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Numerical Analysis of Free Vibration Characteristics in Multilayer Functionally Graded Plates with Coal/Polyester Composites

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Abstract

Functionally graded materials are important in many industries, including automotive, construction, and biomaterial science. In the current work, a functionally graded composite made of multilayers of coal powder and a polyester-based matrix was modelled to examine the free vibration characteristics. The desired models have 5 and 11 layers with three different thicknesses (5, 8, 10) mm. A numerical study was carried out using finite element analysis with the help of ANSYS software tools based on multiple boundary conditions to evaluate the significance of geometrical properties in fundamental frequencies. The reinforced coal material has been added to the mechanical model that characterizes the through-the-thickness distribution of the graded constituents. In terms of dimensionless frequencies, the results show that the frequency parameter decreases with decreasing the length-to-thickness ratio. When the number of layers is increased from 5 to 11, the frequency coefficient improves by 9.35%. The performance of multilayer graded plates is primarily influenced by the type of material distribution and the different geometrical properties. Moreover, the frequency parameter of the plate increases as the boundary conditions are tightened.

Keywords: ANSYS, Aspect ratio, Functionally graded structure, Natural frequency, Power law index.

1. Introduction

In various industries, composite materials have proven helpful over unreinforced materials because of their advantages. Due to the benefits such arrangements offer, such as lightweight and high specific strength, these structures are gaining attention in many applications, including aerospace, automobiles, energy, construction, and biomaterial science [1], [2].

Recently, composite structures, including beams, plates, and shells, have been studied by combining different functionally graded materials (FGMs) spatially to enhance their structural, thermal, and dynamic properties. Other models have been used to understand the effect of the interfaces of the FGM [3], [4]. Functionally graded materials (FGMs) are a sophisticated category of composite materials recognized for their distinctive design characteristics that allow them to carry out diverse functions and serve various applications [5], [6].

Polyester resins are the most broadly utilized thermoset materials and exhibit unique chemical properties compared to other thermosetting resins: no volatiles or byproducts are developed through the reaction of curing, and the cross-linking degree can be governed [7]. Coal possesses various desirable properties that make it suitable for multiple applications. In particular, coal maintains a high melting temperature, high corrosion resistance, strength, chemical stability, excellent electrical insulation characteristics, and low thermal conductivity [8]. Polymer composites with remarkable thermal and mechanical properties can be produced economically using coal particles to synthesize polyester composites [9]. Studies on the dynamic behavior of filler-reinforced polymer-based laminates are still attractive to many researchers.

Burlayenko and Sadowski [10] examined the modal and stability response of supported functionally graded sandwich plates with variable proportions of the (Al2O3) constituent using 3D finite element models. The natural frequencies, mode shapes, displacements, and stresses within ABAQUS were determined by utilizing the FEM for the FGSP. The numerical findings demonstrate a remarkable correlation with analytical solutions, showcasing the reliable performance of a developed 3-D graded finite element. Wang et al. [11] examined the capability of FG corrugated structures using FSDT. The researchers employed the differential quadrature finite element

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method to establish a comprehensive dynamic model for FGCPS. The proposed approach was validated using the ABAQUS finite element software to ensure convergence, stability, and accuracy. The model's shape was found to align well with the results obtained from ABAQUS for different boundary conditions.

Sinha et al. [12] used experimental and finite element methods to study dynamic analyses of a laminated composite plate. This study examined multiple attributes, such as the model layering method, geometrical arrangement, and BCs. Njim et al. [13] presented a comprehensive mathematical model for describing the free vibration problem in an FG rectangular sandwich plate with a supported 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%.

Duc and Minh [14] examined functionally graded carbon nanotube-reinforced composite (FG CNTRC) plates with cracks for the free vibration properties using the finite element method and 3rd-order shear deformation theory (TSDT). The study found that the number of carbon nanotubes (CNTs) per plate, geometrical dimensions, crack characteristics, and boundary conditions all impact the dynamic response of the plates. Gopalakrishnan et al. [15] studied the integrity behavior of the C-resin layered model, having different geometrical configurations. The circular plates were made of a carbon-epoxy composite material commonly used in various engineering applications. Non-perforated composite plates were subjected to free motion using ANSYS to study the effect of height, radius, and fiber arrangement on dynamic properties.

