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Static Behavior of 3D Printed Sandwich Beam with Spherical Core for Aircraft Structure

Rand K. Abdulhussien[1*], Assad D. Abdulsahib[2], Marwah G. Kareem[3], Sadiq E. Sadiq[1], Luay S. Al-Ansari[4]

[1] Department of Aeronautical Technical Engineering, Technical Engineering College of Najaf, Al-Furat Al-Awsat Technical University, Najaf 54001, Iraq
[2] Department of Mechanical Engineering, College of Engineering, University of Al-Qadisiyah, Diwaniyah 58001, Iraq
[3] Department of Materials Engineering, College of Engineering, University of Al-Qadisiyah, Diwaniyah 58001, Iraq
[4] Mechanical Engineering Department, Faculty of Engineering, University of Kufa, Najaf 54001, Iraq

Corresponding Author Email: rand.alhussien@atu.edu.iq

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ABSTRACT

The mechanical response of sandwich structures is strongly governed by the geometry of their core; however, spherical core configurations have received limited attention due to fabrication constraints associated with conventional manufacturing techniques. In this study, additive manufacturing (AM) is utilized to introduce and investigate a novel spherical-core sandwich beam designed for lightweight structural applications. The static bending behavior of cantilever sandwich beams subjected to transverse loading is examined through a combined numerical and experimental approach. Finite element simulations were performed using ANSYS Workbench 2023, covering 72 parametric cases to assess the influence of sphere radius, center-to-center spacing distance, and face sheet thickness on static deflection, von Mises stress, and strain energy. Experimental validation was conducted by fabricating and testing eight specimens using 3D printing technology. The numerical predictions show good agreement with the experimental deflection results, with deviations within an acceptable range. The results reveal that increasing the sphere radius and face sheet thickness enhances the bending stiffness and reduces deformation, stress, and strain energy, while increasing the spacing distance leads to a noticeable deterioration in structural performance. These findings confirm the potential of spherical-core sandwich beams as an effective alternative core configuration for achieving high stiffness-to-weight efficiency under static bending loads.

1. INTRODUCTION

Sandwich panels have three layers: two faces and a core high strength-to-weight ratio is one of the primary features of the Sandwich panel. Here, a priority for these structures is the low cost of construction. It was evidenced that the design of the sandwich core plays a significant role in the mechanical properties of sandwich structures [1]. In recent years, numerous types of core designs for sandwich panels have been industrialized and proposed, meeting the needs of a wide range of modern industrial applications such as aerospace [2] and civil engineering sectors [3, 4]. Besides, some researchers such as Lurie et al. [5] and Patel and Modi [6] manufactured different parts of the vehicles and automotive from sandwich panels to improve the structure characteristics. Han et al. [7] and Ouadday et al. [8] developed innovative sandwich panel designs suitable for turbine applications.

Sandwich panel cores are typically made using materials such as Nomex [9], lightweight alloys [10], or composite materials [11, 12]. Recently, the use of additive manufacturing (AM) techniques has been adopted to fabricate these cores. The use of AM in sandwich panel fabrication provides key benefits such as high production efficiency, cost-effectiveness, and improved precision through a single-step manufacturing process [12].

Generally referring to the American Society for Testing and Materials (ASTM), AM is the process of building layer by layer to create complex 3D-objects from digital models, Moreover, AM allows the production of customized designs in a single step and has found widespread application in automotive, aerospace, medical, energy, manufacturing, and consumer product fields [13]. AM was initially used for prototyping in the 1980s, and these features were often unusable. This process was known as rapid prototyping because it allowed people to quickly create scale models of the final product, without the specific set-up process and costs involved in making prototypes, and as AM developed, its application expanded to high-speed, mold-making tools for final products. By the early 2000s, additives were being used to create functional components. "Companies such as Boeing and General Electric have recently begun using AM as an integral part of their business models" [14].

AM techniques can be classified into seven main types: Material Extrusion, Sheet Lamination, Material Jetting, Binder Jetting, Direct Energy Deposition, VAT Polymerization, and Powder Bed Fusion. Among these, Fused Deposition Modeling (FDM), also referred to as Fused Filament Fabrication (FFF), is a material extrusion-based AM process [15, 16]. Fused Deposition Modeling (FDM) is an AM technique in which a thermoplastic filament is extruded through a heated nozzle and deposited onto a build platform layer by layer. Each deposited layer solidifies before the subsequent layer is applied, and this process is repeated until the digitally designed component is fully fabricated. FDM process is known for its high productivity, good dimensional accuracy, and its ability to produce parts with satisfactory mechanical properties. The technology in the finished products depends on the printing process selected by the user. Several materials are currently used in the FDM process, including polymers such as ABS, PLA, PETG, and PEI, which the machine feeds as lines through a heated nozzle [17].

One of the last advancements in light weight structure is the development of sandwich panels with a core manufactured via 3D printer technology. This structure exhibits excellent properties, included high strength-to-weight ratio exceptional the absorption of energy under different load condition like, such as bending, compression, and impact, as well as dynamic loads [12]. Several studies have been conducted in order to investigate the mechanical properties of these structures [18, 19].

