Engineering and Technology Journal 43 (07) (2025) 507-521

Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Examining the flexural behavior of honeycomb sandwich composites: A numerical and experimental study

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HIGHLIGHTS

- The effect of honeycomb shapes on sandwich panels under three-point bending was analyzed using ANSYS.
- The optimal honeycomb shape was selected for manufacturing samples.
- Manufactured samples were experimentally tested, and results were compared with numerical analysis for validation.
- Circular, hexagonal, and triangular cores showed up to 16.5% more deformation than the rectangular core.
- Elastic strain rose by up to 31.55% in circular cores compared to the rectangular core.

Keywords:

Composite material

Honeycomb

Flexural load

Sandwich panel

ANSYS

ABSTRACT

Composite sandwich panel structures have been widely used in engineering and aerospace applications. Predicting the flexural properties of theoretical composite constructions is crucial for efficiently designing sandwich composite panel products. This research investigates four different cell core forms—circular, hexagonal, rectangular, and triangular—utilized in the manufacture of sandwich composite structures using a numerical program. For each case, the sandwich composite panel structure maintained constant weight and constant thickness for all models. The skin was fabricated from one layer of carbon fiber and two layers of glass fiber, combined with 3% carbide silicon and 6% polysulfide rubber in an epoxy matrix. The volume fraction for both carbon fiber and glass fiber was 35%, embedded in the epoxy mixture containing polysulfide rubber and carbide silicon (SiC). Finite element analysis using ANSYS Workbench 17.2 under three-point bending tests of the models revealed the rectangular cell core form as the optimal choice, exhibiting the least distortion (0.42992 mm) compared to other forms. The circular, hexagonal, and triangular core forms demonstrated deformations of 0.47267 mm, 0.48254 mm, and 0.51483 mm, respectively, representing a 9.05%, 10.91%, and 16.5% increase in deformation compared to the rectangular core. The maximum elastic strain for the rectangular core was 0.0067369, while the circular, hexagonal, and triangular cores exhibited strains of 0.0098421, 0.0092298, and 0.0072145, respectively, showing a 31.55%, 27%, and 6.62% increase in strain compared to the rectangular core. From the results of the finite element analysis, the rectangular model was chosen for manufacturing experimental models. Three models were prepared according to the bending test requirements. The experimental results demonstrated strong agreement with the numerical findings of this study.

1. Introduction

Composite materials, composed of multiple materials, offer superior properties due to their unique structural features and special qualities. These materials have been widely utilized in the automotive and space sectors due to their low weight and high strength, making them valuable in various industries [1-3]. Sandwich composite structures are multilayered structures with outer facings and a core designed for lifetime loading conditions. They can be homogeneous, with material choices based on function, lifetime loading, availability, and cost [4,5]. Many researchers [6-8] studied, experimentally and theoretically, different mechanical characteristics of sandwich composite material, such as impact, tensile, damping, and bending response, to analyze and enhance these properties. Lopez et al. [9], studied sandwich composite structures using LA (Lactic Acid), ABS (Acrylonitrile Butadiene Styrene), and PHS (Polystyrene high impact) materials to enhance mechanical properties such as

http://doi.org/10.30684/etj.2025.155806.1864
Received 11 December 2024; Received in revised form 26 February 2025; Accepted 09 March 2025; Available online 21 April 2025
2412-0758/University of Technology-Iraq, Baghdad, Iraq

strength. FDM 3D printing samples show that (LA-ABS-LA) sandwich structure arrangement provides high mechanical properties, promoting sandwich composite structure layouts as an alternative to conventional, low-cost multi-material components. Sivakumar et al. [10], examined the impact and tensile properties of hybrid glass/kenaf Reinforcement Metals Laminates (RMLs) with varying fiber stacking configurations and orientations. Results stated the tensile and impact strength contrasted to fiber kenaf RMLs exhibited significant performance and the fiber orientation of ±45°, contributing to increasing the impact strength and decreasing the tensile strength of RMLs in comparison with fibers orientation of 0°/90. Amin et al. [11], investigated the mechanical behavior of multi-layer corrugate core laminate sandwich composite panels under a quasi-static three-bending point test. Sandwich composite panels and corrugated cores were manufactured using ML506 EP with (15 %) hardener and (45%) volumetric glass woven fiber. Results showed that multi-layer sandwich plates provided solid structure and absorbed energy significantly, leading to failure. The rectangular geometry of the corrugated core shows promising results, and their numerical simulations aligned with experimental results. Rohit et al. [12], examined the impact of core shape, infill shape, and core orientation on sandwich structures' dynamic behavior. Nine structures with triangle, square, and hexagon shapes in 3 several orientations and denotations (0, 45, and 90) were considered and analyzed. Results showed that square cores with (00) orientation showed high stiffness, whereas hexagonal cores with (00) orientation displayed good stiffness and damping properties. Mojtaba et al. [13], investigated the influences of different core shape materials using FDM by low-velocity impact action of a sandwich panel. The structure consists of (2) composite face sheets fabricated from glass fibers reinforced polymer (GFRP) with polylactic acid (PLA) utilizing a fused deposition model (FDM). The results suggested that adding five composite laminates increases the impact force by 11.4% and decreases the specific stored energy by 64%. Changsheng et al. [14], studied to enhance carbon laminates' damping capabilities by adding a viscoelastic layer to the structure. They used a 30% fiber volume ratio and unidirectional fiber (T300, epoxy resin) with a viscoelastic layer and analyzed the models using FEA. Butyl rubber is a rubber polymer with good damping properties. The structure's modal loss factor and modal natural frequency are determined using the Rayleigh-Ritz method. The good agreement between the findings of the modal test, theoretical derivation, and finite element simulation confirms the validity of the theoretical model and experimental design. Adopting a finite element method to analyze sandwich structures contributes to decreasing costs and saving time.

Nitin et al. [15], studied the composite panel's flexural strength in their research, which was achieved by layering eight different orientations in the fiberglass sheets. Three-point bending stress was used to study the behavior of composites with honeycomb sandwich construction. It was discovered that the composite layup aluminum honeycomb panel's flexural strength increased by 200% of the original aluminum honeycomb panel strength. Essam [16], examined the sandwich panel core shapes—hexagonal, triangular, circular, and rectangular—under three-point bending loads. The honeycomb sandwich panels' flexural strength properties are based on their epoxy-fiber glass face four-layer sheet with (0°, 45°, -45°, and 90°) orientations and epoxy-carbon fiber core, with a 60% volume fraction of fiber in both materials. The results showed that the promising geometry of the core shape was rectangular, with a deflection value of 11.939 mm less than the other shapes. The rectangular core also exhibited a stronger structure due to five stiffeners oriented longitudinally and twelve oriented transversely. Qin et al. [17], studied the behavior of damage in metal honeycomb sandwich constructions using experimental study and numerical methods. It showed that the thickness of the skin had a significant impact on energy absorption that led to increasing the core temperature and, surprisingly, did not influence stiffness. While it has minimal effects on energy absorption, the thickness of the cell wall core has a significant impact on the impact load and structural stiffness of such systems. Many researchers have studied sandwich panels made of composite materials, where they used different materials like metal, fibers, wood panels, and similar materials in the manufacture of skin for sandwich panels, and they also studied the materials used in the composition of the core and the shape of the core and selected the optimal shape. In this study, the shape of the core (honeycomb) was chosen, the volume of the core shapes that were tested was fixed, the skin was strengthened, and the core and skin were strengthened by adding nanomaterials (silicon carbide). The mechanical specifications were improved by adding rubber to the epoxy mixture and obtaining the best shape for the cells. In a similar context, SiC nanoparticles are extremely hard and heat-resistant. The addition of SiC nanoparticles to polymer matrices is said to increase tensile strength and stiffness significantly. For instance, it is demonstrated that the addition of 1 wt.% of SiC nanoparticles to a polycarbonate matrix increased tensile strength and stiffness by 7.6% and 7.8%, respectively, compared to the filled material [18]. Similarly, in another research, it was found that the incorporation of SiC nanoparticle content in composites enhanced flexural strength and impact resistance, with optimum improvements at specific concentrations [19]. Polysulfide rubber was used owing to its flexibility and chemical resistance. It was found that the incorporation of polysulfide rubber in epoxy resins enhances toughness and impact resistance. In a study, it was found that incorporating polysulfide rubber in an epoxy matrix enhanced impact resistance with optimal mechanical properties at 5% weight percentage [20]. Additionally, polysulfide polymers also possess good adhesion and chemical resistance to numerous chemicals and can, therefore, be utilized in applications where resistant and flexible materials are required [21].

This study aims to investigate the effects of mechanical tests, i.e., a three-point bending test, on sandwich panels with four core cell shapes (circular, hexagonal, rectangular, and triangular) at the same thickness and same weight for all models numerically, theoretically selecting the best geometry that sustains high loads. The reason for selecting these geometries is due to their fundamental role in engineering applications and their prevalence in real-world challenges. These shapes provide a systematic basis for comparison, as they are either commercially available or straightforward to fabricate, ensuring reproducibility and relevance. While hybrid or complex geometries could yield additional insights, their adoption introduces practical limitations, such as configurations often require costly, advanced manufacturing techniques and are rarely accessible off the shelf. Finite element analysis models will be established for this purpose, and experiments also will be conducted to validate such results.

