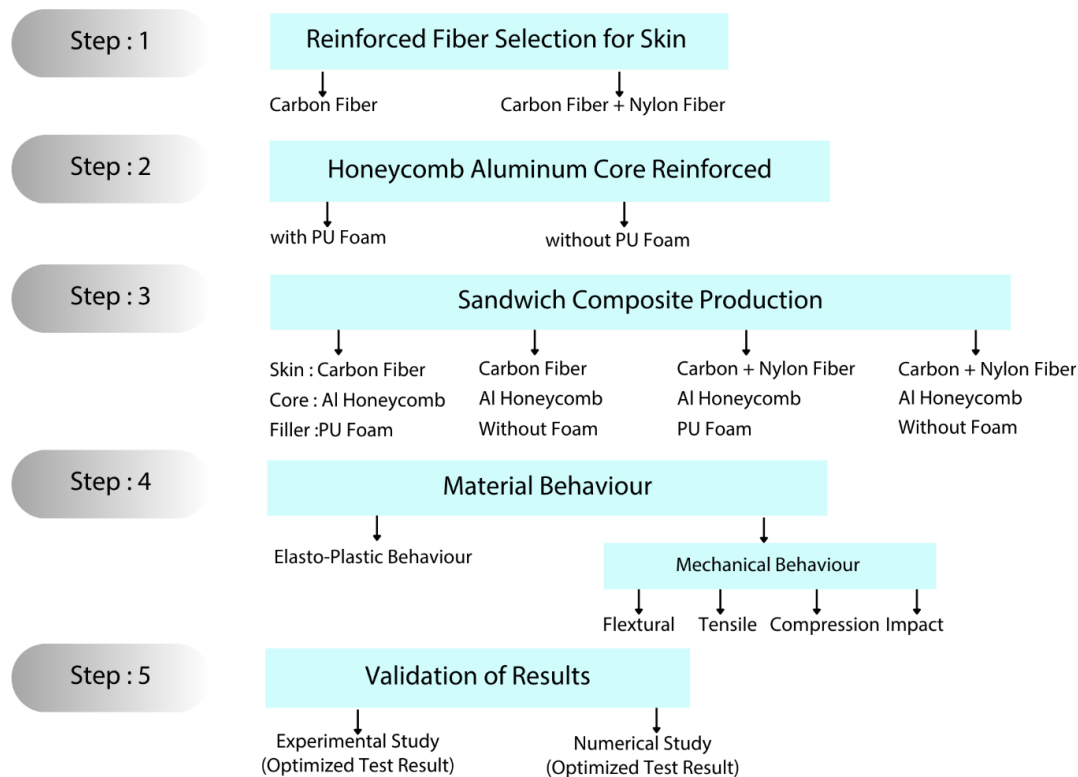


Figure 2. Process flowchart of the study

3. Results and Discussion

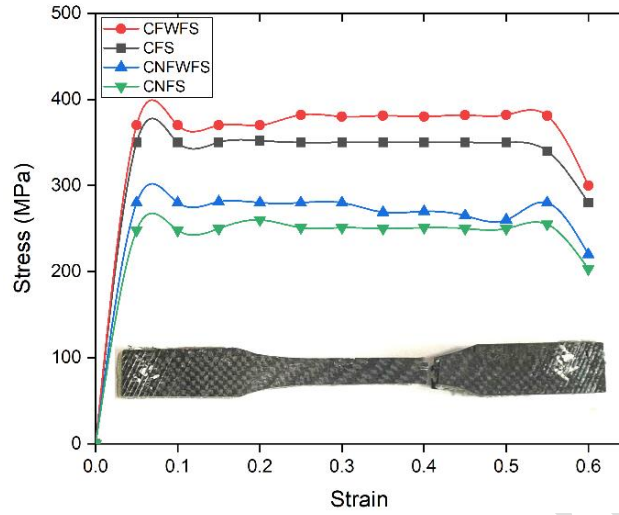
The aluminum core composite structures are fabricated with two different conditions such as with foam and without PU foam as infill for bumper and rub nail applications. The experimental and numerical results inferring the effect of infill in composite structures are discussed in the subsequent sections [28].

