Kufa Journal of Engineering
Vol. 16, No. 1, January 2025, P.P. 265-282
Article history: Received 13 June 2024, last revised 29 July 2024, accepted 16 August 2024

FREE VIBRATION ANALYSIS IN INNOVATIVE 3D PRINTING SANDWICH PANAELS FOR AIRCRAFT STRUCTURE

Sadiq Emad Sadiq[1], Hayder Zuhair Zainy[2], Roaa Mohammed Muneer[3], and Luay S. Al-Ansari[4]

[1] Department of Aeronautical Technical Engineering, Technical Engineering College of Najaf, Al-Furat Al-Awsat Technical University,54001,Najaf,Iraq, Email:sadaiq.emad@atu.edu.iq.

[2] Mechanical Engineering Department, Faculty of Engineering, University of Kufa, Iraq, Email:hayderz.zainy@uokufa.edu.iq.

[3] Al-Mussaib Technical Institute, Al-Furat Al-Awsat Technical University, 51006 Babil, Iraq, Email:roaa.muneer@atu.edu.iq.

[4] Mechanical Engineering Department, Faculty of Engineering, University of Kufa, Iraq, Email:luays.alansari@uokufa.edu.iq.

https://doi.org/10.30572/2018/KJE/160116

ABSTRACT

Sandwich panel structures are composed of three layers: core and two facings. The configuration of the core deeply influences the mechanical properties of the sandwich panel. Numerous innovative core shapes have been proposed to enhance these properties; however, many have not been implemented due to manufacturing difficulties, particularly spherical shapes. This research aims to address this manufacturing challenge by utilizing 3D printing technology to produce sandwich panels with a spherical core. Additionally, the study investigates the effects of varying design parameters like sphere diameter, offset distance and face thickness on the free vibration features of the sandwich panels experimentally and numerically. Experimental tests validated the finite element models with an error margin below 12%. The key parameters explored were spherical diameter (3-12mm), offset distance (10-33mm), and face thickness (1-5mm). The results demonstrate a direct correlation between these parameters and the sandwich beam natural frequency.

KEYWORDS

Free Vibration, Sandwich Beam, ANSYS Software, Natural Frequency, Polylactic Acid (PLA).

1. INTRODUCTION

Sandwich structures, known for their lightweight, strength, and versatility, are built upon a simple yet effective design: two rigid outer skins bonded to a thick, lightweight core. This core, often made of low-density materials, provides significant bending stiffness despite its weight (Shunmugam and Kanthababu, 2020). Imagine the skin handling bending like armor while the core, acting as a spacer, manages shear stresses (Peliński and Smardzewski, 2020). This division of labor, combined with the skin's superior strength and the core's impressive flexural ability, makes sandwich panels masters of bending resistance and champions against buckling (Pandyaraj and Rajadurai, 2021). Evaluating these panels often focuses on their overall effectiveness rather than individual components. Researchers delve into the core's intricate geometry and material properties to determine its characteristics and enhance its mechanical properties (Kausar *et al.*, 2023). This focus on performance has fueled recent research exploring diverse core geometry like a circle, open and closed lattice, rectangle, corrugated, and hexagonal (Sahu, Sreekanth and Reddy, 2022). Researchers have extensively investigated the weight reduction benefits and improved mechanical properties achieved through sandwich construction in aircraft structures. Sadiq et al. (Sadiq, Bakhy and Jweeg, 2021), (E. Sadiq, J. Jweeg and H. Bakhy, 2021) conducted studies to explore the effects of cell angle, core height, and face sheet thickness on the vibration behavior of honeycomb core sandwich structures. Their research employed both experimental and numerical methods. Additionally, Hussam Raad et. al. (Raad *et al.*, 2023) studied the sandwich free vibration with an open and closed lattice core. It has been noted that using a cellular pattern instead of a foam shape or converting a solid substance has a highly beneficial effect. To determine the free vibration characteristics, theoretical formulations are built for two different constructions. formulas for predicting mechanical properties with selected forms based on relative density are derived. Finally, (Hwalah, Obeid and Fadhel, 2020) analyzed the transient response of sandwich structures with three different types of corrugated cores: triangular, trapezoidal, and Y-shaped." Building upon the established benefits of corrugated core structures, researchers have explored even more innovative approaches. (Li *et al.*, 2021) introduced a novel concept by incorporating Kirigami design principles. This involves strategically cutting and folding portions of the corrugated sheet, creating vertical fold-ins that significantly enhance crushing resistance, as observed in their studies (up to a 10-fold increase). (Khoshgoftar and Abbaszadeh, 2021) investigated the use of auxetic structures (materials show negative Poisson's ratio) as core materials. Their research, both experimental and numerical, explored how geometrical parameters like cell component angles, dimensions, thickness, and density impact the mechanical behavior under static loads. (Usta, Türkmen and Scarpa, 2021) compared the low-velocity impact response of sandwich panels composite with various core configurations. They employed 3D-printed PLA cores with different non-auxetic and auxetic designs (hexagonal, hexachiral, re-entrant and arrowhead) and carbon/fiber epoxy composite face sheets. Their findings suggest that non-auxetic cores offer advantages at lower impact energies due to their larger thickness and contact surface. The non-auxetic cores offer advantages at lower impact energies. While, auxetic cores excel in high-impact scenarios due to their ability to densify and resist indentation during collapse, leading to superior impact resistance and energy absorption. Researchers, like (Zhang *et al.*, 2020), have explored combining different core types to optimize properties. Their study focused on square honeycomb-corrugated hybrid cores. These hybrid structures displayed significant improvements in out-of-plane compression behavior compared to individual cores, even in high-density regions. Tests, simulations, and theoretical models all confirmed the superior strength and energy absorption of these hybrid cores.

This study proposes a novel approach to sandwich construction instead of traditional core shapes and materials, it explores the use of 3D-printed spherical cores with a uniform size and distribution. The key contribution lies in overcoming the manufacturing challenges associated with spherical cores through 3D printing. Also, the analysis of free vibration for a 3D printed sandwich beam have a spherical core is studied experimentally and numerically. The sandwich structure natural frequency with a clamp-free boundary condition are obtained using ANSYS workbench. The experimental tests were done on sandwich specimens considering spherical diameter, offset distance and face thickness. Validation models of finite element were conducted by comparing the natural frequencies predicted numerically with those measured experimentally. The agreement between the two methods was excellent, with an error margin below 12%. This incorporates the information about the error margin.