Zang et al. [16] developed an analytical plate formulation based on a 3D elastic approach to examine the static bending and dynamic behavior of (FGM) plates. A power-law scheme was used to represent the mathematical model. The results show that FG parameters significantly influence mechanical properties and free vibration characteristics. By using graded structures in applications subjected to vibration conditions, Segura et al. [17] demonstrate their advantages. With the selection of axial grading of multiple materials in Euler-Bernoulli beams, it is crucial to understand how viscoelastic properties influence damping and energy absorption within the structure and how material distributions in specific directions influence these properties.

This research aims to understand how the FGM structure with different geometrical characteristics behaves under various loading scenarios using numerical analysis. The main aim of this study was to investigate the free vibration behavior of plates that incorporate functionally graded materials with various parameters. Research results highlight several key ways describing techniques can contribute to FGM structural design and innovative engineering approaches.

The use of multilayer functionally graded plates in conjunction with coal/polyester composites can lead to more efficient and sustainable structural designs. Design of such FGM can reduce the dimensions and material usage of structural elements, while geometrical and shape analysis can alter the structure to improve performance. This can result in structures that are stronger, lighter, and more cost-effective.

2. Mathematical Formulation

A power-law distribution for the FG plate shown in Fig. 1 can represent the upper volume fraction (Vu) [13].

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

According to the mixture rule, the sum of the volume fractions of the upper and bottom FG plate components is as follows:

$$V_u + V_b = 1, \ -\frac{h}{2} \le z \le \frac{h}{2} \quad (2)$$

Where the power law index (k) is the graduation index, while the upper and bottom are denoted by the subscripts (u) and (b), respectively, the cartesian coordinate system (x, y, z) describes plate motion on its middle surface, with x and y standing for in-plane coordinates and z for out-of-plane coordinates. The following definitions apply to the FG plate's material characteristics:

$$\varphi(z) = \varphi_b + (\varphi_u - \varphi_b)\left(\frac{2z+h}{2h}\right)^k \quad (3)$$

Here, φ_b and φ_u indicate the material characteristics of the upper and bottom parts of the FG plate. This was obtained from the tensile test, according to ASTM D638. However, Young's modulus, mass density, and Poisson's ratio of the material change as the FG plates get thicker based on the volume fraction index. The same principle mentioned above will be used in the extraction of properties of the materials used in this work.

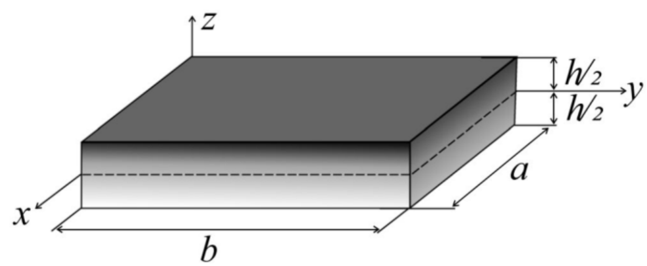


Figure 1. Schematic Diagram of the FG Plate Geometry.

3. Materials and Methods

Thermoplastic resins and thermosetting resins are two types of polymer matrix materials. When heated to a specific temperature, thermoplastic resins melt and solidify. Thermally setting resins can only be shaped once after heating. Thermoplastic resins include polyamides, polypropylenes, and polystyrene, whereas thermosetting resins consist of epoxy and polyester [18]. In addition to being inexpensive, polyester resin is resistant to water and many chemicals, weathering and aging resistant, has reasonable temperature resistance (up to 80°C), wets well with glass fiber, and shrinkage during curing is low (4%–8%), and thermal expansion is linear [19].