3. Mechanical behavior of the Sandwich

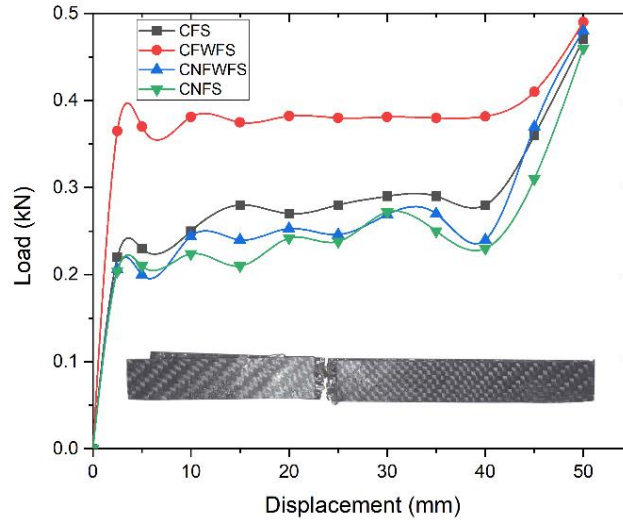
3.1 Tensile Testing

The tensile test, conducted as per ASTM D638, is to measure the elastic and plastic deformation, including elongation at the break of the composite material. This standard specifies the testing methodology for determining the stress-strain response when a material is subjected to uniaxial tensile forces [35]. The specimens are prepared with a length of 165 mm, a width of 19 mm, a gauge length of 50 mm, a gauge width of 13 mm, and a thickness of 10 mm to ensure consistency

with ASTM guidelines and are performed in a Kalpak 100 kN UTM KIC-2-1000-C machine in the longitudinal direction with a cross-head velocity of 0.05 mm/min.



(a) Stress-strain curves of four different samples in the tensile tests



(b) Load-displacement curve of compression tests

Figure 3. Mechanical behavior of the structure in tensile and compression testing

It provides critical insight into the specimen stability to withstand stretching forces, which is essential for applications requiring high strength and flexibility. The average stress value of the sandwich panel's tensile test of sandwich panels CFWFS, CNFWFS are 8%, 9% more than sandwich panels CFS, CNFS, respectively, and it's shown in Fig.3(a). This indicates that the foam inside the core significantly enhances the tensile strength of the sandwich panel due to the enhanced structural integrity and improved load distribution provided by the foam core [39].

3.2 Compression Testing

The Compression tests are performed as per ASTM D3410M-03 in the Kalpak 100 kN UTM KIC-2-1000-C machine (Fig.4) to assess the compressive strength of the panel and the modulus of the material. Specimens are subjected to axial compressive forces to evaluate resistance to compression, simulating conditions in which the material must withstand squeezing or crushing loads. This test is essential for applications where composite materials are used in

structural components subject to compressive forces. The standardized dimensions, 150 mm in length, 25 mm in width, and 16 mm in thickness, enable consistent measurements of compressive properties across samples [36]. Compressive strength of the sandwich panels CFWFS, CNFWFS are compared with the sandwich panels CFS, CNFS the results shows that, at an average 33% and 6% improvement in the performance respectively [39] due to the filler material (PU foam) acts a stabilizing medium inside the core structure which allows the panel to withstand the high compressive loads as an improved composite behavior and its indicated in the Fig. 3(b). Further, the PU foam's inherent compressive properties of the structure by making a strong bond with the face sheet, which results in increased stiffness, resistance to deformation, and strength improvement.

3.3. Flexural Testing

The Flexural testing is performed in the four samples by three-point bending method as per the ASTM D790 to investigate the flexural strength and stiffness of the panel. The three-point bending configuration is performed by supporting the test sample at the two ends, the load is applied on the center of the specimen, and bending stress is induced within the sample. The test provides the resistance opposed to the bending forces, which is a critical property in load-bearing applications. The test sample is prepared for the dimensions, 160 mm in length, 60 mm in width, and 16 mm in thickness to adhere to the ASTM specifications for performing the flexural testing [37].



Figure 4. Examination of the Specimen in the Flexural Test

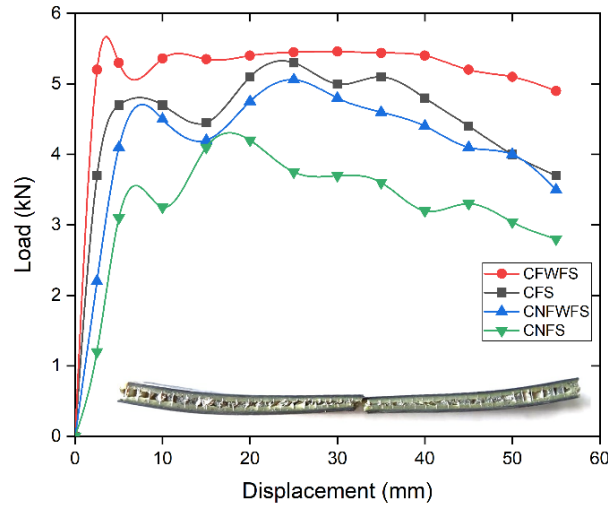


Figure 5. Load-displacement curve - lateral three-point bending tests

The average flexural strength of the sandwich panels CFWFS, CNFWFS are compared with the sandwich panel CFS, CNFS the results shows that, 16% and 28% improvement in the performance respectively [26], as indicated in the Fig .5 - mainly due to the improvement of the bending resistance given by the foam inside the core and additionally it supports the face sheet for maintains their separation under the loading condition by increasing the moment of inertial of the panel. This panel configuration allows the face sheets to withstand the tensile and compressive stress effectively during the process of bending. The PU foam inside the panel helps to distribute the stress uniformly and prevent the skin failure or buckling, while its bonding with the face sheet enhances the structure's overall stiffness, integrity, and leads to higher flexural strength.