2. **METHODOLOGY**

2.1. Finite Element Simulation

This study explores the influence of various design elements on vibration behavior of a 3D-printed spherical core of sandwich beam. Specifically, the effects of sphere diameter, offset distance, and face thickness (detailed in Fig. 1) were investigated. A comprehensive range of values for each parameter was employed, as shown in Table 1.

The finite element model (FEM) of the spherical sandwich beam was created using ANSYS Workbench software (as shown in Fig. 2). The faces and core were separately meshed, then assembling the entire model were take place. A fixed-free boundary condition was applied in the FE simulation. To investigate various scenarios, 57 simulations were conducted. The element type SOLID187 was chosen within the ANSYS model, and mesh convergence was ensured. The resulting model size ranged from approximately 130, 470 to 760, 537 nodes and 65, 099 to 424, 906 elements (Hashim et al., 2022; Njim, 2022; Onoroh, F. et al., 2023).

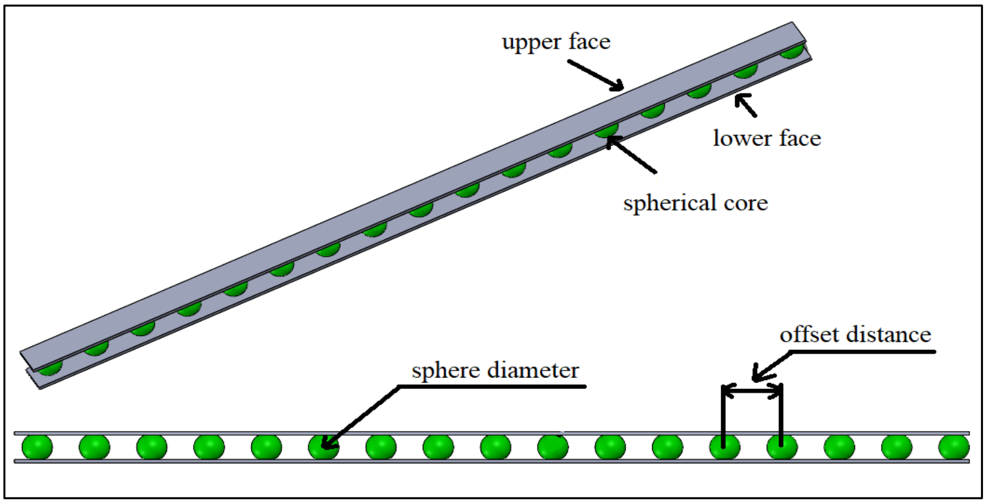


Fig. 1. The schematic of sandwich beam with spherical core

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

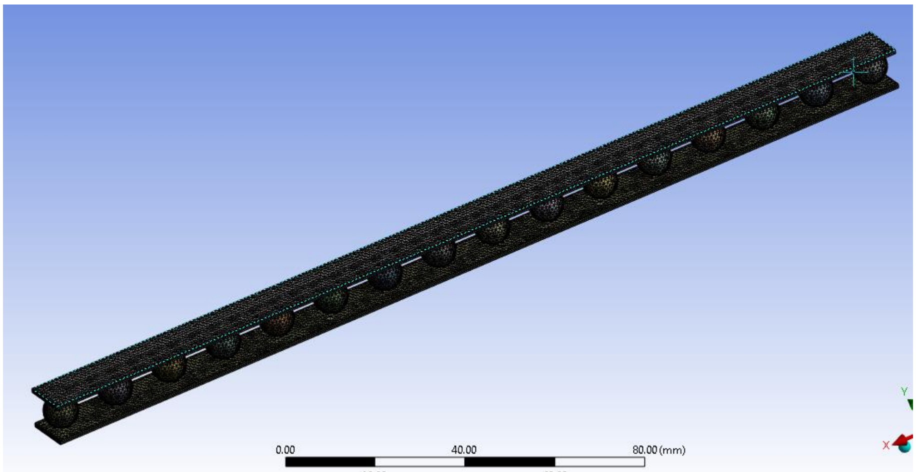


Fig. 2. Geometry and meshing of sandwich beam with spherical core when the sphere diameter is (3mm), the offset distance is (31mm) and face thickness is (1mm)

2.2. Manufacture of Sandwich Beam with Spherical Core:

Additive manufacturing, also known as 3D printing, creates complex objects directly from digital data. It works by building the object layer-by-layer, essentially like stacking thin slices on top of each other. This allows for highly detailed designs compared to subtractive manufacturing techniques, where material is removed from a solid block. Additionally, 3D printing often uses less material than traditional methods. This technology finds applications across various industries due to its versatility and wide range of materials (Wadi et al., 2022). In this study, a CR-10s 3D printer Fig. 3 was used with Polylactic Acid (PLA) filament. PLA is a biomaterial gaining traction due to its biodegradability and eco-friendliness compared to traditional petroleum-based polymers. Its natural origin makes it a promising alternative for various medical and engineering applications (M. Shukur et al., 2024).

Fig. 1 illustrates the schematic diagram of the sandwich beam geometry used for 3D printing. PLA samples with varying parameters were designed as detailed in Table 2. SolidWorks software was employed to create the sample designs, which were then saved in a (*.lst) format. Cura software served as the intermediary to translate these designs into instructions for the 3D printer, ultimately resulting in the fabrication of sandwich beams with various dimensions, Fig.4. The properties of PLA are showed in Table 3, while Table 4 details the specific factors of the 3D printer employed (Hanon, Marczis and Zsidai, 2020).

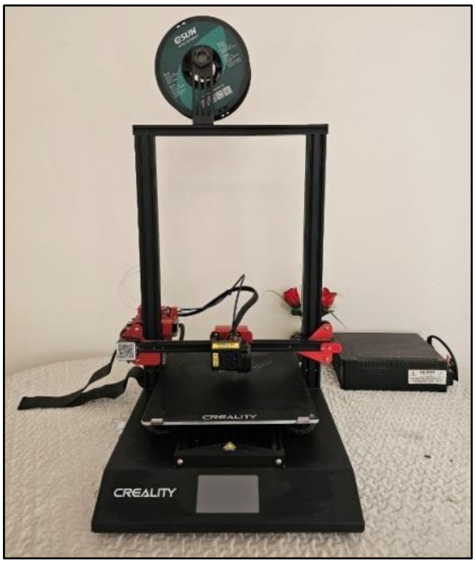


Fig.3. 3D Printer type cr-10s used in this work.