In this study, (TOPAZE 1110 TP), an unsaturated polyester resin manufactured by Industrial Chemicals & Resins Ltd. (ICR), widely used in composite material fabrication, was incorporated as a liquid matrix because of its low viscosity, good physical properties, and mechanical stability. The basic properties of (TOPAZE 1110 TP) are listed in Table 1.

Coal particles were chosen as reinforcements in the composite material due to their unique properties that enhance the mechanical and thermal performance of the material. The coal particles, particularly coal ash, were selected for their ability to improve the mechanical properties of the composite, such as strength, stiffness, and toughness. Coal ash, a byproduct of coal combustion, is known for its high silica content, which can act as a filler and improve the mechanical properties of the composite. At the same time, the Coal particle reinforcements are obtained from the local market, with characteristics shown in Table 2. Different arrangements of Functionally Graded Material (FGM) layers are used in plate structures to optimize the mechanical properties and performance of the composite material. By varying the composition and distribution of materials within the layers, plate structures can achieve specific mechanical characteristics tailored to the requirements of the application. This customization allows for enhanced strength, stiffness, and other properties in different regions of the structure, optimizing its overall performance. The use of FGM layers in various arrangements enables plate structures to achieve a balance of properties such as strength, weight, and thermal conductivity, making them versatile and efficient for a wide range of applications. In this work, two samples were produced in different gradations as shown in Tables 3 and 4. In summary, the weight percentages of coal particles and unsaturated polyester resin are significant because they directly influence the mechanical, thermal, and other properties of the composite material. The specific weight percentages used in the studies provide insights into the optimal composition for achieving the desired performance characteristics of the FGM composite.

4. Numerical Simulation

This work generated a rectangular plate with different geometrical attributes using SOLIDWORKS 2021 and ANSYS (version 2021 R1) program with SOLID186 element type. Total number of elements and nodes (50000, 355015), respectively. This study aims to simulate and analyze the fundamental natural frequencies of FGM in different modes. The dimensions of each model are 50 cm x 50 cm with three heights: 5, 8, and 10 mm. The first sample consists of 5 layers, while the second has 11 layers made of Polyester/Coal. To calculate material properties, (3) can be used. Fig. 2 shows the geometry of the model generated, while Figs. 3 and 4 illustrate the model with Mesh and supported (SSSS) boundary conditions, respectively.

Table 1. Technical properties of (TOPAZE 1110 TP) polyester resin.

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

Table 2. Properties of coal powder.

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

Table 3. FGM type I (5 layers).

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

Table 4. FGM type II (11 layers).

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

Convergence analysis was conducted to determine the optimal mesh size to be used in the model. In the convergence analysis, frequency analysis was performed for each mesh size from 0.2 m to 0.05 m on the model, and the frequency values obtained are given in Table 5. At the same time, Fig. 5 shows the convergence graph performed by Ansys software tools for the free vibration analysis of the supported multilayer FG plate.

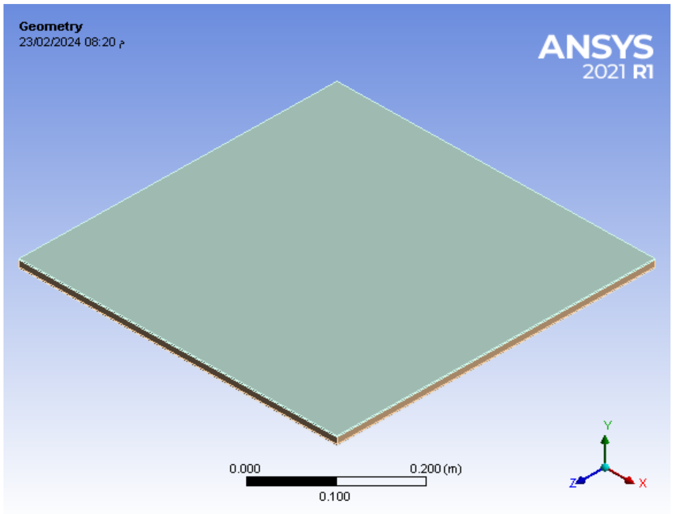


Figure 2. The geometry of the model.

