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FREE VIBRATION ANALYSIS OF COMPOSITE FACE SANDWICH PLATE STRENGTHENS BY Al_2O_3 AND SiO_2 NANOPARTICLES MATERIALS

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Abstract

The main novelty of the paper is that analytical, experimental, and numerical analyses are used to investigate the free vibration problem of a sandwich structure in which Nanocomposites skins (SiO_2/epoxy and Al_2O_3/epoxy) at different densities are used as the face sheet. The volume fraction's of nanoparticle addition varies (0% to 2.5%). The present free vibration was derived based on Kirchhoff's theory and aspiration to obtain the natural frequency. The results show that in structures with SiO_2 nanoparticles with a density of 1180 kg/m^{3,} the optimum increase (V_F = 2.5%) is 50% in Young's modulus and 22% in natural frequency, while at a density of 1210 kg/m^3 is 56 % in Young's modulus and 24.5% in natural frequency. Furthermore, the same structures reinforced with Al_2O_3 Nano-particles show that at the density of 1180 kg/m^3, the optimum (V_F=2.5%) parentage increase in Young's modulus is 41% and 19% in natural frequency, while at the density of 1210 kg/m^3 is 46% in Young's modulus and 21% in natural frequency. A numerical investigation was used to validate the obtained results of the analytical solution. The findings also show an acceptable convergence between analytical and numerical techniques with a maximum discrepancy not exceeding 3%.

Keywords: Sandwich panel, Analytical solution, Composite-face, Nanoparticles

List of Symbols/Acronyms

h_f – The thickness of the skin [mm];
h_c – The thickness of the core [mm];
V_f – Volume fraction [%];
I_o – The inertial coefficient for plate;
E_f – Young modulus of the skin [GPa];
E_c - Young modulus of the core [GPa];
G – Shear modulus (Gpa);
ν_f, ν_c – Poisson's ratio of skin and plate core, respectively;
ρ_f, ρ_c – The mass density of skin and plate core, respectively [kg/m^3];
ω – Natural frequency [rad/sec].

1. INTRODUCTION

Sandwich structures have attractive stiffness properties to satisfy lightweight construction demands by sandwiching a low-density core between two rigid faces, resulting in a structure with a higher strength-to-mass ratio [1-6]. The sandwich structure is built of cores, face sheet materials, and adhesives, with mechanical qualities required depending on the application. The face sheets of a sandwich structure fulfill various functions, but they always bear the majority of the imposed loads [7-15]. The features of the face sheets as stabilized by the core dictate the stiffness, stability, configuration, and to a significant degree, the part's strength; the face sheets must be adequate and appropriately attached to a high quality to perform these tasks [16-22].

Face sheets can also serve as a profile with adequate aerodynamic smoothness, a rough non-skid surface, or a robust, wear-resistant floor covering. One facing sheet of a sandwich is occasionally made thicker or of a somewhat different structure than the other to better serve these unique duties. As a sandwich face sheet, you can use any thin sheet material that could be metallic, non-metallic, or composite [23-30]. Face sheets, in many circumstances, help to protect the core against external impacts such as moisture, necessitating the usage of impermeable materials for face sheets. However, some acoustic panel applications, for example, may not require face sheet materials to seal the core components. So faces main properties: high stiffness, high tensile and compression strength, impact resistance, surface finish, and environmental resistance. Composite face sheets for aeronautical sandwich structures are usually made out of laminates of pre-impregnated unidirectional glass or carbon fiber plies embedded in a polymer matrix (epoxy, bismaleimide, etc.). Such laminates need long processing durations at high temperatures and pressures in autoclaves, producing good quality (no void content) and a high fiber volume fraction [31-37]. Various methods to analyze the free vibration problems of layered beams, plates, and shells have been described in numerous papers; for example, Roman Lewandowski et al. (2021) conducted numerical studies on dynamic characteristics for composite sandwich beams made from elastic and viscoelastic layers based on refined zig-zag theory [38]. Vibration behaviors of a composite plate resting on the nonlinear elastic foundation using the finite element method are also discussed in [39].

Dastjerdi and Behdinan (2021) analyzed the free vibration problem of smart sandwich plates with porous nanoparticles reinforced and piezoelectric layers [40]. Ambreen Kalsoom et al. (2021) investigated the stiffness and damping characteristics of the sandwich beam with 3D printed thermoplastic composite face sheets using higher-order beam theory based on various parameters such as support conditions, non-homogeneous magnetic flux, geometrical properties [41].