Table 2. Dimensions of samples used in experimental work

No.	Sphere Diameter (d) (mm)	Offset Distance (x) (mm)	Face Thickness (t) (mm)	Beam Length (L) (mm)	Beam Width (w) (mm)	Beam Thickness (Tb)(mm)
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

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

Table 3. Mechanical Properties of PLA (Al-Raheem *et al.*, 2024)

Property	Value	Units
Modulus of Elasticity (E)	1.2	(GPa)
Density (ρ)	1360	(kg/m^3)
Poisson Ratio (ν)	0.36	---

Table 4. Printing Setting of 3D Printer Type CR-10s Used in this Work.

Nozzle diameter.	0.40 mm
Layer thickness.	0.28 mm
Infilling density.	100 %
Infilling pattern.	lines
Printing temperature.	200° C
Bed temperature.	60° C
Printing speed.	100 mm/sec

2.3. Free Vibration Test

This test details the experimental determination results of the first natural frequency for the sandwich beam specimens. The natural frequency was obtained by analyzing the accelerometer signal using Sigview software. This software employs the Fast Fourier Transform (FFT) function to convert the vibration signal from the time domain (time-based measurement) to the frequency domain (frequency-based measurement). Fig. 5 depicts the sandwich beam samples tested for their fundamental natural frequency. The experimental vibration signal was acquired from an oscilloscope and plotted using Microsoft Excel, Fig. 6. and Fig. 7 illustrates the corresponding FFT analysis, which is representative of the behavior observed for all specimens. Table 5 summarizes the natural frequencies obtained for all the sandwich beam samples.

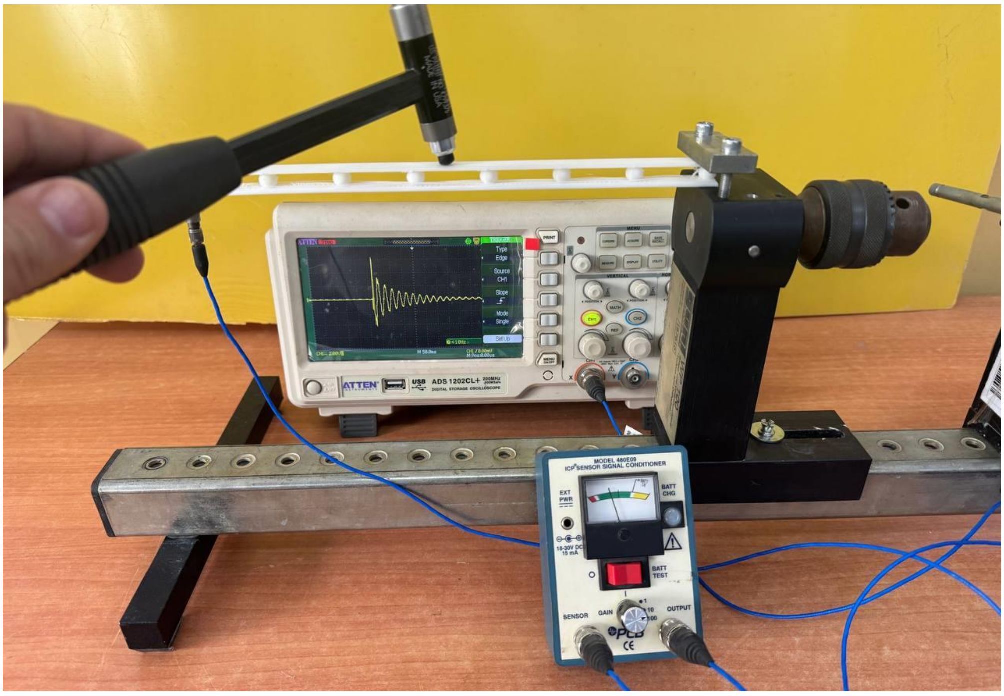


Fig. 5: The Experimental vibration test for sandwich beam with spherical core

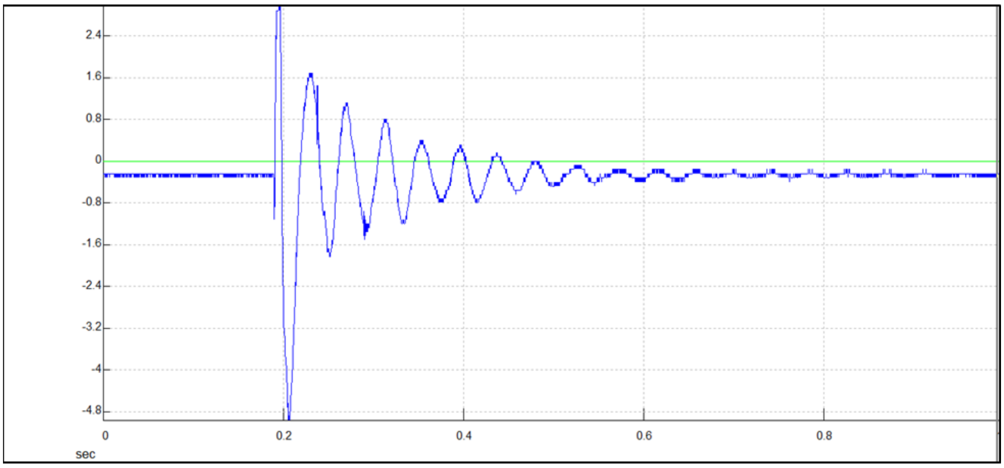


Fig.6. The experimental vibration signal for sandwich beam with spherical core in time domain.

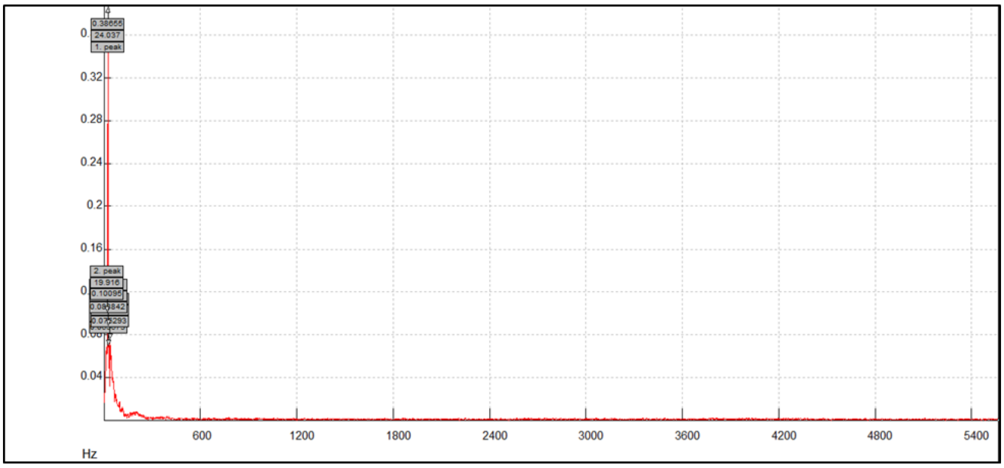


Fig. 7. The experimental vibration signal for sandwich beam with spherical core in frequency domain

