Al-Nahrain Journal for Engineering Sciences

Al-Nahrain J. Eng. Sci. 29(2) 313-318, 2026
Original Article

Analysis of Free Vibration Features in FGM Plates

Sanaa Samir[1]●, Haneen Alaa Abdel-Hade[2]●, Dalia j. Al ibadi[3]●, Wasan Mahmood Ahmed[4]● and Engin Sansarci [5]●.

1,2,3,4 Dept. of Refrigeration &Air Conditioning Technical Engineering, Dijlah University College, Baghdad - Iraq
5 Beykoz University, Istanbul- Turkey

●*These authors contributed equally to this work*

DOI: https://www.doi.org/10.29194/NJES.29020313

Received: Sep. 21, 2025 **Revised:** Oct. 29, 2025 **Accepted:** April 6, 2026 **Published:** June 20, 2026

Abstract

Functionally graded materials (FGM) are a category of composite materials distinguished by specific design attributes that allow them to serve various purposes and applications. This study used FGM samples made from carbon particles and a polyester matrix to manufacture micro-shapes and study the changes in vibration characteristics at different parameters. The manufactured samples contained different weight percentages, ranging from 0% to 20%, and a subsequent step involved manufacturing two different grades of FGM samples: one consisting of five layers and the other of eleven layers. The free vibration characteristics of the FGM structure were determined experimentally and numerically. The effect of varying several parameters on the natural frequency was monitored, including the number of FGM layers, thickness, and gradient coefficient. The Ansys Workbench (version 2022 R1) was used to analyze free vibration to verify the experimental results.

Vibration testing of square FGM panels showed that the natural frequency increased with the number of layers. Improving the thickness of the panels also resulted in increased natural frequency values, when changing the thickness from 5mm to 10mm increases the natural frequency by an amount of 173.34 Hz at 11 layers. Model analysis using finite element analysis (FEA) tools confirmed the validity of the experimental solution, with a maximum discrepancy of 9.72%. Based on numerical calculations, the natural frequency coefficient decreased with increasing power law index under different boundary conditions and increased with increasing number of constraints in the sample

Keywords: *FEA, FGM, Free Vibration, Frequency, Polymer.*

Corresponding author: Provide the corresponding author information and publisher here. E-mail address: sanaa.samir@duc.edu.iq