Barati et al. (2022) improved mechanical activity by GPL-reinforced nanocomposites as skin sheets. The findings showed various dimensionless waveform values and skin thickness [42].

Arshid and Amir (2021), based on higher-order shear deformation and modified couple stress theory, skin sheets are constructed of epoxy-graphene platelets. Typical frequencies are examined as base findings [43]. Ravindran and Bhaskar (2021) studied the goal of developing an elasticity solution for cylindrical bent. Adopting FGM face sheets highly depends on the plate's span-to-thickness ratio [44].

Changsheng Zheng et al. (2022) proposed the dynamic analytical model of the composite sandwich structure by arranging rubber layers to determine damping characteristics based on the Rayleigh-Ritz method [45].

Arani and Jamali (2021) investigated vibration issues of cylindrically bent with CNTs-Nanocomposite skin sheets. Energy and Hamilton's are used to formulate equations of motion. The results show that the natural frequency of the whole structure becomes tougher with an increased volume fraction of CNTs [46]. Shakouri and Mohseni (2020) graphene nanoplatelet supporting faces and Fourier series describe the displacement. Numerical results show that the structure's load-bearing capacities significantly improved after addition [47]. Mohseni and Shakouri (2020) investigated the responses, free and forced vibration of the FGM structure. Hamilton's philosophy is used to get equations of motion and influence various parameters studied. Results are coupled with available studies [48]. Moghaddam et al. (2020) examined skin lay-ups made of composite face sheets and SMA wires. The results revealed that the adequate performance of the plate was enhanced after implanting SMA wires [49]. Using experimental and numerical analysis, Kumar and Fazeel (2022) studied the vibration characteristics of polymer composites with viscoelastic material properties [50].

By employing Finite Element Analysis (FEA), P. Mohammadkhani et al. (2021) used Abaqus/Explicit software to study the impact behavior of reinforced foam Core/Composite skin sandwich panels [51]. Saibaba et al. (2022) employed numerical analysis to study the free vibration characteristics of a reinforced polymer composite sandwich panel [52]. Kamarian et al. (2021) conducted many experimental test results to show that adding 0.3% CNTs to carbon fiber/epoxy composite face sheets significantly increases the longitudinal and transverse Young's and shear modulus [53]. Amir et al. (2020) used piezoelectric and (FGMs) materials to study the buckling behavior of FGM structures. The voltage is considered, and influences of flexoelectricity take essential roles in defining the critically buckling load [54]. Mohammadi et al. (2022) proposed isogeometric analysis to analyze the free and forced vibration analyzes of sinusoidally corrugated functionally graded carbon nanotube reinforced thin composite panels based on Kirchhoff- Love theory [55].

Rajeshkumar et al. (2022) studied the mechanical behavior and dynamic characteristics of natural fiber reinforced composite sandwich plates with multiple-core layers using experimental work, and the results are verified using a finite element method [56]. M. Botshekanan Dehkordi and Khalili (2015) suggested a new constitutive model to check natural frequencies due to the core's characteristics. The result shows that when the temperature rises, the stiffness is enhanced due to the adding nanoparticles [57].

The experimental investigation is carried out to validate the frequency vibration bandgaps by combining the design concepts of locally resonant 3D printed meta-structures sandwich structures [58].

Some studies used Graphene, carbon fiber, and glass fiber in reinforcing sandwich faces. Hamidreza and Sattar (2022) employed extended Higher-Order sandwich panel theory to investigate nonlinear vibrations of GPLs sandwich beams [59].

From the discussed literature, it can be noticed that the previous studies were carried out experimentally and numerically, and few of them were theoretical. Also, some were using the free while others were free and forced vibrations.

The present article deals with the free vibration analysis of sandwich panels with polymer core integrated with face sheets which are reinforced with two types of nanoparticles (Al_2O_3 and SiO_2). The work included deriving an analytical solution for the rectangular plate structure having composite faces using Kirchhoff plate theory to calculate the natural frequency based on different parameters. A numerical solution using ANSYS software 2021 R1 is conducted to validate the analytical solution. The influence of nanoparticle type on the plate performance and the geometrical parameters on the free vibration characteristics of composite plates are also investigated and discussed. The results of this study might be used to design and manufacture smart materials in the future. The rest of the paper is organized as follows. The mathematical background of the problem is provided in Section 2, and the equations of motion form based on the principle of energy, along with the eigenvalue problem used, are described. The numerical examples and detailed discussion are presented in Section 3. Finally, in Section 4, concluding remarks are presented.