For example, Pirouzfar and Zeinedini [18] utilized the 3D printing to manufactured sandwich panel to enhance their performance under flexural load, instance of traditional material such as aluminum and Nomex. The performance of two configurations of honeycomb paths: vertical and horizonal were calculated. The results show the horizontal path of honeycomb has maximum energy absorption, Njim et al. [20] investigated the mechanical characteristics of sandwiched with composite and hybrid core under bending at three points. 3D printing technology used to manufacture the sandwich core, producing two types: open-cell and closed-cell a, employing APL and TPU materials for each type. Subsequently, the sandwich core was re-manufactured, and the voids between core cells were filled with PUR foam combined with aluminum powder at varying ratios. Test discovery Flexural The hybrid polyurethane/polytropic acid (PUR/PLA) core has a final bending load that is 127.7% better than the open cell structure core. Besides, the maximum deflection rose by 163.3%. Wu et al. [21] investigated the mechanical performance of 3D printed sandwich panels with graded grid cores when subjected to in-plane compression and three-point bending, and developed their failure maps to analyze the behavior of graded grid cores under these loading conditions. Guo et al. [22] conducted extensive vibration analysis and investigated the passive control technique of a cantilever sandwich beam with hourglass grid truss core fabricated using 3D printing technology. The governing equation of the beam was established using a homogeneous model and the Hamilton principle to determine the natural frequency of the beam. Haldar et al. [23] studied the compression behavior sandwich beam with a corrugated core designed using 3D printing. Two types of corrugated geometric, triangular and trapezoidal were examined. Impacts of several parameters, such as "core thickness, skins, height of core, and the contact area between core and skins on the mechanical properties of the sandwich panels" were considered through a series of experimental tests. Zoumaki et al. [24] manufactured three different shapes of hierarchical honeycomb cores by the 3D printing technique, PLA material as the raw material for printing. They conducted tensile and bending tests to study the mechanical properties. The hierarchical honeycomb cores included HC0 for the regular honeycomb, HC1 for the first level of hierarchy, and HC2 for the second level of hierarchy. Hou et al. [25] presented a sandwich panel with corrugated core manufactured by a 3D printing process based on continuous fiber reinforced thermoplastic composites as a novel process in AM. The specimens were tested under compression loading. Azzouz et al. [26] overcome difficulties of manufacturing a lattice-shaped core using a 3D printer. The results indicate that AM is a viable approach for producing lightweight, cost-effective, and high-strength sandwich panels.

Based on the discussions above, it is evident that the core shape significantly influences the mechanical properties of sandwich panels. One type of core that has not been previously studied due to manufacturing challenges is the spherical core. Spherical core geometries offer potential advantages over conventional lattice or truss cores. Their curved shape promotes more uniform stress distribution and near-isotropic mechanical behavior under multi-directional loads. Additionally, they allow high strength-to-weight ratios, achieving lightweight designs without significant loss of stiffness or durability. However, due to manufacturing difficulties, such cores have been rarely explored in sandwich structures.

In the current study, we aim to overcome this obstacle by utilizing 3D printing technology to manufacture a sandwich beam with spherical cores. Additionally, the research will focus on studying the impact of sphere radius, spacing distance, and face thickness as geometric parameters of this novel sandwich beam on total deflection, equivalent stress, and strain energy under transverse load. Static deflection under transverse load test implemented to achieve the experiment work, besides that finite-element-model was achieved using ANSYS program to simulate the cantilever sandwich beam with various sandwich parameters under transverse load.

2. FINITE ELEMENTS MODELING

2.1 Model setup

In the current research, a sandwich beam with a spherical core was modeled to analyze its mechanical behavior under a static load. The beam configuration was a cantilever with one end fixed and the other end free, subjected to a concentrated load of 1 Newton at the free end. The simulations were conducted using ANSYS Workbench version 2023. Parameters such as sphere diameter, offset distance, and face thickness (as illustrated in Figure 1) were carefully chosen. Table 1 presents the wide range of values considered for each parameter in the study.

2.2 Static structural analysis

ANSYS, which is relevant to the study through the use of a static structural analysis, can be used to comprehend the mechanical behavior of materials and structures with different loading conditions. This analysis assists to estimate the static deflection, strain energy and von Mises stress which is required to maintain the structural uprightness and security of the engineering designs.

Knowledge of the deflection of static objects is important in determining the damage to structures when subjected to loads, so they can be used within acceptable limits. Strain energy provides an understanding of the energy taken up by the material which is important in analyzing the resistance of the structure to impact and dynamic loads, Von Mises stresses are important in the failure prediction, as they add other stress components but it dictates whether the material will yield under the dynamic loads or conditions You can configure material and design parameters, to achieve efficient and reliable products.

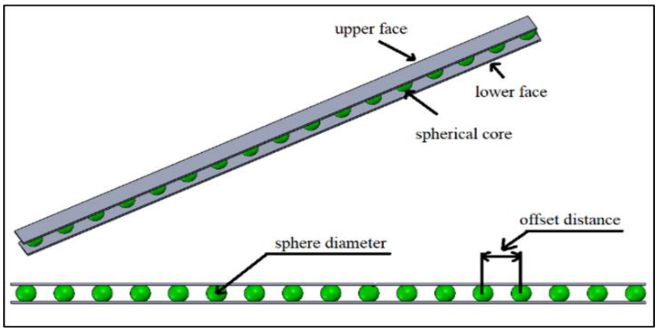


Figure 1. The geometry and parameters of the sandwich beam with spherical core

Table 1. Sandwich parameters

Parameter	Value (mm)
Spherical diameter (d)	3, 4, 5, 6, 8, 10 and 12
Offset distance (x)	10, 11, 15, 22, 31 and 33
Face thickness (t)	1, 2 and 3

2.3 Material properties for simulation

In this study, Polylactic Acid (PLA) has been selected as the material for the spherical core of the sandwich beam. PLA is a biodegradable thermoplastic produced from renewable sources, such as corn starch or sugar, which makes it an eco-friendly material. Its ease of processing and favorable technical properties make it a popular choice in 3D printing applications. In order to ensure that the simulation is accurate and close to real-world conditions, it is important that the material properties are properly calibrated and that the same materials are used in the process.