3. COMPARISION BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

To validate the finite element model, the natural frequencies obtained experimentally were compared to the numerical results Table 5. Excellent agreement was observed between the two methods, with a maximum absolute error percentage of only 11.9%. This error occurred for a specific configuration with a sphere diameter of 8 mm, offset distance of 31 mm, face thickness of 3 mm, and overall beam thickness of 14 mm. Probable sources of error involve measurement errors, product tolerances, and environmental factors. Calibration of measuring devices and control during 3D printing reduced these errors. Further accuracy was ensured by post-publication surveys and controlled experimental sites. The error rate between the experimental and numerical results did not exceed 10 percent, and this percentage gives more reliability (Dookhi, M. A. and Tahir, A. A., 2023).

Table 5. Comparison Between the Experimental and Numerical Natural Frequency Results

No.	(d) (mm)	(x) (mm)	(t) (mm)	L (mm)	w (mm)	Tb (mm)	Natural Frequency		Error%
							ANSYS	Exp.	
1	8	15	1	227	10	10	22.467	24.037	6.5316
2	8	22	1	227	10	10	24.247	26.184	7.3976
3	8	31	1	227	10	10	23.857	25.269	5.5879
4	10	22	1	227	12	12	25.657	28.077	8.6192
5	12	22	1	227	14	14	24.617	26.276	6.3137
6	8	31	1	227	10	10	23.857	24.719	3.4872
7	8	31	3	227	10	14	29.032	32.959	11.9148
8	8	31	5	227	10	18	29.908	33.508	10.7437

Table 5 provides the data for the effects of key parameters on the vibration frequency of the spherical core sandwich beam. These effects are further visualized in Fig. 8, 9, and 10.

- **Offset Distance (x):** Fig. 8 illustrates the impact of offset distance (x) on the frequency when the sphere diameter (d) is 8 mm and the face thickness (t) is 1 mm. The highest frequency is observed at an offset distance of x = 22 mm.
- **Sphere Diameter (d):** Fig. 9 explores the influence of sphere diameter (d) on the frequency when the offset distance (x) is 22 mm and the face thickness (t) is 1 mm. The frequency reaches a maximum value at a sphere diameter of d = 10 mm.
- **Face Thickness (t):** The effect of face thickness (t) on the frequency is depicted in Fig.10. Here, the offset distance (x) is fixed at 31 mm and the sphere diameter (d) is 8 mm. The trend shows a clear increase in frequency as the face thickness increases.

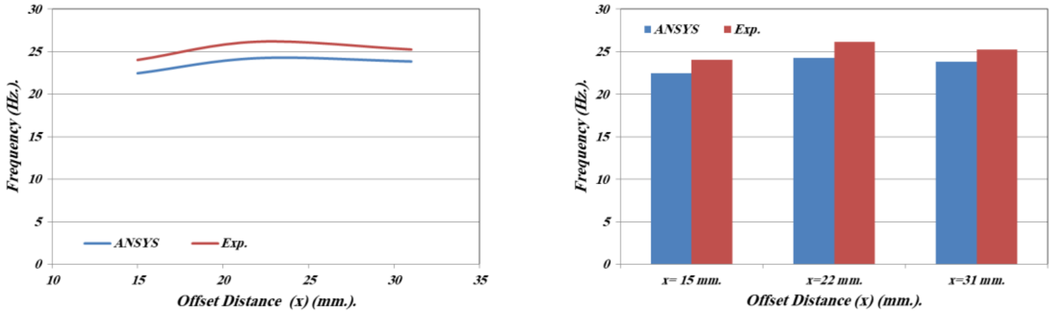


Fig. 8. Comparison of experimental and numerical fundamental frequency of sandwich beam with spherical core at different offset distance (x) when (d=8 mm) and (t=1 mm).

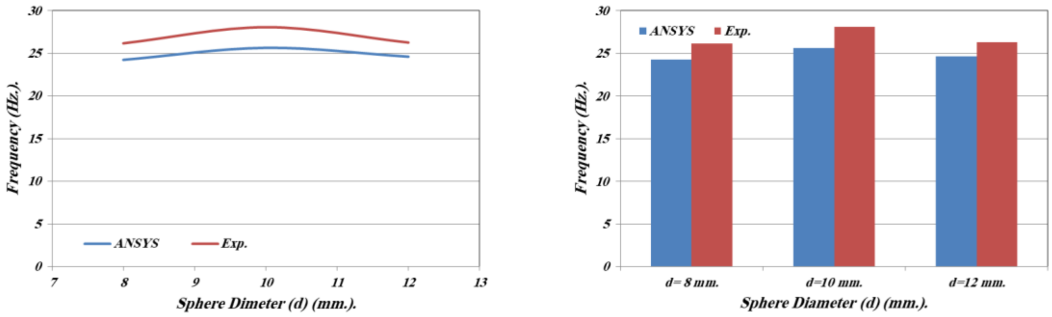


Fig.9 Comparison of experimental and numerical fundamental frequency of sandwich beam with spherical core at different sphere diameter (d) when (x=22 mm) and (t=1 mm).

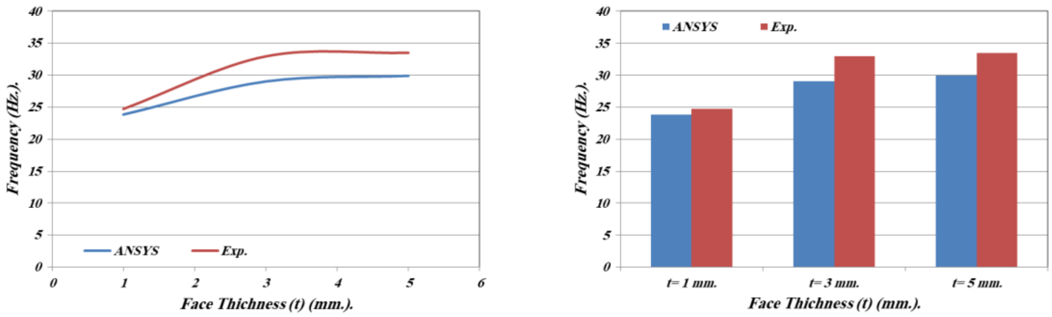


Fig.10. Comparison of experimental and numerical fundamental frequency of sandwich beam with spherical core at different face thickness (t) when (d=8 mm) and (x=31 mm).

