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Free Vibration Analysis on Functionally Graded Material Plates with Diverse Porosity Layers

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ABSTRACT

This research addresses the challenge of optimizing the dynamic performance of functionally graded porous plates, which are widely used in aerospace, automotive, and structural applications, where internal porosities can significantly impact their stability and functionality. This study mainly uses an effective layer wise model to examine how the internal porosities affect the mechanical stability and natural frequencies of FGP plates. According to the ratio of porosity distribution, porosity locations, and three typical thicknesses, the vibration behaviors of functionally graded plates are analyzed. The effective material properties are modeled employing a power law. The primary objective of this study is to understand how these factors impact the vibrational behavior of FGM plates and to provide validated results that can serve as a reliable reference for future research. The model's validity and efficiency were established through a rigorous comparison with existing literature. The investigation findings highlight the significant influence of porosity distribution on the mechanical behavior of functionally graded plates. The highest frequency obtained was 259.81 Hz for a plate thickness of 20 mm and a porosity ratio of 0.3 when the porous layer was located in the middle, resulting in an 11.9% increase in the frequency compared to other porosity distributions. These results hold potential as a valuable reference point for future research endeavors in this domain.

1. INTRODUCTION

Functionally graded porous structures have gained prominence owing to their lightweight properties and exceptional energy absorption capabilities. These structures find application across diverse fields like aerospace, biomedical science, and engineering [1, 2]. Badri and Al-Kayiem [3] developed an analytical solution procedure of a simply supported plate constructed by a smart multi-layered Magneto-Thermo-Electro-Elastic functional graded material. The developed procedure has been utilized by Albarody et al. [4] to predict the transverse shear deformation behavior of Magneto-Electro-Elastic shell and by Badri and Al-Kayiem [5] to study the dynamic response, i.e., the vibrations, of a Magneto-Thermo-Elastic shell structure subjected to a closed-circuit surface condition.

Porosity, whether inherent to the manufacturing process or deliberately introduced, is a prevalent feature in materials [6]. Functionally Graded Porous Materials (FGPMs) have demonstrated remarkable traits, including substantial bending toughness, low weight, efficient sound absorption, and superior damping characteristics. Consequently, they have enjoyed extensive application in various mechanical and civil engineering Njim et al. [7]. The material used in the present study is Polylactic acid because it has emerged as a leading biomaterial in various industries and medical applications, replacing traditional petrochemical-based polymers due to the environmental and economic concerns associated with petrochemical-based polymers. Polylactic acid is a highly biodegradable thermoplastic that has been extensively researched and utilized for decades, making it one of the most exciting biopolymers in use today [8]. Much extensive research has examined this field for its increasing significance in various applications. Barati and Zenkour [9] presented a new method to investigate how porous functionally graded piezoelectric plates vibrate based on their electrical, thermal, and mechanical properties. Long et al. [10] proposed a novel finite element method to analyze the bending and free vibrations of plates with different characteristics. Vinh [11] investigated the static bending, free vibration, and buckling behavior of functionally graded sandwich panels with porosity based on a new hyperbolic shear deflection theory and a finite element model.

Merdaci et al. [12] investigated functionally graded plates (FGPs) with two unique porosity distributions. The plates were modeled using high-order shear deformation plate theory, ignoring shear correction variables. The natural frequencies of a simply supported porous smart plate were obtained through free oscillation studies using the Hamilton approach. In another study carried out by Singh and Harsha [13], the impact of porosity on the vibration and buckling responses of sandwich panels with different boundary conditions was investigated. Tran et al. [14] presented numerical simulations for analyzing the static bending and free vibration of functionally graded porous plates with varying thicknesses. Kumar et al. [15] considered the free vibration analysis of a tapered plate made of a porous functionally graded material (FGM). The plate was supported on a two-parameter elastic base that incorporates Winkler and Pasternak effects. Leite et al. [16] studied the influence of various 3D printing parameters, such as infill density, extrusion temperature, screen angle, and layer thickness, on the mechanical properties of polylactic acid, and its water absorption was also examined. Rezaei et al. [17] conducted an analytical study on the free vibration analysis of rectangular plates made of functionally graded porous materials based on FSDT. In the study presented by Ibnorachid et al. [18], a porous graded functional beam (P-FGB) was subjected to free oscillation analysis using a sophisticated high-order shear strain theory and Hamilton's principle.