2. Sample preparation

2.1 Matrix

The EP (manufactured by Quick Mast Company [22, 23] resin was mixed in a 4:1 ratio with the firm's (Quick Mast) hardened component. Table 1 states EP's material properties [24, 25]. PSR is a class of chemical compounds composed of sulfur atom chains. It comes in the form of white dough, and when combined with 1:16 black PbO_2 dough, it transforms into a flexible shape [26, 27]. Table 1 presents the features of PSR. Silicon carbide, employed as the reinforcing material in this study at a weight percentage of 3%, is also characterized in Table 1. To allow SiC to disperse in the matrix finely, EP and SiC were combined and subjected to ultrasonic equipment for thirty minutes. The PSR resin and EP carbide will then be combined and allowed to mix for 30 minutes. Afterward, the mixed group will be supplemented with EP and PSR hardeners. The matrix containing fibers was poured into the model once the components had thoroughly combined [28-30]. SiC were chosen due to their well-established mechanical properties, which are critical for load-carrying structures. Numerical simulations revealed that these materials' stiffness and strength characteristics influenced their flexural response[31]. Carbon fibers with high modulus and tensile strength had better flexural properties than glass fibers with low stiffness and high strain-to-failure ratios. SiC, due to its extreme hardness and brittleness, added stiffness and altered failure modes. The results showed that hybrid blends of such materials achieved strength-flexibility equivalency while maximizing overall structural effectiveness. For Instance, the combination of carbon and glass fibers generated the best stiffness-ductility ratio. Because the focus of this study was mostly on numerical analysis, experimental confirmation is conceivable in the future to investigate the properties of such materials under actual flexural loading circumstances.

Table 1: Physical and mechanical properties of resin materials

No.	Material	Property			
1	Epoxy	Density 1.1 g/cm^3	Modulus Young's 3.4 GPa	Modulus Shear 1.27 GPa	Poisson's Ratio 0.34
2	Polysulfide Rubber	Density 1.522 g/cm^3	Vulcanization time at RT 3-4 h	Tensile strength ≥ 10 MPa	Tear strength 26±2 kN/m
3	SiC	From/ Color Nanopowder/ Grayish white	Average particle size 50 nm	Specific surface area90 m^2/g	Purity 99%

2.1.1 Fiber-reinforced composites (FRC)

The primary use of fibers in sandwich composite materials is to enhance the mechanical and physical properties of matrix resin by increasing its strength-to-weight ratio. Fibers are a significant class of reinforcing elements. Fiber-based materials have high tensile strength and elastic modulus. Being the most subjected to loads, they transfer these attributes to the composites to which they are collected, increasing the stiffness of these composites [32, 33]. There are several types of fibers: metal fibers in the form of wires, steel and copper wires, polymeric fibers like Kevlar, and ceramic fibers like carbon and fiberglass [34, 35]. Glass fibers are frequently used to reinforce composite polymer materials because of their many beneficial qualities, which include an elevated melting point, remarkably high tensile strength, and chemical resistance [36, 37]. Because fiber carbon has better qualities when used to reinforce polymeric composite materials, it is another popular form of fiber used in industrial applications. Good resistance to creep and fatigue, high hardness, abrasion, and good tensile strength are among carbon fiber's most important characteristics [38, 39], Table 2 states the specifications of the carbon and glass fibers adopted in this work.

Table 2: Physical and mechanical properties of carbon and glass fiber

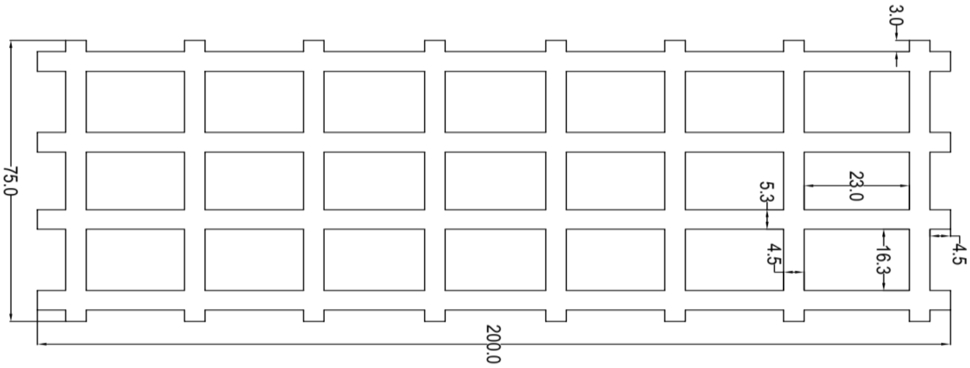
No.	Material	Property			
1	Carbon Fiber	Tensile strength 5,600 MPa	Elongation 1.9%	Tensile modulus 290 GPa	Density 1.81 g/cm^3
2	Glass Fiber	Compressive strength 1,080 MPa	Tensile strength 3,445 MPa	Young modulus 72.5 GPa	Density 2.58 g/cm^3

2.1.2 Preparing molds and specimens

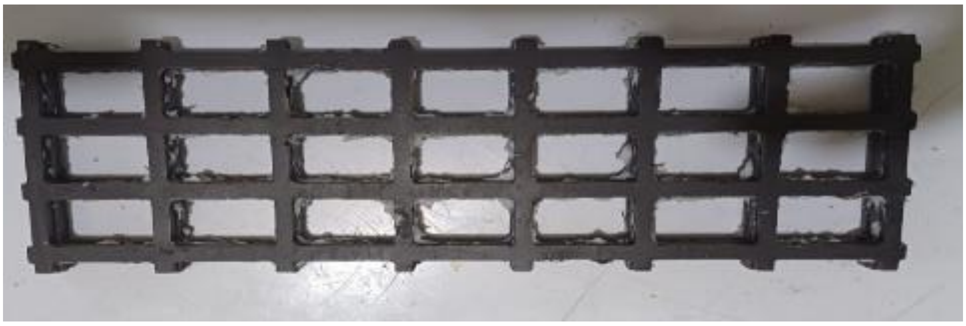
The molds are produced in accordance with the measurements needed to meet ASTM testing requirements. To avoid any adhesion between the polymeric material and the mold, the interior walls of the mold were thoroughly cleaned, greased with Vaseline, and then covered with nylon paper (Fablon). This guarantees an even dispersion and a flawless, imperfect-free surface. The resin was created using epoxy plus 6% PSR enhanced with varying amounts of SiC nanoparticles. A high-intensity ultrasonic liquid processor was used to disperse SiC in a blend polymer. To achieve proper dispersion, SiC nanoparticles were combined with EP resin using ultrasonic equipment for thirty minutes. To make sure that all of the components are thoroughly combined, add PSR to the mixes and sonicate for thirty minutes.

The reinforced blended copolymer was then mixed with polysulfide and epoxy hardeners. Install the mold after pouring the mixture into it in the same way as before, making sure that both components contain a low-viscosity liquid. The mold was taken out after all samples that were made in less than ton four hours at room temperature had finished solidifying. Samples were then allowed to post-cure for one hour at 60 °C in the oven.

In a second mold, the skin is made by placing a layer of the mixture, then a layer of fiber is placed and immersed in the mixture well, making sure that all the fiber is immersed in the mixture. After that, another layer of the mixture is placed, and then the second layer of fiber is placed so that it is completely immersed in the mixture. This process is repeated for the third layer so that the model consists of four layers of the mixture and three layers of fiber. After that, the mold is left for twenty-four hours to harden, and then the sample is taken and stuck with the core. The sandwich is placed in an electric oven at a temperature of 60 degrees Celsius for a full hour, and then the sample is taken out so that it is ready for examination. Figure 1A shows the dimensions of the mold designed for the rectangular honeycomb. Figure 1B shows the manufactured rectangular honeycomb sample, which is made from a mixture of polysulfide rubber, silicon carbide, and epoxy.



A) Geometry dimensions for the sample



B) Rectangular Core Sample

Figure 1: A) Geometry dimensions of the core model (mm) , B) Rectangular core sample

3. Finite element analysis (FEA)

The sandwich structure composite is analyzed using the finite element method using ANSYS Workbench 17 [40-42]. Four three-dimensional finite element models with different cell core forms (circular, hexagonal, rectangular, and triangular) were utilized to characterize the distribution of deformations and major direction stresses in the materials of the honeycomb sandwich structure by examining the models under quasi-static three-point bending test. The sandwich body consists of two skins constructed of fiberglass epoxy composite and a carbon fiber epoxy core composite [43-45].

The element utilized in the solution is solid 185 elements having a 3D geometric shape that is frequently utilized in computational modeling, and finite element analysis (FEA) is the hexahedral element. It has six faces, twelve edges, eight vertices, or corners. Usually, each face has four sides, making it a quadrilateral. Because they can accurately represent intricate geometries and material behaviors in three dimensions, hexahedral components are particularly common in engineering and physics simulations. A structured meshing was used, with finer meshing at support and load zones to enhance the accuracy of results without using up a lot of computational resources. Mesh convergence analysis was used to select an optimum size of the element and to ensure validation of the numerical solution with reduced computational costs. The study involved incremental mesh refinement and monitoring of significant response parameters, including maximum displacement and peak stress. The results showed that further refinement beyond 7500 mesh elements did not cause an appreciable change in the output, which indicated convergence. Therefore, the 7500 mesh elements were chosen to meet the requirements of computational efficiency and precision. Test conditions were replicated by applying boundary conditions. Bottom supports were constrained completely (fixed support) in such a way that it would not be capable of performing translational or rotational movement, and displacement-controlled loading was applied in the center of the top skin in such a way that the three-point bending test could be replicated. Furthermore, bending loads were applied to a honeycomb structural composite material with varying shapes, all while maintaining a constant core volume. The resulting honeycomb structural deformity features were then reported. It is worth mentioning that, as one volume, the two skins and core are fused. Contact between the skins and core was represented as an ideal bond with no slip and delamination at the interface [46, 47]. The mesh convergence plot is also given in Figure 2.