4. RESULTS AND DISCUSSION

In this work, two cases are considered to study the impact of sphere diameter (d), offset distance (x) and face thickness (t) on the first three natural frequencies of clamped-free sandwich beam with spherical core.

(a) First Case:

In the first case, the face thickness is assumed constant (t=1 mm), the values of offset distance (x) are (8, 11, 15, 22, 31 and 33) mm and the values of sphere diameter (d) are (3, 4, 5, 6, 8, 10 and 12) mm. Fig. 11 shows the variation of first, second and third natural frequencies of sandwich beam with spherical core due to change the sphere diameter (d) for the different offset distance (x) and face thickness (t) is (1 mm). In the first mode, the natural frequency increases when the sphere diameter increases at the same offset distance (x). In other side, the frequency increases slightly with increasing offset distance when the sphere diameter is (5 mm). This means that the offset distance is approximately has no effect on natural frequency when d=5 mm. But the increasing of offset distance (x) causes decreasing the natural frequency when the sphere diameter is less than (5 mm) and when the sphere diameter is greater than (5 mm), the increasing of offset distance (x) causes increasing the natural frequency. For explaining this variation of first natural frequency, the natural frequency equation of uniform beam can use equation 1 (Rao, 2019).

$$\omega_i = (\beta_i L)^2 * \sqrt[2]{\frac{E_{eq} * I_{eq}}{\rho_{eq} * A_{eq} * L^4}} \qquad i = mode\ number \tag{1}$$

The ($\beta_i L$) value depends on the supporting type, (Aeq) and (Ieq) are the equivalent cross section area and equivalent second moment of area of sandwich beam, E_{eq} and ρ_{eq} are the equivalent modulus and equivalent density of the of sandwich beam. The value ($E_{eq} * I_{eq}$) is the stiffness of sandwich beam and its varied according to the sphere diameter and offset distance as well as the face thickness (its constant in this case). The decrease of sphere diameter leads to decrease the stiffness of sandwich beam at any offset distance, while the stiffness of sandwich beam increases with decreasing the offset distance at any sphere diameter. In other side, the value ($\rho_{eq} * A_{eq} * L$) represents the mass of sandwich beam and it also depends on the sphere diameter, offset distance and the face thickness (its constant in this case). The impact of sphere diameter and offset distance on the mass of sandwich beam is illustrated in Fig. 12. The maximum mass of sandwich beam is happened when the sphere diameter is (12 mm) and offset distance is (8 mm). Generally, when the offset distance decreases, the mass of the sandwich panel increases for the same sphere diameter because of increasing the material in the core. Also, the mass of the sandwich panel increases when the sphere diameter increases for the same offset distance because of increasing the dimension of sphere and width of sandwich panel. Depending on Equation 1, the effect of sphere diameter and offset distance on the stiffness of sandwich beam is greater than that of the mass of sandwich beam as shown in the first natural frequency in Fig.11. In other side, the effect of offset distance is not appear when the sphere diameter is approximately (5 mm). In second mode, the second natural frequency deceases when the offset distance is increases at the same sphere diameter and the sphere diameter (d) is slightly effect on the second natural frequency, Fig. 11. While, the offset distance (x) is slightly effect on the third natural frequency when d=3 mm and when the sphere diameter increases, the variation of third natural frequency will change with diffract rate, Fig. 11. Fig. 13 shows the combined effect of sphere diameter and offset distance on first, second and third natural frequency of the clamped-free sandwich beam with spherical core. The variation of first, second and third frequencies are not the same function because of changing the mass and stiffness distributions of clamped-free beam with respect to sphere diameter and offset distance.