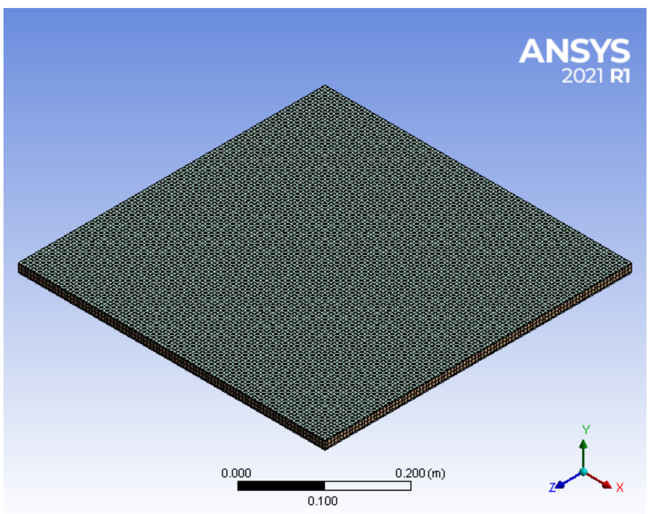


Figure 3. The Mesh of the model.

5. Results and Discussion

The finite element solutions for the functionally graded material (FGM) and homogeneous element models demonstrate nearly identical results, although they slightly overestimate the analytical reference values. The plate consists of multilayers with different aspect ratios subjected to boundary conditions. The results in Table 6 exemplify the Ansys analysis for the SSSS plate solid containing 5 and 11 layers. A similar procedure can be implemented for models with various characteristics and boundary conditions. Moreover, it is noted that changes in the frequency parameter occur by increasing the number of layers from 5 to 11, which means that the equivalent mechanical properties of the structure show a difference. Fig. 6 illustrates the mode shape number and the corresponding fundamental natural frequencies for the supported plate (SSSS), gradient index k=1, and thickness ratio (a/H=100). These frequencies represent the lowest resonant frequencies at which the plate can vibrate in specific mode shapes. In this study, the analysis focused on identifying the plate's fundamental natural frequencies, which indicate its dynamic behavior. Mode number 1 corresponds to the lowest frequency, with a value of 182.16 Hz, in which plates are subjected to a bending load and deformed.

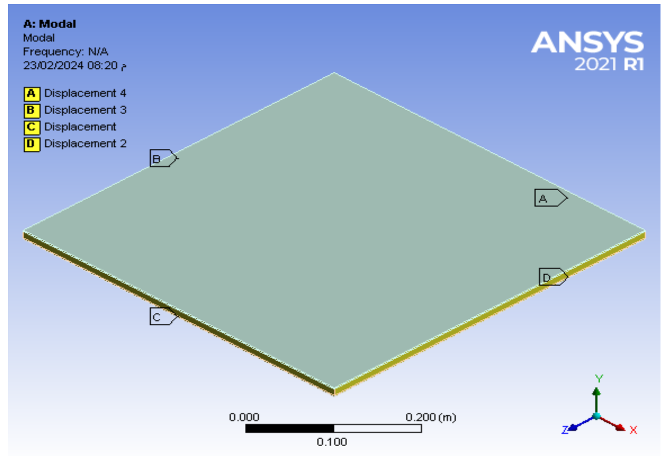


Figure 4. The Boundary conditions of the model.

Table 5. The 1st mode natural frequency convergence results.

Mesh size	1st mode Frequency (Hz)	Node number
0.2	150	50000
0.19	155	55000
0.18	160	57500
0.17	170	60000
0.15	175	75000
0.13	177	80550
0.1	178	90000
0.09	180	110700
0.06	181	203100
0.05	182	355015

The following formula [20] can be used to calculate the frequency parameter:

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

Here, (ω) is the free vibration fundamental frequency value that could be estimated (ρ_o = 1 Kg/m3 and E_o=1000 MPa), and H is the total height of the structure [13].