3.4 Elastoplastic behavior

An aluminum 6065 honeycomb structure of wall thickness 0.0508 mm is modelled using Creo Parametric software. The Numerical modeled of the Sandwich core is shown in Fig.6, and the structure modeled for the flexural study is shown in Fig.7. The mechanical properties assigned to each component of the sandwich structure were based on experimentally measured values and validated literature data. The aluminum honeycomb core was modelled as an isotropic elastoplastic material, whereas the carbon fiber and carbon-nylon composite face sheets were assumed to exhibit homogeneous linear elastic behaviour within the applied loading range. The polyurethane (PU) foam filler was modelled as a low-density isotropic material to represent its contribution to load transfer and energy absorption. The material properties used in the numerical analysis, including Young's modulus, Poisson's ratio, density, and yield strength, are summarized in Table 3. Both the faces of the honeycomb structures are covered by composite plates of 3 mm made of carbon and nylon as fiber and epoxy as resin [29].

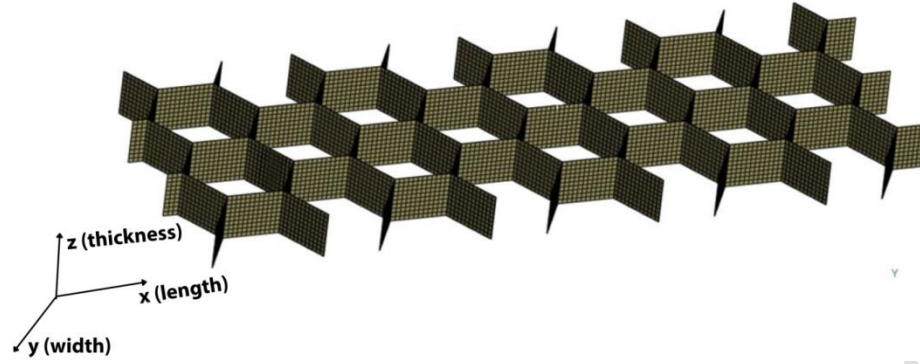


Figure 6. Sandwich Core Modeled for Numerical Study

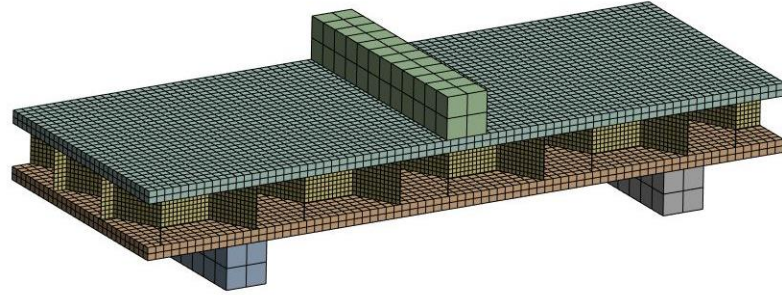


Figure 7. Numerical Model for the Flexural Test

The honeycomb structure, along with the face plate, is imported into Ansys Workbench, and is finite element model was developed using higher-order hexahedron elements (20-node Solid 186) [30]. The element is defined by 20 nodes, having each node is having three degrees of freedom: translations in the nodal x (along the length), y (along the width), and z (along the thickness) directions as shown in Fig. 6. The element behaves under the stress and deformation, which has capabilities of handling plasticity, hyperelasticity, creep, stress stiffening as well as large deflection and large strain. A mesh convergence study was carried out in the model, and the optimal element size was considered as 1 mm for the honeycomb structure and 2 mm for the face plates [31].

Meshing generates 19674 elements with 124933 nodes, as shown in Fig. 7. The flexural test is carried out by two support bars A and B, which are fixed at the bottom, and a loading support C was placed at the top of the component, as shown in Fig.7. Perfect bonding was assumed between the aluminum honeycomb core, polyurethane foam filler, adhesive layer, and composite face sheets using bonded surface-to-surface contact conditions. The lower support rollers were fully constrained in all translational degrees of freedom, while displacement-controlled loading was applied through the upper loading roller to reproduce the experimental three-point bending test. Large deformation effects were activated throughout the analysis to accurately capture the nonlinear structural response during flexural loading. Convergence was achieved when the residual force and displacement errors satisfied the default convergence tolerance specified by the software.

