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Enhancing Analysis of Cross-Ply Laminated Composite Plates: A Simplified Approach for Flexural and Stability Evaluation

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Abstract: In this article, we examine cross-ply laminated composite plates using a simple sinusoidal shear deformation model to analyze their flexural and stability behaviors. Our model, which contains only four unknown variables, offers a more concise alternative to first-order shear deformation theories (FSDT) or other higher-order models. By integrating undetermined integral terms into the in-plane kinematics, we accurately capture the influence of shear deformation. Our proposed theory ensures adherence to the conditions of zero shear stress at the bottom and top faces of the plates, without resorting to the shear correction coefficient. The equations of motion stem from our formulation using the principle of virtual work in its dynamic version. The an analytical solution is obtained through double trigonometric series proposed by Navier. We then compare the stresses, displacements and natural frequencies, forces calculated using our method with other published data, thereby demonstrating a good level of agreement between the results.

Keywords: Shear deformation, Flexural, Navier, Cross-ply laminates, Laminated plates.

Introduction

Composite materials are increasingly utilized across various engineering sectors due to their remarkable attributes, such as high strength, stiffness, lightweight nature, exceptional thermal properties, corrosion resistance, prolonged fatigue life, and resilience to wear. The accurate assessment of their structural behavior, including both free vibration and bending, is paramount.

In thicker structures, the influence of transverse shear strain becomes more pronounced compared to thinner counterparts, necessitating advanced plate models capable of accurately predicting both free vibration and bending characteristics. Classical plate theory (CPT), pioneered by Kirchhoff (1850). Proves inadequate for thick structures as it neglects transverse shear deformation. Similarly, first-order shear deformation theory (FSDT), proposed by Mindlin (1951). Lacks in meeting zero stress conditions at plate surfaces and necessitates the use of shear correction factors.

To overcome these shortcomings, several higher-order shear deformation theories have been proposed. In recent years, novel plate models, characterized by minimal variables, have emerged. For instance introduced a two variable model tailored for the dynamic study of orthotropic plates, later extending its application to account for thermo-mechanical effects in functionally graded plates. (Shimpi & Patel,2006). Another notable development involves models incorporating undetermined integral terms to simplify governing equations, aiming to enhance the accuracy of both free vibration and bending analyses of composite plates without relying on shear correction coefficients.

In this study, we evaluate the effectiveness of a refined four-variable shear deformation theory in analyzing the free vibration and bending behavior of composite plates. The model integrates undetermined integral terms into its kinematic description to accommodate shear deformation effects, ensuring zero shear stress at plate surfaces. By deriving equations of motion through the virtual work principle and obtaining analytical solutions via a double trigonometric series method, we compare our findings with exact elasticity solutions reported by Pagano (1970). For free vibration analysis, for dynamic analysis, and for stability analysis of laminated composite plates (Noor,1973, 1975). This comparative analysis provides insights into the efficacy of our proposed model in accurately predicting both the free vibration and bending characteristics of composite plates.

Theoretical Formulation

Consider a rectangular plate with sides of lengths *aa* and *bb*, a uniform thickness *hh*, and an origin at point *oo* as illustrated in Fig. 1. The plate is composed of *nn* homogeneous layers, perfectly bonded together, and each layer is made of linearly elastic, orthotropic material. This plate occupies the region defined by these dimensions. $0 \leq x \leq a$, $0 \leq y \leq b$, $-h/2 \leq z \leq h/2$ in Cartesian coordinate system. A transverse load q(x, y) is applied on the upper surface of the plate.