Al Rjoub and Alshatnawi [19] aimed to predict the natural frequencies of a simply supported plate composed of functionally graded material (FGM) with uniform porosity distribution and lateral cracks using both analytical and artificial neural network (ANN) methods. Njim et al. [20] used a novel analytical model to conduct a free vibration analysis of a rectangular functional graded sandwich panel (FGSP) with a porous metal core and uniform top and bottom surfaces. Zghal et al. [21] conducted a study on a modified mixed finite element beam model that was used to examine the impact of porosity on the bending analysis of functionally graded (FG) beams. The material properties of the FG beams were determined based on modified power law distributions with uniform and non-uniform porosity distributions. Kurpa et al. [22] studied the effect of various parameters such as porosity distribution, volume fraction index, elastic foundation, FGM types, and boundary conditions on vibrations. The study concluded that as the volume fraction index increases, frequencies decrease for FGM-1 and FGM-3 materials, while the others show insignificant changes. Frequencies for FGM-2 were found to be lower than those for FGM-1, and FGM-3 frequencies were significantly higher than in other cases. Additionally, the frequencies for FGM-4 remained practically unchanged.

Njim et al. [23] examined the natural frequencies of rectangular sandwich plates and porosities that are functionally graded using a new approximation analytical solution to the free vibration analysis. Rezaei and Saidi [24] investigated and analyzed the free vibration in a thick rectangular porous plate saturated with an inviscid fluid.

Despite the extensive use of FGMs in advanced engineering applications, limited research has focused on the effect of different porosity distributions on the dynamic behavior of FGM plates. Most existing studies either assume uniform porosity or neglect its spatial variation across thickness. This gap makes it difficult to understand and optimize the performance of FGM sheet porous structures under vibrational loads. Therefore, this study aims to fill this gap by investigating the effects of different porosities and their locations on the natural frequencies of FGM porous laminates using ANSYS analysis. A free vibration analysis model of the FGM is built to examine the impact of various factors, including porosity ratio, different porosity locations across the plate layer, and plate thickness, on the natural frequencies of porous rectangular functionally graded plates. Compared with existing literature, the model can be constructed and has high efficiency. Additionally, the FEM model has been conducted using ANSYS software to examine the sensitivity of FEM.

2. COMPUTATIONAL PROCEDURE

Due to the significant mathematical complexity required in solving initial and boundary value problems, analytical techniques for addressing initial and boundary value issues are restricted to situations with relatively basic geometry and boundary conditions. The solution is made much more laborious by the nonlinear change in material characteristics caused by the thickness of FGM plates. As a result, numerical techniques are widely used to solve challenging engineering issues. Software ANSYS 2022 R1 was used to perform the numerical simulation and analyze the free vibration of the plate structure for several layers with different porosities through the thickness and different thicknesses.

Free vibration is a type of structural vibration that takes place when a system is perturbed from its equilibrium state and then allowed to oscillate freely without external excitations. ANSYS, as a powerful FEM software tool for structural analysis, offers the capability to simulate the free vibration of various types of simple and complex structures. In ANSYS, free vibration analysis is performed by applying initial conditions to the model and then allowing the structure to vibrate freely. The natural frequencies and mode shapes of the structure are determined from the simulation results.

It is assumed that the natural frequency is the frequency at which the structure vibrates freely and is dependent on the structure's stiffness and mass properties. The results of a free vibration analysis can be used to evaluate the dynamic response of the structure and identify potential vibration problems that may occur during operation. The natural frequencies and mode shapes obtained from the simulation results could be used to evaluate the dynamic response and identify potential vibration problems that may cause damage and fatigue failure in the case of excessive vibration [25-27]. The numerical study is divided into two parts. The first is a comparison with Njim et al. [28], i.e., the validation test, and the other covers the present work.

2.1 Model and geometry

Two models were designed for the current work, as shown in Figure 1. Each model considers a 300 × 300 mm square plate structure with its four edges simply supported. The model in Figure 1(a) is the geometry of the GFM plate used by Njim et al. [28] and used here for validation. The validation model has a skin with a thickness of 0.65 mm and a core with a thickness of 10, 15, and 20 mm constructed in a sandwich structure. The model in Figure 1(b) is the developed laminated plate with a multilayer for the analysis of the current work. The Laminated plate model has no skin, and it consists of five layers. It was simulated with different total plate thicknesses of 10, 15, and 20 mm. The porous layer has the same thickness as each layer and is made of the same material but varies in porosity and location within the layers.