1. Introduction

Structures experience severe conditions, requiring material performance that varies according to location. Materials are developed with special chemical and physical properties that merge two or more materials, called functionally graded material (FGM)[1-3]. A functionally graded material (FGM) is a class of composite material recognized for its unique design properties that allow it to perform diverse functions and serve various applications. This graded characteristic can eradicate discontinuities in the material's characteristics across its thickness, [4–6] where (FGMs) are sophisticated materials characterized and a high degree of control over the direction and concentration of these properties. Due to the constraints associated with conventional materials, such as pure metals, ceramics, and traditional composites, FGMs present a novel manufacturing approach that enhances their applicability. Consequently, these materials are extensively utilized across various sectors, including aerospace, marine, and prominent mechanical and civil engineering industries [7–9]. Since the mid-eighties, processing functionally graded materials has become a subject of academic interest. In (1987-1992), a team from Japan conducted the first processing of functionally graded materials in spacecraft parts to withstand the high temperatures used [10, 11]. Hasani Baferani et al. [12] discovered the analytical solution for the free vibration study of the FG plate. Using the Nevier method, the motion equations were modified to determine the plate's normal frequency in various boundary conditions. The frequency decreases as the aspect ratio increases, excluding the plate with free edges. The effect of material heterogeneity on the natural frequency becomes increasingly important as plate thickness increases. Mohammad Talha and B.N. Singh [13] studied the static analysis and free vibration of rectangular and square FG plates. The study is based on finite element models combined with higher-order shear deformation theory, specifically modified for lateral displacements. Continuous isoperimetric Lagrangian limited factors, with 13 degrees of freedom per node, were used to obtain the results. The frequency parameter rises as the plate thickness ratio (a/h) and aspect ratio (a/b) increases. Also, as the volume fraction value increase, the frequency parameter for FG plates decreases. In contrast, for a given density, the dimensionless central deviation ratio increases as N increases. Increasing the frequency parameter is achieved by shifting the support condition from simply supporting all edges to clamping all edges (CCCC). I. Ramu and S. C. Mohanty [14] inspected the effects of four different border cases and the power indicator on the normal frequency of an operatively graded substance plate employing the finite element technique. Compared with the analogous frequency gained for SCSC, SSSS, and SFSF border cases, the normal frequency for the CCCC border cases is the highest. R. Muni Rami Reddy and W. Karunasena [15] studied the effect of the percentage on the weight fraction, the reinforcement distribution pattern, the GPL size, and different boundary conditions at natural frequencies. Compared to square GPL nanoparticles, quadrate nanoparticles participate in the largest proportion of the rise in natural frequency than rectangular GPL. When the border case alternates from FSSF to CCCC for a moderately thick plate, the normalized natural frequency increases for GPL-reinforced plates by 8.9 times and clear resin sheets by 10.2 times. The percentage increase in the basic natural frequency of a thin plate reinforced with 1% GPL is 149%. For a thick plate, it is 121%. Yasser Chikera et al.[16] investigated the natural oscillation of FG multilayer plates reinforced with carbon fillers and graphene fillers, using the finite element method based on the first-order shear method. The frequency was found for different parameters, including the geometric aspect ratio, GPL size, filler distribution pattern, weight fraction, and number of layers. This was done under various boundary conditions. It was found that the frequency increases when the number of layers increases from 10 to 20, but remains constant when the number of layers exceeds 20. The most effective approach is to distribute an increased concentration of nanofillers near its lateral surfaces to enhance the stiffness of the reinforced composite panel. A rise in the width/thickness ratio (b/h) leads to an increase in the natural frequency of the reinforced composite plate. E. Njim et al. [17] presented a comprehensive mathematical model describing the free vibration problem in an FG rectangular sandwich plate with a simple support system. The sandwich plate's core is made from a porous material. The classical plate theory determines the unconstrained vibration parameters of defective media. The FEA and modal analysis were performed numerically in ANSYS-2020-R2 to verify the analytical solution. Analytical solutions and numerical results agree with a maximum error of 8%. Sanaa Samir and Bashar [18] examined the free vibration of the installed FG panel to see if the properties of the material vary according to the power distribution through thickness. The accuracy of the experimental results was determined by comparing them with the numerical results. Frequency was measured numerically for various parameters, such as boundary conditions, power law index, and thickness. The results showed that when the thickness of the plate increases, this will increase the frequency, and changing the thickness increases the normal frequency by 169.68 Hz. The maximum difference between experimental and numerical values was 6.4%.

The complementary effects of different materials on plates were investigated by Jing Zhao et al. (2022)[19], this study proposes a unified modeling method to analyze the behavior of magnetorheological elastomer sandwich plates with functionally graded graphene-reinforced layers. The results obtained from the analysis reveal that the presence of graphene plates (GPLs) causes a noticeable rise in the resonance frequencies, implying that GPLs enhance the stiffness of the plate and improve its vibrational properties.

The purpose of this study is to investigate the free vibration of a functionally graded plate made of polyester resin and ground coal in which the properties of the material vary along the thickness in accordance with the power distribution law. The experimental test was carried out on the sample using a simple mechanical mixing method. A numerical solution was performed via the finite element method to determine the accuracy of the experimental solutions.