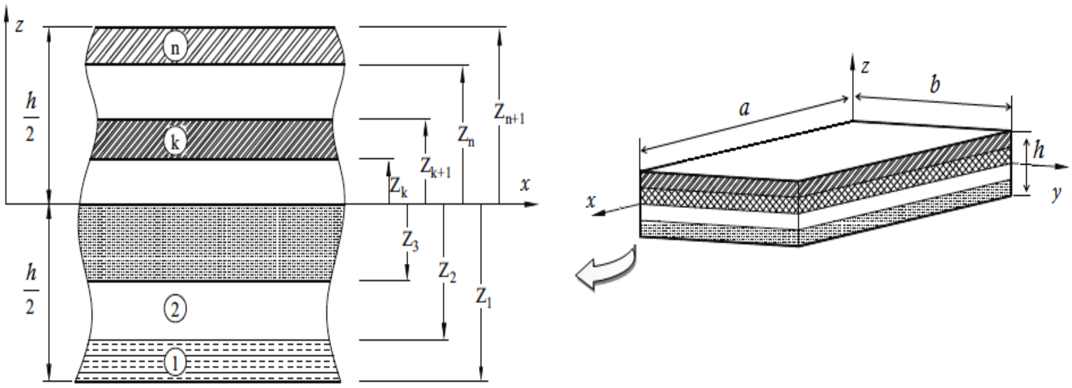

Figure 1. Rectangular plate

Kinematics and Strains

In the unified shear-deformable plate theory, the displacement field at a point in the laminated plate is expressed as (Bakhadda et al., 2018).

$$
\begin{aligned}
u(x,y,z) &= u_0(x,y) - z\frac{\partial w_0}{\partial x} + f(z)\varphi_x(x,y) \\
v(x,y,z) &= v_0(x,y) - z\frac{\partial w_0}{\partial y} + f(z)\varphi_y(x,y) \qquad (1) \\
w(x,y,z) &= w_0(x,y)
\end{aligned}
$$

a shape function determining the changes in the transverse shear strain and the stress distribution along the thickness of the plate and is defined as (Touratier,1991).

$$f(z) = \left(\frac{h}{\pi}\right)\sin\left(\frac{\pi z}{h}\right) \qquad (2)$$

The strains associated with the present theory are obtained using strain-displacement relationship from theory of elasticity.

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial u}{\partial x} \\ \dfrac{\partial v}{\partial y} \\ \dfrac{\partial u}{\partial y} + \dfrac{\partial v}{\partial x} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + z \begin{Bmatrix} \varepsilon_x^1 \\ \varepsilon_y^1 \\ \gamma_{xy}^1 \end{Bmatrix} + f(z) \begin{Bmatrix} \varepsilon_x^2 \\ \varepsilon_y^2 \\ \gamma_{xy}^2 \end{Bmatrix} \tag{3a}$$

$$\begin{Bmatrix} \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial v}{\partial z} + \dfrac{\partial w}{\partial y} \\ \dfrac{\partial u}{\partial z} + \dfrac{\partial w}{\partial x} \end{Bmatrix} = g(z) \begin{Bmatrix} \gamma_{yz}^0 \\ \gamma_{xz}^0 \end{Bmatrix} \tag{3b}$$

Constitutive Relations

Given that the laminate consists of multiple orthotropic layers, the stress-strain relations for the layer of the laminated plate in the material coordinate system are expressed as:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{xz} \end{Bmatrix}^{(k)} = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} & 0 & 0 \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} & 0 & 0 \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} & 0 & 0 \\ 0 & 0 & 0 & \overline{Q}_{44} & 0 \\ 0 & 0 & 0 & 0 & \overline{Q}_{55} \end{bmatrix}^{(k)} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix}^{(k)} \tag{4}$$

the plane stress-reduced stiffness coefficients defined in terms of the engineering constants in the material axes of the layer:

$$Q_{11} = \frac{E_{11}}{1-\nu_{12}\nu_{21}}, Q_{22} = \frac{E_{22}}{1-\nu_{12}\nu_{21}}, Q_{12} = \frac{\nu_{12}E_{11}}{1-\nu_{12}\nu_{21}}, \tag{5a}$$

$$Q_{66} = G_{12}, Q_{44} = G_{23}, \quad Q_{44} = G_{23}, Q_{55} = G_{13} \tag{5b}$$

Equations of Motion

The governing equations and boundary conditions of the present higher order shear deformation theory are derived using principle of virtual work. The principle of virtual work is applied in the following analytical form (Bourada et al., 2019).

$$\begin{aligned} &\int_{-h/2}^{h/2} \int_A \left(\sigma_x \delta\varepsilon_x + \sigma_y \delta\varepsilon_y + \tau_{xy}\delta\gamma_{xy} + \tau_{yz}\delta\gamma_{yz} + \tau_{xz}\delta\gamma_{xz}\right) dAdz + \int_{-h/2}^{h/2} \int_A \rho \left(\frac{\partial^2 u}{\partial t^2}\delta u + \frac{\partial^2 v}{\partial t^2}\delta v + \frac{\partial^2 w}{\partial t^2}\delta w \right) dAdz \\ &- \int_A q(x,y)\delta w dA - \int_A \left(N_x^0 \frac{\partial^2 w}{\partial x^2} + N_y^0 \frac{\partial^2 w}{\partial y^2} + 2N_{xy}^0 \frac{\partial^2 w}{\partial x \partial y} \right) \delta w dA = 0 \end{aligned} \tag{6}$$