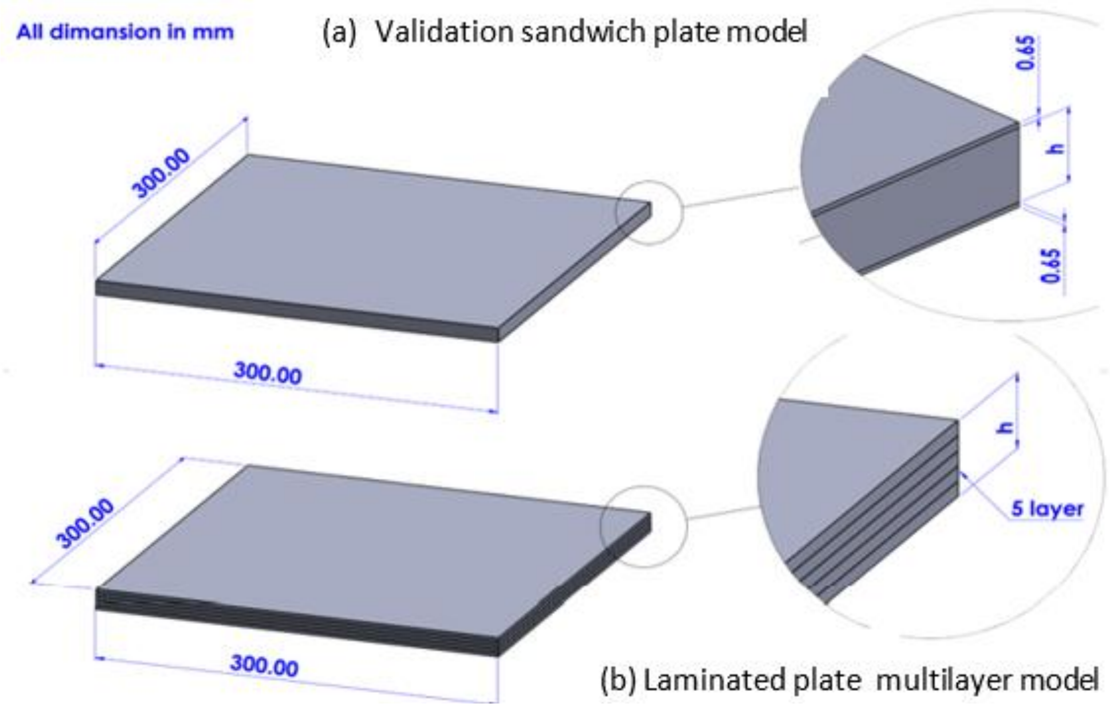

Figure 1. The geometries of the computational models of the plate: (a) Validation model with sandwich structure, (b) Laminated Multilayer plate model

2.2 Material properties

The two models described in section 2.1 are made of functionally graded materials. The material properties of an FGM structure embarking layers with different porosities and thicknesses are assumed. In the validation model, the skin is made of AL- 6061-T6, while the core is made of Polylactic acid (PLA). The properties of the materials are shown in Table 1.

Table 1. The material properties used in the validation and investigation models [20, 28]

Material	Modules of Elasticity (GPa)	Density (kg/m^3)	Poison Ratio
Skin [in the validation sandwich model]	70	2702	0.3
Polylactic acid Core material In the validation model	1.2	1360	0.38

Table 2. Polylactic acid properties measured experimentally and used for the investigation

Porosities β	Modules of elasticity E (GPa)	Density ρ (kg/m^3)	Poisson's Ratio ν
Zero	1.64	1253.8	0.38
0.1	1.48	1128.42	0.38
0.2	1.312	1003.04	0.38
0.3	1.148	877.66	0.38

However, when it comes to the investigation, the selected PLA has been subjected to experimental measurements to characterize the properties and feed them to the ANSYS simulation. The solid PLA, with zero porosity, used in the layers, and the porous PLA, with 0.1, 0.2, and 0.3 porosity, have been subjected to Laboratory measurements. The measurement results are shown in Table 2.