Table 7 illustrates the numerical results of frequency parameters obtained by Ansys for functionally plates subjected to four boundary conditions (CCCC, CCCS, CSCS, and SSSS) and four aspect ratios a/b (0.5, 0.75, 1, and 2), respectively.

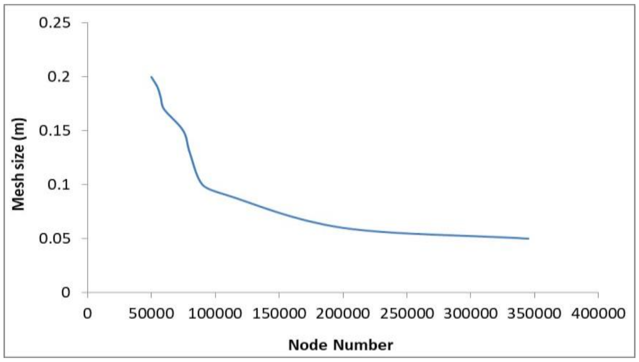


Figure 5. Convergence graph of the supported FG sandwich plate.

Table 6. Numerical variation of SSSS plate with various thicknesses and number of layers at power-law index k=1.

No. of layers	H(mm)	Frequency parameter
5	5	0.995
	8	0.878
	10	0.760
11	5	0.903
	8	0.789
	10	0.728

A correlation is found between the ψ value and the limitation or restriction in the chosen type. For instance, the frequency parameter in the CCCC model has an aspect ratio of 0.5 at the solid plate with a plies number of (n =11), and 5 mm total height is (0.825), while in CCCS, it was (0.790), and in CSCS (0.745), whereas in SSSS it was (0.555). The results indicate that the natural frequency increases with the number of constraints in plate mounting. Furthermore, the results recorded in the table suggest that the frequency parameter increases with the aspect ratio, signifying that the plate behaves stiffly. However, regarding the number of plies, the same conclusion is expected to be obtained when the plate loses more stiffness with decreasing plies and, simultaneously, the free vibration damping and the mechanical stability increase. Here, the possibility of increased porosity inside the plate structure plays a vital role in identifying the mechanical performance of the FGM structure.

Fig. 7 shows the numerical results of the frequency parameter at the power–law index (k=1 to 5) for various FGM thickness ratios (a/h = 5 to 100). Increasing the gradient index leads to a decrease in the fundamental frequency. The possible reason is that the plate structure's stiffness increases with the plate's thickness, and the material properties increase with a reduction in k.

Table 7. Model numerical results with four aspect ratios and different boundary conditions of FG plates for an 11-layer sample.

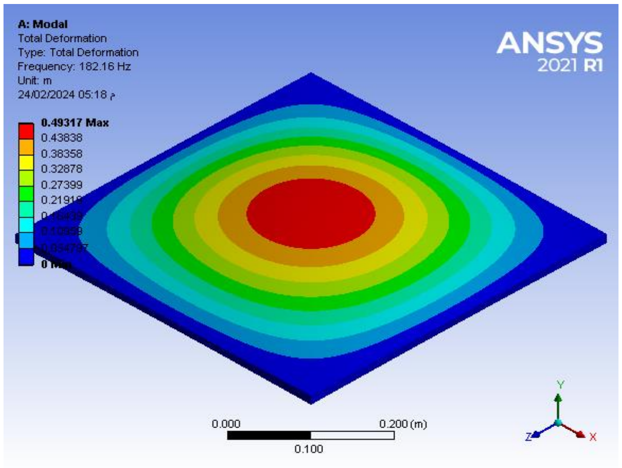
BCs	H(mm)	Aspect ratio			
		0.5	0.75	1	2
CCCC	5	0.825	0.990	1.174	3.318
	8	0.819	0.947	1.011	3.137
	10	0.766	0.930	0.972	3.019
CCCS	5	0.790	0.917	1.034	3.000
	8	0.730	0.869	0.945	2.876
	10	0.700	0.820	0.887	2.769
CSCS	5	0.745	0.866	1.005	2.880
	8	0.727	0.835	0.916	2.739
	10	0.670	0.814	0.855	2.668
SSSS	5	0.555	0.768	0.903	2.545
	8	0.542	0.679	0.789	2.470
	10	0.515	0.659	0.728	2.400