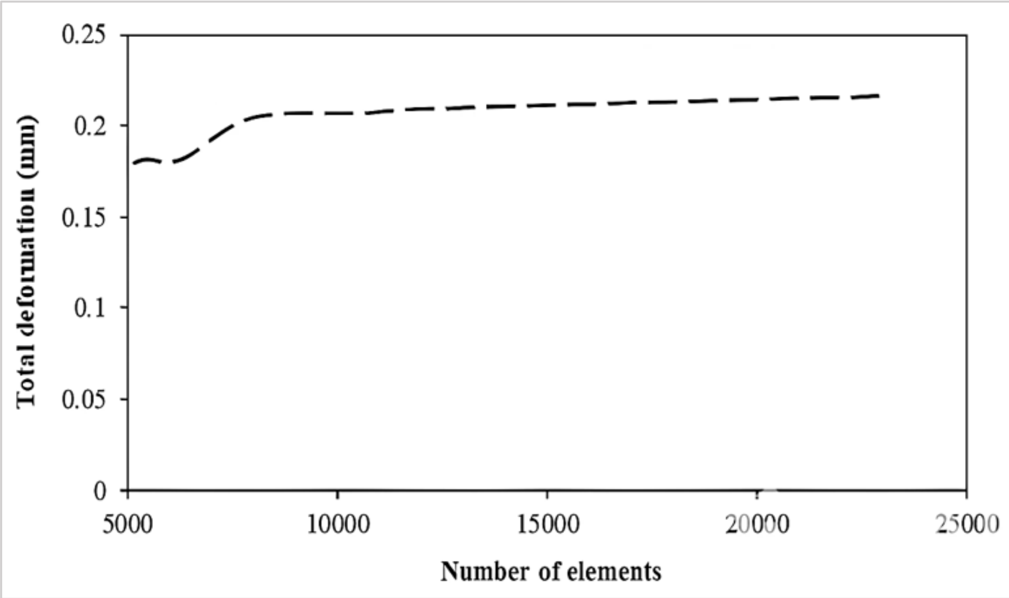


Figure 2: Mesh convergence plot for the analysis

3.1 Geometry

A sandwich panel structure is a particular type of laminated composite made up of two thin, highly strong-facing sheets attached to a thick, light core. Four models were constructed using FEA with different core shapes, as depicted in Figure 3 (A-D) represented the foure core cell choosen in this work. Table 3 shows the dimensions of the supports and the models.

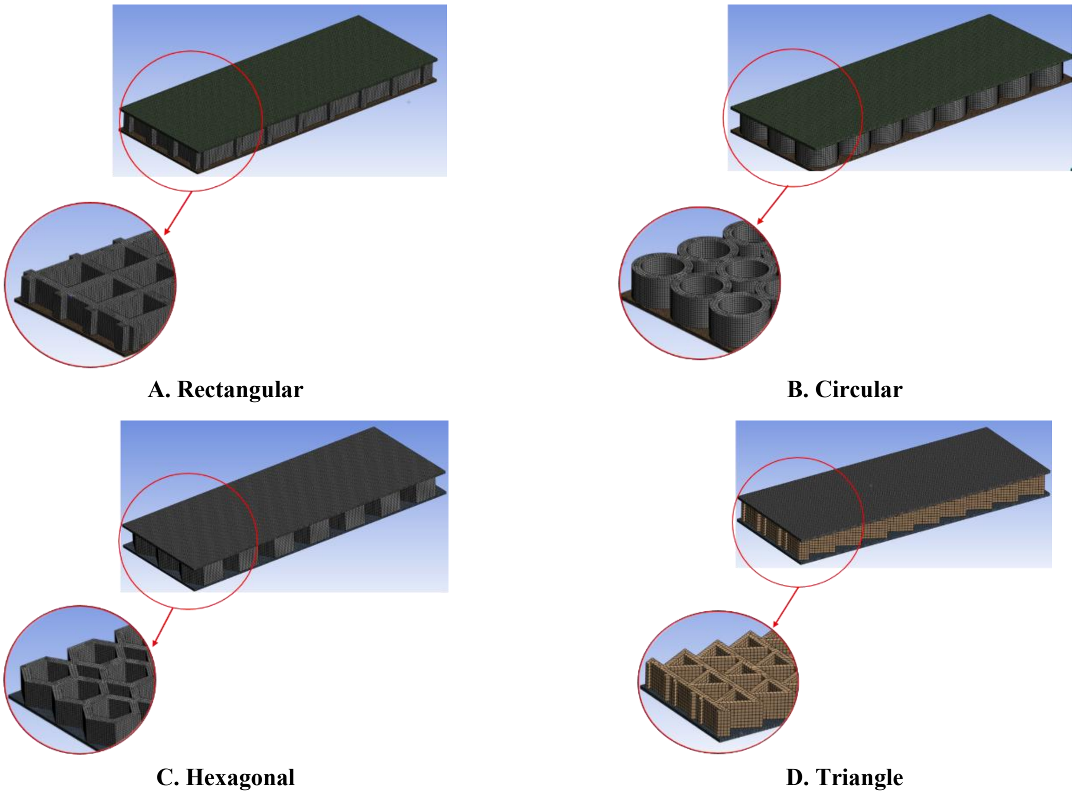
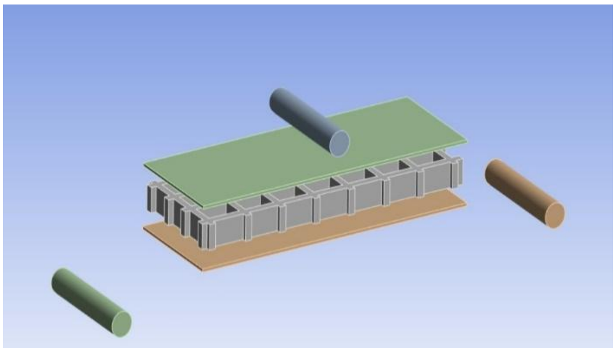
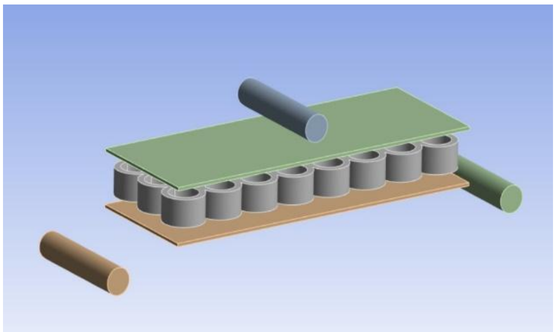


Figure 3: Meshing details with different core shapes: A) Rectangular core, B) Circular core, C) Hexagonal core, and D)Triangular core

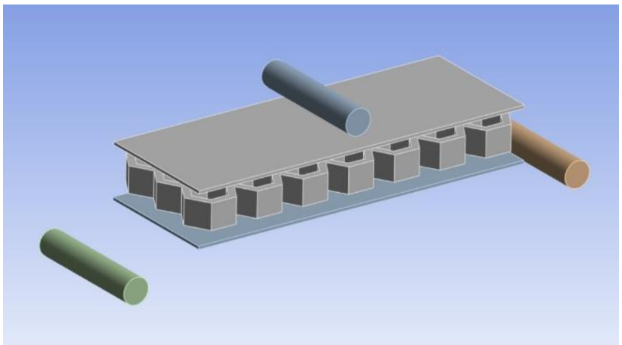
As seen in Figure 4 (A, B, C and D) the core shape cells have the same diamensions, weight and skin stacking sequence and was exposed for the same load to examine bending test.



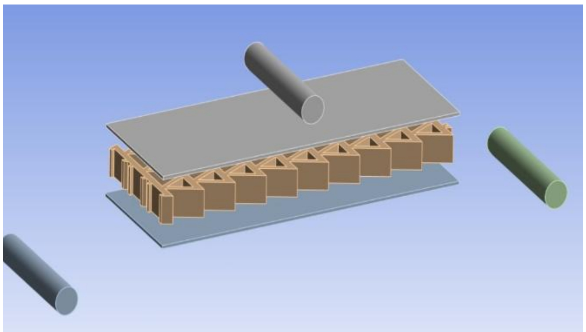
A. Rectangular



B. Circular



C. Hexagonal



D. Triangle

Figure 4: Sandwich structure with different core shapes: A) Rectangular core, B) Circular core, C) Hexagonal core, and D) Triangular core

Table 3: Dimensions of plate and supports

Width (b)	75 mm
Length (a)	200 mm
Top face sheet thickness (t_f)	3 mm
Core height (h_c)	15 mm
Bottom face sheet thickness (t_f)	3 mm
Span Length (distance between supports)	150 mm
Diameter of supports	30 mm
Length of supports	138 mm

3.2 Material Parameters

The properties (Shear modulus, Young's modulus, Density, and Poisson's ratio) of the composite materials are calculated theoretically using the following Equations (1-5) [48, 49]:

$$E_1 = E_f V_f + E_m V_m \quad (1)$$

$$E_2 = \frac{E_m E_f}{E_f + V_f (E_f - E_m)} \quad (2)$$

$$\nu_{12} = \nu_f V_f + \nu_m V_m \quad (3)$$

$$\nu_{23} = \frac{E_2}{2G_{2S}} - 1 \quad (4)$$

$$\rho = \rho_f V_f + \rho_m V_m \quad (5)$$

where E1, E2: major and minor modulus of elasticity respectively (GPa), Ef: modulus of elasticity of fiber (GPa), Em: modulus of elasticity of matrix (GPa), Vf: fiber volume fraction, Vm: matrix volume fraction, υ12, υ23: major and minor

Poisson's ratio respectively, υf: Poisson's ratio of fiber, υm: Poisson's ratio of matrix, ρ: density of composite (g/cm3), ρf: fiber density (g/cm3), ρm: matrix density (g/cm3).