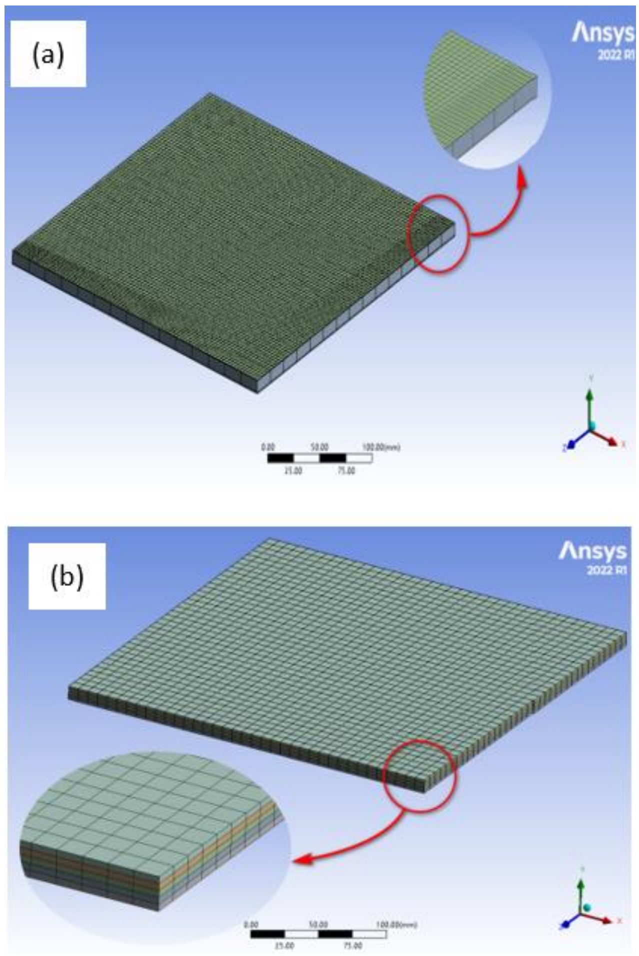

Figure 2. Meshing criteria: (a) for the validation model and (b) for the laminated plated with multilayers

2.3 Meshing and mesh independence check

The plate shown in Figure 1(a) is meshed as the 3D and boundary constraints are applied to either side of the construction, as shown in Figure 2(a). The FG laminated plate, shown in Figure 1(b), is meshed as detailed in Figure 2(b). The element size was altered from 5 mm, which generated 96 elements, to 1 mm, which generated 7,530 elements for the bare case. To realize the dependency of the simulation on the mesh size, the displacement parameter has been chosen as an indicator for comparison between different cases of mesh size. Figure 3 shows that the displacement value stabilizes at a mesh size of 1 mm. As a result, the mesh employed in the study is 1 mm in size. The precise mesh size was chosen after mesh convergence research, as shown in Figure 3. Then, the mesh generation process employed the hexahedron type (8-node SOLID186 element type), which is considered one of the most effective mesh types. The model was meshed with a total number of 49,780 nodes and 6,845 elements.

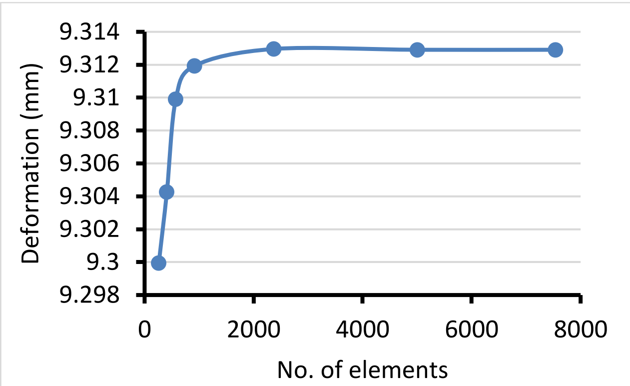

Figure 3. Mesh sensitivity analysis

3. RESULTS AND DISCUSSION

3.1 Validation of the numerical approach

The results of Njim et al. [28] were utilized for the validation of the current simulation. The geometry of the sandwich plates was 300 × 300 mm, and functionally graded porous materials (FGPM) were employed. The core height of the plate was fixed at 15 mm, with an upper and lower skin thickness of 0.65 mm. Furthermore, the plates were characterized by four distinct values of porosity, β of 0.0, 0.1, 0.2, and 0.3.