2. FGM Plate Properties

A functionally graded material plate with a thickness h composes of a carbon and polymer mixture, as illustrated in Figure 1. The properties vary progressively with location. The characteristic gradient in the material results from a position-dependent chemical composition. The variations in material characteristics P along the thickness of FGM composed of two constituent materials can be articulated as [20, 21][20], [21] :

$$P_z = (P_u - P_l)V_u + P_l \qquad (1)$$

P may denote Young's modulus E, Poisson's ratio, and mass density, whereas V(u) represents the volume fraction of the upper section, articulated through the power distributing law as follows:

$$V_u(z) = \left(z + \frac{1}{2}\right)^k \qquad (2)$$

Where $\frac{-1}{2} \le z \le \frac{1}{2}$ is a non−dimensional coordinate. representing the thickness from the mid−surface upward, and k is a power−law variation index ($0 \le k \le \infty$). The fractions of volume Vu of the top constituent and Vb of the lower component materials in the entire cross−section are derived by integrating the volume fraction function across the thickness as follows:

$$V_u + V_b = 1 \qquad (3)$$

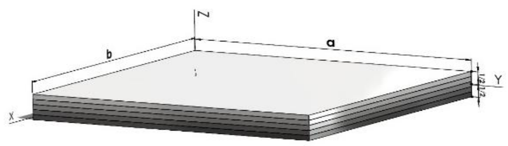


Figure 1. Coordinate of FG Plate.

3. FGM Plate Material and Method

The branded polyester resin (TOPAZE-1110 TP) was used as the matrix. It is a low-viscosity resin compared to other thermosetting materials and was solidified by adding a hardener at a ratio of 2:100, from (Industrial Chemicals & Resins Co. Ltd.) [22–24]. According to the data, figure 2 shows the technical characteristics of (TOPAZ-1110 TP)[25]. The nanoparticle reinforcers are made of carbon. Figure 3 shows their technical characteristics.

Two gradient was manufactured, and the gradient consisted of three different thicknesses (5,8 and 10) mm and the dimensions of each model are 30 cm x 30 cm. The first mode consists of 5 layers made of (FGM), while the second has 11 layers. Where both modes are made for the same thicknesses. Figures 4 and 5 show the layer distribution of the model. The polyester was mixed with the carbon at room temperature by simple mechanical stirring, and the hardener was added at a 100:2 ratio, as recommended. The mixture was gradually and slowly poured into the wooden mold to prevent air bubbles from forming inside. The inner walls and base of the mold were coated with an anti-sticking agent to prevent the mixture from sticking to the mold. This process was repeated using molds of different thicknesses.

Compressive strength MPa	Tensile strength MPa	Tensile Modulus MPa	Density g/cm^3
50	80	3000	1.13

Figure 2. Technical characteristics of TOPAZ-1110 TP.

Properties	Values
Appearance	Black powder
Purity (%)	75
Average particle size (nm)	120
Morphology	powder
Bulk density (g/cm^3)	1.0
Specific gravity (g/cm^3)	2.3

Figure 3. Technical characteristics of Carbon

0 wt.% C+ 100 wt.% SP
05 wt.% C + 95 wt.% SP
10 wt.% C + 90 wt.% SP
15 wt.% C + 85 wt.% SP
20 wt.% C + 80 wt.% SP

Figure 4. layers FGM model

0 wt.% C+ 100 wt.% SP
02 wt.% C+ 98 wt.% SP
04 wt.% C+ 96 wt.% SP
06 wt.% C+ 94 wt.% SP
08 wt.% C+ 92 wt.% SP
10 wt.% C+ 90 wt.% SP
12 wt.% C+ 88 wt.% SP
14 wt. % C+86 wt.% SP
16 wt.% C+ 84 wt.% SP
18 wt.% C+ 82 wt.% SP
20 wt.% C+ 80 wt.% SP

Figure 5. 11 layers FGM model.

4. Experimental Work

Vibration tests determined the natural frequency of the FGM panel. A vibration rig was used to conduct the test, and specimens were mounted on it, as shown in Figure 6. Two ADXL accelerometers and a data acquisition device (DAQ NI-6009) were used. LabVIEW software installed on a computer was used to receive the signals from the DAG. To conduct the test, a vibrating platform (Rig) was used, and samples were fixed on it. The plates had dimensions of 30 cm x 30 cm and variable thicknesses of (5, 8, 10) mm. After the plate is excited by an excitation source, such as a hammer, the resulting signal is received by the accelerometer and converted to LabVIEW software via DAG. These signals are displayed in the SIGVIEW program, which converts the signal into the frequency domain (FFT). The results were validated experimentally for a panel mounted on four sides. The frequency was found at different parameters, including thickness and the number of layers.