3.3 Bending behavior of sandwich composite panel

In this investigation, a three-point bending load was employed. The sandwich structures, shown in Figure 5, included two bearing supports and a single loading point in the middle.

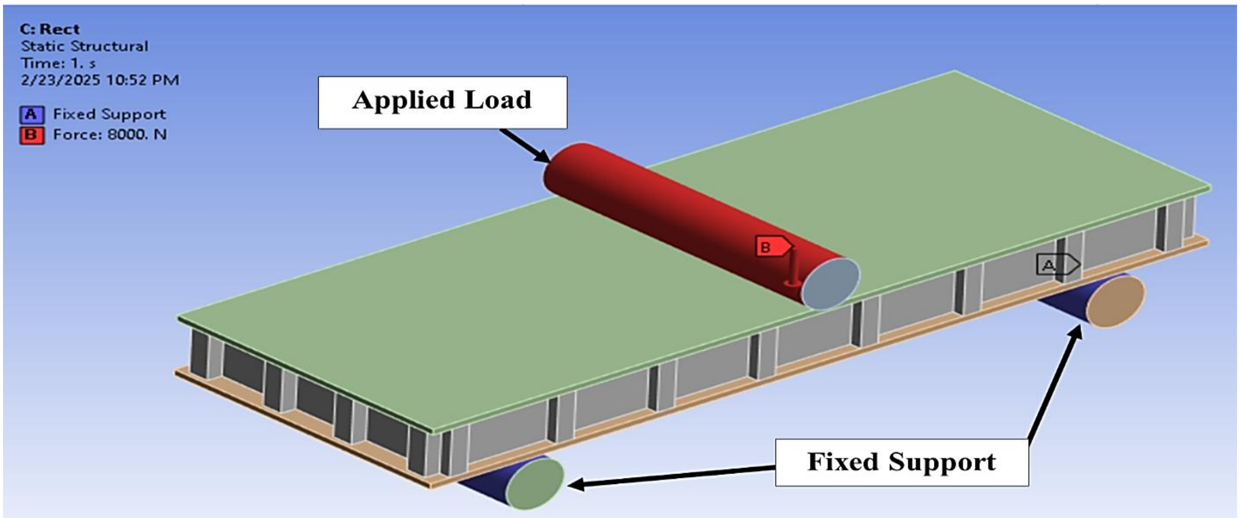


Figure 5: Finite Element model with bending load

4. Validation of the model

To ensure that the model design was correct, the bending test behavior of the ANSYS program was compared with the bending test performed for the experimental model, as shown in Figure 6 (A, B).

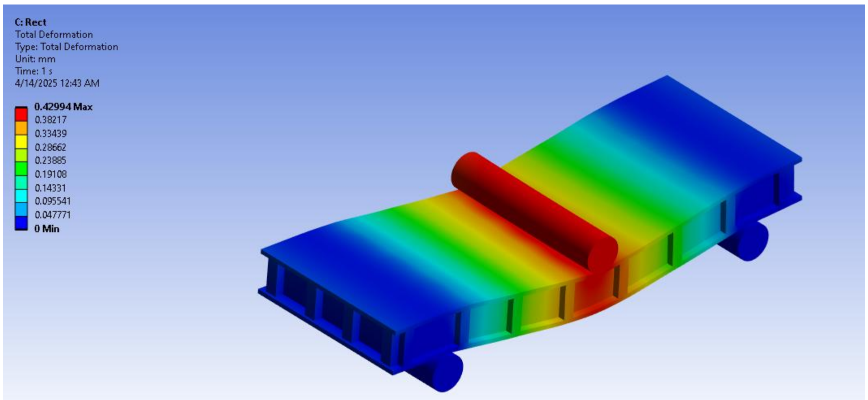
A. Design Model **B. Experimental Model**

Figure 6: A) Numerical design model under 3-point bending, B) Experimantal sample test under 3-point

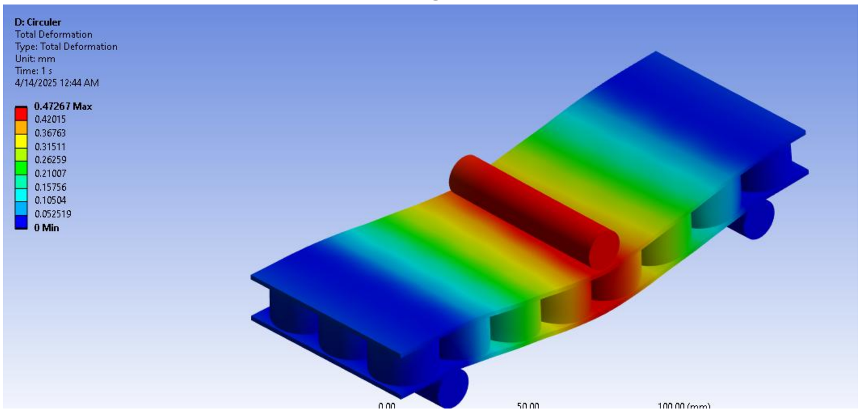
From the figure above, it can be noted that when starting to apply force in the middle of the sample to conduct a bending test, the sample goes down from the middle span as a result of the effect of the applied force. In contrast, the support area remains fixed at the same level. This indicates the conformity of the same behavior of the test from a theoretical and practical point of view. It can also give an impression of the reliability of the sample design using the ANSYS program with the experimental model, which is the desired result for this research.

5. Results and discussion

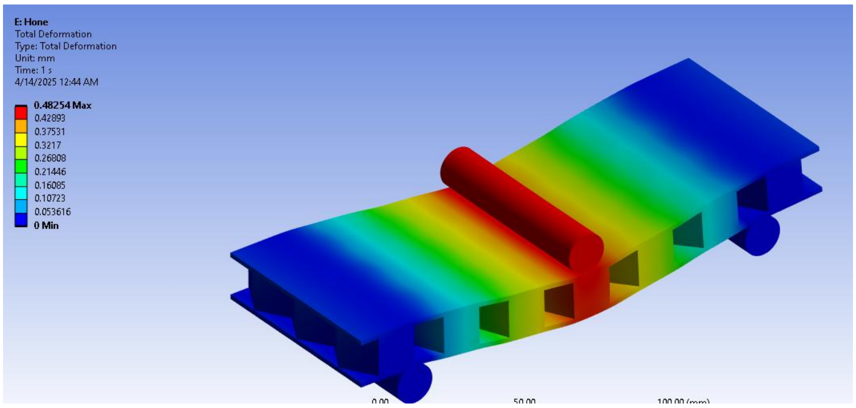
Figures 7, 8 and 9 (A, B, C and D) presents the deformation of four different shape core structure models, i.e., circular, hexagonal, rectangular, and triangular, which were designed by ANSYS workbench 17.2. All models were analyzed by considering the same weight and thickness and the thickness of the internal incisors and voids to eliminate any discrepancy in the results. Models were examined under three-point bending, where the load was applied on the sandwich core composite structures to calculate the flexural specifications of the panel. The investigation of honeycomb specifications is a task that defines the domain of application for those materials. Several basic cell shapes can be taken for the core of the honeycomb. It is worth mentioning that the cell's sandwich structure was modeled with the same volume ratio and material properties in both the core and the face sheets of the sandwich structure panel. For all cases, 10 kN of load was applied. It can be noted from Figure 7 that the rectangular core cell structure shows less deformation and more rigidity than other cases of cell shapes such as circular, hexagonal, and triangular forms. This outcome is due to the fact that the wall cell structures are more consolidated in the rectangular core cell and that these wall cell structures collect together in two directions, longitudinal and transverse. These results are listed in Table 4.



