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On free vibration of laminated skew sandwich plates: A finite element analysis

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Abstract: The present work emphasizes the determination of the fundamental frequency of skew sandwich plates with orthotropic core and laminated facings using different design parameters. Finite elements CQUAD4 and CQUAD8 of MSC/NASTRAN are used for obtaining fundamental frequencies, which are validated against available literature results. The influence of the skew angle, the ratio of the length-to-total thickness (a/h) of the sandwich plate, and the ratio of the thickness of the core to face sheet (t_c/t_h) on the fundamental frequency of skew sandwich plates are studied. Also, the influence of parameters such as the number of layers in the face sheet, laminate sequence, and fiber orientation angle on the fundamental frequency of laminated skew sandwich plates have been studied. It is found that the CQUAD8 element yields better results than the CQUAD4 element in the present study. The fundamental frequencies are found to increase with the increasing skew angle. The variation in fundamental frequency is negligible when the number of layers is large in the face sheet.

Keywords: fundamental frequency, non-dimensional frequency parameter, skew sandwich plate, skew angle, antisymmetric laminate, fiber orientation angle

1 Introduction

Skew sandwich plates are now a day frequently used in numerous areas like aeronautical, automobile, civil engineering, and in most structural applications. In skew sandwich plates, the effect of shear deformation is considerably more as compared to laminated composite skew plates, which was the reason behind the widespread applications of such plates. Also skew sandwich plate exhibits less weight, more stiffness, more structural efficiency, and more durability. Much research was made on sandwich plates on the free vibration behavior for more than two decades.

A linear analysis for bending and vibration of sandwich plates was employed for analytical and experimental investigations [1]. Also, refined plate theory was proposed on sandwich plates [7]. The free vibration analysis using higher-order shear deformation theory of sandwich plates [18], laminated composite and sandwich plates [6], skew sandwich plate with laminated composite faces were presented [8]. Free vibrations and buckling of the sandwich panel with a flexible core was investigated using a new improved high-order sandwich panel theory [11]. Free vibration analysis of laminated composite and sandwich plates using trigonometric shear deformation theory was performed [15]. Quasi-3D shear deformation theory was employed for thermo-mechanical bending analysis of functionally graded material (FGM) sandwich plates [35] and buckling and the post-buckling response was recorded from functionally graded carbon nanotube (FG-CNT) - magnesium (Mg) nanocomposite plate with interphase effect [31]. The modified stiffness method was applied to the dynamic analysis of sandwich plates [2]. An experimental modal study was conducted on a cantilever flexible plate underwater due to the hydrodynamic effect [32]. A study dealing with the comparison of free vibration responses obtained from four theories on composite truss core sandwich plates were presented. The natural frequencies of the sandwich plate are calculated by using the classic laminated plate theory, the first-order shear deformation theory, Reddy’s third-order shear deformation theory, and a Zig-Zag theory [12]. Various shear deformation theories [13] were considered for the comparison based on the displacement fields [14].

Finite element analysis of composite sandwich plates was carried out based on Mindlin’s plate theory [3]. The bending behavior [16] and free vibration response [17] using a four nodded rectangular finite element formulation based on a layer-wise theory, Static analysis [9], and the free vibration response [10] using an improved dis-
Free vibration analysis of plates and sandwich plates was discussed using $C^0$ iso-parametric finite element model [20]. Two new $C^0$ assumed strain finite element [21], $C^0$ finite element model [22]. Fundamental flexural frequencies of isotropic and laminated composite skew plates [23], skew sandwich composite plates [27, 28] have been obtained using finite elements. Also, the experimental and finite element studies were carried out on free vibration of isotropic and laminated composite skew plates [24, 25]. The nonlinear static, buckling, and finite element studies were carried out on a sandwich plate to improve the dynamic effects of geometric design variables and material alteration [4]. The vibration parameters of sandwich plates were predicted by a spline finite strip method [19], harmonic quadrature element method [26].