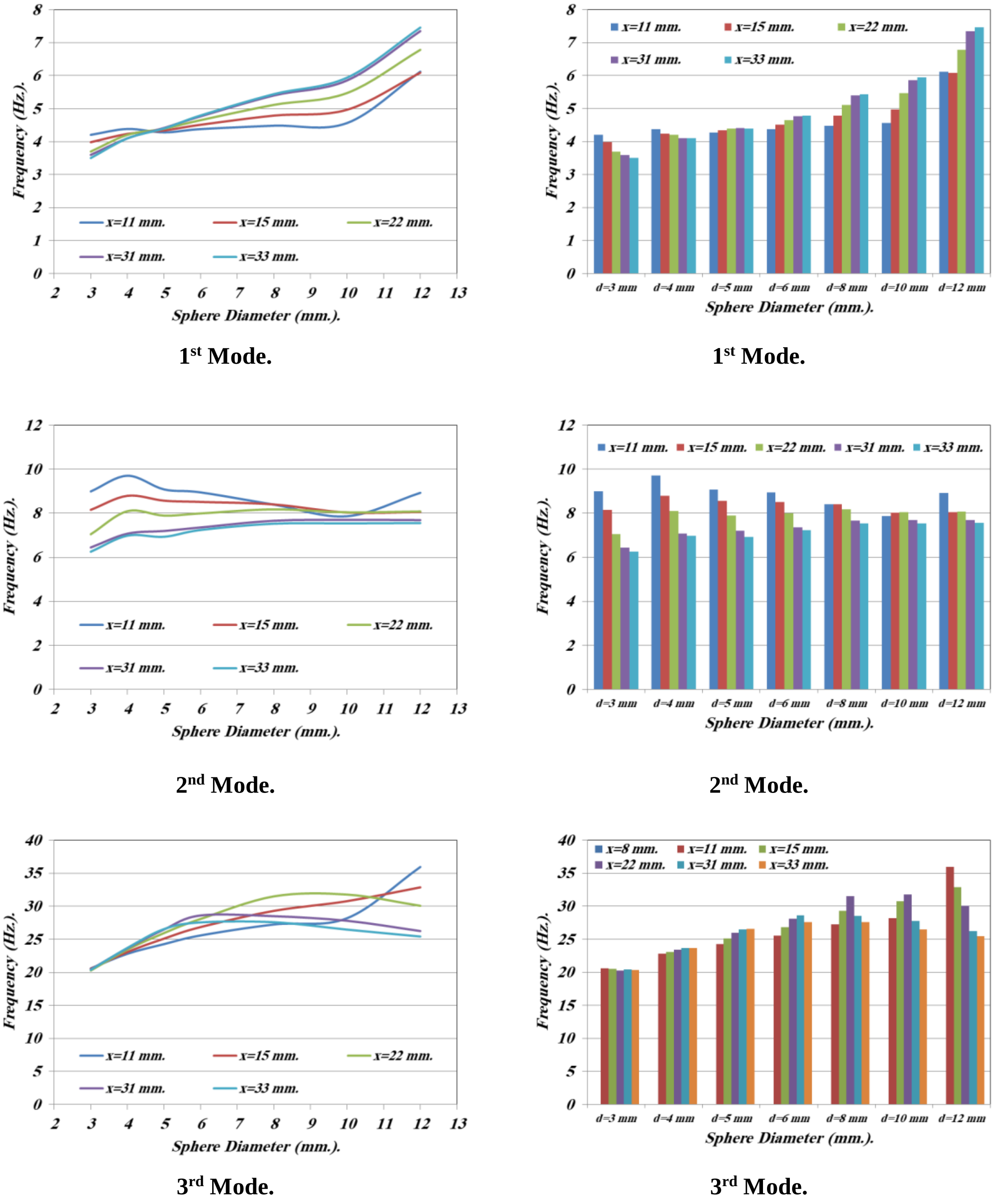


Fig. 11. The influence of sphere diameter on the first, second and third natural frequencies of the sandwich beam with spherical core at different offset distance(x) when the face thickness (t) is (1 mm).

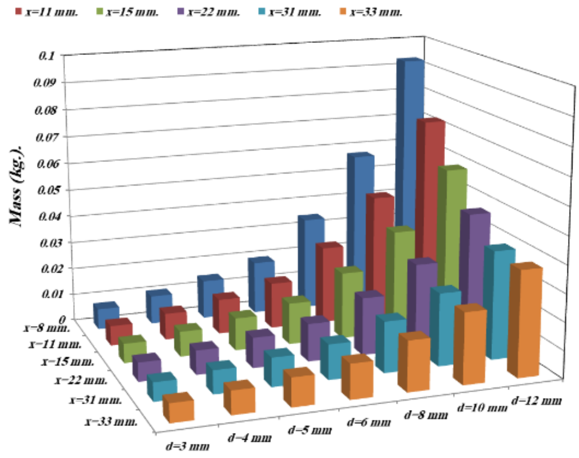
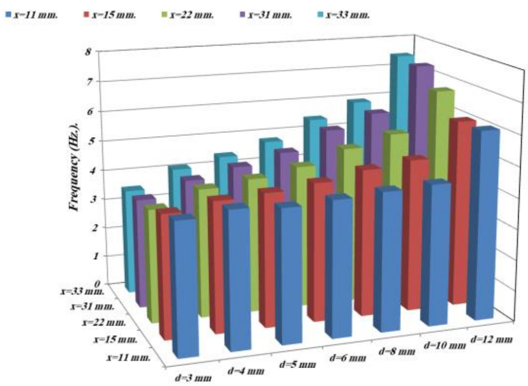
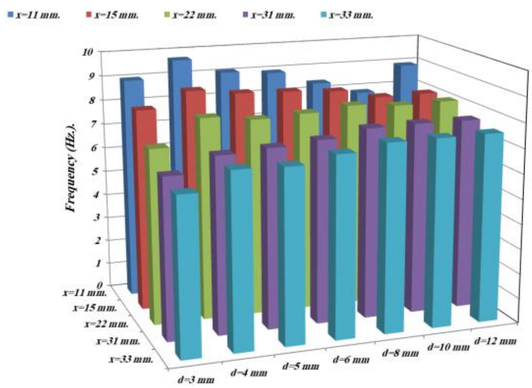


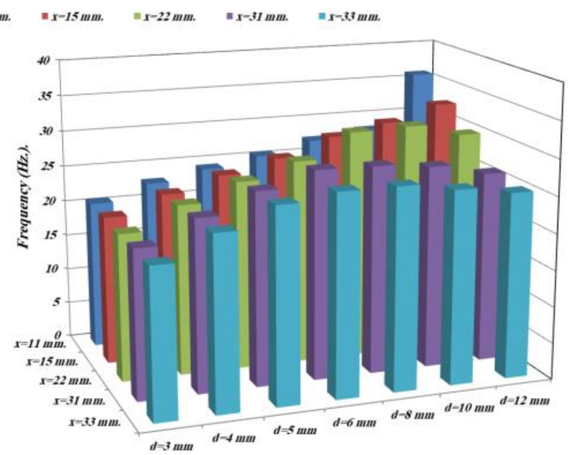
Fig. 12. The impact of sphere diameter and offset distance on the mass of the sandwich beam with spherical core when the face thickness (t) is (1 mm).



1st Mode.



2nd Mode.



3rd Mode.

Fig. 13. The variation of first, second and third natural frequency of clamped – free sandwich beam with spherical core due to change the sphere diameter and offset distance when the face thickness is (1 mm.)

(b) Second Case:

In this case, five samples set of sandwich beam with spherical core were considered and these samples are listed in Table 6. In this case, the effect of face thickness of sandwich beam with spherical core is studied. At the beginning, the masses of these sets are calculated as shown in Fig. 14. The mass of sandwich beam increases with increasing the face thickness for any set sample. In other side, the increase of face thickness, it also increases the stiffness of sandwich beam. The effect of increasing of the face thickness on the first, second and third natural frequency is illustrated in Fig. 15. For the first mode and first set of samples, the frequency decreases with increasing face thickness, but, the frequency increases with increasing face thickness for the remaining sets. In the second mode, the second natural frequency of the sandwich beam with face thickness is (1 mm) decreases with number of set sample but the second natural frequency increases when the face thickness is (3 mm).

Table 6. The Five Samples Set of Sandwich Beam with Spherical Core.