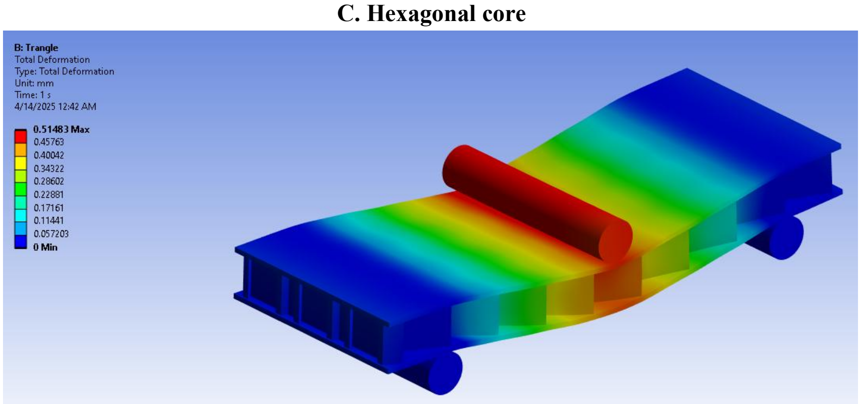
A. Rectangular core



B. Circular core



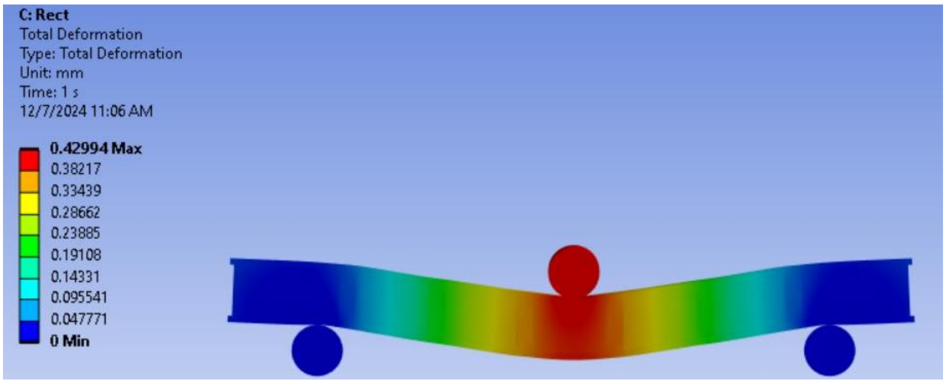
C. Hexagonal core



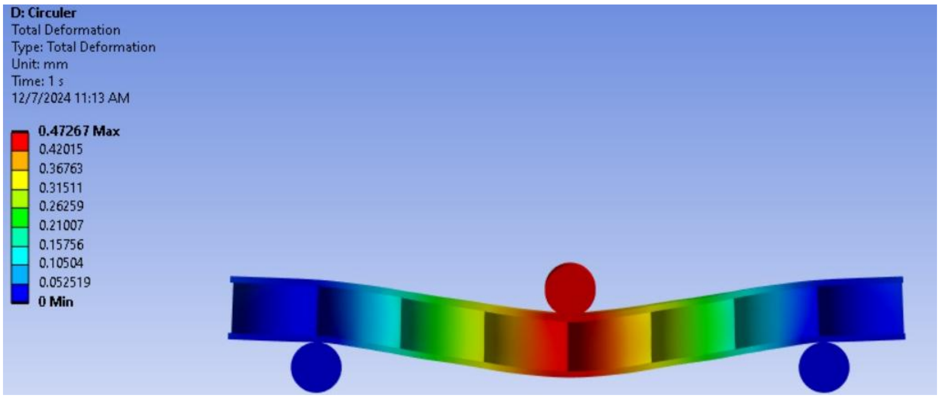
D. Triangular core

Figure 7: Modeling flexural deformation under the three-point bending test (A. Rectangular core, B. Circular core, C. Hexagonale core and D. Triangar core)

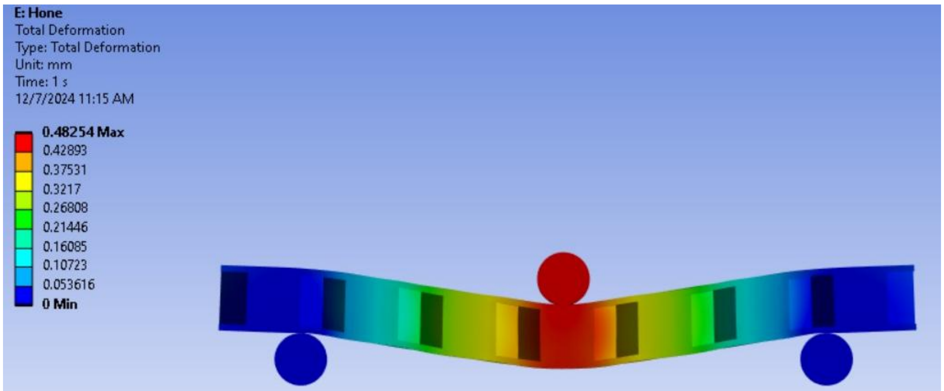
In addition, through the elastic strain Figure 9, the distribution of stresses can be observed after applying force to each model. The rectangular cells have given the least elongation in the middle region, and this is due to the fact that the wall cell structures collect together in both longitudinal and transverse directions and are more consolidated in the rectangular core cell.



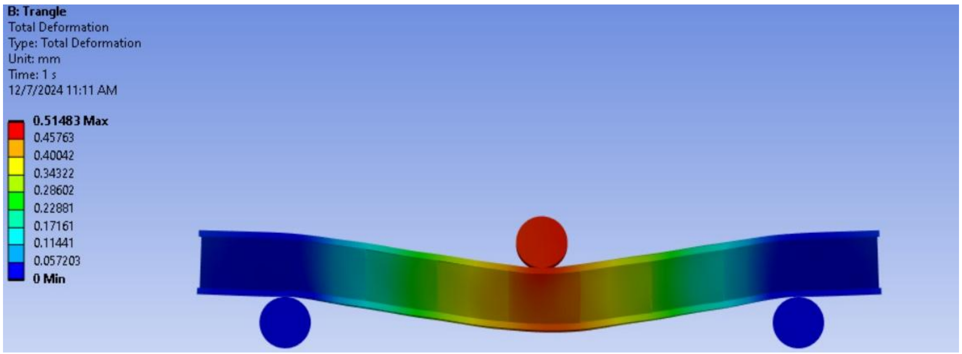
A. Rectangular core



B. Circular core

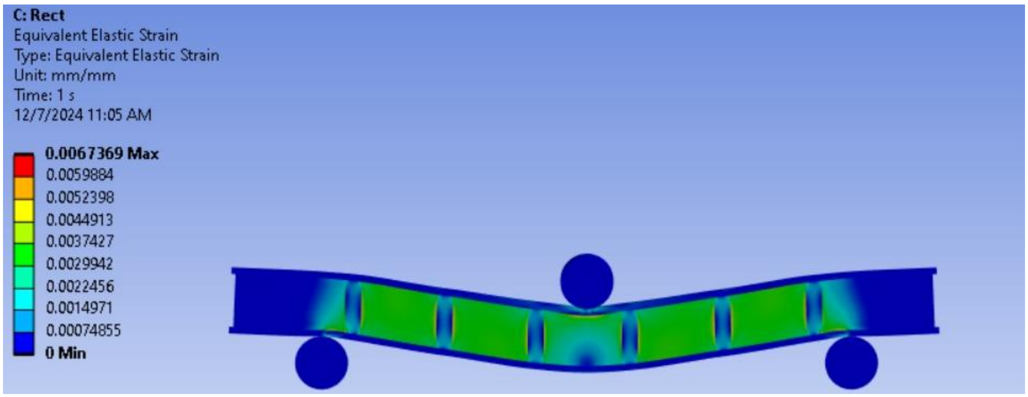


C. Hexagonal core

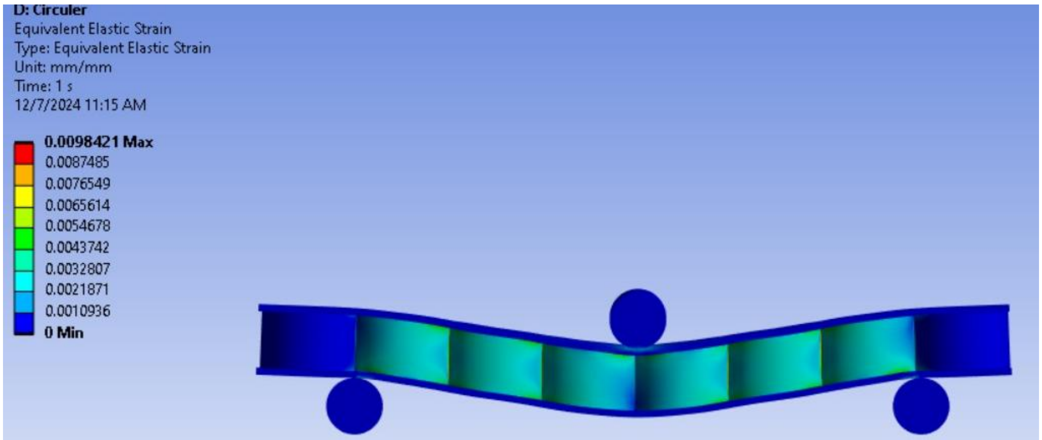


D.Triangular core

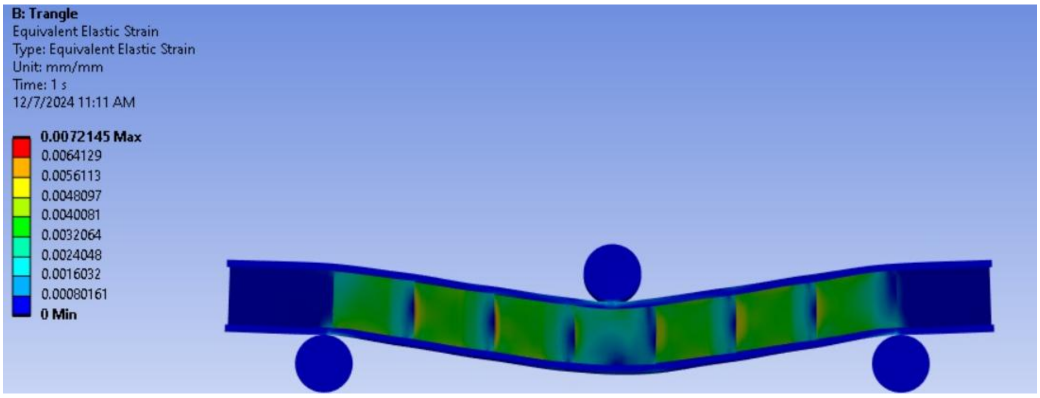
Figure 8: Flexural deformation under the three-point bending test (A. Rectangular core, B. Circular core, C. Hexagonale core and D. Triangar core)