The present research focuses on the free vibration studies on laminated sandwich skew plates with simply supported and clamped boundary conditions. The face sheet consists of a laminated composite reinforced with graphite-epoxy and a heavy core (orthotropic). The key objective is to investigate the influence of the number of layers in the face panel, the ratio $[a/h]$, the ratio $[t_c/t_f]$, the effect of fiber orientation, the effect of the laminate sequence, the effect of boundary conditions, the effect of the skew angle on the sandwich plate’s free vibration response. The paper is organized as follows: Firstly, for the free vibration analysis of the sandwich plate, convergence of the results gathered by both CQUAD4 and CQUAD8 elements is evaluated. The validation of the result by the present approach is compared to those available in the literature using converged element density. By implementing the mechanical properties as implemented in [20] for both the orthotropic face sheet (GFRPC) and the orthotropic core (Heavy), computational analysis is finally carried out to describe the effect of various geometric parameters, boundary conditions, and skew angle.

## 2 Finite element formulation

For thick plates the following equation (1) holds good:

$$\begin{align*}
\begin{bmatrix}
u \\
n \\
w
\end{bmatrix} = \begin{bmatrix}
u_0 + z\theta_x \\
n_0 + z\theta_y \\
w_0
\end{bmatrix} \quad \text{and} \quad \begin{bmatrix}	heta_x \\
n_y \\
w
\end{bmatrix} = \begin{bmatrix}w, x + \phi_x \\
n_y + \phi_y
\end{bmatrix}
\end{align*}$$

(1)

Using five components $u$, $v$, $w$, $\theta_x$, $\theta_y$, the displacement of the plate are fully described where $u$, $v$, and $w$ are displacements along Cartesian $x$, $y$ and $z$-directions also $\theta_x$ ($w$, $x$, and $\varphi_x$) and $\theta_y$ ($w$, $y$, and $\varphi_y$) are total (bending and shear) rotations about $y$- and $x$-axes, respectively, whereas, $u_0$, $v_0$, and $w_0$ are the mid-plane translations along $x$, $y$ and $z$ directions, respectively. Nodal displacements are used to describe the displacement $\delta_j$ at any point within the element by the following equation.

$$\delta_j = N_j \delta_{ij}$$

(2)

Where $N_j$ are isoparametric shape functions [30]. The stiffness matrix of the plate element assumes the form.

$$[K]e = \int_{A_e} [B]^T [D] [B] dA$$

(3)

Where,

$$\{\varepsilon\} = [B] \{\delta\} \ldots$$

(4)

$\{\varepsilon\}$ being the strain vector, and $\{\delta\}$ the nodal displacement vector. $[B]$ is the strain-displacement matrix, and $[D]$ is the stiffness matrix given below.

$$[D] = \begin{bmatrix}
A_{ij} & B_{ij} & 0 \\
B_{ij} & D_{ij} & 0 \\
0 & 0 & A_{lm}
\end{bmatrix}$$

(5)

Where,

$$A_{ij}, B_{ij}, D_{ij} = \sum_{k=1}^{N} \int_{z_{k-1}}^{z_k} (Q_{ij})_k (1, z, z^2) dz, i, j = 1, 2, 6 \ldots$$

(6a)

And

$$A_{km} = \sum_{k=1}^{N} \int_{z_{k-1}}^{z_k} k (Q_{lm}) dz, l, m = 4, 5, \kappa = 5/6 \ldots$$

(6b)

Here, $Q_{ij}$ is the element of off-axis stress-strain relations. $Q_{ij}^k$ relates stresses and strains in a $k^{th}$ layer by the relation $\sigma^k = Q^k \varepsilon^k$. Here $\sigma_1$, $\sigma_2$, and $\sigma_6$ denote $\sigma_x$, $\sigma_y$ and $\tau_{xy}$ respectively and $\varepsilon_1$, $\varepsilon_2$, $\varepsilon_6$ denote $\varepsilon_x$, $\varepsilon_y$, $\gamma_{xy}$.
respectively. Whereas \( \sigma_l = Q_{lm}^k \epsilon_m^k \) where \( l,m = 4,5 \) and \( \kappa \) is the shear correction factor taken as 0.8334. The mass matrix of the plate element is given by

\[
[M]_e = \int_{A_e} [N]^T [\rho] [N] \, dA \tag{7}
\]

\([\rho]\) being the density matrix functions.