Table 3. Material Properties used for Finite Element Analysis

Material	Density (kg/m ³)	Young's Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Material Model
Aluminum 3003 Honeycomb Core	270	69.0	0.33	145	Elastoplastic
Carbon Fiber Composite Face Sheet	1800	340.0	0.28	650	Linear Elastic
Carbon–Nylon Hybrid Composite Face Sheet	1650	170.0	0.30	385	Linear Elastic
Polyurethane (PU) Foam Filler	60	0.045	0.30	1.8	Linear Elastic
Epoxy Adhesive	1150	3.2	0.35	65	Linear Elastic

The elastoplastic behaviour of carbon fiber aluminum honeycomb composites (Fig.8) refers to the material's mechanical response under loading, including elastic deformation, plastic deformation, and failure. In the elastic region, the sandwich composite of carbon fiber and aluminum honeycomb bends to a convex curve during the application of load. Even though the carbon fiber provides high stiffness and strength, the aluminum honeycomb core ensures lightweight and energy absorption which substantiates the linear elastic behaviour up to the yield point [32].

During plastic deformation, the aluminum honeycomb core experiences plastic deformation during the application of load when it is bent above the yield point. In spite of carbon fibers contributing to the structural integrity to resist the deformation, the cell walls of the core buckle or collapse when it exceeds the plastic limit [33]. The aluminum honeycomb core effectively absorbs energy during plastic deformation, making the composite structure preferable for impact-resistant applications such as automotive bumpers and rub rails in boats. The composite sandwich failures often depend on load exceeding the plastic deformation and held by stages like delamination, core crushing, and fiber breakage [34].

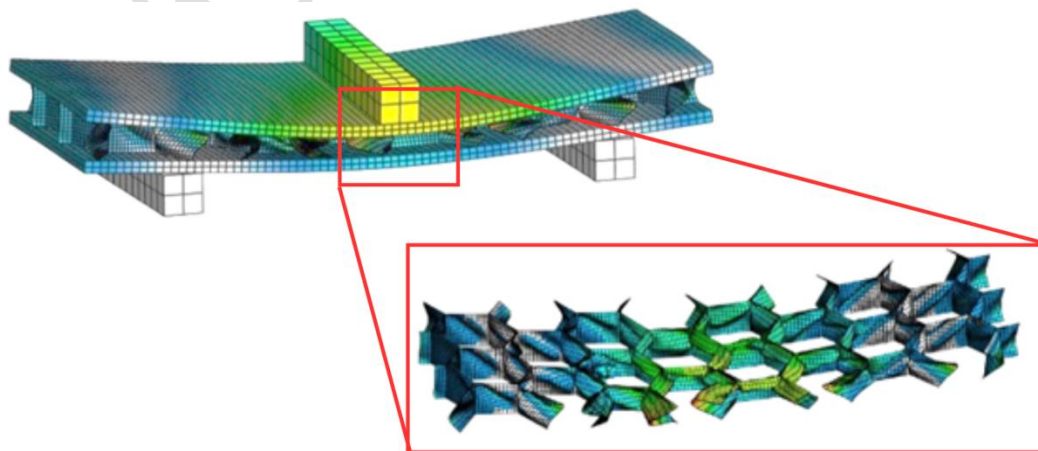


Figure 8. Simulation of the elastoplastic behaviour of the sandwich panel

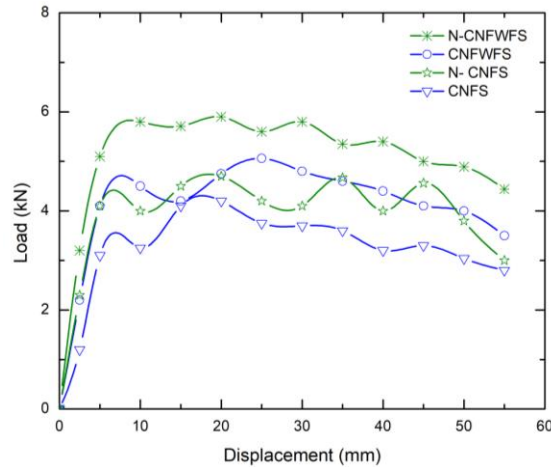


Figure 9. Load-displacement comparison of Experimental and Numerical Flexural test

Experimental and numerical analysis are conducted in the sandwich structure to compare performance in the flexural test to validate the model under the bending loads which is indicated in the Fig .9. The finite element analysis indicated that the highest equivalent stresses were concentrated beneath the loading roller and near the support locations, corresponding to the regions of maximum bending moment. The total deformation increased progressively with the applied load, while the equivalent elastic strain remained localized around the compressed honeycomb cell walls. The PU-filled configurations exhibited lower peak deformation and higher strain energy absorption than the corresponding unfilled specimens, indicating improved structural stability and enhanced resistance to localized collapse. The Numerical analysis of the sandwich panels CFS and CNFWFS shows 19.26% of error with the experimental value while and Numerical analysis of the sandwich panels CNFS and CNFWFS shows 18.13% of error due to assigning of material properties, boundary conditions and numerical modeling simplifications. This difference (18–20%) can be attributed to several practical factors that are difficult to incorporate into the finite element model, including manufacturing imperfections, local variations in adhesive thickness, slight inconsistencies in polyurethane foam distribution, fiber waviness, and unavoidable void formation during composite fabrication. Furthermore, the numerical model assumes ideal material properties and perfect interfacial bonding, whereas the experimental specimens inevitably contain localized defects that influence structural response. Despite these simplifications, the predicted deformation patterns showed good agreement with the experimental observations, confirming the validity of the numerical approach.