No.	Sphere Diameter (d) (mm.)	Offset Distance (x) (mm.)	Face Thickness (mm.)
1	4	8	1, 3 and 5
2	6	11	1, 3 and 5
3	8	15	1, 3 and 5
4	10	22	1, 3 and 5
5	12	31	3 and 5

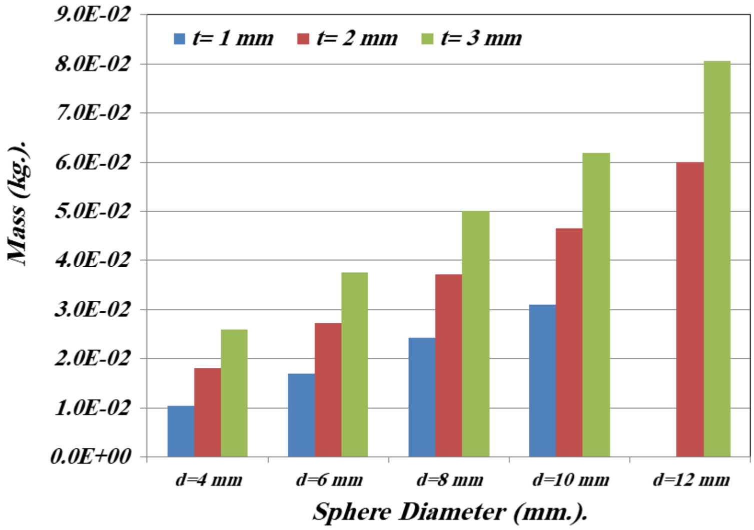
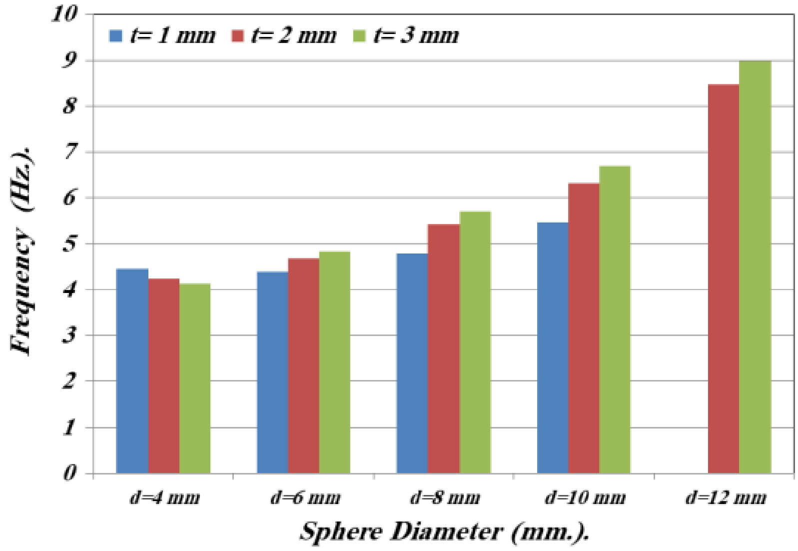
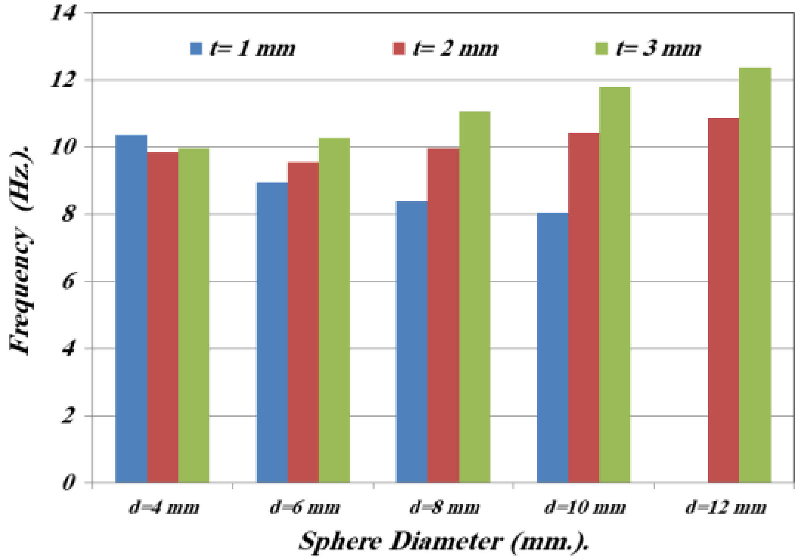


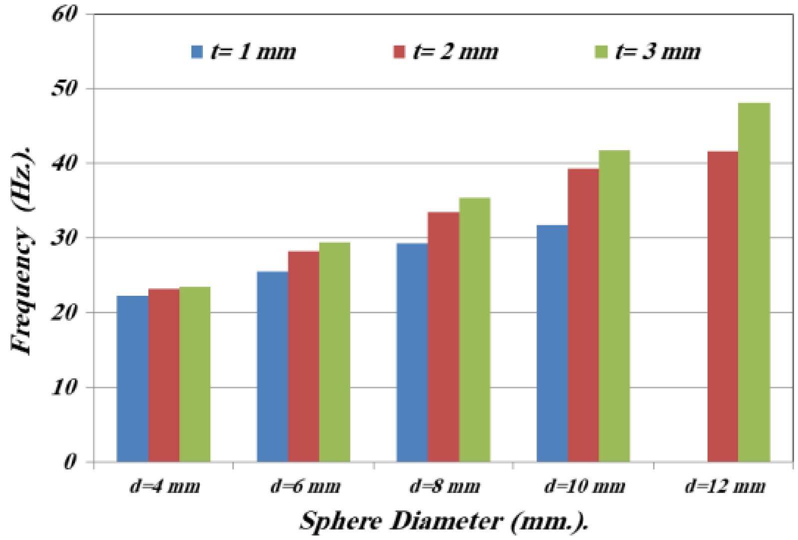
Fig. 14. Masses of the five-set sandwich beam with three different face thickness.



1st Mode.



2nd Mode.



3rd Mode.

Fig.15.The variation of first, second and third natural frequency of clamped – free sandwich beam with spherical core due to change the face thickness for the five set.

5. CONCLUSIONS AND FUTURE WORKS:

Utilizing additive manufacturing through 3D printing, sandwich beams with a spherical core can surpass traditional methods. This advancement not only overcomes the challenge of manufacturing innovative structures but also extends their application in engineering. Variations in parameters—such as sphere diameter, offset distance, and face thickness—significantly influence vibration characteristics.

1- The 3D printer is a suitable method to manufacture the sandwich panel with spherical core.

2- Utilizing the Finite Element Method via ANSYS software efficiently simulates sandwich beams, with an error margin below 12% compared to experimental outcomes.

3- The first natural frequency of sandwich panel is proportional directly with the sphere diameter and offset distance. The increasing in sphere diameter leads to increase the mass and stiffness of beam and the increasing in stiffness of beam is greater than increasing in the mass of beam. While the increasing in offset distance leads to decrease the mass and stiffness of beam and the decreasing in stiffness of beam is smaller than decreasing in the mass of beam.

4- The first natural frequency of sandwich panel is proportional directly with the face thickness because of increasing the (stiffness / mass) ratio.

In future works, the static and dynamic analysis of sandwich panel with spherical and elliptical core are studied using experimental and theoretical (Finite element and Rayleigh methods) methods.