The integration in every case is carried out over the area of the plate element. Generally, a 3-point Gauss quadrature is adopted to compute the bending stiffness of the elements, whereas 2-point integration is applied to calculate the shear stiffness, mass matrix, and element force vector. The governing equations, without damping being accounted for free vibration is

\[
M \ddot{x} + Kx = 0 \tag{8}
\]

3 Convergence and validation

3.1 Convergence

The geometrical representation of the sandwich plate is as shown in Figure 1. The skewed sandwich plate with global and local coordinate systems is as shown in Figure 2. The displacement boundary conditions cannot be applied directly, due to the inclination of displacements to the skew edges. To overcome this, a local coordinate system \((x', y')\) normal and tangential to the skew edges is preferred.

A total number of elements in the plate model is optimized to get exact and consistent values. Consequently, it is essential to analyze the convergence of the values. The convergence was made on simply supported and clamped skew sandwich plates using CQUAD4 (four-node plate element) and CQUAD8 (eight-node isoparametric curved shell element) elements of MSC/NASTRAN. Skew sandwich plates with varying aspect ratio, length to thickness ratio, and the ratio of a thickness of core to facing for skew angles 0°, 15°, 30°, and 45° using both the elements are evaluated. The converged detailed results are conveyed in Table 1. The material properties used are, for face sheets

\[
E = 68.948 \text{ GPa}, \quad G = 25.924 \text{ GPa}, \quad \nu = 0.33, \quad \rho = 2768.0 \text{ kg/m}^3
\]

\[
\text{core } G_{23} = 0.05171 \text{ GPa}, \quad G_{13} = 0.13445 \text{ GPa}, \quad \rho = 121.83 \text{ kg/m}^3
\]

3.2 Validation

Validation of the results from the elements used in the present study is made by matching up the values for the natural frequency found in the present study to the available literature values. The comparison is shown in Table 2 and 3, for clamped and simply supported boundary conditions respectively of a skew sandwich plate in Hz. The material constants employed are similar to those used in [19]. The values found in the study are in good harmony with the literature results. Also for simply supported sandwich skew plates, the material constants are referred to as in [8].

Non-dimensional frequency parameter \((K_f)\) of simply supported five-layered symmetric laminated composite skew sandwich plates with orthotropic core was determined by using the formula

\[
K_f = 100 \omega a \sqrt{(\rho/E)}
\]

The validation results for simply supported boundary conditions are shown in Table 6. The material properties employed for the study were as mentioned in [22].

From Table 1 to 4 it is observed that the CQUAD8 element gives accurate and converged results as then the CQUAD4 element. From now CQUAD8 is adopted in further work.
Table 1: Convergence study for fundamental natural frequencies (Hz) of simply supported skew sandwich plates (a/b=1,a/h=10, tc/tf =10).

| Element Density | S-S-S-S | C-C-C-C | Skew Angle (α) |
|-----------------|---------|---------|---------------|
| P                 | 2594.79 | 2506.42 | 301.724 |
| Present (18114)  | 2520.71 | 2508.25 | 301.724 |
| Present (1816)   | 2520.71 | 2508.25 | 301.724 |
| Present (1416)   | 2520.71 | 2508.25 | 301.724 |
| Present (1016)   | 2520.71 | 2508.25 | 301.724 |

Table 2: Fundamental frequencies (Hz) of clamped laminated composite sandwich plates with orthotropic core.