The elastic modulus of the PLA is 1.2 GPa, which shows the toughness of the material and the fact that it is capable of elastic deformation under the influence of force. PLA density is 1360 $kg/m^{3,}$ hence the product is light which makes it practical in situations where lightweight products are needed. The Poisson ratio 0.36 relates to how the material tends to move in the stress direction and does not change in direction of the stress. All these characteristics make PLA the best option to be used in applications that demand a combination of strength, flexibility and light weight [27].

Accurately inputting these properties ensures that the simulation reflects the actual behavior of the material under various loads. PLA will also be used in the manufacturing process, as detailed in the subsequent paragraph, to maintain consistency between the simulation and practical implementation.

2.4 Mashing

Figure 2 shows the meshing procedure, where the skins and the core were meshed independently before assembling the complete sandwich beam model. A total of 72 simulation scenarios were carried out to investigate the stated objectives. In the ANSYS model, the element (SOLID187) was used, and the convergent criteria were checked and the total number of nodes was about (130470-760537) while the total number of elements was about (65099-424906).

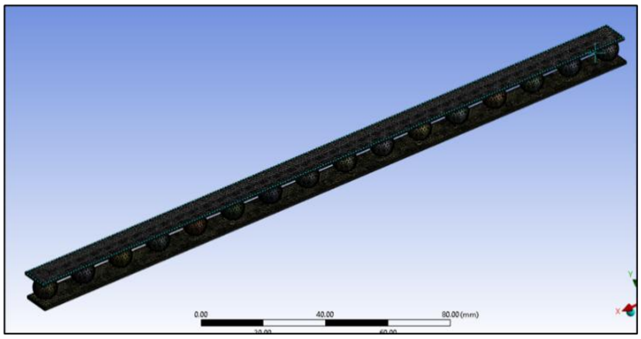


Figure 2. Geometry and meshing of the sandwich beam with spherical core

Note: Sphere diameter = 3 mm, offset distance = 31 mm, face thickness = 1 mm. The beam is cantilevered, and a transverse load of 1 N is applied at the free end.

3. EXPERIMENTAL WORKS

3.1 Sandwich beam with spherical core manufacture

As previously discussed, one of the main challenges in utilizing this type of sandwich panel and many other geometric shapes is the manufacturing process. In this study, 3D printing technology is employed to overcome this issue. Figure 3 shows the 3D printer model CR-10s used in this study, with PLA as the raw material. For the current manufacturing process, the CR-10s is configured with settings such as a 0.40 mm nozzle diameter, 0.28 mm layer thickness, 100% infilling density with a lines pattern, printing temperature maintained at 200℃, bed temperature set to 60℃, and a printing speed of 100 mm/sec.

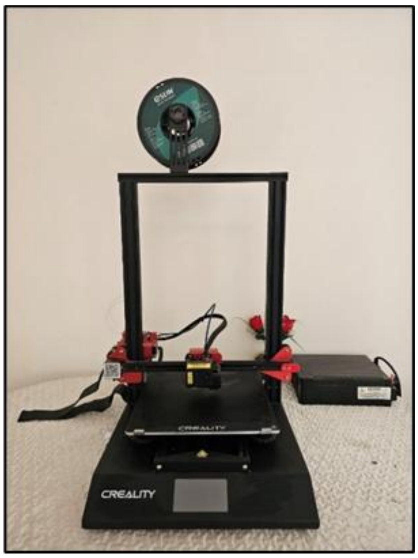


Figure 3. 3D printer type CR-10s used in this work

Figure 1 illustrates the schematic diagram of the sandwich beam, where 8 samples were carefully fabricated with dimensions selected to study the mechanical behavior of the sandwich beam under varying geometric parameters, as detailed in Table 2. Solid works software is used to construct samples and save them as a (*.lst) file, and then manufacture them on a 3D printer by using Cura software and samples of the sandwich beam with various dimensions, as shown in Figure 4.

Table 2. Dimensions of samples used in experimental work (all dimensions in mm)

No.	Sphere Diameter (D)	Offset Distance (X)	Face Thickness (T)	Beam Length (L)	Beamwidth	Beam Thickness
1	8	15	1	227	10	10
2	8	22	1	227	10	10
3	8	31	1	227	10	10
4	10	22	1	227	12	12
5	12	22	1	227	14	14
6	8	31	1	227	10	10
7	8	31	3	227	10	14
8	8	31	5	227	10	18

Figure 4. Samples sandwich beam with spherical core used in experimental work

The spherical cores were arranged in a one-dimensional array along the beam length. The center-to-center spacing distance (Sd) was defined as:

$$S_d = \frac{L - D}{n - 1}$$

where, *n* is the number of spheres along the beam length, and *D* is the sphere diameter. The first and last spheres were positioned at a distance equal to half the sphere diameter (D/2) from the beam edges. Along the beam width, the beam was filled according to the beam thickness, and the spheres were not arranged across the width.