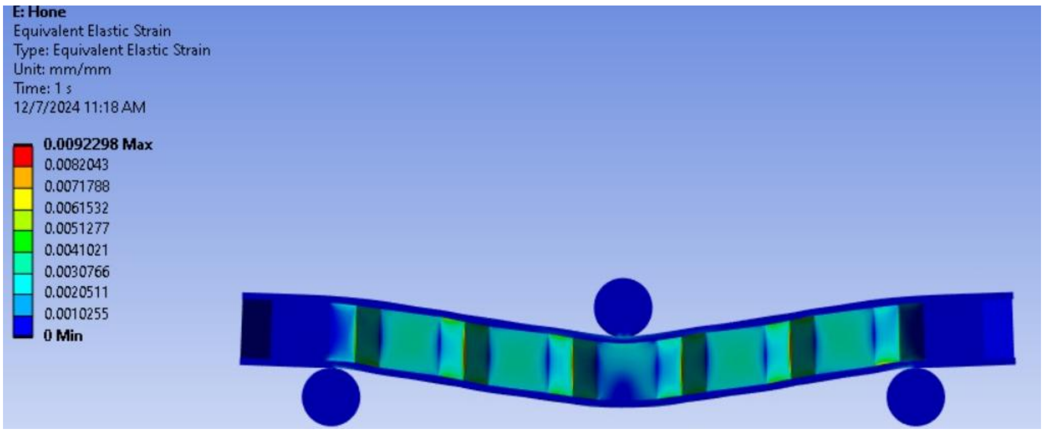
A. Rectangular core



B. Circular core



C. Hexagonal core



D. Triangular core

Figure 9: Elastic strain under the three-pint bending test (A. Rectangular core, B. Circular core, C. Hexagonale core and D. Triangar core)

Moreover, it can be observed that the maximum flexural deformation occurs in the middle of the model where the load is applied. It is also clear that the rectangular cell cores have high flexural strength compression when compared with other cell cores forms. This is because the geometric distribution of the rectangular cell walls relative to the longitudinal supports is close along the load application line, and it provides higher support than other forms. The hexagonal and triangular cell cores have high distortions under the flexural load, which indicates that these cell cores run to yield strength points before the rectangular cell core. Fore the same resone the rectangular core shape give the less elastic strain as shown in Figure 9 (A, B, C and D).

The flexural strength of the sandwich composite panel is considered a particularly important feature, as this characteristic builds on the power-absorbing ability of the total body. Subsequently, the yielding strength for the body materials and geometrical dimensions such as wall thickness and cell size were major parameters to calculate flexural stress. Moreover, the top face skin bears compression strength, and the down face skin bears tension strength during the flexural load process. Equation (6) was used to calculate a percentage ratio for difference structure distortion for all models.

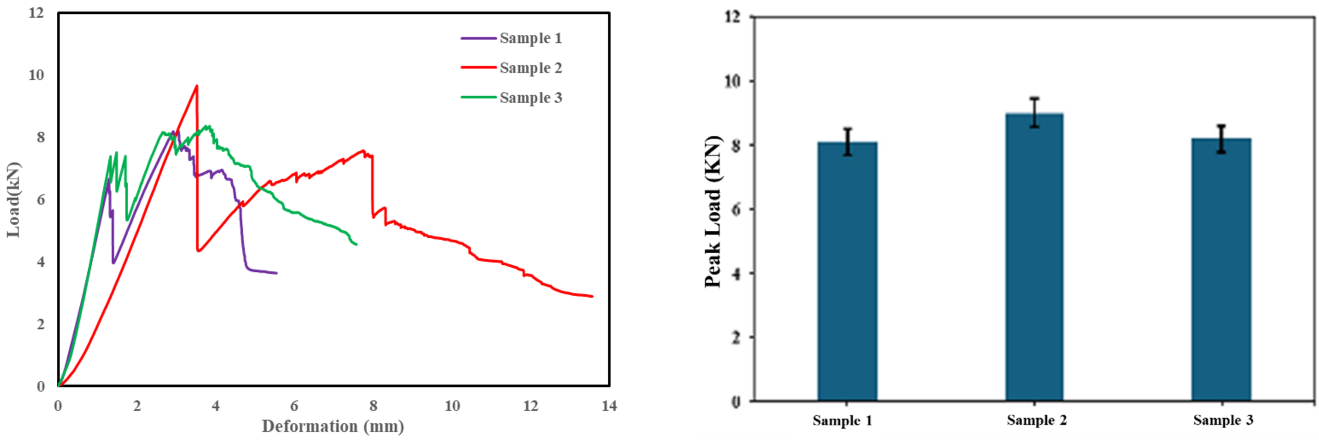
$$\text{Percentage difference} = \frac{cell\ deformation - rectangular\ cell\ deformation}{cell\ deformation} x100\% \quad (6)$$

It can be seen from Table 3 that the percentage deformation and elastic strain values of circular, hexagonal, and triangular cell core forms are greater than the deformation magnitude of the rectangular cell core form body. These findings agree with the reported result in [13].

Table 4: Represents the deformation percentage differences of honeycomb structure for all core shapes

Core form	Max. Deformation (mm)	Standard deviation (Def)	Percentages difference %	Max Elastic Strain	Standard deviation (Elastic Strains)	Percentages difference %
Rectangle	0.42992	0.03503	0	0.0067369	0.00151	0
Circular	0.47267	0.035	9.05	0.0098421	0.0058	31.55
Hexagonal	0.48254	0.041	10.91	0.0092298	0.0045	27
Triangular	0.51483	0.032	16.5	0.0072145	0.0021	6.62

Since finite element analysis (FEA) results indicate that rectangular cell cores exhibit promising performance in terms of reduced deformation under quasi-static three-point bending tests, the experimental work focuses on examining the deformation response of such samples under the same loading conditions to validate the FEA findings. Three bending tests examined the stiffness of sandwich panels. As seen in Figure 7, honeycomb sandwich specimens were evaluated using a universal testing machine (model WDW-5). Applying force via a 30 mm-diameter roller. The ASTM C393-00 standard was followed in choosing the span length of 150 mm and keeping a constant crosshead speed of 3 mm/min and environmental conditions as and humidity conditions were 23 ℃ ± 1 ℃ and (50 ± 2)% RH. This work investigated the effects of honeycomb cell core shape on the flexural behavior of the sandwich composite panels. The rectangular cell core shape was tested in this work, and three rectangular structural samples were tested. The deformation-force curves of samples under the three-point bending test were recorded, as shown in Figure 10 (A, B).

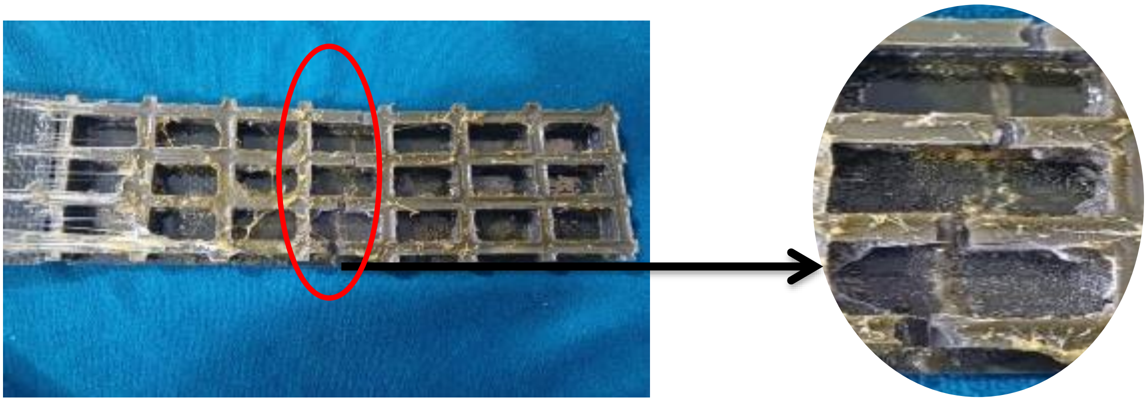


(A) Load deformation curve fore the rectangulare core **(B) Maximum load to failure**

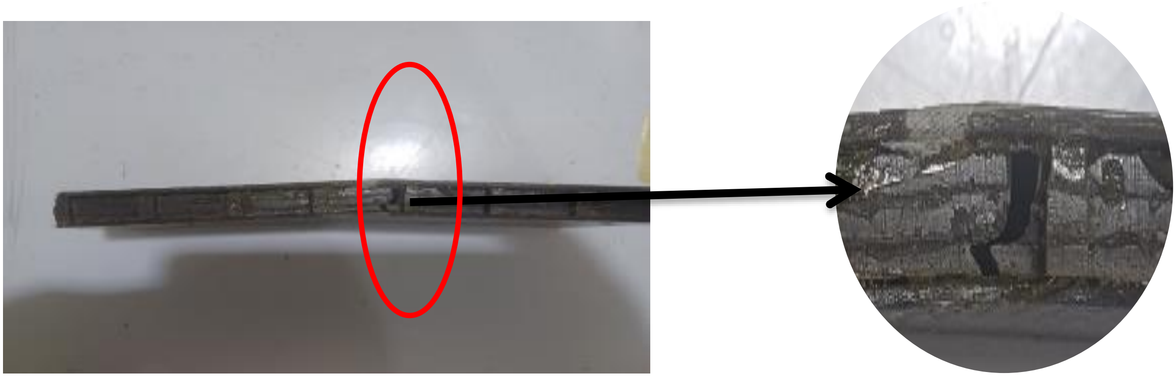
Figure 10: Forcedeformation of rectangular core shape sandwich panel under three-point bending test A) Load deformation curve fore the rectangulare core, B) Maximum load to failure

It can be seen in Figure 10 (A and B) that the behavior of sample 1 is similar to the response of sample No. 3, specifically in the plastic area. In contrast, sample 2 differs slightly in its behavior in this region. The average failure load is 8.4 ± 0.49 kN. These differences in behaviors between samples could be related to many factors. For example, during the examination, sample No. 2 had an imperceptible movement in the fixation area as well. These samples were manufactured manually, which may lead to inaccuracy in adjusting the dimensions of the longitudinal and transverse stiffeners for the sandwich core, in addition to the difference in temperatures during the sample manufacturing process and the amount of time required for the epoxy to harden, which gave a slight difference in the behavior of these samples in the plastic area. Also, for samples 1 and 3, the discrepancy was noted, and it is possible to observe an increase and decrease in the applied load more than once. The reason for this is that the fracture condition of these samples did not occur in one stage but rather in several stages. Also, it can be noted from Figure 10 that there are differences between the values of the applied load for the three samples, as sample number two showed the highest value of the applied load, 9.653 kN, while the other two samples are less than that. The reason is that the distribution of the layer thicknesses of sample 2 (fibers + resin) was fabricated better than the other two samples, as each fiber layer took the sufficient thickness of the epoxy. Thus, the distribution of the layers in the skin is better for the upper and lower faces, which gives a better result.