| Layup Sequence | Authors | Mode | 0° | 15° | 30° | 45° |
|----------------|---------|------|----|----|----|----|
| 30° / 30° / 30° | Yuan [19] | 708.00 | 1153.00 | 1620.00 | 1999.00 | 2388.00 |
| 30° / 30° / 30° | LEE (1965) [13] | 708.00 | 1153.00 | 1620.00 | 1999.00 | 2388.00 |
| 30° / 30° / 30° | Kanematsu (1988) [15] | 708.00 | 1153.00 | 1620.00 | 1999.00 | 2388.00 |
| Present CQUAD | 762.9808 | 120.6400 | 1527.7000 | 1755.7000 | 2231.0000 | 2515.0000 |
| Present CQUAD | 763.0000 | 120.6400 | 1527.7000 | 1755.7000 | 2231.0000 | 2515.0000 |
| Present CQUAD | 762.9808 | 120.6400 | 1527.7000 | 1755.7000 | 2231.0000 | 2515.0000 |
| Present CQUAD | 763.0000 | 120.6400 | 1527.7000 | 1755.7000 | 2231.0000 | 2515.0000 |
| Present CQUAD | 763.0000 | 120.6400 | 1527.7000 | 1755.7000 | 2231.0000 | 2515.0000 |

Table 3: Fundamental frequencies (Hz) of simply supported laminated composite skew sandwich plates with orthotropic core.

| Layup Sequence | Authors | Skew Angle (α) |
|----------------|---------|---------------|
| 0° / 0° / 0° | Ibrahim [2] | 152.6000 |
| 0° / 15° / 0° | Yuan and Dawe [19] | - |
| 0° / 30° / 0° | Ayaj Kumar Garg [20] | - |
| 0° / 45° / 0° | Yuan and Dawe [19] | - |
| Present CQUAD | 152.3300 | 166.3896 | 177.6942 | 217.7630 | 310.6456 |
| Present CQUAD | 152.3300 | 166.3896 | 177.6942 | 217.7630 | 310.6456 |
| Present CQUAD | 152.3300 | 166.3896 | 177.6942 | 217.7630 | 310.6456 |
| Present CQUAD | 152.3300 | 166.3896 | 177.6942 | 217.7630 | 310.6456 |

4 Results and discussion

The present numerical study considers a variety of parameters, such as aspect ratio, a ratio of length to thickness of sandwich plates, ratio thickness of face sheet to thickness of the core, skew angle, and boundary conditions of the sandwich skew plates. The results from the numerical methods are obtained by adopting material properties for further study hereafter as for Face sheet, E₁=206.84 GPa, E₂=5.1711 GPa, G₁₂=5.1711 GPa,ν₁₂=0.25, and ρ=1603.1kg/m³ and core G₃=0.1171 GPa, G₂₃=0.24132 GPa and p=2351.2 kg/m³ [20].

4.1 Study on the effect of number of layers

The effect of the number of layers on the fundamental frequency is assessed and results are graphically presented in Figure 3 and 4 in non-dimensional form Kₚ as well as the mode shapes in Table 5. The aspect ratio kept constant to 1, skew angle, and the number of layers in the face sheet is varied for all sides simply supported and clamped edge condition. The following observations were made from the results,

- An initial increase in the layers increases the stiffness of the plate, later the added layers do not contribute to the sandwich plate’s vibration response. Adding the number of layers in the face sheet allows the sandwich skew plate to accumulate in its weight. The largest impact is the core thickness that takes the majority of the impact.
Table 5: Mode shapes of anti-symmetric 5 layer (0°/90°/C/0°/90°) skew sandwich plates.