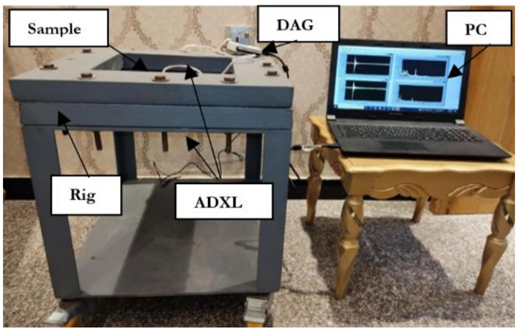


Figure 6. Vibration test setup

5. Finite Element Modelling

The experimental solution was verified using numerical methods, as in many cases. The finite element method was used in this study to find the numerical solution, which was performed using ANSYS software (version 2022 R1) with SOLID186 element type [25, 26]. The properties of each layer were entered into the software library and saved for easy retrieval during simulation. SolidWorks software was used to create the model; the number of nodes and elements were (340807and 67500), respectively. The convergence of the mesh optimization was investigated to produce the most accurate numerical result possible, as shown in the figure 7. Figure 8 shows the meshing of the plate. Equation 1 was used to find the properties in the experimental work of each layer then the data is applied in ANSYS. The frequency was found at different boundary conditions.

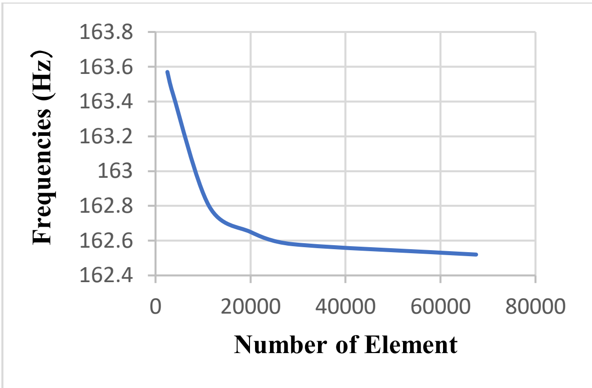


Figure 7. Convergence Curve.

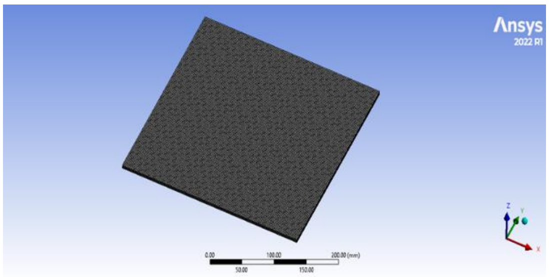


Figure 8. The meshing of the plate

6. Results and Discussion

This research employed experimental methods to examine the free vibration characteristics of functionally graded materials (FGM) plates. The findings encompass the natural frequency and frequency parameters of the FGM plate. These properties are superimposed on different parameters, including the number of layers, plate thickness, and gradient index. The material in each layer is graded throughout the thickness so that it is homogeneous in each layer. The experimental work was verified numerically using ANSYS, where figure 10 has matching FFT analyses for the outcome of the free vibration test conducted on the 5 mm thickness and 11-layer FG plate.