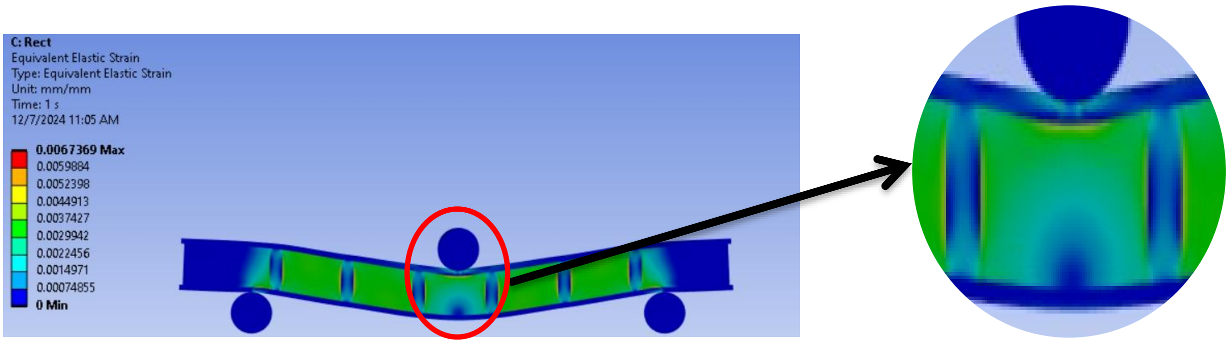
Therefore, it was noticed that the behavior is not alike because the fracture occurred in the transverse stiffeners, as shown in Figure 11 (A, B), and the fracture propagation was transferred from one support to another. It can also be noted from Figure 11 (C) that the stress concentration areas for the rectangular model at the longitudinal and transverse contact stiffeners, and when compared to the experimental model, are the same failure areas during the test, which confirms the validity of the convergence of the theoretical and experimental results.



A. Top view of sample failure



B. Side view for failure sample



C. Ansys sandwich model rectangular core

Figure 11: Failure behavior of sample under three-point bending test (A. Top view sample, B. Side view sample and C. Ansys model)

Figure 11 (A, B and C) represents the comparison between numerical and experimental results for the rectangular cell core shape. It can be seen that there is a good agreement between the numerical and experimental results. However, there is a minor difference between numerical and experimental results due to many assumptions needed to run the FEA model, such as treating the model as isotropic material while the samples were considered orthotropic materials. Subsequently, these discrepancies are not out of the range of the FEA results, and they can be accepted.

It can also noted from Figure 12 that there is agreement between the numerical and experimental work . This indicates that the samples that were manufactured in the experimental part are somewhat identical to the numerical , which gave similar stresses values and the behavior of the material under the influence of Applying force is identical.

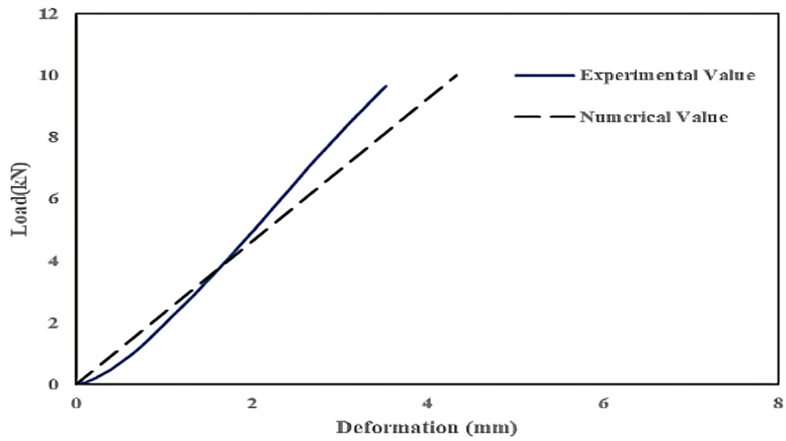


Figure 12: Comparing experimental and numerical results under a three-point bending test

6. Conclusion

Many conclusions can be drawn from this study, such as:

1) The rectangular core cell forms provide the best results in terms of less deforming under bending tests than the other honeycomb structures (circular, hexagonal, and triangular) cell core.
2) The rectangular cell core body gives a low deflection value of (0.42992 mm) among the other cell core forms.
3) Utilized engineering software packages such as ANSYS to design complex structures that could provide accurate results and save time.
4) The FEA program's experimental and analytical results show that it can be applied to the development of skin material or fiber skin orientation.
5) Study the effect of changing the number of core cells and the thickness of the cell wall on the mechanical specifications of the sandwich composite materials.
6) Different nanoparticles are used in the manufacture of sandwiches for the core and skin to reach the optimal sandwich design and obtain the best mechanical properties.

Author contributions

Conceptualization, **S. AlHumairee, I. Mahmood, M. Hunain,** and **H. Raheem**.; data curation, **S. AlHumairee**.; formal analysis, **S. AlHumairee**.; investigation, **S. AlHumairee**.; methodology, **S. AlHumairee**.; project administration, **H. Raheem**, resources, **M. Hunain**.; software, **S. AlHumairee**.; supervision, **I. Mahmood**.; validation, **I. Mahmood**., **M. Hunain**. and **H. Raheem**.; visualization, **S. AlHumairee**.; writing—original draft preparation, **S. AlHumairee**.; writing—review and editing, **H. Raheem**. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] A. Kumar, S. Angra, and A. K. Chanda, Analysis of the effect of variation of honeycomb core cell size and sandwich panel width on the stiffness of a sandwich structure, Res. Eng. Struct. Mater., 8 (2022) 45-56. http://dx.doi.org/10.17515/resm2021.308me0606

[2] A. E. Krauklis, C. W. Karl, A. I. Gagani, and J. K. Jørgensen, Composite material recycling technology—state-of-the-art and sustainable development for the 2020s, J. Compos. Sci., 5 (2021) 28. https://doi.org/10.3390/jcs5010028

[3] S. A. Khan, H. A. Khan, R. Awais, and S. Khushbash, Classification of progressive failure and mechanical behavior of dissimilar material hybrid joints at varying temperatures, Thin-Walled Struct., 182 (2023) 110212. https://doi.org/10.1016/j.tws.2022.110212

[4] V. Birman and G. A. Kardomateas, Review of current trends in research and applications of sandwich structures, Composites, Part B, 142 (2018) 221-240. https://doi.org/10.1016/j.compositesb.2018.01.027

[5] W. Nsengiyumva, S. Zhong, J. Lin, Q. Zhang, J. Zhong, and Y. Huang, Advances, limitations and prospects of nondestructive testing and evaluation of thick composites and sandwich structures: A state-of-the-art review, Compos. Struct., 256 (2021) 112951. https://doi.org/10.1016/j.compstruct.2020.112951

[6] J. Galos, R. Das, M. P. Sutcliffe, and A. P. Mouritz, Review of balsa core sandwich composite structures, Mater. Des., 221 (2022) 111013. https://doi.org/10.1016/j.matdes.2022.111013

[7] M. A. Ahmad, H. Rafiq, S. I. A. Shah, S. A. Khan, S. T. u. I. Rizvi, and T. A. Shams, Selection methodology of composite material for retractable main landing gear strut of a lightweight aircraft, Appl. Sci., 12 (2022) 5689. https://doi.org/10.3390/app12115689

[8] S. A. Khan, H. A. Khan, A. Khan, S. Salamat, S. S. Javaid, and R. M. A. Khan, Investigation of the mechanical behavior of FDM processed CFRP/Al hybrid joint at elevated temperatures, Thin-Walled Struct., 192 (2023) 111135. https://doi.org/10.1016/j.tws.2023.111135

[9] D. M. Baca Lopez and R. Ahmad, Tensile mechanical behavior of multi-polymer sandwich structures via fused deposition modeling, Polym., 12 (2020) 651. https://doi.org/10.3390/polym12030651

[10] S. Mirzamohammadi, R. Eslami-Farsani, and H. Ebrahimnezhad-Khaljiri, The experimental assessment of carbon nanotubes incorporation on the tensile and impact properties of fiber metal laminate fabricated by jute/basalt fabrics-aluminum layers: as hybrid structures, Proceedings of the Institution of Mechanical Engineers, Part C: J. Mech. Eng. Sci., 237 (2023) 1877-1886. https://doi.org/10.1177/09544062221134223

[11] A. Farrokhabadi, S. A. Taghizadeh, H. Madadi, H. Norouzi, and A. Ataei, Experimental and numerical analysis of novel multi-layer sandwich panels under three-point bending load, Compos. Struct., 250 (2020) 112631. https://doi.org/10.1016/j.compstruct.2020.112631

[12] R. Rajpal, K. Lijesh, and K. Gangadharan, Parametric studies on bending stiffness and damping ratio of Sandwich structures, Addit. Manuf., 22 (2018) 583-591. https://doi.org/10.1016/j.addma.2018.05.039

[13] M. Charekhli-Inanllo and M. Mohammadimehr, The effect of various shape core materials by FDM on low-velocity impact behavior of a sandwich composite plate, Eng. Struct., 294 (2023) 116721. https://doi.org/10.1016/j.engstruct.2023.116721

[14] C. Zheng, S. Yan, and B. Liu, Investigation on dynamic characteristics of composite sandwich plates with co-cured damping core, Appl. Acoust., 192 (2022) 108735. https://doi.org/10.1016/j.apacoust.2022.108735

[15] N. R. Gir, A. Patel, and A. Ghalke, FEA and Experimental analysis of Honeycomb sandwich panel using glass fiber, Int. J. Mech. Eng. Educ., 4 (2016) 16-23.