6. Conclusions

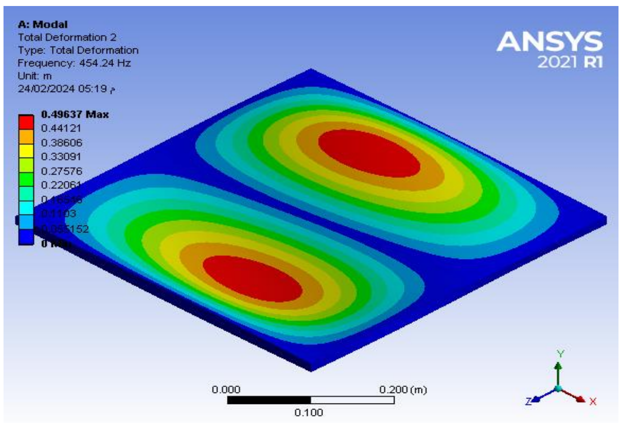
In this work, numerical analysis is presented to characterize the vibrational properties of FGM samples. Several interpretations can be recorded to sustain the nanocomposite shell, mechanical and natural frequency properties, where the frequency parameter of the plate increases as the boundary conditions are tightened, such as when going from CCCS to CCCC. This pattern is consistent with other boundary conditions, such as CSCS. Provide specific frequency values or percentages before and after the introduction of coal particles.

Increasing the number of layers from 5 to 11 sustains the frequency parameter by 9.35 % at a plate with an aspect ratio of 1. As the power law index k increases, the frequency parameter decreases at different thickness ratios.

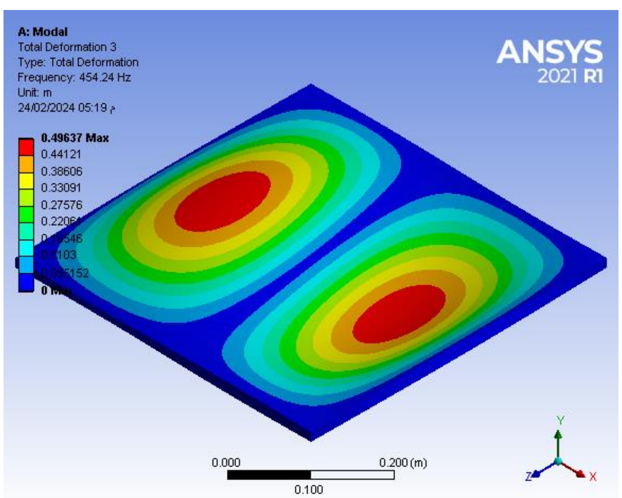
Based on the provided sources, additional experiments or analyses that could further validate or expand upon the findings include: conducting comparative studies with different weight percentages of coal particles in the composite material to assess the impact on mechanical properties like strength, stiffness, and toughness. Investigate the durability and stability of the composite material over time, especially under different environmental conditions. By incorporating these additional experiments and analyses, it can further validate the findings, explore new insights, and enhance the understanding of the properties and performance of the FGM composite material with coal particle reinforcements.