3.2 Static deflection test for sandwich beams with spherical core

The static deflection test measures the deflection of sandwich beams with a spherical core under a known load, providing insights into their mechanical properties such as stiffness and flexural strength. This test is crucial for evaluating the performance of sandwich beams, helping determine their suitability for various engineering applications. The experimental setup is shown in Figure 5, including a Dial Indicator Gauge for measuring small deflections accurately, a test specimen which are sandwich beam with a spherical core, weights applied via a hanger to create a controlled load, and supports and clamps to securely hold the beam in place [27].

Figure 5. The experimental setup of the static deflection test

Position and secure the sandwich beam horizontally. Calibrate and position the dial indicator to measure deflection at the free end. Incrementally add weights to apply a controlled load. Record the deflection for each increment [28, 19]

A Cartesian coordinate system was defined with its origin fixed at the clamped end of the beam. The fixed support was located at x = 0, while the transverse load was applied at the free end of the beam at x = 227 mm. A vertical point load of 1 N was applied in the y-direction. The dial gauge was positioned at the same location (x = 227 mm) to measure the vertical deflection in the y-direction. The experiment was repeated three times for each specimen to ensure the repeatability and reliability of the measurements.

4. RESULTS AND DISCUSSION

This study investigates the effect of various structural parameters of a sandwich beam with a spherical core on the static behavior of sandwich structures under transverse loading, such as face thickness (t), spherical radius (r), and spacing distance (Sd), focusing on static deflection, von Mises stress, and strain energy. The analysis is divided into three main parts. The first one, the validation analysis, determines the extent to which the experimental results agree with those obtained by simulation, thus confirming the validity of the model used. The second and third sections investigate the effect of spacing distance and sphere radius, and the thickness of the face on static behavior, respectively.

4.1 Validation study

A validation study is a crucial process in engineering research and development, aimed at ensuring the accuracy and reliability of simulation models. The primary objective of a validation study is to compare the results obtained from computational models with those derived from experimental tests. This comparison helps to identify the degree of correlation between the simulated data and real-world behavior, thereby verifying the effectiveness and precision of the models used. Figure 6 shows a variation of experimental and numerical static deflection with offset distance when the sphere diameter is 8 mm, and the face thickness is 1 mm. Figure 7 shows the variation of static deflection with sphere diameter when the offset distance is 22 mm, and the face thickness is 1 mm. In the case where the offset distance and sphere diameter are 33 mm and 8 mm, respectively, Figure 8 displays a variation of static deflection with face thickness. It can be observed from the three figures that the experimental static deflection values show good agreement with the numerical simulation results, with a maximum percentage difference of approximately 7%.

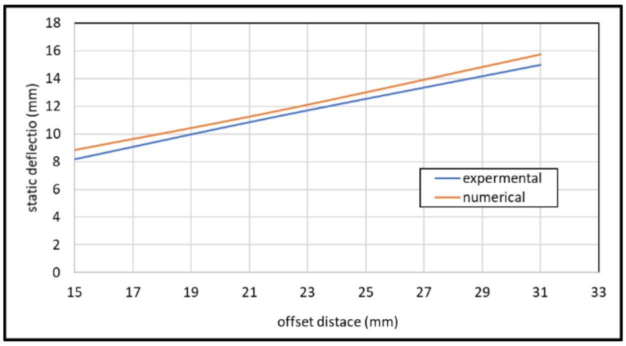


Figure 6. Variation of static deflection with offset distance for a sphere diameter of 8 mm and a face thickness of 1 mm under a 1 N transverse load

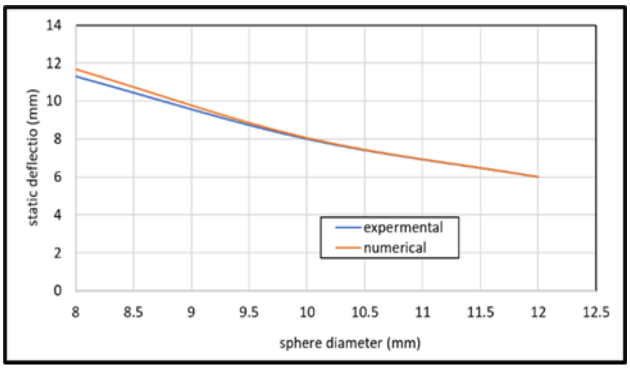


Figure 7. Variation of static deflection with sphere diameter for an offset distance of 22 mm and a face thickness of 1 mm under a 1 N transverse load

4.2 Spacing distance and sphere radius on static behavior

The spacing distance, defined as the distance between the centers of adjacent spheres in the longitudinal and transverse axes within the spherical core, plays a significant role in determining the mechanical behavior of the sandwich beam, which includes static deflection, strain energy, and equivalent stress (von Mises stress). Figures 9, 10, and 11 illustrate the impact of this spacing distance on static deflection, strain energy, and equivalent stress (von Mises stress) for various values of sphere radius and face thickness equal to 1 mm.