where *A* is the area of the top surface of the plate, ρ is the density of material, $q(x, y)$ and N_x^0, N_y^0, N_{xy}^0 are transverse and in-plane applied loads, respectively. The symbol δ denotes the variational operator. Substituting expressions for stresses and virtual strains into the principle of virtual work and integrating Eq. (6) by parts and collecting the coefficients of $\delta \boldsymbol{u_0}$, $\delta \boldsymbol{v_0}$, $\delta \boldsymbol{w_0}$ and $\delta\theta$ the following equations of motion of the plate are obtained in terms of stress resultants, Cartesian coordinate system and the stress resultants (N_x, N_y, N_{xy}), (M_x^b, M_y^b, M_{xy}^b), (M_x^s, M_y^s, M_{xy}^s) and (S_{xz}^s, S_{yz}^s) are defined as:

$$\left(N_x, N_y, N_{xy}\right) = \sum_{k=1}^{n} \int_{z_k}^{z_{k+1}} \left(\sigma_x, \sigma_y, \tau_{xy}\right) dz,$$
$$\left(M_x^b, M_y^b, M_{xy}^b\right) = \sum_{k=1}^{n} \int_{z_k}^{z_{k+1}} \left(\sigma_x, \sigma_y, \tau_{xy}\right) z dz,$$
$$\left(M_x^s, M_y^s, M_{xy}^s\right) = \sum_{k=1}^{n} \int_{z_k}^{z_{k+1}} \left(\sigma_x, \sigma_y, \tau_{xy}\right) f(z) dz, \tag{7}$$
$$\left(Q_{xz}^s, Q_{yz}^s\right) = \sum_{k=1}^{n} \int_{z_k}^{z_{k+1}} \left(\tau_{xz}, \tau_{yz}\right) g(z) dz$$

and the inertia constants I_i $(i = 0, 2, 3, 4, 5)$ are defined by the following equations:

$$\left(I_0, I_1, I_2, I_3, I_4, I_5\right) = \sum_{k=1}^{n} \int_{z_k}^{z_{k+1}} \rho^{(k)} \left(1, z, z^2, f(z), z\, f(z), [f(z)]^2\right) dz \tag{8}$$

Analytical Solution for Laminated Composite Plates

The Navier approach is employed to determine the analytical solutions for the free vibration analysis of simply supported laminated rectangular plates. The following simply supported boundary conditions at all four edges are given by:

$$u_0 = w_0 = N_y = M_y^b = M_y^s = \theta = 0 \quad \text{on edges } (y = 0, b) \tag{9a}$$

$$v_0 = w_0 = N_x = M_x^b = M_x^s = \theta = 0 \quad \text{on edges } (x = 0, a) \tag{9b}$$

The displacement variables which automatically satisfy the above boundary conditions can be expressed in the following Fourier series:

$$\begin{Bmatrix} u_0 \\ v_0 \\ w_0 \\ \theta \end{Bmatrix} = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} \begin{Bmatrix} U_{mn} \cos(\alpha\, x) \sin(\beta\, y)\, e^{i\,\omega\, t} \\ V_{mn} \sin(\alpha\, x) \cos(\beta\, y)\, e^{i\,\omega\, t} \\ W_{mn} \sin(\alpha\, x) \sin(\beta\, y)\, e^{i\,\omega\, t} \\ \Phi_{mn} \sin(\alpha\, x) \sin(\beta\, y)\, e^{i\,\omega\, t} \end{Bmatrix} \tag{10}$$

where U_{mn}, V_{mn}, W_{mn} and Φ_{mn} are the unknown Fourier coefficients to be determined for each (m, n) value, as well as the parameters α and β are defined as:

$$\alpha = m\pi / a,\ \beta = n\pi / b \tag{11}$$

The transverse load $q(x, y)$ is expanded in the double-Fourier sine series as:

$$q(x, y) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} q_{mn} \sin(\alpha\, x) \cos(\beta\, y) \tag{12}$$

where $q_{mn} = q_0$ for sinusoidally distributed load $m = 1, n = 1$ and q_0 is the maximum intensity of distributed load at the centre of plate. Substituting the solution form from Eq. (10) and the transverse load from Eq. (7) into the equations results in the following matrix representation.