ACKNOWLEDGEMENTS

The authors sincerely acknowledge the Department of Aeronautical Technical Engineering at the Technical Engineering College of Najaf, Al-Furat Al-Awsat Technical University, Iraq, for their invaluable support in manufacturing the sandwich panel samples with a spherical core. Additionally, we extend our gratitude to the mechanical engineering laboratories at the University of Kufa for conducting the experimental tests in this study.

6. REFERENCES

Al-Raheem, S.K. et al. (2024) ‘Static deflection of pre-twisted beam subjected to transverse load’, Results in Engineering, 21, p. 101953. Available at: https://doi.org/10.1016/j.rineng.2024.101953.

Dookhi, M. A. and Tahir, A. A. (2023) ‘STUDY THE EFFECT OF EXTERNAL CRACK ON THE MECHANICAL PROPERTIES OF COMPOSITE MATERIALS: Composite Materials’, Kufa Journal of Engineering. Kufa, Najaf, IRAQ, 14(4), pp. 1–10. doi: 10.30572/2018/KJE/140401.

E. Sadiq, S., J. Jweeg, M. and H. Bakhy, S. (2021) ‘Strength Analysis of an Aircraft Sandwich Structure with a Honeycomb Core: Theoretical and Experimental Approaches’, Engineering and Technology Journal, 39(1A), pp. 153–166. Available at:https://doi.org/10.30684/etj.v39i1A.1722 .

Hanon, M.M., Marczis, R. and Zsidai, L. (2020) ‘Influence of the 3D Printing Process Settings on Tensile Strength of PLA and HT-PLA’, Periodica Polytechnica Mechanical Engineering, 65(1), pp. 38–46. Available at: https://doi.org/10.3311/PPme.13683 .

Hashim, W.M. et al. (2022) ‘Investigating Static Deflection of Non-Prismatic Axially Functionally Graded Beam’, Material Design & Processing Communications. Edited by G. Qian, 2022, pp. 1–12. Available at: https://doi.org/10.1155/2022/7436024 .

Hwalah, S.M., Obeid, H.H. and Fadhel, E.Z. (2020) ‘Study Different Core Types Of Sandwich Plate On The Dynamic Response Under Impact Loading’, 15.

Kausar, A. et al. (2023) ‘State-Of-The-Art of Sandwich Composite Structures: Manufacturing—to—High Performance Applications’, Journal of Composites Science, 7(3), p. 102. Available at: https://doi.org/10.3390/jcs7030102 .

Khoshgoftar, M. and Abbaszadeh, H. (2021) ‘Experimental and finite element analysis of the effect of geometrical parameters on the mechanical behavior of auxetic cellular structure under static load’, The Journal of Strain Analysis for Engineering Design, 56(3), pp. 131–138. Available at: https://doi.org/10.1177/0309324720957573 .

Li, Z. et al. (2021) ‘Impact response of a novel sandwich structure with Kirigami modified corrugated core’, International Journal of Impact Engineering, 156, p. 103953. Available at: https://doi.org/10.1016/j.ijimpeng.2021.103953 .

M. Shukur, Z. et al. (2024) ‘calculating the natural frequency of pre-twisted beam’, Journal of Engineering and Sustainable Development, 28(1), pp. 1–16. Available at: https://doi.org/10.31272/jeasd.28.1.1 .

Njim, E.K. (2022) ‘Analytical and numerical flexural properties of polymeric porous functionally graded (PFGM) sandwich beams’, Journal of Achievements in Materials and Manufacturing Engineering, 110(1), pp. 5–10. Available at: https://doi.org/10.5604/01.3001.0015.7026 .

Onoroh, F., Ogbonnaya, M. and Agberegha, L. O. (2023) ‘PERFORMANCE EVALUATION OF HOT AIR THERMOELECTRIC GENERATOR USING BIOMASS ENERGY SOURCE’, Kufa Journal of Engineering. Kufa, Najaf, IRAQ, 14(4), pp. 69–85. doi: 10.30572/2018/KJE/140406.

Pandyaraj, V. and Rajadurai, A. (2021) 'Experimental investigation on flexural behaviour of spherical core sandwich structure', Journal of Reinforced Plastics and Composites, 40(3–4), pp. 143–164. Available at: https://doi.org/10.1177/0731684420947801 .

Peliński, K. and Smardzewski, J. (2020) 'Bending Behavior of Lightweight Wood-Based Sandwich Beams with Auxetic Cellular Core', Polymers, 12(8), p. 1723. Available at: https://doi.org/10.3390/polym12081723 .

Raad, H. et al. (2023) 'Sandwiched Plate Vibration Analysis with Open and Closed Lattice Cell Core', Physics and Chemistry of Solid State, 24(2), pp. 312–322. Available at: https://doi.org/10.15330/pcss.24.2.312-322 .

Rao, S.S. (2019) Vibration of continuous systems. Second edition. Hoboken, NJ, USA: John Wiley & Sons Ltd.

Sadiq, S.E., Bakhy, S.H. and Jweeg, M.J. (2021) 'optimum vibration characteristics for honey comb sandwich panel used in aircraft structure', Journal of Engineering Science and Technology, 16(2).

Sahu, S.K., Sreekanth, P.S.R. and Reddy, S.V.K. (2022) 'A Brief Review on Advanced Sandwich Structures with Customized Design Core and Composite Face Sheet', Polymers, 14(20), p. 4267. Available at: https://doi.org/10.3390/polym14204267 .

Shunmugam, M.S. and Kanthababu, M. (eds) (2020) Advances in Simulation, Product Design and Development: Proceedings of AIMTDR 2018. Singapore: Springer Singapore (Lecture Notes on Multidisciplinary Industrial Engineering). Available at: https://doi.org/10.1007/978-981-32-9487-5 .

Usta, F., Türkmen, H.S. and Scarpa, F. (2021) 'Low-velocity impact resistance of composite sandwich panels with various types of auxetic and non-auxetic core structures', Thin-Walled Structures, 163, p. 107738. Available at: https://doi.org/10.1016/j.tws.2021.107738 .

Wadi, K.J. et al. (2022) 'Static deflection calculation for axially FG cantilever beam under uniformly distributed and transverse tip loads', Results in Engineering, 14, p. 100395. Available at: https://doi.org/10.1016/j.rineng.2022.100395 .

Zhang, Z. et al. (2020) ‘Enhanced mechanical performance of brazed sandwich panels with high density square honeycomb-corrugation hybrid cores’, Thin-Walled Structures, 151, p. 106757. Available at: https://doi.org/10.1016/j.tws.2020.106757 .