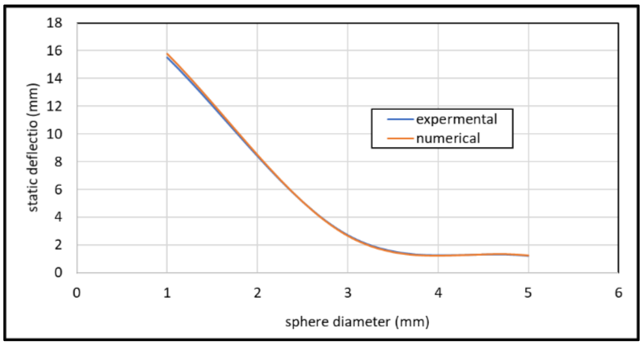


Figure 8. Variation of static deflection with face thickness for an offset distance of 33 mm and a sphere diameter of 8 mm under a 1 N transverse load

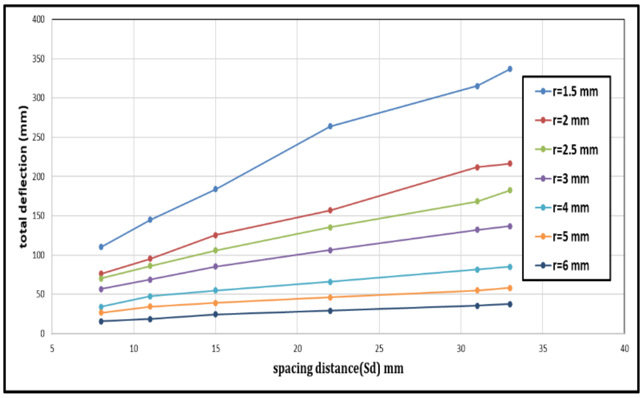


Figure 9. Variation of total deformation with spacing distance for different values of sphere radius when the face thickness is 1 mm

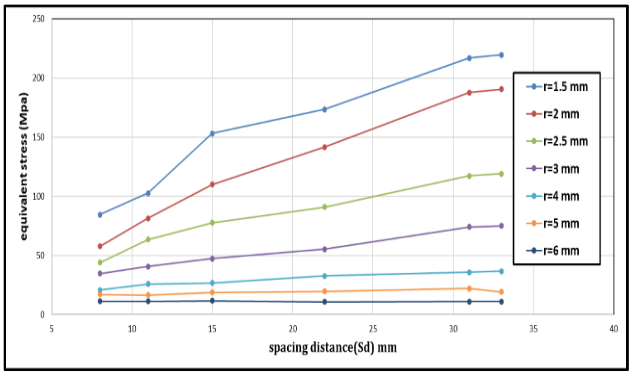


Figure 10. Variation of von Mises stress with spacing distance for different values of sphere radius when the face thickness is 1 mm

From these Figures, it was observed that increasing the spacing distance led to an increase in static deflection, stress, and strain energy at any given sphere radius. The logical explanation for these results, where an increase in spacing distance leads to higher static deflection, can be attributed to changes in stiffness (K), calculated by the equation K = EI.

Here, K represents stiffness, E is Young's modulus, and I is the moment of inertia. In a sandwich structure made from a one material, E remains constant. Therefore, changes in spacing distance directly influence the moment of inertia (I) of the structure. Increased spacing distance results in a decrease in I, indicating that the structure is less resistant to deformation under load. Consequently, increased deformation leads to higher stress (σ) and strain (ε), thereby increasing strain energy (SE) according to the relationship SE = 0.5 * Stress * Strain. In summary, the observed increase in static deflection with greater spacing distance is logically explained by the corresponding decrease in stiffness (K), influenced by changes in the moment of inertia (I). This, in turn, results in higher stress, strain, and strain energy within the structure under applied loads. The increase in stiffness leads to increases the shear area and consequently increases the shear effect.

Conversely, increasing the sphere radius at any given spacing distance resulted in a decrease in static deflection, stress, and strain energy. Increasing the sphere radius results in a larger contact area between the spheres and the faces of the sandwich beam, which enhances the load distribution across the core. This increased contact area improves the overall stiffness and reduces the deformation, stress, and strain energy for a given load.

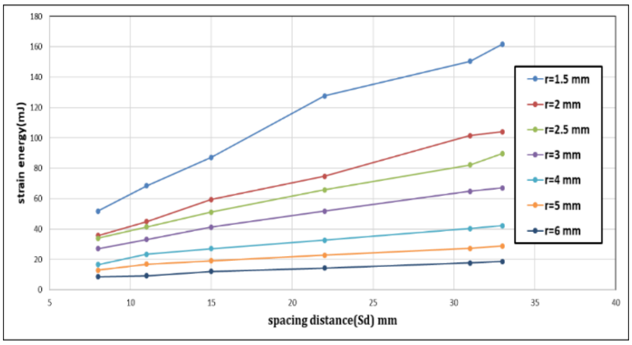
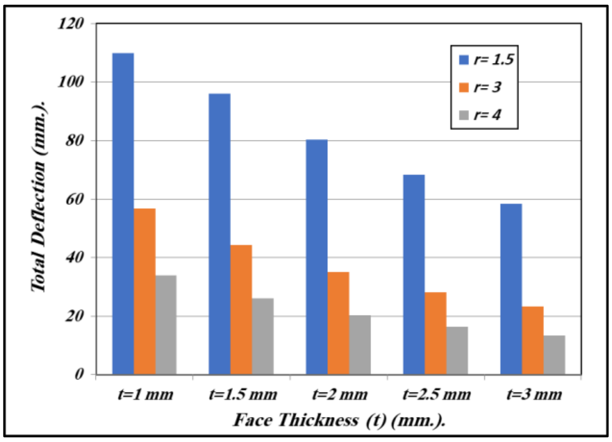