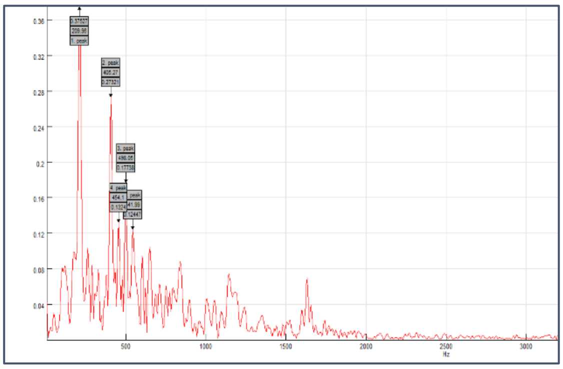


Figure 10. FFT Results for 11 Layer at 5mm Thickness

Equation 4 describes non-dimensional frequency parameters:

$$\psi = \frac{\omega a^2}{h}\sqrt{\frac{\rho_o}{E_0}} \qquad (4)$$

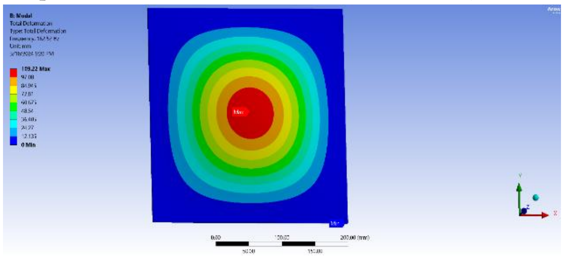
Here, (ω) is the free vibration fundamental frequency value that could be estimated (ρo = 1 Kg/m3 and Eo=1000 MPa), and h is the total height of the structure [25] .

Table 1 presents the contrast between the natural frequency of numerical results and experimental results. It may be inferred that the natural frequencies of the plate rise with the increase in the number of layers and the thickness of the plate due to the increased hardness of the layers. The experimental and numerical solutions exhibit a suitable error rate, with a maximum difference of (9.72%) and an aspect ratio (a/b = 1). There is sufficient agreement between the numerical solution to the problem and the experimental results. In addition, the sample consisting of 11 layers was found to have the highest bounce compared to the sample comprising 5 layers. This is due to the thickness of the layers in the sample comprising 5 layers. The first layer is made of pure polyester, which acts as a damper for these frequencies; the higher the thickness of this layer, the lower the frequency.

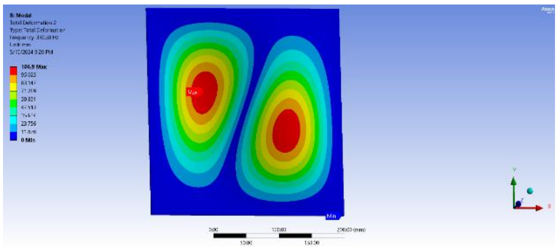
Table 1. The natural frequency experimentally and numerically in Hz for the CCCC boundary condition.

	H(mm)	Exp.	Num.	Difference%
5 Layers	5	152.59	162.٥٢	6.1
	8	261.23	262.1	0.33
	10	322.27	326.13	1.2
11 Layers	5	209.96	232.57	9.72
	8	297.85	300.9	1.024
	10	383.3	39١.77	2.9

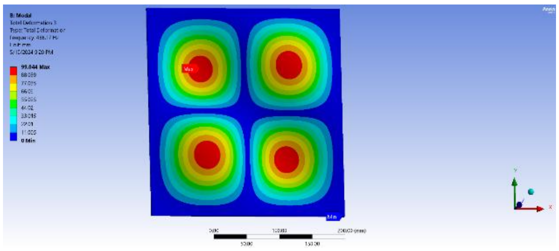
Figure 11 depicts the mode shape number and the related main natural frequencies for a fixed plate (CCCC) with a thickness of 5mm and 5 layers. These frequencies correspond to the minimum resonant frequencies where the plate can vibrate in particular mode forms. This study primarily aimed to find the plate's main natural frequencies, which serve as indicators of its dynamic behavior.