2. ANALYTICAL SOLUTION

2.1. The suggested analytical solution

This study investigates the free vibration behavior of the sandwich structure with a Polylactic acid (PLA) core with composite-face sheets strengthened by nano Al_2O_3 & SiO_2. Two-step must be completed; first, the differential equation of motion that governs the sandwich structure's vibration behavior is developed; second, the natural frequency is calculated using the various parameters.

The acquired findings are the natural frequencies for sandwich structures with composite faces exposed to bending loads, and they may be described using a computational program.

Assuming the classical or Kirchhoff's plate theory (CPT) given on the plate, In the case of pure bending, the displacement field is given by [60],

$$u_x(x,y,z) = -z\frac{\partial w}{\partial x} \quad u_y(x,y,z) = -z\frac{\partial w}{\partial y} \quad u_z(x,y,z) = w(x,y) \tag{1}$$

Where u_x, u_y, and u_z represent the displacement parameters through the line of coordinates of a specific point on the x-y plane, and w is the transverse deflection of a point on the mid-plane (x–y plane). Transverse shear deformation is neglected in Kirchhoff's case; deformation is due to bending and in-plane stretching. The stress-strain relations are given by,

$$\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \gamma_{xy}\end{Bmatrix} = \begin{Bmatrix}\frac{\partial u_x}{\partial x}\\ \frac{\partial u_y}{\partial y}\\ \frac{\partial u_x}{\partial y}+\frac{\partial u_y}{\partial x}\end{Bmatrix} = \begin{Bmatrix}-z\frac{\partial^2 w}{\partial x^2}\\ -z\frac{\partial^2 w}{\partial y^2}\\ -2z\frac{\partial^2 w}{\partial x\,\partial y}\end{Bmatrix} \tag{2}$$

In Eq. 2, the normal strains in terms of x and y directions are ε_{xx} and ε_{xx}, while γ_{xy} indicates the shear strain component. According to Hooke's law, the following matrix form can be used to describe the relationships of the stress and strain expressions at a given point of the functionally graded plate,

$$\begin{Bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \tau_{xy}\end{Bmatrix} = \begin{pmatrix}A_{11} & A_{12} & 0\\ A_{21} & A_{22} & 0\\ 0 & 0 & A_{66}\end{pmatrix}\begin{Bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \gamma_{xy}\end{Bmatrix} \tag{3}$$

The components of the normal and shear stress σ_{xx}, σ_{yy}, and τ_{xy} can be used to construct the reduced stiffness parameters A_{ij} (i, j = 1, 2, 6),

$$A_{11} = A_{22} = \frac{E(z)}{1-v^2} \quad A_{12} = A_{21} = \frac{vE(z)}{1-v^2} \quad A_{66} = \frac{E(z)}{2(1+v)} \tag{4}$$

The materials properties E, ν represent Young's modulus and Poisson's ratio of the sandwich plate. The linear constitutive relations of the plate, such as the bending and twisting moments M_{xx}, M_{yy}, and M_{xy}, respectively, on a plate element. The pure bending case can be written as

$$\begin{Bmatrix}M_x\\ M_y\\ M_{xy}\end{Bmatrix} = \int_{-h/2}^{h/2}\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{Bmatrix} z\,dz \tag{5}$$

The governing equations of the classical plate theory (CPT) can be found using the energy method. The strain energy U stored in an elastic body, for a general state of stress, is given by,

$$U = \frac{1}{2}\iiint_V \begin{bmatrix}\sigma_x\varepsilon_x + \sigma_y\varepsilon_y + \sigma_z\varepsilon_z +\\ \tau_{xy}\gamma_{xy} + \tau_{xz}\gamma_{xz} + \tau_{yz}\gamma_{yz}\end{bmatrix} dx\,dy\,dz \tag{6}$$