$$\left(\begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} \\ K_{12} & K_{22} & K_{23} & K_{24} \\ K_{13} & K_{23} & K_{33}+N_{33} & K_{34} \\ K_{14} & K_{24} & K_{34} & K_{44} \end{bmatrix} - \omega^2 \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{12} & M_{22} & M_{23} & M_{24} \\ M_{13} & M_{23} & M_{33} & M_{34} \\ M_{14} & M_{24} & M_{34} & M_{44} \end{bmatrix}\right) \begin{Bmatrix} U_{mn} \\ V_{mn} \\ W_{mn} \\ \Phi_{mn} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ q_{mn} \\ 0 \end{Bmatrix} \quad (13)$$

Discussion of Numerical Results

Bending Analysis of Laminated Composite Plates

The bending analysis of simply supported anti-symmetric laminated composite square plates under sinusoidally distributed load is conducted using the following material properties.

$$E_{11} = 25E_{22}\,,\; G_{12} = G_{13} = 0.5E_{22}\,,\; G_{23} = 0.2E_{22}\,,\; \nu_{12} = 0.25\,,\; \nu_{21} = \frac{E_{22}}{E_{11}}\nu_{12} \quad (14)$$

The displacements and stresses are presented in the following non-dimensional form.

$$\bar{u}\left(0,\frac{b}{2},-\frac{h}{2}\right) = \frac{uE_2h^2}{q_0a^3}\,,\; \bar{w}\left(\frac{a}{2},\frac{b}{2},0\right) = \frac{100wh^3E_2}{q_0a^4}\,,\; \bar{\sigma}_x = \frac{h^2}{q_0a^2}\sigma_x\left(\frac{a}{2},\frac{b}{2},-\frac{h}{2}\right),$$
$$\bar{\sigma}_y = \frac{h^2}{q_0a^2}\sigma_y\left(\frac{a}{2},\frac{b}{2},-\frac{h}{2}\right),\; \bar{\tau}_{xy} = \frac{h^2}{q_0a^2}\tau_{xy}\left(0,0,-\frac{h}{2}\right), \quad (15)$$
$$\bar{\tau}_{xz} = \frac{h}{q_0a}\tau_{xz}\left(0,\frac{b}{2},0\right),\bar{\tau}_{yz} = \frac{h}{q_0a}\tau_{yz}\left(\frac{a}{2},0,0\right)$$

Table 1. Comparison of non-dimensional displacements and stresses for the two layered (0°/90°) laminated composite square plate subjected to sinusoidally distributed load.

a/h	Theory	$\bar{u}$	$\bar{w}$	$\bar{\sigma}_x$	$\bar{\sigma}_y$	$\bar{\tau}_{xy}$	$\bar{\tau}_{xz}$	$\bar{\tau}_{yz}$
4	Present	0.0114	1.9766	0.9143	0.0889	0.0577	0.1274	0.1274
	Sayyad et al. (2016)	0.0114	1.9793	0.9154	0.0890	0.0578	0.0660	0.1276
	Sayyad and Ghugal (2014a)	0.0111	1.9424	0.9062	0.0964	0.0562	0.1270	0.1270
	Reddy (1984)	0.0114	2.0256	0.9172	0.0932	0.0713	0.1270	0.1270
	Mindlin (1951)	0.0088	1.9682	0.7157	0.0843	0.0525	0.0910	0.0910
	Kirchhoff (1850)	0.0088	1.0636	0.7157	0.0843	0.0525	—	—
	Pagano (1970)	—	2.0670	0.8410	0.1090	0.0591	0.1200	0.1350
10	Present	0.0093	1.2132	0.7483	0.0851	0.0533	0.1304	0.1304
	Sayyad et al. (2016)	0.0093	1.2135	0.7484	0.0851	0.0534	0.1270	0.1306
	Sayyad and Ghugal (2014a)	0.0092	1.2089	0.7471	0.0876	0.0530	0.1300	0.1300
	Reddy (1984)	0.0095	1.2479	0.7652	0.0889	0.0680	0.1310	0.1310
	Mindlin (1951)	0.0088	1.2083	0.7157	0.0843	0.0525	0.0910	0.0910
	Kirchhoff (1850)	0.0088	1.0636	0.7157	0.0843	0.0525	—	—
	Pagano (1970)	—	1.2250	0.7302	0.0886	0.0535	0.1210	0.1250