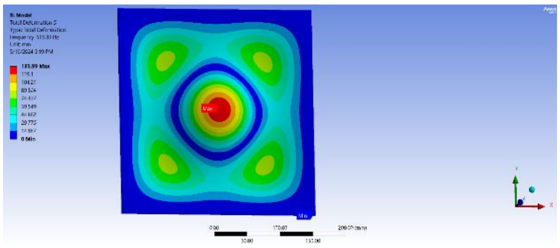
Mode 1



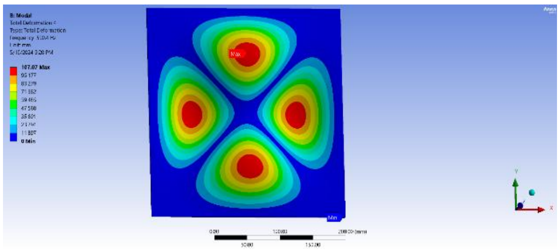
Mode 2



Mode 3



Mode 4



Mode 5

Figure 11. The five mode shapes of a CCCC plate with a thickness of 5mm and consisting of 5 layers.

Table 2 shows the numerical results for different boundary conditions at 5 mm thickness and 5 layers, with a varying power-law index. It was found that the frequency coefficient increases with the increase in the constrained edges of the model. For example, in the case of CCCC, the frequency coefficient at k = 0 has the highest value, 0.5809, compared to the other boundary conditions, because the more constrained edges in the model, the higher the frequency coefficient. In other words, the FCFC model has a lower frequency coefficient than CCCC because it contains two free edges. To explain this behavior, changing the boundary conditions affects the stiffness. It was noted that as the power-law index ascends, the frequency coefficient diminishes, this is due to the frequency transmission through the thickness.

Tabel 2. Numerical Results for a 5mm Thickness and 5-Layer Plate Under Various Boundary Conditions.

B. Cs	Power law index, k				
	0	0.5	1	5	20
CCCC	0.5809	0.5054	0.439	0.233	0.213
CCCS	0.5186	0.446	0.387	0.205	0.188
CSCS	0.471	0.405	0.352	0.187	0.170
SSSS	0.317	0.262	0.237	0.072	0.066
FCFC	0.3596	0.309	0.268	0.141	0.13

Figure 12 illustrates the relationship between the power-law index and the natural frequency, showing the magnitude of the frequency decrease with varying boundary conditions.

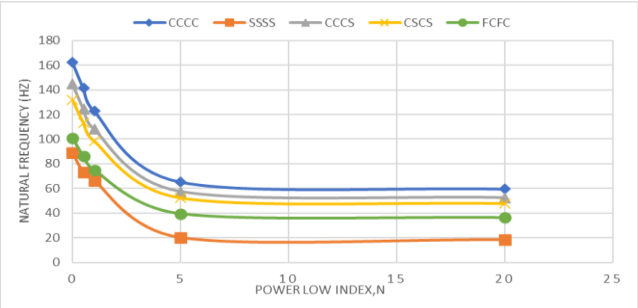


Figure 12. Power law index for a 5 mm thick sample at a/b=1

7. Conclusion

This study examined the free vibration of a meshed functionally graded plate and the variation of material properties in relation to energy distribution throughout the thickness. The precision of the experimental outcomes is assessed by juxtaposing them with numerical data. The frequency is numerically measured for multiple factors, including boundary conditions, power law index, and thickness, to confirm the experimental solution through model and finite element analysis (FEA) methods. The vibration test of square FG samples revealed that an increase in the number of layers elevates their natural frequency relative to other samples. The results show that increasing the thickness of the board leads to an increase in frequency, changing the thickness from 5mm to 10mm increases the natural frequency by an amount of 173.34 Hz at 11 layers plate. The most significant discrepancy between the numerical and experimental values was 9.72%. Frequency parameters were quantitatively assessed under various boundary conditions. The results indicate that an increase in the power index correlates with a decrease in the frequency parameter. Moreover, the frequency parameters for the CCCC example exhibit the highest amplitude relative to all frequencies associated with other boundary conditions, with frequency escalating alongside increased constrained edges.