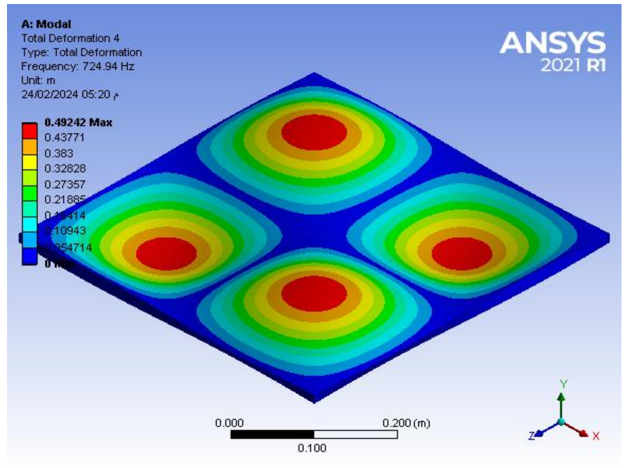
(a) 1st mode shape



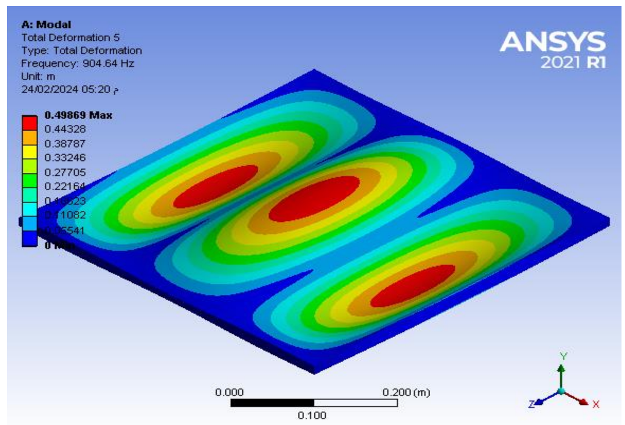
(b) 2nd mode shape



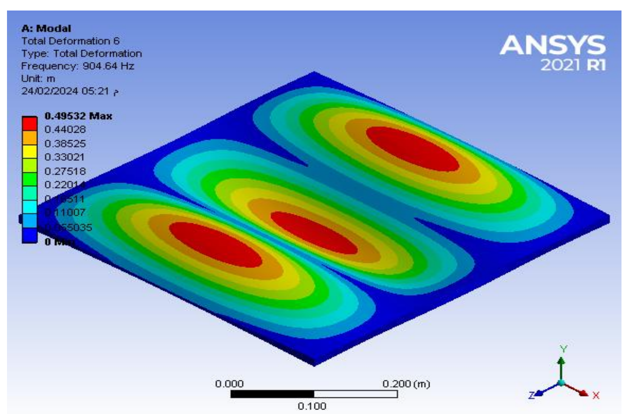
(c) 3rd mode shape



(d) 4th mode shape



(e) 5th mode shape



(f) 6th mode shape

Figure 6. The sixth mode shapes of the (SSSS) FGM plate for 11 layers at (*a/H* =100) and power-law index *k*=1.

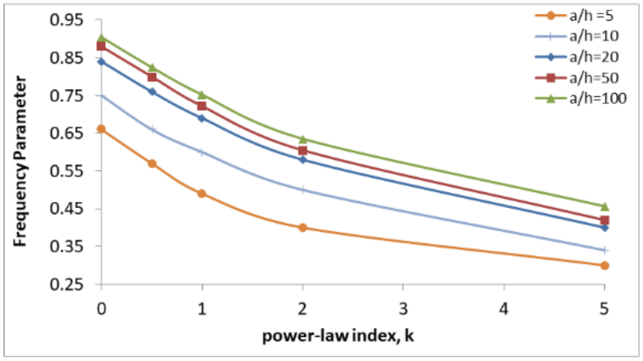


Figure 7. Various FGM thickness ratios are analyzed for the frequency parameter of a simply-supported (SSSS) plate.

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The authors sincerely thank everyone who contributed to completing this work.

Abbreviations

a/b	Aspect ratio
C	Coal
E	Modulus of elasticity
FGM	Functionally graded materials
H	Height
k	Power-law index
SP	Unsaturated polyester resin
V	Volume fraction
ρ	Density of material
φ	The material characteristics of the
ω	The free vibration fundamental
ψ	Non-dimensional frequency

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Sanaa Samir: developed the theory and performed the computations.

Bashar Owaid proposed the research problem.

Both authors discussed the results and contributed to the final manuscript.

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