In this numerical illustration, we showcase the efficacy of the current theory in analyzing the bending behavior of simply supported two-layered (0°/90°) anti-symmetric laminated composite square plates under sinusoidally distributed loads. We compare and discuss the non-dimensional displacement and stresses computed using our model with those obtained from classical plate theory (CPT) by Kirchhoff (1850), first-order shear deformation theory (FSDT) by Mindlin (1951), higher-order shear deformation theory (HSDT) by Reddy (1984), sinusoidal shear and normal deformation theory (SSNDT) by Sayyad and Ghugal (2014), and the exact elasticity solution provided by Pagano (1970). The non-dimensional results are tabulated in Table 1. It is observed that the in-plane displacement computed using our theory exhibits good agreement with results from other models. Specifically, the in-plane displacement is maximized in the 90° layer and minimized in the 0° layer (see Figure

2). While our proposed model slightly underestimates the transverse displacement for an aspect ratio of 4, it aligns well with exact solutions and other higher-order models for an aspect ratio of 10.

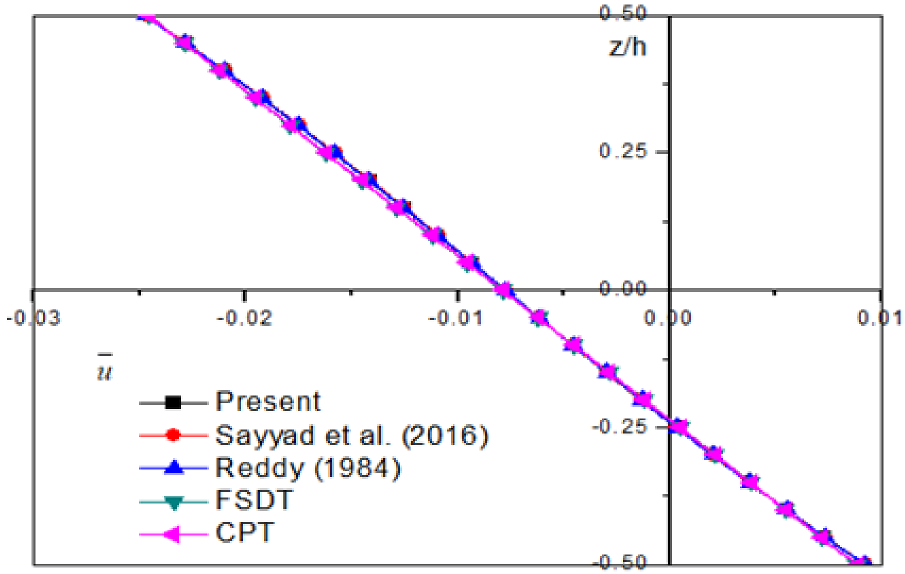

Figure 2. Through thickness distribution of in-plane displacement ($\bar{u}$) for two layered (0°/90°) laminated composite plate subjected to sinusoidally distributed load (*b/a*=1, *a/h*= 10)

Free Vibration Analysis of Laminated Composite Plates

For this study, the material properties given by Eq. (14) are employed. Natural frequencies are presented in the following non-dimensional form:

$$\bar{\omega} = \omega\sqrt{\rho h^2 / E_{22}} \qquad (16)$$

Table. 2. Comparison of non-dimensional natural frequencies of simply supported square laminated composite plates (*a/h*= 10)

Lay-up	Theory	E_{11} / E_{22}			
		10	20	30	40
0/90	Present	0.27988	0.31355	0.34130	0.36499
	Sayyad et al. (2016)	0.27987	0.31354	0.34128	0.36498
	FSDT	0.27757	0.30824	0.33284	0.35353
	CPT	0.30968	0.35422	0.39335	0.42884
0/90/0	Present	0.34309	0.40641	0.44510	0.47165
	Sayyad et al. (2016)	0.34261	0.40623	0.44502	0.47162
	FSDT	0.32739	0.37110	0.39540	0.41158
	CPT	0.42599	0.55793	0.66419	0.75565
0/90/0/90	Present	0.3281	0.3852	0.4211	0.44658
	Sayyad et al. (2016)	0.3422	0.4055	0.4441	0.4706
	FSDT	0.3319	0.3826	0.4130	0.4341
	CPT	0.4260	0.5579	0.6642	0.7556
0/90/0/90/0	Present	0.3434	0.4066	0.4451	0.4718
	Sayyad et al. (2016)	0.3430	0.4063	0.4449	0.4715
	FSDT	0.3368	0.3930	0.4271	0.4506
	CPT	0.4259	0.5579	0.6641	0.7556