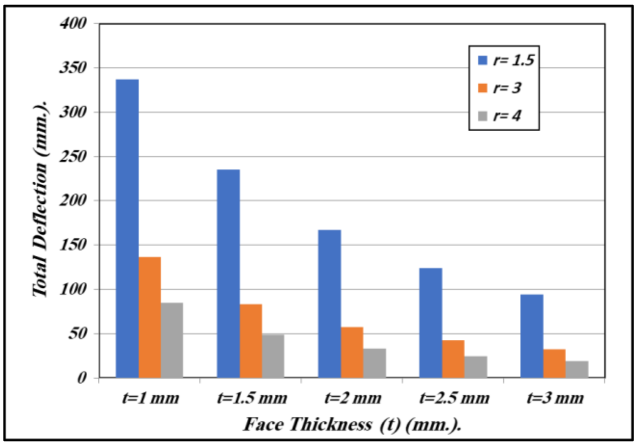
Figure 11. Variation of strain energy with spacing distance for different values of sphere radius when the face thickness is 1 mm

4.3 Effect of face thickness

Figures 12, 13, and 14 illustrate the variation of total deformation, von Mises stresses, and strain energy, respectively, as functions of face thickness across different values of sphere radius and spacing distance. Each one of them has two scenarios: (a) at an 8 mm spacing distance and (b) at a 33 mm spacing distance.

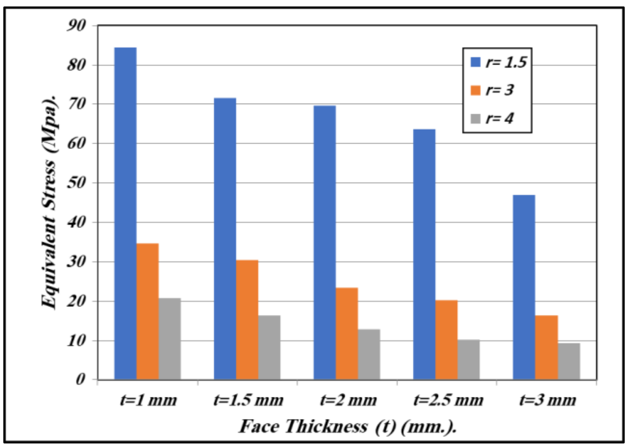


(a) Spacing distance is 8 mm

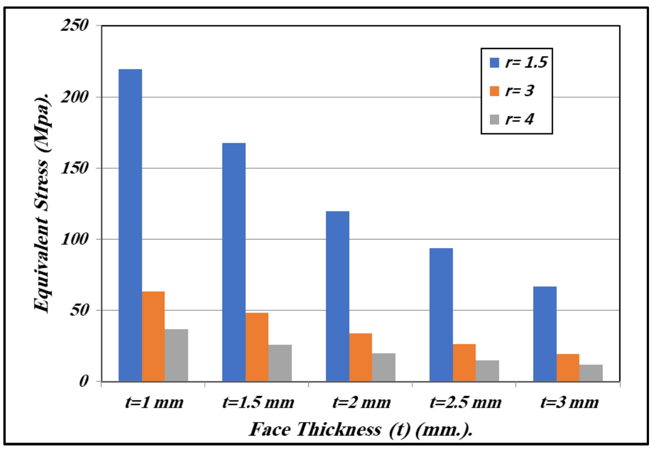


(b) Spacing distance is 33 mm

Figure 12. Variation of total deformation with face thickness for different values of sphere radius and spacing distances

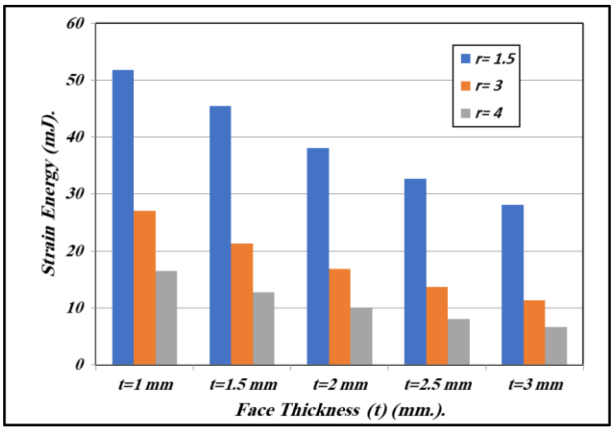


(a) Spacing distance is 8 mm

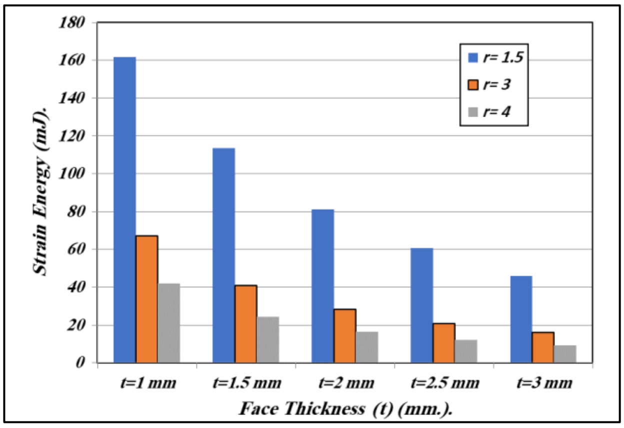


(b) Spacing distance is 33 mm

Figure 13. Variation of von Mises stresses with face thickness for different values of spacing distances and the sphere radius