Integration extends over the entire body volume. for thin plates $\sigma_z, \gamma_{xz}, \gamma_{yz}$ can be omitted. Thus, introducing Hooke's law, the above expression reduces to the following form involving only stresses and elastic constants,

$$U = \iiint_V \left[\frac{1}{2E}\left(\sigma_x^2 + \sigma_y^2 - 2v\sigma_x\sigma_y\right) + \frac{1}{2G}\tau_{xy}^2\right] dxdydz \tag{7}$$

$$U = \frac{1}{2}\int_\Omega \left[\int_{-h/2}^{h/2}\left(\sigma_{xx}\varepsilon_{xx} + \sigma_{yy}\varepsilon_{yy} + \tau_{xy}\gamma_{xy}\right)dz\right] dx\,dy \tag{8}$$

Thus, the kinetic energy (T) of the plate in cartesian coordinates at any instant can be expressed as,

$$T = \frac{1}{2}\int_\Omega \left[\int_{-h/2}^{h/2}\rho(z)\left(\frac{\partial u_z}{\partial t}\right)^2 dz\right] dx\,dy \tag{9}$$

Where Ω denotes the mid-plane (domain) of the plate. Using Eqs. (1), (2), and (3) in Eqs. (8) and (9) lead to the total potential energy function U,

$$U = \frac{1}{2}\int_\Omega \begin{bmatrix} D_{11}\left(\left(\frac{\partial^2 w}{\partial x^2}\right)^2 + \left(\frac{\partial^2 w}{\partial y^2}\right)^2\right) +\\ 2D_{12}\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2} + 4D_{66}\left(\frac{\partial^2 w}{\partial x\,\partial y}\right)^2\end{bmatrix} dx\,dy \tag{10}$$

Where the flexural rigidity coefficients D11, D12, and D66 in Eq. 10 can be evaluated as,

$$(D_{11}, D_{12}, D_{66}) = \int_{-h/2}^{h/2}(A_{11}, A_{12}, A_{66})z^2 dz \tag{11}$$

12)

$$D_{11} = \int_{-h/2}^{h/2} A_{11}z^2 dz = \int_{-h/2}^{h/2}\frac{E(z)}{1-v^2}z^2 dz \tag{12a}$$

$$D_{12} = \int_{-h/2}^{h/2} A_{12}z^2 dz = \int_{-h/2}^{h/2}\frac{vE(z)}{1-v^2}z^2 dz \tag{12b}$$

$$D_{66} = \int_{-h/2}^{h/2} A_{66}z^2 dz = \int_{-h/2}^{h/2}\frac{E(z)}{2(1+v)}z^2 dz \tag{12c}$$

$$I_0 = \int_{-\frac{h}{2}}^{\frac{h}{2}}\rho(z)dz \tag{13}$$

Where I_o is the total inertial coefficient of the sandwich plate.

Consider a rectangular plate of length *a* and width *b* with its four edges simply supported, as shown in

Figures 1 and 2, assume the solution of mode deflection for the plate to be

$$w = \text{Sin}\frac{m\pi x}{a}\ \text{Sin}\frac{n\pi y}{b} \quad (14)$$

And the free vibration eigenvalue problem is

$$([K]_{n\times n} - \lambda^2 [M]_{n\times n})\{\delta\} = 0 \quad (15)$$

Where $[K]_{n\times n}$ represents the stiffness coefficients matrix while $[M]_{n\times n}$ is the inertia coefficients matrix of the functionally graded sandwich plate, and (δ) is the column vector of unknown constant coefficients. Solutions to the standard generalized eigenvalue problem, the frequencies and mode shapes of the sandwich plate are obtained from Eq. (15). By equating U_{max} and T_{max}, the w is the respective maximum deflection. The natural frequency equation of the free vibration can be found as:

$$\omega^2 = \frac{U_{max}}{\int_\Omega I_0 W^2\, dx\, dy} \quad (16)$$

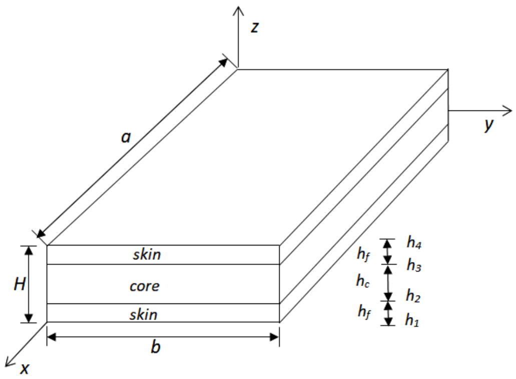

Fig. 1. Sandwich plate with PLA core and composites skins

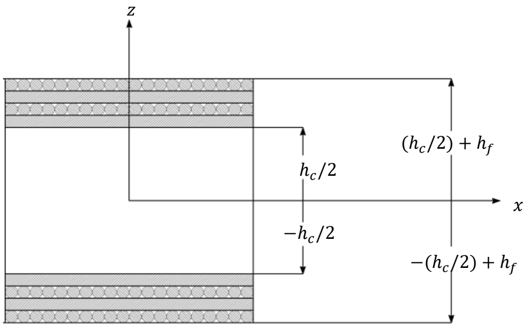

Fig. 2. Geometry of the sandwich structure layers

3. RESULTS AND DISCUSSION

The free vibration analysis of sandwich construction with a PLA core and composite face sheets strengthened by nanoparticles of Al_2O_3 and SiO_2 is carried out in this paper. The differential equation of motion that regulates the sandwich structure's layers is created first, then calculating the natural frequency using various parameters. The results include the natural frequencies of SSSS sandwich constructions with composite faces exposed to bending forces. Assume the mechanical properties of the sandwich structure's two faces are the same properties.

A code written using MATLAB software is used to solve the above equations.

The effective mechanical properties for sandwich layers are,

1. Polylactic acid core (PLA), $E_c = 1.2$ Gpa, $\rho_c = 1360\ kg/m^3$, $\nu_c = 0.38$ [61], and the core height h_c=14 mm.
2. Nanocomposite faces at the top and bottom surfaces of the panel with thickness h_f=3mm each. The nanoparticle volume fraction goes between (0% to 2.5%).
3. Young modulus is increased on two different densities, as shown in tables (1) to (4).

Material properties were averaged for matrix and fillers, [62-65]. The effects of nanoparticles on the free vibration of simply supported sandwich plates with nanocomposite faces are explored in this research. Kirchhoff's theory for slight deflection uses as the governing equation. As previously mentioned, assumptions were made to simplify the solution in two different ways by applying varying volume fractions between (V_f = 0% - 2.5%) with two types of nanoparticles (SiO_2 & Al_2O_3). The results show the behavior of the fundamental natural frequency of sandwich plates with reinforced skins by nanoparticles at two mass density values. The results indicate that skin strengthening significantly affects how sandwich plates can achieve their task. Numerical results are presented for composite sandwich plates demonstrating the validity and efficiency of the present method. Two important notes can be recorded to clarify the behavior of the free vibration of the reinforced sandwich plate structure.

The increase in nanoparticle volume fraction increases Young's modulus, leading to an increase in composite face strength. Additionally, the sandwich plate stability is sustained by the increase in the mass density. At a density of 1180 kg/m^3 and volume fraction (V_f=2.5%), SiO_2 nanoparticles will have a 50% increase in Young modulus, while at a density of 1210 kg/m^3, it will increase by 56% (see Figure 3). The significant change occurred at (V_f=2.5%) when the Al_2O_3 nanoparticles skins were used with a density of 1180 kg/m^3, increasing 41%, while at a density of 1210 kg/m^3, the percentage was 46 % (see Figure 4).

As density and Young's modulus increase, the natural frequency of the sandwich plate increases accordingly. Composite faces have a higher natural frequency than composite cores. Also, the natural frequency of the composite faces and the core is higher than that of the sandwich structure. In the case of SiO_2 nanoparticles at a density of 1180 kg/m^3, the optimum parentage (V_f = 2.5%) increases to 22%, while at 1210 kg/m^3, it increases to 24.5%. Furthermore, it is noticed that Al_2O_3 nano-particles at the density of 1180 kg/m^3 are the optimum (V_f=2.5%), and the overhaul parentage increase to 19% while at the density of 1210 kg/m^3 is only 21% (see Figure 5).

Table 1. Results of the first natural frequency with the addition of Al_2O_3 nanoparticles at skin density (ρ_f=1180 kg/m^3).

S	V_f (%)	E_f (GPa)	ν_f	E_c (GPa)	ν_c	ω (rad/sec)
1	0.00	15.85	0.22	1.20	0.38	3874.60
2	0.50	17.34	0.22	1.20	0.38	4049.19
3	1.00	18.42	0.22	1.20	0.38	4171.18
4	1.50	19.83	0.22	1.20	0.38	4325.27
5	2.00	20.88	0.22	1.20	0.38	4436.54
6	2.50	22.47	0.22	1.20	0.38	4599.91

Table 2. Results of the first natural frequency with the addition of Al2O3 nanoparticles at skin density(ρf=1210 kg/m3).