8.References:

[1] E. K. Njim, M. J. Jweeg, O. S. Abdullah, M. A. Al-Shammari, M. Al-Waily, and S. H. Bakhy, "Mechanical properties of sandwiched construction with composite and hybrid core structure," Adv. Polym. Technol., vol. 2024, p. 3803199, 2024. https://doi.org/10.1155/2024/3803199

[2] M. J. Jweeg, E. K. Njim, O. S. Abdullah, M. A. Al-Shammari, M. Al-Waily, and S. H. Bakhy, "Free vibration analysis of composite cylindrical shell reinforced with silicon nano-particles: Analytical and FEM approach," Phys. Chem. Solid State, vol. 24, no. 1, pp. 26-33, 2023. https://doi.org/10.15330/pcss.24.1.26-33

[3] A. Fadhil, A. Al-Kawaz, and A. Ehsan, "Numerical and experimental investigation of functionally graded rubber-nano-composite core for sandwich structure," Int. J. Civ. Eng. Technol., vol. 9, no. 13, pp. 199-206, 2018.

[4] W. R. Chen and H. Chang, "Vibration analysis of functionally graded Timoshenko beams," Int. J. Struct. Stab. Dyn., vol. 18, no. 1, 2018. https://doi.org/10.1142/S0219455418500074

[5] V. N. Burlayenko and T. Sadowski, "Free vibrations and static analysis of functionally graded sandwich plates with three-dimensional finite elements," Meccanica, vol. 55, no. 4, pp. 815-832, 2020. https://doi.org/10.1007/s11012-019-01001-7

[6] M. Song, S. Kitipornchai, and J. Yang, "Free and forced vibrations of functionally graded polymer composite plates reinforced with graphene nanoplatelets," Compos. Struct., vol. 159, pp. 579-588, 2017. https://doi.org/10.1016/j.compstruct.2016.09.070

[7] N. K. Kareem, M. Takhakh, and A. A. Ali, "An overview of functional gradient biomaterials manufacturing process of implants types," Al-Nahrain J. Eng. Sci., vol. 27, no. 2, pp. 169-184, 2024. https://doi.org/10.29194/NJES.27020169

[8] S. S. Hafidh, H. M. Hasan, and F. M. Mohammed, "Nonlinear vibration analysis of functionally graded carbon nanotubes sandwich cylindrical panels," Phys. Chem. Solid State, vol. 23, no. 2, pp. 127-136, 2020. https://doi.org/10.29194/NJES.23020127

[9] R. T. Abdulhussein, "Damage detection in composite plate based on vibration measurements using genetic algorithm," Al-Nahrain J. Eng. Sci., vol. 20, no. 3, pp. 709-718, 2017.

[10] G. J. H. Melvin, H. M. Ling, and W. M. J. Karen, "Feasibility study: Resin-based functionally graded material incorporated with carbonized waste rice husk," IOP Conf. Ser. Mater. Sci. Eng., vol. 1217, no. 1, p. 012009, 2022. https://doi.org/10.1088/1757-899X/1217/1/012009

[11] Y. Yilmaz and S. Evran, "Free vibration analysis of axially layered functionally graded short beams using experimental and finite element methods," Sci. Eng. Compos. Mater., vol. 23, no. 4, pp. 453-460, 2016. https://doi.org/10.1515/secm-2014-0161

[12] A. Hasani Baferani, A. R. Saidi, and E. Jomehzadeh, "An exact solution for free vibration of thin functionally graded rectangular plates," Proc. Inst. Mech. Eng. Part C J. Mech. Eng.

Sci., vol. 225, no. 3, pp. 526-536, 2011. https://doi.org/10.1243/09544062JMES2171

[13] M. Talha and B. N. Singh, "Static response and free vibration analysis of FGM plates using higher order shear deformation theory," Appl. Math. Model., vol. 34, no. 12, pp. 3991-4011, 2010. https://doi.org/10.1016/j.apm.2010.03.034

[14] I. Ramu and S. C. Mohanty, "Modal analysis of functionally graded material plates using finite element method," Procedia Mater. Sci., vol. 6, pp. 460-467, 2014. https://doi.org/10.1016/j.mspro.2014.07.059

[15] R. M. R. Reddy and W. Karunasena, "Free vibration of functionally graded-GPL reinforced composite plates with different boundary conditions," Aerosp. Sci. Technol., vol. 1, pp. 1-10, 2018.