3.5. Impact Testing

Impact testing, conducted according to ASTM D3029-95, evaluates the material's toughness and energy absorption under sudden impact loading. The small specimen dimensions allow precise measurement of the structure's behavior to absorb the impact energy without fracturing, an essential property for applications where materials are exposed to dynamic or sudden loading conditions. This test helps predict the material's performance in real-world scenarios where impact resistance is crucial [38]. The Specimen dimension of 70 x 10 x 16 mm is maintained during the testing.

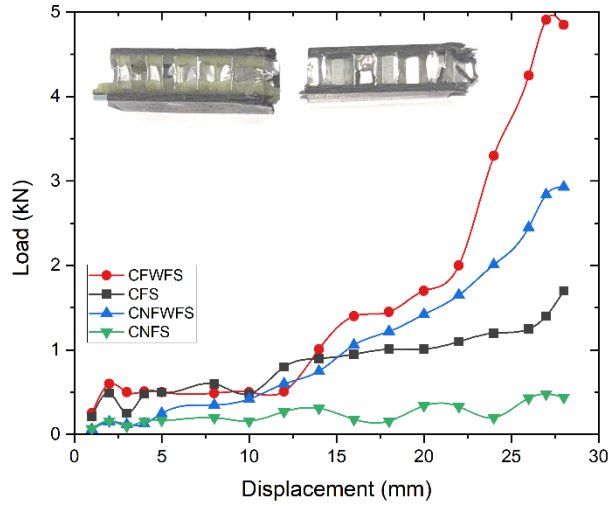


Figure 10. Load-displacement curve - impact tests

During impact loading, the carbon fiber sandwich panels exhibited brittle fibre fracture accompanied by localized matrix cracking and core indentation. In contrast, the hybrid carbon–nylon panels failed through progressive fibre pull-out, interfacial debonding, and controlled matrix cracking. The presence of polyurethane foam further reduced localized core collapse by supporting the aluminum cell walls and distributing the impact load over a larger area. These observations explain the higher impact resistance and greater energy absorption measured for the PU-filled hybrid sandwich structures. The average impact strength of the sandwich panels CFWFS, CNFWFS, were 20% and 34% than that of sandwich panels CFS, CNFS, respectively [39] as shown in Fig .10. It is mainly to the foam inside the core that enhances the structural performance by maintaining the separation between the skins and increasing the panel’s overall stiffness. This configuration improves the moment of inertia, allowing the skins to more efficiently resist the tensile and compressive stresses during bending. Furthermore, the PU foam distributes the loads more evenly across the panel, reduces local deformation or buckling of the skins, and improves the bond between core and skins, all of which contribute to a significant enhancement in the flexural strength of the structure. The enhanced impact performance can also be interpreted in terms of energy absorption. Polyurethane foam increases the capacity of the sandwich structure to absorb deformation energy by delaying cell wall collapse and promoting progressive damage within the face sheets. Consequently, a larger proportion of the impact energy is dissipated through controlled deformation rather than sudden catastrophic failure.

Table 4. Mechanical Response of Aluminum 3003 Honeycomb Sandwich

Specimen	Maximum Tensile Stress (MPa)	Maximum Compressive Stress (MPa)	Maximum Flexural Load (kN)	Maximum Impact Load (kN)
CFS	352	0.47	5.30	1.70
CFWFS	382	0.49	5.46	4.91
CNFS	260	0.46	4.20	0.48
CNFWFS	281	0.48	5.06	2.93

Table 4 summarizes the peak experimental responses obtained from the tensile, compression, flexural, and impact tests for all sandwich configurations. The results demonstrate that the incorporation of polyurethane (PU) foam enhanced the mechanical behaviour of both the carbon fiber and carbon–nylon sandwich structures. The CFWFS specimen exhibited the highest tensile stress (382 MPa), compressive stress (0.49 MPa), flexural load (5.46 kN), and impact load (4.91 kN), indicating excellent stiffness and load-bearing capability. Meanwhile, the CNFWFS specimen also showed noticeable improvements over the unfilled CNFS configuration, achieving higher tensile stress (281 MPa), compressive stress (0.48 MPa), flexural load (5.06 kN), and impact load (2.93 kN). These findings confirm that PU foam contributes to improved load transfer and structural stability in both sandwich configurations, Carbon fiber face sheets provided higher stiffness and initial load-carrying capacity, their brittle failure characteristics limited their ability to absorb impact energy. Incorporating nylon fibers improved toughness, delayed crack propagation, and promoted progressive damage evolution, resulting in greater impact resistance. While the hybrid laminates exhibited a slight reduction in stiffness, the improvement in damage tolerance and crashworthiness makes them more suitable for applications where impact loading is a primary design consideration. Therefore, the selection of face sheet material should be based on the intended service conditions rather than mechanical strength alone. The experimental results support the conclusion that PU foam reinforcement enhances the structural performance of Aluminum 3003 honeycomb sandwich panels for lightweight engineering applications.