The validation process was done on FGM plates to demonstrate the efficacy of the created computational approach in the current investigation and to secure the precision of the numerical findings. The boundary conditions applied were a simply supported plate. An 8-node SOLID186 element was utilized in this investigation to mesh the 3D model of an FG plate.

The findings of the natural frequencies obtained from the current simulation and Njim et al. [28] are displayed in Table 3. Table 3 shows the verification of the accuracy of the numerical model used in this study by comparing the natural frequency results of the FGM porous plate at β = 0.1, 0.2, 0.3 with the results published in Njim's et al. [28]. There is an excellent agreement of the results, with the difference ranging from 0.22% to 4.78%, which is acceptable and proves the accuracy of the numerical procedure. The results obtained were verified with an error rate not exceeding 5%.

Table 3. Validation results for free vibration plate

Case	β	h (mm)	Frequency results (Hz) by		(%) of difference
			Njim et al. [28]	Present	
1		10	474.9	467.52	1.55
2	0.1	15	595.5	582.05	2.26
3		20	711	676.98	4.78
4		10	480	485.24	1.09
5	0.2	15	617	604.15	2.08
6		20	730.8	701.78	3.96
7		10	484.2	505.31	4.36
8	0.3	15	628	629.39	0.22
9		20	743.3	730.2	1.76

3.2 Bare plate vibration analysis

Figure 4 shows the free vibration analysis of a plate using ANSYS. The total deformation of the plate was calculated at a natural frequency of 124.06 Hz. The Parameter Set feature in ANSYS was used to facilitate the introduction of variable parameters, such as the thickness value and the type of material used, which increases the efficiency and accuracy of the analysis. The results in Figure 4 show the distribution of deformations on the plate, where it is observed that the highest value of deformation occurs in the center, while it gradually decreases towards the edges, which is an expected behavior that reflects the nature of the free vibration of this plate.

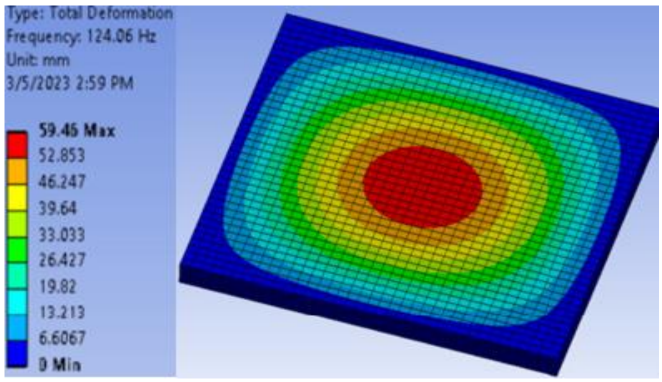

Figure 4. Deformation contour at 124.06 Hz natural frequency of 10 mm thickness plate without porosity

3.3 Plate thickness effect on the vibration

Table 4 shows the natural frequencies of a five-layer laminate plate at various thicknesses of 10, 15, and 20 mm with zero porosity (β = 0). These values were calculated using ANSYS software with the Parameter Set feature, which enabled the effect of changing the thickness to be analyzed. The outcomes point out that the frequency was directly proportional to the thickness at the same value of the porosity. With values of h = 10 mm, the natural frequency was 124.06 Hz. While at h = 15 mm and 20 mm, the natural frequency increased to 185.13 Hz and 245.08 Hz, respectively. This behavior is quite similar to the basic principles in free vibration analysis, as increasing the thickness increases the overall stiffness of the plate (Flexural Rigidity), which reduces the displacement caused by the vibration and thus raises the value of the natural frequency. Physically, an increase in thickness corresponds to an increase in moment of inertia, which leads to greater resistance to deformations, making the system more resistant to low-frequency vibrations and shifting the natural frequencies to higher levels.