(a) Spacing distance is 8 mm



(b) Spacing distance is 33 mm

Figure 14. Variation of strain energy with face thickness for different values of spacing distance and the sphere radius

It was observed that the mechanical behavior of sandwich structures is significantly influenced by variations in spacing distance, sphere radius, and face thickness. Increasing the spacing distance typically leads to higher static deflection, stress, and strain energy, as structures become less compact and effective in load distribution. Conversely, a larger sphere radius improves load distribution, decreases stress concentrations, and reduces deflection by increasing the contact area between spheres and face sheets. Meanwhile, thicker face sheets enhance the structure's stiffness and durability, leading to lower deflections and stress levels under load. The interplay of these parameters is crucial for optimizing the structural integrity and performance of sandwich structures, highlighting the need for a balanced design approach to meet specific mechanical requirements.

5. CONCLUSIONS AND RECOMMENDATION

From the above simulations of practical experiments on a sandwich beam with a spherical core, the following can be concluded:

1. The AM process was used to fabricate the sandwich beams with spherical cores, as it allows the production of complex geometries with high accuracy and reproducibility, which would be difficult to achieve using conventional methods.
2. Finite elements modeling by ANSYS software shows reliable and high accuracy in the simulation sandwich beam with spherical core through validation with experimental results.
3. The increasing the thickness of the faces and the spherical radius leads to a decrease in the value of deformation, stress, and strain energy, in contrast to the spacing distance.

The study is limited to static bending tests, PLA material, and a specific geometric scale, which may affect the generalization of the results. Future work should consider dynamic and impact loading, compressive behavior, the use of alternative materials, and potential scale effects to further validate and extend the findings of this work.

REFERENCES

[1] Sadiq, S.E., Bakhy, S.H., Jweeg, M.J. (2020). Crashworthiness behavior of aircraft sandwich structure with honeycomb core under bending load. IOP Conference Series: Materials Science and Engineering, Institute of Physics Publishing, 881(1): 1-16. https://doi:10.1088/1757-899X/881/1/012046

[2] Sadiq, S.E., Abada, H.H., Al-Baidhani, H., Flayyih, M.A., Bakhy, S.H., Kazimierczuk, M.K., Jweeg, M.J. (2025). Theoretical investigation of forced vibration of an aircraft sandwich panel structure under transient load. Mathematics, 13(914): 1-25. https://doi.org/10.3390/math13060914

[3] Mustapha, K.B. (2020). Manufacturing, applications and mechanical properties of lightweight wood-based sandwich panels. Encyclopedia of Renewable and Sustainable Materials, 1(1): 411-416. https://doi.org/10.1016/B978-0-12-803581-8.11156-7

[4] Proença, M., Sousa, A.N., Garrido, M., Correia, J.R. (2020). Acoustic performance of composite sandwich panels for building floors: Experimental tests and numerical-analytical simulation. Journal of Building Engineering, 32: 101751. https://doi.org/10.1016/j.jobe.2020.101751

[5] Lurie, S.A., Solyaev, Y.O., Volkov-Bogorodskiy, D.B., Bouznik, V.M., Koshurina, A.A. (2017). Design of the corrugated-core sandwich panel for the arctic rescue vehicle. Composite Structures, 160: 1007-1019. https://doi.org/10.1016/j.compstruct.2016.10.123

[6] Patel, J.M., Modi, B.A. (2013). Stiffness and thermal analysis of doubly curve sandwich panel for an automobile application. Procedia Engineering, 51: 655-664. https://doi.org/10.1016/j.proeng.2013.01.093

[7] Han, B., Xin, F.X., Jin, F., Lu, T.J. (2012). Numerical simulations for hail impact on lightweight sandwich structures. Advanced Materials Research, 410: 321-324. https://doi.org/10.4028/www.scientific.net/AMR.410.321

[8] Ouadday, R., Marouene, A., Morada, G., Kaabi, A., Boukhili, R., Vadean, A. (2018). Experimental and numerical investigation on the impact behavior of dual-core composite sandwich panels designed for hydraulic turbine applications. Composite Structures, 185: 254-263. https://doi.org/10.1016/j.compstruct.2017.11.007

[9] Liu, L., Feng, H., Tang, H., Guan, Z. (2016). Impact resistance of Nomex honeycomb sandwich structures with thin fibre reinforced polymer face sheets. Journal of Sandwich Structures and Materials, 20(5): 531-552.