4. SEM and EDAX Analysis

The SEM analysis of the carbon fiber composite at higher magnification clearly reveals that the dominant failure mechanisms are brittle fiber fracture, fiber splitting, matrix cracking, and fiber–matrix interfacial debonding, indicating a highly brittle and catastrophic failure behavior, as indicated in the Fig.11. The presence of smooth, clean fracture surfaces along the fiber direction confirms that carbon fibers fail abruptly with minimal plastic deformation, while longitudinal splitting suggests crack propagation along the fiber axis under tensile loading. Matrix cracking and interfacial debonding initiate early and contribute to stress concentration, reducing load transfer efficiency and accelerating fiber breakage. The absence of fiber pull-out further emphasizes the limited toughness and poor energy absorption capability of the material. These microstructural observations strongly correlate with the experimentally observed high stiffness and strength but low impact resistance of carbon fiber reinforced composites, making them suitable for stiffness-critical applications but less effective in energy-absorbing or impact-dominated environments.

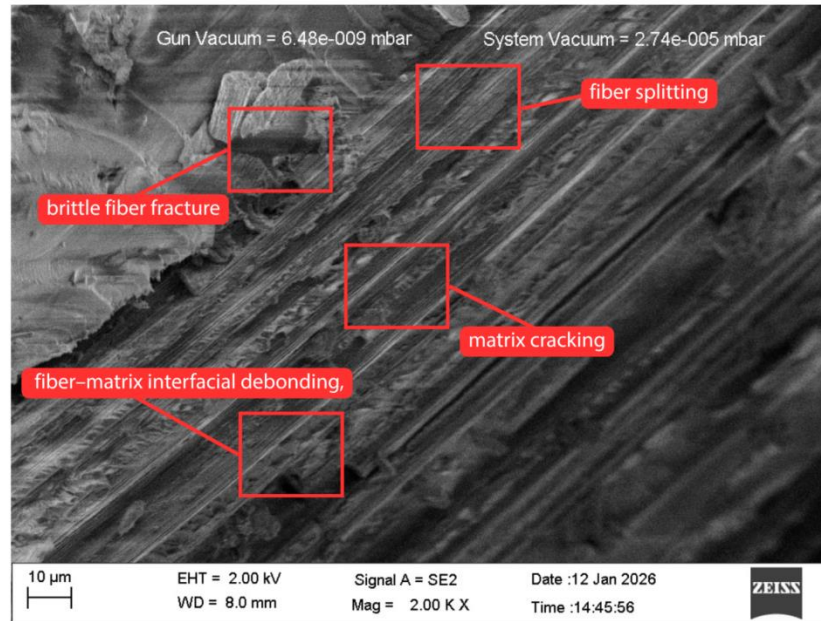


Figure 11. SEM Analysis of the Carbon Fiber Composite

The SEM analysis of the core-fiber bonding region indicates that the dominant failure mechanisms are interfacial debonding, matrix cracking, fiber pull-out, and localized void-induced damage, suggesting that the overall failure is governed primarily by weak bonding between the fiber and matrix, as indicated in the Fig.12. The presence of clear interfacial gaps confirms that load transfer between constituents is compromised, leading to premature failure under mechanical loading. Matrix cracking is observed to initiate and propagate from stress concentration regions, particularly around voids and resin-rich areas, which further accelerates damage progression. Fiber pull-out and partial exposure indicate some level of energy absorption; however, it also highlights insufficient interfacial strength. Additionally, the presence of voids and discontinuities plays a critical role in crack initiation and propagation. These microstructural features confirm a progressive failure behavior dominated by interfacial weaknesses, which directly affects the mechanical performance, stiffness, and durability of the composite structure.