S	V_f (%)	E_f (GPa)	ν_f	E_c (GPa)	ν_c	ω (rad/sec)
7	0.00	16.56	0.18	1.20	0.38	3966.11
8	0.50	18.23	0.18	1.20	0.38	4157.73
9	1.00	19.47	0.18	1.20	0.38	4294.48
10	1.50	20.44	0.18	1.20	0.38	4398.49
11	2.00	21.89	0.18	1.20	0.38	4549.54
12	2.50	24.13	0.18	1.20	0.38	4773.50

Table 3. Results of the first natural frequency with the addition of SiO2 nanoparticles at skin density (ρ_f = 1180 kg/m^3).

S	V_f (%)	E_f (GPa)	ν_f	E_c (GPa)	ν_c	ω (rad/sec)
1	0.00	15.85	0.22	1.20	0.38	3874.60
2	0.50	17.92	0.22	1.20	0.38	4115.15
3	1.00	19.12	0.22	1.20	0.38	4248.38
4	1.50	20.33	0.22	1.20	0.38	4378.60
5	2.00	21.74	0.22	1.20	0.38	4525.63
6	2.50	23.87	0.22	1.20	0.38	4739.10

Table 4. Results of the first natural frequency with the addition of SiO2 nanoparticles at skin density (ρf=1210 kg/m3).

S	V_f (%)	E_f (GPa)	ν_f	E_c (GPa)	ν_c	ω (rad/sec)
7	0.00	16.56	0.18	1.20	0.38	3966.11
8	0.50	19.46	0.18	1.20	0.38	4293.39
9	1.00	20.74	0.18	1.20	0.38	4430.16
10	1.50	22.31	0.18	1.20	0.38	4592.36
11	2.00	23.85	0.18	1.20	0.38	4746.08
12	2.50	25.78	0.18	1.20	0.38	4931.97

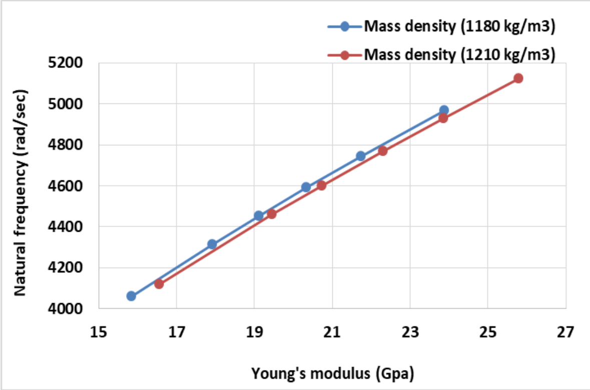

Fig. 3. The relationship of the first natural frequency with various Young's modulus of sandwich panel reinforced by SiO2 nanoparticles at two mss densities.

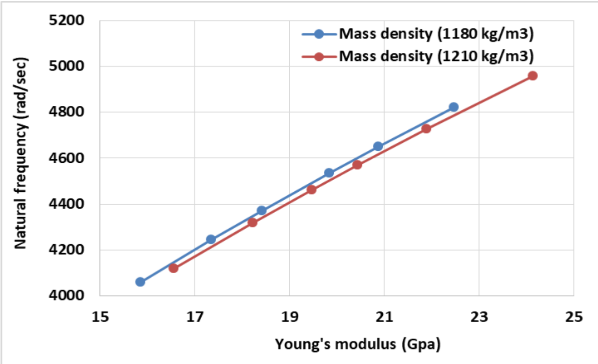

Fig. 4. Natural frequency with various Young's modulus at two densities of Al2O3

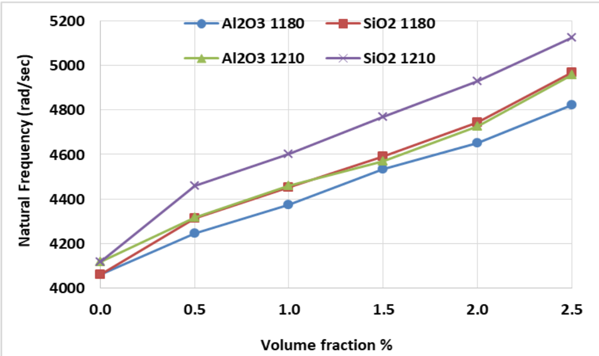

Fig. 5. The first natural frequency results of the sandwich panel at two densities for Al_2O_3 & SiO_2 nanoparticles