https://doi.org/10.1177/1099636216664076
[10] Jweeg, M.J., Bakhy, S.H., Sadiq, S.E. (2021). Effects of core height, cell angle and face thickness on vibration behavior of aircraft sandwich structure with honeycomb core: An experimental and numerical investigations. Materials Science Forum, 1039: 65-85. https://doi.org/10.4028/www.scientific.net/MSF.1039.65
[11] Pei, Z., Xu, Y., Wei, F., Liu, T., Su, D. (2020). Electromagnetic property of a novel gradient honeycomb composite fabricated by 3D forming. Journal of Magnetism and Magnetic Materials, 439: 165742. https://doi.org/10.1016/j.jmmm.2019.165742
[12] Rebelo, H.B., Lecompte, D., Cismasiu, C., Jonet, A., Belkassem, B., Maazoun, A. (2019). Experimental and numerical investigation on 3D printed PLA sacrificial honeycomb cladding. International Journal of Impact Engineering, 131: 162-173. https://doi.org/10.1016/j.ijimpeng.2019.05.013
[13] Kesavarma, S., Kong, C.K., Samykano, M., Kadirgama, K., Pandey, A.K. (2020). Bending properties of 3D printed coconut wood-PLA composite. IOP Conference Series: Materials Science and Engineering, Institute of Physics Publishing, 736: 052031. https://doi.org/10.1088/1757-899X/736/5/052031
[14] Touri, M., Kabirian, F., Saadati, M., Ramakrishna, S., Mozafari, M. (2019). Additive manufacturing of biomaterials-The evolution of rapid prototyping. Advanced Engineering Materials, 21(2): 1800511. https://doi.org/10.1002/adem.201800511
[15] Taresh, O.F., Mezher, M.T., Daway, E.G. (2023). Mechanical properties of 3D-Printed PETG samples: The effect of varying infill patterns. Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials, 33(5): 339-345. https://doi.org/10.18280/rcma.330508
[16] Hanoon, W.H., Namer, N.S.M., Nama, S.A. (2022). Bending titanium sheets with 3D-printed PETG tools. Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials, 32(1): 39-43. https://doi.org/10.18280/rcma.320106
[17] Ali, H.B., Oleiwi, J.K., Othman, F.M. (2022). Compressive and tensile properties of ABS material as a function of 3D printing process parameters. Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials, 32(3): 117-123. https://doi.org/10.18280/rcma.320302
[18] Pirouzfar, S., Zeinedini, A. (2021). Effect of geometrical parameters on the flexural properties of sandwich structures with 3D-printed honeycomb core and E-glass/epoxy Face-sheets. Structures, 33: 2724-2738. https://doi.org/10.1016/j.istruc.2021.06.033
[19] Al-Raheem, S.K., Zainy, H.Z., Almawash, A.D., Alansari, L.S., Mohammed Ali, S.W. (2024). Static deflection of pre-twisted beam subjected to transverse load. Results in Engineering, 21: 101953. https://doi.org/10.1016/j.rineng.2024.101953
[20] Njim, E.K., Hasan, H.R., Jweeg, M.J., Al-Waily, M., Hameed, A.A., Youssef, A.M., Elsayed, F.M. (2024). Mechanical properties of sandwiched construction with composite and hybrid core structure. Advances in Polymer Technology, 2024: 3803199. https://doi.org/10.1155/2024/3803199
[21] Wu, Q., Gao, Y., Wei, X., Mousanezhad, D., Ma, L., Vaziri, A., Xiong, J. (2018). Mechanical properties and failure mechanisms of sandwich panels with ultra-lightweight three-dimensional hierarchical lattice cores. International Journal of Solids and Structures, 132: 171-187. https://doi.org/10.1016/j.ijsolstr.2017.09.024
[22] Guo, Z., Hu, G., Jiang J., Yu, L., Li, X., Liang, J. (2021) Theoretical and experimental study of the vibration dynamics of a 3D printed sandwich beam with an hourglass lattice truss core. Frontiers in Mechanical Engineering, 7: 651998. https://doi.org/10.3389/fmech.2021.651998
[23] Haldar, A.K., Managuli, V., Munshi, R., Agarwal, R.S., Guan, Z.W. (2021). Compressive behaviour of 3D printed sandwich structures based on corrugated core design. Materials Today Communications, 26: 101725. https://doi.org/10.1016/j.mtcomm.2020.101725
[24] Zoumaki, M., Mansour, M.T., Tsongas, K., Tzetzis, D., Mansour, G. (2022). Mechanical characterization and finite element analysis of hierarchical sandwich structures with PLA 3D-printed core and composite maize starch biodegradable skins. Journal of Composites Science, 6(4): 118. https://doi.org/10.3390/jcs6040118
[25] Hou, Z., Tian, X., Zhang, J., Li, D. (2018). 3D printed continuous fibre reinforced composite corrugated structure. Composite Structures, 184: 1005-1010. https://doi.org/10.1016/j.compstruct.2017.10.080
[26] Azzouz, L., Chen, Y., Zarrelli, M., Pearce, J.M., Mitchell, L., Ren, G., Grasso, M. (2019). Mechanical properties of 3D printed truss-like lattice biopolymer non-stochastic structures for sandwich panels with natural fibre composite skins. Composite Structures, 213: 220-230. https://doi.org/10.1016/j.compstruct.2019.01.103
[27] Wadi, K.J., Yadeem, J.M., khazaal, S.M., Al-Ansari, L.S., Abdulsamad, H.J. (2022). Static deflection calculation for axially FG cantilever beam under uniformly distributed and transverse tip loads. Results in Engineering, 14: 100395. https://doi.org/10.1016/j.rineng.2022.100395
[28] Xu, K., Liu, H., Xiao, J. (2021). Static deflection modeling of combined flexible beams using elliptic integral solution. International Journal of Non-Linear Mechanics, 129: 103637. https://doi.org/10.1016/j.ijnonlinmec.2020.103637