In Table 1, non-dimensional natural frequencies of simply supported square laminated composite plates for different modular ratios (E_{11} / E_{22}) are given and compared with those predicted SSNDT of (Sayyad et al.,2016). FSDT of (Mindlin,1951). CPT of (Kirchhoff,1850). Table 2 demonstrates that the proposed model accurately predicts the natural frequencies of laminated composite plates. In contrast, the CPT tends to overestimate these frequencies because it neglects the influence of transverse shear deformation. Additionally, it is observed that the natural frequencies of laminated composite plates increase as the modular ratios increase. (E_{11} / E_{22}).

Fig. 3 illustrates the variation of the natural frequency for simply supported square laminated composite plates with respect to the a/h ratio, based on the current refined sinusoidal shear deformation theory. It can be observed that the natural frequency decreases with increasing the ratio. This decrease is attributed to the plate becoming thinner as the a/h ratio increases. In other words, an increase in the a/h ratio corresponds to a decrease in the relative thickness of the plate, leading to a reduction in its stiffness and, consequently, its natural vibration frequency. This observation underscores the importance of considering not only material properties but also geometric dimensions when designing and analyzing laminated composite plates to ensure their desired vibrational performance.

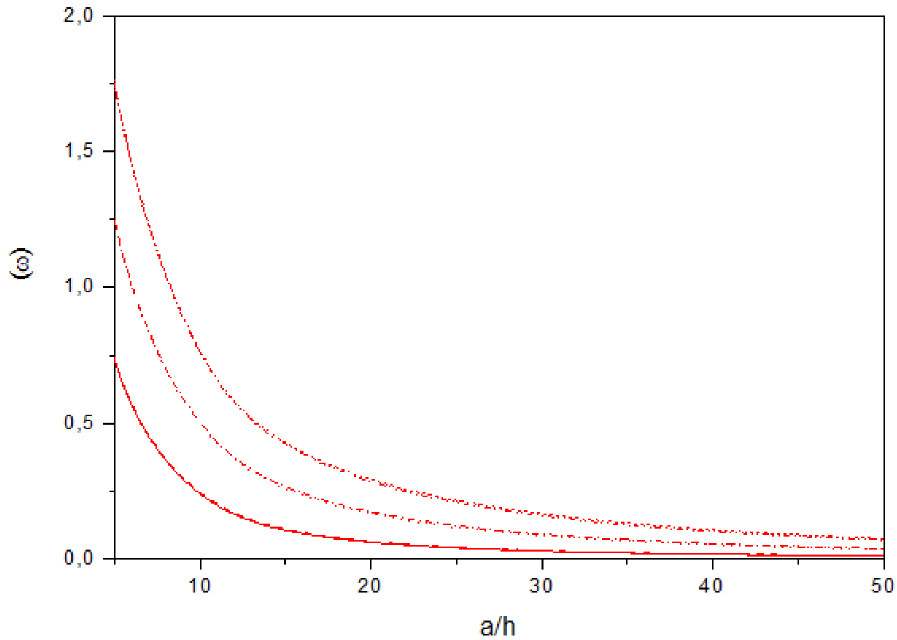

Figure 3. Variation of the natural frequency for the simply supported square laminated composite plates with respect to the a/h ratio

Conclusions

In this study, we have utilized a refined theory of sinusoidal shear deformation to analyze both the free vibrations and bending behavior of laminated composite plates. The simplicity of this theory, with only four unknowns compared to five in first-order shear deformation theory and other higher-order theories, significantly reduces computational complexity. Moreover, our theory effectively addresses the tensile conditions on the upper and lower surfaces of the plates without requiring a shear correction factor. This not only enhances efficiency but also improves accuracy in predicting the natural frequencies and bending responses of laminated composite plates. Numerical results demonstrate that our proposed theory closely aligns with experimental solutions reported in the literature, providing reliable predictions of both free vibration behavior and bending characteristics. Accurately predicting these aspects is vital for designing and analyzing composite structures where dynamic performance and bending integrity are paramount. In conclusion, our refined approach offers a more efficient and precise method for comprehensively analyzing the dynamic and bending characteristics of laminated composite plates, thus contributing to improved structural design and performance evaluation.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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