Table 4. Natural frequency values of the plate at zero porosity (β = 0), at h = 10, 15, 20 mm

Height (mm)	Frequency (Hz)
10	124.06
15	185.13
20	245.08

3.4 First-mode vibration analysis

The total deformation at 1st mode is shown as contours in Figure 5 (a), (b), and (c) for slabs with different thicknesses of 10, 15, and 20 mm, respectively, at β = 0.1. The results show an increase in frequency with increasing thickness, which is very logical according to the laws of vibration. The results also illustrate that the amount of deformation is inversely proportional to increasing thickness in the middle of the plate while the free edges remain zero.

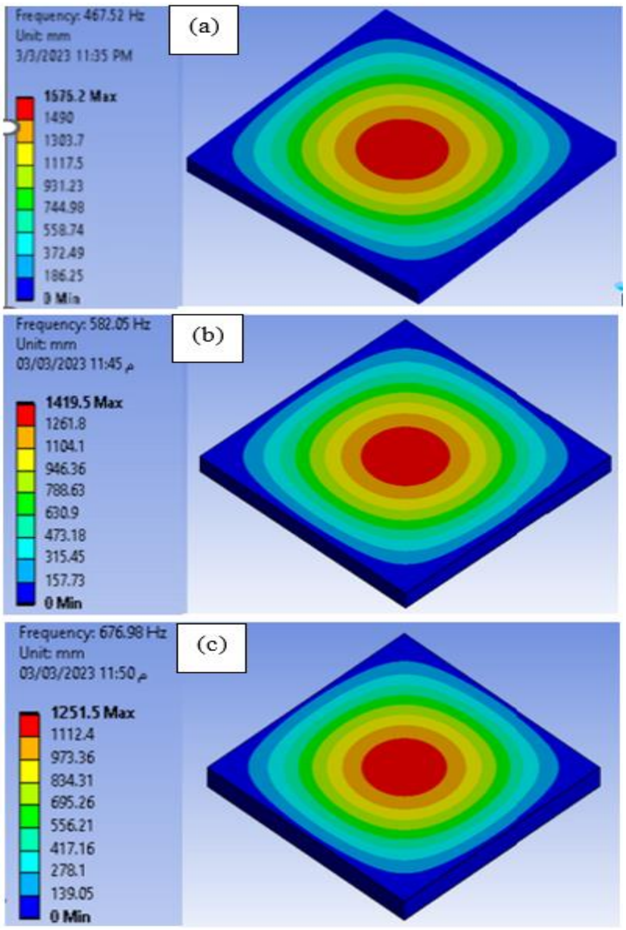

Figure 5. Deformation counters of the 1st Mode shape of the plate with thicknesses of (a) 10 mm, (b) 15 mm, and (c) 20 mm, with 0.1 porosity

An increase in the plate thickness resulted in a significantly higher natural frequency, as thicker slabs are more rigid, which reduces the displacements and increases the natural frequency. For example, at β = 0.1, the frequency increased from 467.52 Hz at h = 10 mm to 676.98 Hz at h = 20 mm. In terms of the effect of the porosity ratio, *β,* it was observed that an increase in β has a nonlinear effect on the frequency. In some cases, increasing *β* led to a higher frequency (as in Case 7 compared to Case 1) due to the inhomogeneous distribution of stiffness caused by the gradient in the material. However, in other cases, increasing *β* caused the frequency to decrease due to the loss of solid mass and an increase in voids, weakening the mechanical properties. The value of the maximum displacement decreases as the thickness increases, reflecting the increased stiffness and, hence, higher natural frequency. The maximum displacement appeared in the case of h = 10 mm, as shown in Figure 5(a), while the minimum was at h = 20 mm, as shown in Figure 5(c).

3.5 Laminated plate analysis at various porosity

The resulting natural frequency predicted by the simulations at various porosity values of 0.1, 0.2, and 0.3 for a plate with 10 mm thickness is shown in Table 5. The table also helps to investigate the influence of the location of the porous layer in the multilayer structure. Wherever the porous layer is illustrated, the least values of the frequency occur with the highest porosity of 0.3, compared to the frequencies with 0.1 and 0.2 porosities.