[16] E. Z. Fadhel, Numerical Optimization of Sandwich Composite Structure under Flexural Load, Iraqi J. Mech. Mater. Eng., 18 (2018) 616-627. http://dx.doi.org/10.32852/iqjfmme.v18i4.224

[17] Q. Qin, W. Zhang, S. Liu, J. Li, J. Zhang, and L. Poh, On dynamic response of corrugated sandwich beams with metal foam-filled folded plate core subjected to low-velocity impact, Composites Part A: Appl. Sci. Manuf., 114 (2018) 107-116. https://doi.org/10.1016/j.compositesa.2018.08.015

[18] M. Petousis, N. Vidakkis, N. Mountakis, S. Grammatikos, et al., Silicon carbide nanoparticles as a mechanical boosting agent in material extrusion 3D-printed polycarbonate, Polymers, 14 (2022) 3492. https://doi.org/10.3390/polym14173492

[19] M.S. Al Ansari, S. Kaliappan, G.V. Sree, P.K. Prabhakar, R. Maranan, P.D. Meshram, Enhancing Mechanical Properties of Composites with Plasma-Treated Linear Low-Density Propylene Matrix, SiC Nanoparticles, and Carbon Fiber Filler, in E3S Web of Conferences, 556, 2024, 1-8. http://dx.doi.org/10.1051/e3sconf/202455601018

[20] I. A. Mahmood and M. Z. Shamukh, Characteristics and properties of epoxy/polysulfide blend matrix reinforced by short carbon and glass fibers, Al-Nahrain J. Eng. Sci., 20 (2017) 80-87.

[21] V. Burkhardt, Liquid Polysulfide Polymers for Chemical- and Solvent-Resistant Sealants, Adhesives Mag., (2025).

[22] H. Rydarowski and M. Koziol, Repeatability of glass fiber reinforced polymer laminate panels manufactured by hand lay-up and vacuum-assisted resin infusion, J. Compos. Mater., 49 (2015) 573-586. http://dx.doi.org/10.1177/0021998314521259

[23] S. S. Abbas, R. M. Raouf, and H. H. Al-Moameri, Preparation of Calcium Titanate Nanoparticles with Investigate the Thermal and Electrical Properties by Incorporating Epoxy, Mater. Sci. Forum, 1083 (2023) 13-22. https://doi.org/10.4028/p-ep913a

[24] J. B. Torrez, Light-weight materials selection for high-speed naval craft, Massachusetts Institute of Technology, 2007.

[25] A. Ç. Boyacı and M. Ç. Tüzemen, Multi-criteria decision-making approaches for aircraft-material selection problem, Int. J. Mater. Prod. Technol., 64 (2022) 45-68. https://doi.org/10.1504/IJMPT.2022.120246

[26] K. K. Rao, K. J. Rao, A. Sarwade, and B. M. Varma, Bending behavior of aluminum honey comb sandwich panels, Int. J. Eng. Adv. Tech., 1 (2012) 268-272.

[27] K. Sukhyy, E. Belyanovskaya, A. Nosova, I. Sukha, et al., Dynamic Mechanical Properties of Epoxy Composites Modified with Polysulphide Rubber, Chemistry, 16 (2022) 432-439. http://dx.doi.org/10.23939/chcht16.03.432

[28] R.-M. Wang, S.-R. Zheng, and Y. G. Zheng, Polymer matrix composites and technology. Elsevier, 2011.

[29] S. H. AlHumairee, M. B. Hunain, and I. A. Mahmood, Effect of SiC nanoparticles on mechanical and damping properties of epoxy/polysulfide rubber blend composite, Phys. Scr., 99 (2024) 065934. https://doi.org/10.1088/1402-4896/ad43a0

[30] E. Edan and A. S. Al-Ezzi, Optimization and analysis of Sic reinforced copolymer blend composite structural springs, Proc. Inst. Mech. En.g, Part E: Process Mech. Eng., 2023. https://doi.org/10.1177/09544089231217925

[31] L. Zhang, W. Liu, L. Wang, and Z. Ling, Mechanical behavior and damage monitoring of pultruded wood-cored GFRP sandwich components, Compos. Struct., 215 (2019) 502-520. https://doi.org/10.1016/j.compstruct.2019.02.084

[32] A. Karim, E. Kader, A. Hamod, and A. Abdulrahman, Mechanical properties of a hybrid composite material (epoxy-polysulfide rubber) reinforced with fibres, IOP Conference Series: Materials Science and Engineering, 433, 2018, 1-8. https://doi.org/10.1088/1757-899X/433/1/012050

[33] S. A. Khan, H. Liaqat, F. Akram, and H. A. Khan, Development of a design space for dissimilar materials joining in aerospace applications, The Aeronaut. J., 128 (2024) 1284-1301. http://dx.doi.org/10.1017/aer.2023.109

[34] Z. I. Khan, A. Arsad, Z. Mohamad, U. Habib, and M. A. A. Zaini, Comparative study on the enhancement of thermo-mechanical properties of carbon fiber and glass fiber reinforced epoxy composites, Mater. Today: Proceedings, 39 (2021) 956-958. https://doi.org/10.1016/j.matpr.2020.04.223

[35] D. Matykiewicz, Hybrid epoxy composites with both powder and fiber filler: a review of mechanical and thermomechanical properties, Materials, 13 (2020) 1802. https://doi.org/10.3390/ma13081802

[36] Q. K. Al-Jubouri, Mechanical Properties Study of Composite Materials Reinforced with Metal Wire, M.Sc. Thesis, University of Technology, 1998.

[37] P. Morampudi, K. K. Namala, Y. K. Gajjela, M. Barath, and G. Prudhvi, Review on glass fiber reinforced polymer composites, Mater. Today: Proceedings, 43 (2021) 314-319. https://doi.org/10.1016/j.matpr.2020.11.669

[38] S. Hegde, B. S. Shenoy, and K. Chethan, Review on carbon fiber reinforced polymer (CFRP) and their mechanical performance, Mater. Today: Proceedings, 19 (2019) 658-662. https://doi.org/10.1016/j.matpr.2019.07.749

[39] A. Y. Chen, S. Baehr, A. Turner, Z. Zhang, and G. X. Gu, Carbon-fiber reinforced polymer composites: A comparison of manufacturing methods on mechanical properties, Int. J. Lightweight Mater. Manuf., 4 (2021) 468-479. https://doi.org/10.1016/j.ijlmm.2021.04.001

[40] C.-H. Li, J.-B. Yan, and H.-N. Guan, Finite element analysis on enhanced C-channel connectors in SCS sandwich composite structures, Struct., 30 (2021) 818-837. https://doi.org/10.1016/j.istruc.2021.01.050

[41] E. Dereli, J. Mbendou II, V. Patel, and C. Mittelstedt, Analytical and numerical analysis of composite sandwich structures with additively manufactured lattice cores, Composites Part C: Open Access, 14 (2024) 100484. https://doi.org/10.1016/j.jcomc.2024.100484

[42] M. Nazim, H. A. Khan, S. A. Khan, H. Liaqat, and K. Rehman, Design, development, and performance evaluation of FDM-based fastening techniques for single-lap joints, JOM, 76 (2024) 930-940. https://doi.org/10.1007/s11837-023-06324-1

[43] Q. Ma, M. Rejab, J. Siregar, and Z. Guan, A review of the recent trends on core structures and impact response of sandwich panels, J. Compos. Mater., 55 (2021) 2513-2555. https://doi.org/10.1177/0021998321990734

[44] T. Önal and Ş. Temiz, Experimental and numerical investigation of flexural behavior of balsa core sandwich composite structures, Mater. Test., 65 (2023) 1056-1068. https://doi.org/10.1515/mt-2022-0375

[45] M. K. H. Pulok, M. S. Rahman, and M. A. S. Akanda, Numerical analyses of stress and deformation in sandwich-structured composites, J. Strain Anal. Eng. Des., 56 (2021) 339-358. https://doi.org/10.1177/0309324720976621

[46] L. Uğur, H. Duzcukoglu, O. S. Sahin, and H. Akkuş, Investigation of impact force on aluminium honeycomb structures by finite element analysis, J. Sandw. Struct. Mater., 22 (2020) 87-103. https://doi.org/10.1177/1099636217733235

[47] V. Pourriahi, M. Heidari-Rarani, and A. Torabpour Isfahani, Influence of geometric parameters on free vibration behavior of an aluminum honeycomb core sandwich beam using experimentally validated finite element models, J. Sandw. Struct. Mater., 24 (2022) 1449-1469. https://doi.org/10.1177/10996362211053633

[48] L. P. Kollar and G. S. Springer, Mechanics of composite structures. Cambridge university press, 2003.

[49] S. Sharma, Composite Materials: Mechanics, Manufacturing and Modeling. CRC Press, 2021.