| Boundary Condition | Skew Angle | Mode Shapes [NL=4] |
|--------------------|------------|-------------------|
|                    | 0°         | ![Mode Shapes](image1) |
|                    | 15°        | ![Mode Shapes](image2) |
|                    | 30°        | ![Mode Shapes](image3) |
|                    | 45°        | ![Mode Shapes](image4) |
| S-S-S-S            |            |                   |
|                    | 0°         | ![Mode Shapes](image5) |
|                    | 15°        | ![Mode Shapes](image6) |
|                    | 30°        | ![Mode Shapes](image7) |
|                    | 45°        | ![Mode Shapes](image8) |
| C-C-C-C            | 0°         | ![Mode Shapes](image9) |
|                    | 15°        | ![Mode Shapes](image10) |
|                    | 30°        | ![Mode Shapes](image11) |
|                    | 45°        | ![Mode Shapes](image12) |

- The clamped condition has no degree of freedom free to rotate or oscillate in the plate element. This makes the plate stiffer compared to the simply supported one. Because of this, the value of $K_f$ is higher for all sides' clamped condition than all sides simply supported.
- With the skew angle of the sandwich skew plates is increased, the value of $K_f$ is found increasing in all cases of the parametric study.

4.2 Effect of ratio of $t_c/t_f$

Aspect ratio and $a/h$ ratio kept constant as 1 and 10 respectively, only the ratio $t_c/t_f$ is varied. The results are obtained for antisymmetric cross-ply, 5 layers simply supported and clamped boundary conditions for different skew angles. The $K_f$ values are graphically presented in Figure 5 and 6. From the graph, the following observations are drawn.

Core Thickness, which takes the most of shear stress, is the key influencer for the vibration response of the sandwich skew plate. With the ratio of $t_c/t_f$ is increased, the
Table 6: Mode shapes of symmetric 3 layer \((\theta^\circ/C/\theta^\circ)\) skew sandwich plates.

| Boundary Condition | Skew Angle | Mode Shapes [Fiber Angle=50°] |
|--------------------|------------|-------------------------------|
|                    | 0°         |                               |
| S-S-S-S            |            |                               |
|                    | 15°        |                               |
|                    | 30°        |                               |
|                    | 45°        |                               |
| C-C-C-C            |            |                               |
|                    | 0°         |                               |
|                    | 15°        |                               |
|                    | 30°        |                               |
|                    | 45°        |                               |

core thickness will also increase relative to the face sheet thickness. The higher the core thickness, the sandwich skew will become less stiff, and the \(K_f\) value for a given skew angle will be greatly decreased.

4.3 Effect of ratio of \(a/h\)

Aspect ratio and \(t_c/t_f\) ratio kept constant as 1 and 10 respectively, only the ratio \(a/h\) is varied. The results are obtained for antisymmetric cross-ply, 5 layers simply supported and clamped boundary conditions for different skew angles. The \(K_f\) values are graphically presented in Figure 7 and 8. From the graph, the following observations are drawn. A potential influencer is the core thickness compared to face sheet thickness. It is inappropriate to add more layers to the face sheet rather than vary the core thickness. The length of the sandwich plate kept constant only variable is the total thickness of the sandwich skew plate. When the ratio of \(a/h\) is increased, the \(K_f\) value decreases considerably for a given skew angle.
Table 7: Mode shapes of symmetric 5 layer \((\theta^\circ/-\theta^\circ/C/-\theta^\circ/\theta^\circ)\) skew sandwich plates.

| Boundary Condition | Skew Angle | Mode Shapes [Fiber Angle=50°] |
|--------------------|------------|--------------------------------|
|                    | 0°         | ![Mode Shape](image1)          |
| S-S-S-S            | 15°        | ![Mode Shape](image2)         |
|                    | 30°        | ![Mode Shape](image3)         |
|                    | 45°        | ![Mode Shape](image4)         |
|                    | 0°         | ![Mode Shape](image5)         |
|                    | 15°        | ![Mode Shape](image6)         |
|                    | 30°        | ![Mode Shape](image7)         |
|                    | 45°        | ![Mode Shape](image8)         |

4.4 Effect of laminate sequence

A symmetric angle ply laminated skew sandwich plate is considered. Aspect ratio 1, a/h=10, and t_c/t_f=10 kept constant, only skew angle and fiber angle are varied for the study.