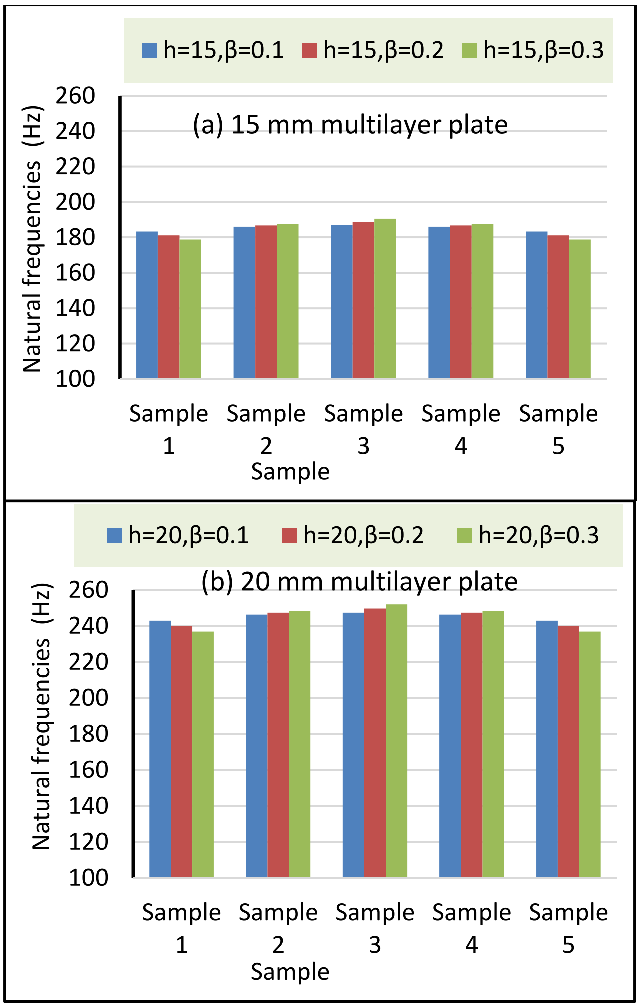

Figure 6. Frequency variation with different porosity of (a) 15 mm multilayer plate height, (b) 20 mm multilayer plate height

Frequency results in Figure 6 show the simulation results of the frequencies of a laminated plate with 15 mm thickness. The results indicate that the allocation of the porous layer in the middle of the plate thickness produces the highest frequency. The predicted frequencies when illustrating the porous layer in the middle are 125.26, 126.48, and 127.73 Hz for 0.1, 0.2, and 0.3 porosity, respectively.

It was observed that when the plate thickness increases, the stiffness of the plate increases, leading to an increase in the natural frequency. For the five specimens, the natural frequency was predicted at a constant value of β = 0.3 and three various thicknesses (h = 10, 15, and 20). The outcomes illustrate that the natural frequency was proportional directly to the thickness, as depicted in Figure 7.

Table 5. Natural frequency values of five samples of plates with different porosity and thicknesses h = 10 mm

Case	Position of the Porous Layer	Frequency Value at Porosity, β of		
		0.1	0.2	0.3
Sample 1	β=0 β=0 β=0 β=0 β= 0.1- 0.2 - 0.3	122.9	121.4	119.8
Sample 2	β=0 β=0 β=0 β= 0.1- 0.2 - 0.3 β=0	124.7	125.2	125.8
Sample 3	β=0 β=0 β= 0.1- 0.2 - 0.3 β=0 β=0	125.3	126.5	127.7
Sample 4	β=0 β= 0.1- 0.2 - 0.3 β=0 β=0 β=0	124.7	125.2	125.8
Sample 5	β= 0.1- 0.2 - 0.3 β=0 β=0 β=0 β=0	122.9	121.4	119.8

Table 6. Natural frequency of six samples with different positions of porosity at h = 20 mm and β = (0 and 0.3)

Sample NO.	Position and Position of Porous Layer	Frequency (Hz)
1	β=0.3 β=0.3 β=0 β=0	242.22
2	β=0 β=0 β=0.3 β=0.3	242.22
3	β=0 β=0.3 β=0.3 β=0	259.81

4	β=0.3 β=0 β=0 β=0.3	228.93
5	β=0 β=0.3 β=0 β=0.3	244.25
6	β=0.3 β=0 β=0.3 β=0	244.25