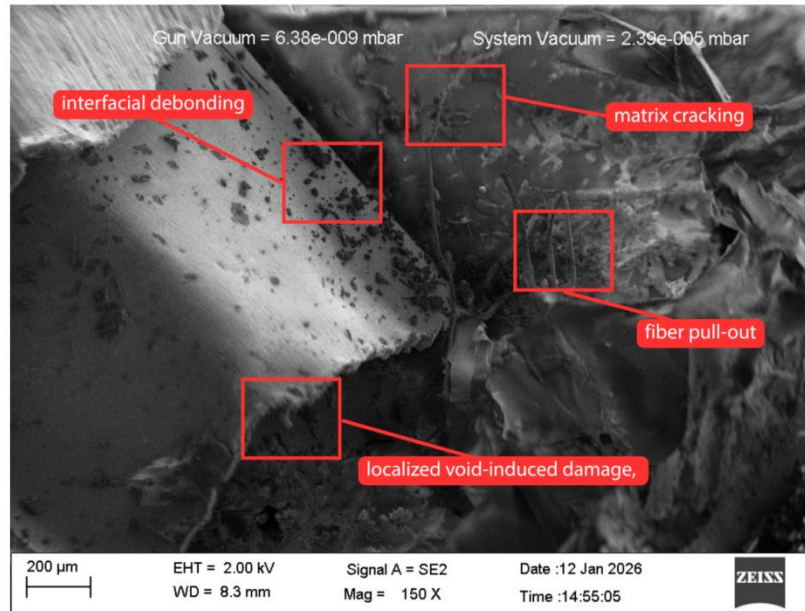


Figure 12. SEM Analysis of the Core-Fiber Bonding

The SEM image of the fiber-bonding region reveals that the dominant failure mechanisms are fiber pull-out, fiber-matrix interfacial debonding, matrix cracking, and localized void-induced damage, indicating that the failure is primarily governed by interfacial weakness and matrix-dominated fracture behavior, as indicated in the Fig.13. The presence of partially extracted fibers suggests some degree of energy absorption; however, the clear interfacial gaps confirm poor bonding between the fiber and matrix, leading to inefficient load transfer. Matrix cracking is observed to initiate and propagate around these weak regions, particularly near voids and debris clusters, which act as stress concentrators and accelerate crack growth. The combined effect of these mechanisms results in progressive damage evolution rather than abrupt failure, ultimately reducing the overall mechanical performance and structural integrity of the composite system.

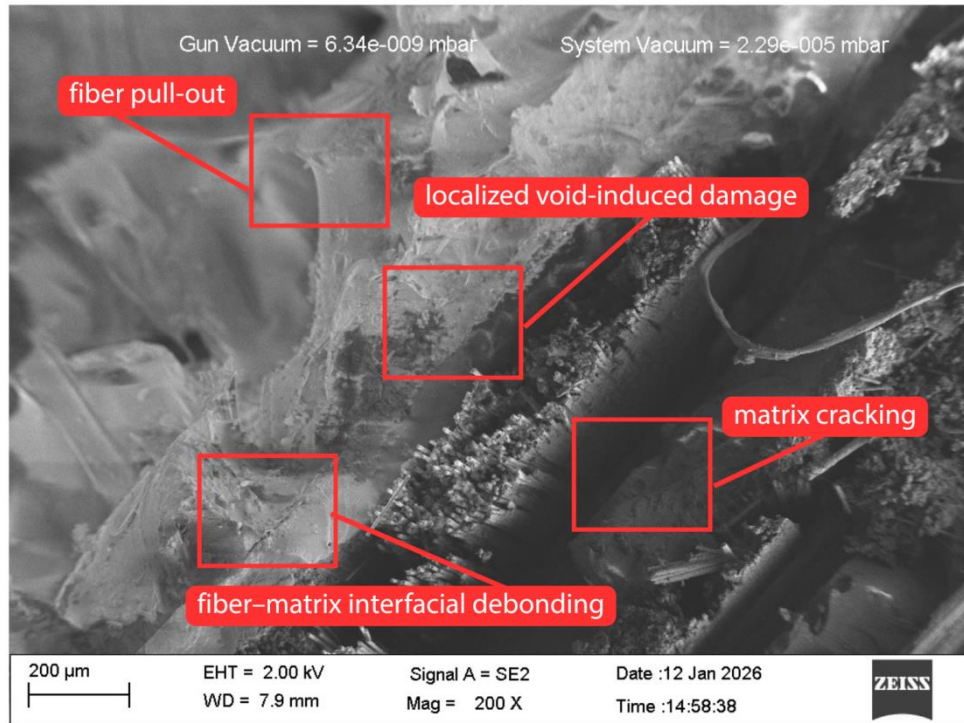


Figure 13. SEM Image of the Carbon fiber-bonding

The EDAX analysis of the composite sample indicates that carbon (C) is the dominant constituent with a weight percentage of 63.18% and an atomic percentage of 70.02%, confirming the strong presence of carbon-rich reinforcement, likely originating from the carbon fiber structure, as shown in the Fig. 14. Oxygen (O) exhibits a significant concentration of 34.99 wt.% and 29.11 at.%, suggesting the presence of oxide compounds, surface oxidation, or oxygen-containing bonding regions within the matrix material. Silicon (Si) is detected in a minor amount of 1.83 wt.% and 0.87 at.%, which may be attributed to silica-based residues, filler materials, or impurities introduced during fabrication or processing. The elemental distribution confirms the effective incorporation of carbon fibers within the composite matrix while also indicating interfacial oxidation and localized inorganic inclusions. The EDAX results validate the carbon-dominant composition of the specimen and support the observed microstructural features associated with matrix bonding and composite failure behavior.