4.5 Symmetric three layer angle ply skew sandwich plates

The results are obtained for the symmetric 3 layers simply supported and clamped boundary conditions. The \(K_f\) values are graphically presented in Figure 9 and 10 also the mode shapes in Table 6. From the graph, the following observations are drawn. For the 0° skew angle, the \(K_f\) increases as an increase in the value of fiber angle. As the fiber angle is increased for skew angle 15°, 30°, and 45°, the value of \(K_f\) initially decreases and then increases.
4.6 Symmetric five layer angle ply skew sandwich plates

The results are obtained for the symmetric 5 layers simply supported and clamped boundary conditions. The $K_f$ values are graphically presented in Figure 11 and 12, and mode shapes in Table 7. From the graph, the following observations are drawn. As the fiber orientation angle increases, the $K_f$ value increases and reaches a maximum value or symmetric about $52.5^\circ$ then decreases for simply supported and $50^\circ$ for clamped boundary conditions.
Conclusion

Sandwich skew plates exhibit excellent high stiffness to weight ratio as compared to other laminated structures. The material properties at the interface of the face sheet and core components create complexities to accurately evaluate the mechanics of the sandwich skew plates by the analytical method. The finite element method (FEM) provides the flexibility in designing the structure and recording the response of the skew sandwich plate effortlessly. The present analysis uses CQUAD4 and CQUAD8 elements to evaluate the vibration response of the skew sandwich plate. A convergence study is performed by imposing simply supported and clamped boundary edge conditions. Results obtained by the present method are validated with
those available in the literature. Aspect ratio, skew angle, the thickness of face sheet and core, number of layers in the face sheet, edge conditions, etc are considered in evaluating vibration response of skewed sandwich plates. Concluding remarks are made after performing numerical analysis as:

- Both CQUAD4 and CQUAD8 elements have good agreement with the available literature results. But CQUAD8 element yields more converged, accurate results since the element has 8 nodes while CQUAD4 has 4 nodes.
- The number of layers in the face sheet, when increased, the $K_f$ initially increases up to 4 layers due to the initial increase in the stiffness of the face sheet, after that the change is constant or negligible.
- When increasing the core thickness (increasing $t_c/t_f$ and $a/h$ ratios) an increase in total plate thickness, the stiffness of the plate decreases, $K_f$ value decreases considerably for a given skew angle. Higher core thickness does not contribute to stiffness and vibration response of the skewed sandwich plate.
- While the skew angle is increased, the side length shortens. This leads to an increase in stiffness of the skewed sandwich plate. Because of which the increased value of $K_f$ is observed for a given ratio of $t_c/t_f$ and $a/h$.
- Considerable influence is observed while studying fiber orientation on the sandwich skew plate for vibration response. For 3 layers and 5 layers symmetrically laminated composite sandwich plate, the value of $K_f$ initially decreases then increases. A similar variation can be seen [5] for both simply supported and clamped boundary conditions.
- The value of $K_f$ is higher for all side clamped condition than all sides simply supported. In the clamped edge condition, the plate becomes stiffer than simply supported edge condition.

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Abbreviations:
- $a$ - length of the sandwich plate (mm)
- $b$ - width of the sandwich plate (mm)
- $t_c$ - core thickness (mm)
- $t_f$ - face sheet thickness (mm)
- $h$ - total thickness of the sandwich plate (mm)
- $E$ - Young's modulus (GPa)
- $G_{ij}$ - rigidity modulus (GPa)
- $\nu$ - Poissons' ratio
- $\rho$ - density (kg/m$^3$)
- S-S-S-S - all sides simply supported
- C-C-C-C - all sides clamped
- $\alpha$ - skew angle in degree
- $\omega$ - circular frequency (rad/s)

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