[16] Y. Chiker, M. Bachene, M. Guemana, B. Attaf, and S. Rechak, "Free vibration analysis of multilayer functionally graded polymer nanocomposite plates reinforced with nonlinearly distributed carbon-based nanofillers using a layer-wise formulation model," Aerosp. Sci. Technol., vol. 1, p. 105913, 2020. https://doi.org/10.1016/j.ast.2020.105913

[17] E. K. Njim, S. H. Bakhy, and M. Al-Waily, "Analytical and numerical investigation of free vibration behavior for sandwich plate with functionally graded porous metal core," Pertanika J. Sci. Technol., vol. 29, no. 3, pp. 1655-1682, 2021. https://doi.org/10.47836/pjst.29.3.39

[18] S. Samir and B. Owaid, "Free vibration analysis of polyester resin-coal functionally graded plates," AIP Conf. Proc., vol. 070035, 2024. https://doi.org/10.1063/5.0237163

[19] J. Zhao, T. Wang, X. Ma, H. Li, J. Hu, J. Liu, and Z. Gao, "Complementary effects on vibration characteristics of functionally graded graphene-reinforced magnetorheological elastomer sandwich plates," Eng. Struct., vol. 270, p. 114864, 2022. https://doi.org/10.1016/j.engstruct.2022.114864

[20] E. K. Njim, S. H. Bakhy, and M. Al-Waily, "Optimisation design of functionally graded sandwich plate with porous metal core for buckling characterisations," Pertanika J. Sci. Technol., vol. 29, no. 4, pp. 3113-3141, 2021. https://doi.org/10.47836/pjst.29.4.47

[21] E. K. Njim, S. E. Sadiq, M. S. A.-D. Tahir, M. A. Flayyih, and L. Hadji, "Flexural bending and fatigue analysis of functionally graded viscoelastic materials: Experimental and numerical approaches," Phys. Chem. Solid State, vol. 24, no. 4, pp. 628-639, 2023. https://doi.org/10.15330/pcss.24.4.628-639

[22] S. M. Mbeche, P. M. Wambua, and D. N. Githinji, "Mechanical properties of sisal/cattail hybrid-reinforced polyester composites," Adv. Mater. Sci. Eng., 2020. https://doi.org/10.1155/2020/6290480

[23] S. D. Al-Qahtani, A. M. Al-Qahtani, A. M. Al-Qahtani, A. M. Al-Qahtani, and A. M. Al-Qahtani, "Simple preparation of photoluminescent and color-tunable polyester resin blended with alkaline-earth-activated aluminate nanoparticles," ACS Omega, vol. 7, no. 12, pp. 10599-10607, 2022. https://doi.org/10.1021/acsomega.2c00149

[24] A. M. Hameed and M. T. Hamza, "Characteristics of polymer concrete produced from wasted construction materials," Energy Procedia, vol. 157, pp. 43-50, 2019. https://doi.org/10.1016/j.egypro.2018.11.162

[25] S. Samir and B. Owaid, "Numerical analysis of free vibration characteristics in multilayer functionally graded plates with coal/polyester composites," J. Eng. Appl. Sci. Dev., vol. 2, no. 0, pp. 626-633, 2025. https://doi.org/10.31272/jeasd.2554

[26] S. E. Sadiq, M. J. Jweeg, and S. H. Bakhy, "The effects of honeycomb parameters on transient response of an aircraft sandwich panel structure," IOP Conf. Ser. Mater. Sci. Eng., July 2020. https://doi.org/10.1088/1757-899X/928/2/022126