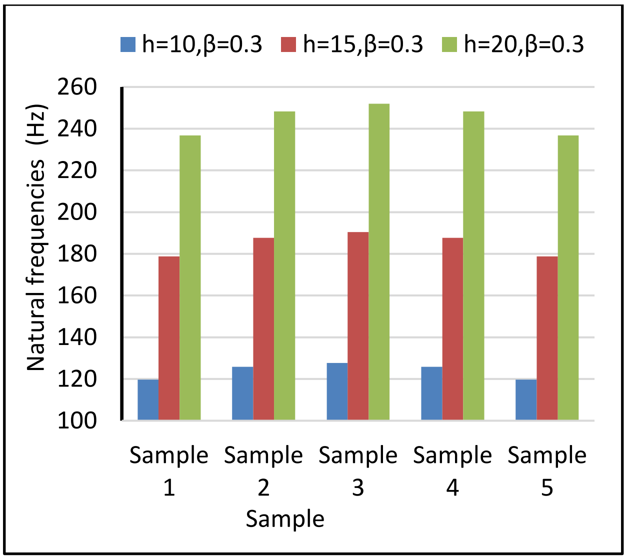

Figure 7. Plot between No. of sample and natural frequency at (β = 0.3) and (h = 10, 15, and 20 mm) respectively

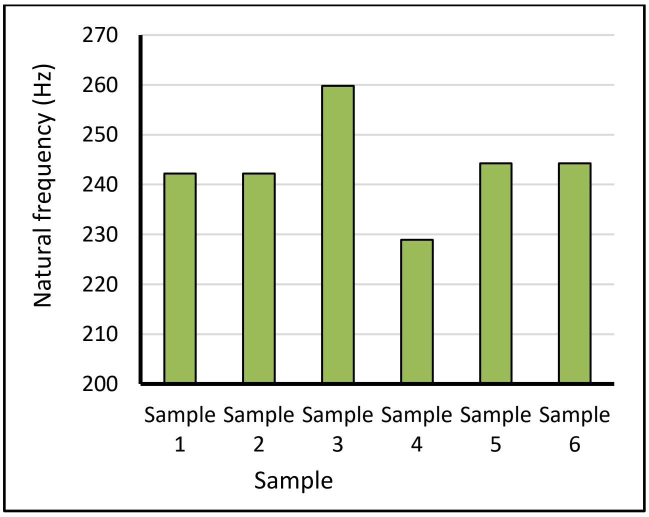

Figure 8. The natural frequency of six samples at h = 20 mm and $\beta = 0.3$

The effect of changing the number of porous layers and their location on the natural frequency was investigated numerically. The effect of locations of layers with porosity distributions (β = 0 and 0.3) on the natural frequency under the constant thickness of 20 mm was explored. Table 6 shows the results obtained from this investigation with four layers through the thickness. Figure 8 shows the numerical results of the normalized frequency of the six samples. The results showed that the highest frequency occurred when the porosity was in the neutral axis of the plate. The effect of changing the number and location of porous layers on the natural frequency was studied numerically.

4. CONCLUSIONS

This work presents the effect of porosity values and installation positions on the vibration characteristics of plate structures. Free vibration tests at different thicknesses, porosity, and locations of the porous layer for functionally graded plates were performed. The highest obtained frequency is 259.81 Hz when the porous layer is in the middle. It was observed that the distribution of porosity, as well as changes in the location of the porous layer and different heights, play a significant role in influencing mechanical properties and vibrations. Placing the porous layer in the middle of the sample may improve stress distribution and reduce edge effects, increasing the structure stiffness and subsequently raising its natural frequencies.

It is recommended to consider future works in the direction of:

1. Different porous distributions could also be implemented to study and compare with the current results. This could help identify which types of porous materials are most effective for specific applications.

2. Analyzing the economic and environmental impact of using FGMs. In addition, analyzing the mechanical and physical properties of the composite material could examine the economic and environmental benefits of using these materials in various applications. This could include factors such as reduced weight, improved energy efficiency, and reduced waste in manufacturing.

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NOMENCLATURE

h	Thickness, mm
f	Frequency, Hz
E	Young Modules of elasticity, GPa

Greek symbols

β	Porosity parameter
ν	Poisson's ratio
ρ	Density, kg/m^3

Abbreviations

FEM	Finite Element Method
FG	Functionally graded
FGP	Functionally graded porous
FGPMs	Functionally graded porous materials
FGSP	Functionally graded sandwich panel