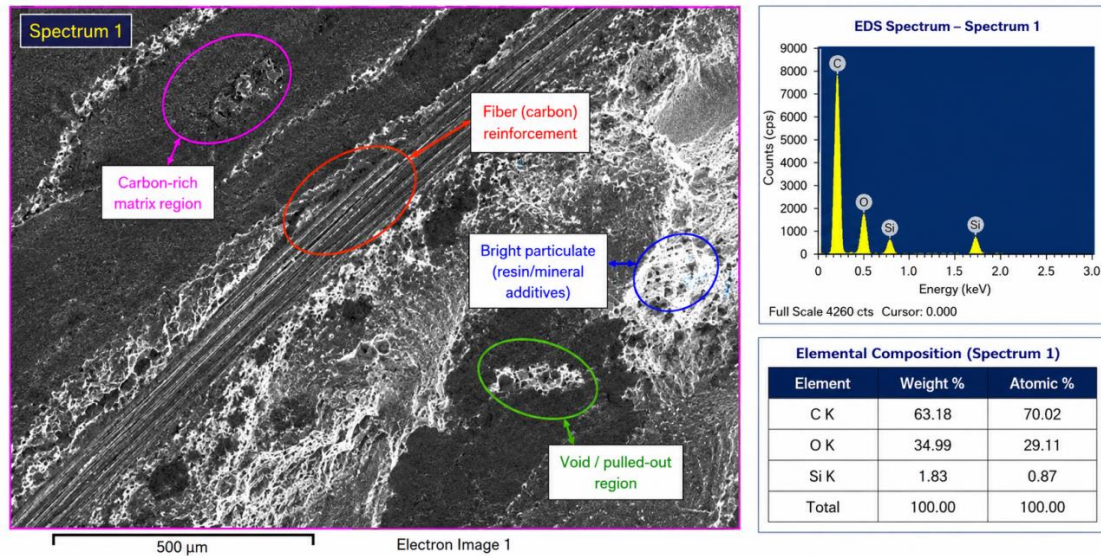


Figure 14. EDAX Analysis of the Specimen

5. Conclusion

This study investigated the mechanical behavior of the sandwich panels with aluminum honeycomb cores filled with polyurethane (PU) foam and faced with either carbon fiber or a hybrid of carbon and nylon fiber. Mechanical tests, including tensile, compression, flexural and impact, revealed that PU foam significantly enhances the mechanical behavior of the panels across all loading conditions.

Compared with the corresponding unfilled sandwich structures, the PU foam-filled panels exhibited improvements of 8% and 9% in tensile strength, 33% and 6% in compressive strength, 16% and 28% in flexural strength, and 20% and 34% in impact resistance for the carbon fiber and carbon–nylon hybrid face-sheet configurations, respectively. These improvements indicate that the PU foam effectively enhanced load transfer, delayed local buckling of the aluminum honeycomb cells, and improved the overall structural integrity of the sandwich structures.

The carbon fiber sandwich panels exhibited the highest stiffness, superior strength-to-weight ratio, and improved resistance to bending and compressive loading owing to the high elastic modulus and fatigue resistance of carbon fibers. However, their relatively brittle nature resulted in lower impact resistance under high-energy loading. In contrast, the carbon–nylon hybrid sandwich panels exhibited slightly lower stiffness but significantly improved impact resistance, energy absorption capability, and damage tolerance. The incorporation of nylon fibers promoted progressive failure mechanisms, reduced crack propagation, and minimized the risk of catastrophic failure. Furthermore, the hybrid configuration provides a more economical alternative by reducing the overall carbon fiber content without significantly compromising the structural performance.

The finite element analysis showed good agreement with the experimental flexural results, with a maximum deviation of approximately 18–19%. Although minor differences were observed because of idealized modelling assumptions and manufacturing variations, the numerical model successfully predicted the overall deformation behaviour and load-carrying response of the developed sandwich structures. The present investigation confirms that PU-filled carbon fiber sandwich panels are more suitable for lightweight structural components requiring high stiffness, superior compressive performance, and excellent flexural rigidity, whereas PU-filled carbon–nylon hybrid sandwich panels are more appropriate for applications demanding enhanced impact

resistance, greater energy absorption, and improved damage tolerance. These conclusions are directly supported by the measured improvements obtained in this study and demonstrate the potential of the developed sandwich structures for lightweight engineering applications in the automotive, marine, aerospace, and protective structural sectors.

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