Figures 6 shows the comparison between analytical and numerical results of the fundamental natural frequency for sandwich plate reinforced with Al_2O_3 nanoparticles at a mass density of 1180 kg/m^3. From the results, one can conclude that there is a good variation between the two solutions, with a maximum discrepancy of 3% occurring at V_f=2.0. Figure 7 illustrates the same phenomenon with skin reinforced with SiO_2 nanoparticles. The maximum discrepancy between the two approaches is 2.2 % at V_f=2.5. It is observed that the numerical solution converges with that of the analytical formulation. In general, the current study's findings appear helpful in understanding the behavior of sandwich plate vibration patterns and their relationships.

Consequently, the paper reports a comprehensive study of composite sandwich panels, with helpful analysis and results for using them in engineering applications.

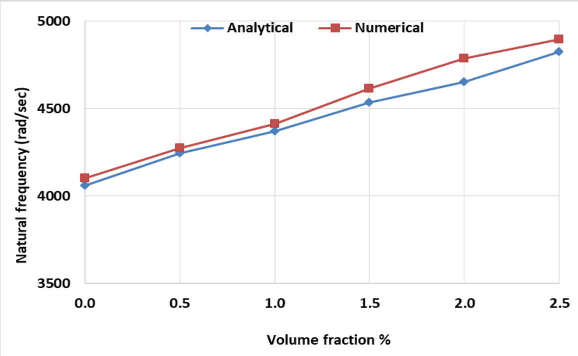

Fig. 6. Analytical and Numerical results of fundamental natural frequency for skin reinforced by Al2O3 nanoparticles at mass density 1180 kg/m3

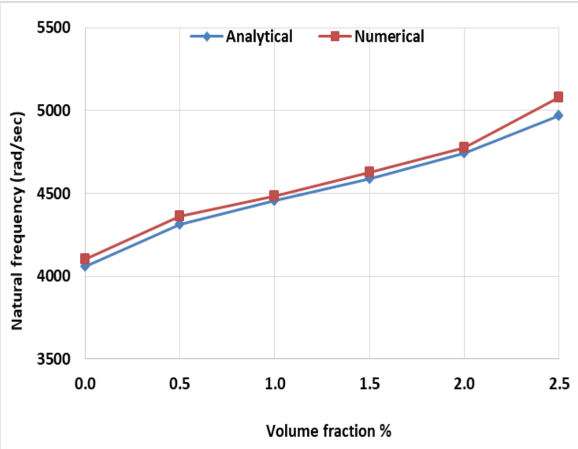

Fig. 7. Analytical and Numerical results of fundamental natural frequency for skin reinforced by SiO2 nanoparticles at mass density 1180 kg/m3

4. CONCLUSION

The layered structures, like beams and plates consisting of composite layers embedded between elastic ones, are widely used in many engineering fields such as aerospace, automobile, nuclear and biomedical. This study investigated the vibration characteristics of the composite face plate enhanced by the addition of nanoparticles. The obtained results are compared with numerical solutions, and the conclusions of this study were as follows,

1. The mechanical properties are improved when replacing the skins of the partial structure with a composite material. Hence, lower weight and greater strength are obtained using composite materials compared to classical materials.
2. For sandwich panels with SiO_2 reinforced skins, the natural frequency increased by (10%) when changing the density from (1180 kg/m^3 to 1210 kg/m^3) at V_f =2.5 % core height 14mm, and skin 3 mm.
3. In the same structures reinforced with Al_2O_3 Nano-particles, the parentage increase in Young's modulus is 10.8 % and 9.5 % in natural frequency when changing the density from (1180 kg/m^3 to 1210 kg/m^3).
4. For further research, the results show that adding nanomaterials increases the mechanical properties and thus reduces vibrations.
5. The same approach can be investigated for future work using functionally graded core and composite faces of sandwich plate structures considering shear locking.
6. Various plate theories, such as the first and higher deformation theories, should be examined to make the theoretical analysis more efficient.

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Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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