Polish Society of Composite Materials
Polskie Towarzystwo Materiałów Kompozytowych

20: 3-4 (2020) 118-127

COMPOSITES THEORY AND PRACTICE
ISSN: 2084-6096
ISSN (online): 2299-128X

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Received (Otrzymano) 18.10.2020

FREE VIBRATION STUDIES ON SKEW SANDWICH PLATES

The present work focuses on determining the fundamental frequencies of skew sandwich plates with face sheets considered to be classical thin plates, which are made of a graphite-epoxy material and an orthotropic core made of glass reinforced-epoxy using different boundary conditions. The fundamental frequencies were obtained using finite elements, which are validated with available literature results. The effects of the skew angle, ratio of the length to total thickness of the sandwich plate, and ratio of the thickness of the core to the face sheet on the fundamental frequency of skew sandwich plates were obtained. In addition, the effect of parameters such as the number of layers in the face sheet, the laminate stacking sequence and the fiber orientation angle on the fundamental frequencies of laminated skew sandwich plates was also ascertained. It was found that the CQUAD8 element yields better results than the CQUAD4 element in the present study. The fundamental frequencies were found to increase with an increasing skew angle. The variation in the fundamental frequency is negligible when there are a large number of layers in the face sheet.

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

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]
ν	–	Poisson's ratio
ρ	–	density [kg/m^3]
S-S-S-S	–	all sides simply supported
C-C-C-C	–	all sides clamped
C	–	core
α	–	skew angle in degrees
ω	–	circular frequency [rad/s]

INTRODUCTION

Currently, skew sandwich plates are frequently used in numerous areas like aeronautics, 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. Moreover, skew sandwich plates have less weight, greater stiffness, greater structural efficiency, and greater durability. Due to these superior features over composite or layered structures, sandwich plates have attracted much attention from researchers for more than two decades. One of the fundamental studies of sandwich structures is free vibration response, which has a key role in designing sandwich structures that may be subjected to dynamic loading in practical applications. Many theories, numerical methods and finite element methods have been proposed to accurately predict and optimize the obtained free vibration responses. Literature related to the present work is discussed below.

Nine-node isoparametric finite elements used for the flexural and vibration analysis of composite sandwich plates based on Mindlin plate theory accounting for transverse normal and shear deformations of both the face sheet and orthotropic core is one of the works in the same area [1]. As the sandwich plate contains a stiff face sheet and a low density core, it exhibits displacement discontinuity at the interfaces. To simulate this, in the finite element method, an efficient six-noded triangular element based on refined plate theory was developed adopting C^1 continuity of the transverse displacement at the element interfaces [2]. In sandwich plates, material anisotropy and the number of layers demand the inclusion of more independent constants in the equation of motion, and more computational time required to solve the equation of motion. To overcome this deficiency, a higher-order layer-wise C° continuous isoparametric finite element was developed, enforcing continuity of the interlaminar displacement [3]. The C° isoparametric finite element modeled using higher-order shear deformation theory implements a realistic nonlinear variation of displacements through the laminate thickness, and eliminates the use of shear correction coefficients or interlaminar displacement continuity functions [4]. Two new C° assumed strain finite element formulations based on Reddy's higher-order theory [5] and the C° finite element model for flexural and free vibration studies of laminated soft core skew sandwich plates based on higher-order zigzag theory (HOZT) [6] were presented. For moderately thick and thin sandwich plates, third-order zigzag theory was used to develop an improved four-node discrete Kirchhoff quadrilateral element [7]. The harmonic quadrature element method was presented for free vibration analysis of soft-core sandwich panels with general boundary conditions [8]. The vibration parameters of sandwich plates were predicted by the spline finite strip method [9]. A numerical method was used to extract the fundamental frequencies of simply supported and clamped isotropic and skew sandwich plates with an orthotropic core and laminated faces [10]. More articles dealing with finite element methods for sandwich plates were reviewed in [11].

The present study focuses on the free vibration studies of laminated skew sandwich plates with an orthotropic core adopting simply supported and clamped boundary conditions. The face sheet is made up of a graphite/epoxy reinforced laminated composite and a heavy core considered to be orthotropic. The main goal of the present work is to study the effect of the number of layers in the face sheet, the ratio of length to total thickness, the ratio of thickness of core to face sheet, the effect of fiber orientation, the effect of the laminate sequence, the effect of the boundary conditions, the effect of the skew angle on the free vibration response of the sandwich plate. The paper is organized as follows: Firstly, convergence of the results obtained by both CQUAD4 and CQUAD8 elements is studied for the free vibration response of the sandwich plate. Using converged element density, validation of the results obtained by the present method to those available in the literature is compared. By adopting the mechanical properties as mentioned by Ajay et al. [4] for both the GFRPC (graphite fiber reinforced polymer composites) face sheets and the orthotropic (heavy) core, finally a numerical study is made to characterize the effect of different geometric parameters, boundary conditions and skew angles.

CONVERGENCE AND VALIDATION

Convergence

The skew sandwich plate is modeled with aluminum plate as the face sheet and aluminum honeycomb as core. The material properties, for the face sheets E = 68.948 GPa, G = 25.924 GPa, ν = 0:33, ρ = = 2768.0 kg/m^3 and for the core G_{23} = 0.05171 GPa, G_{13} = 0.13445 GPa, ρ = 121.83 kg/m^3 are used [12].

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 inclination of the displacements to the skew edges. To overcome this, a local coordinate system (x', y') normal and tangential to the skew edges is preferred.

The total elements in the plate model are optimized to obtain 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 having an aspect ratio (a/b = 1), length to thickness ratio (a/h = 10) and thickness of core to facing ratio (t_c/t_f = 10) for skew angles 0°, 15°, 30° and 45° using both elements. The results from the convergence study are presented in Table 1, which were extracted from previous work [10].

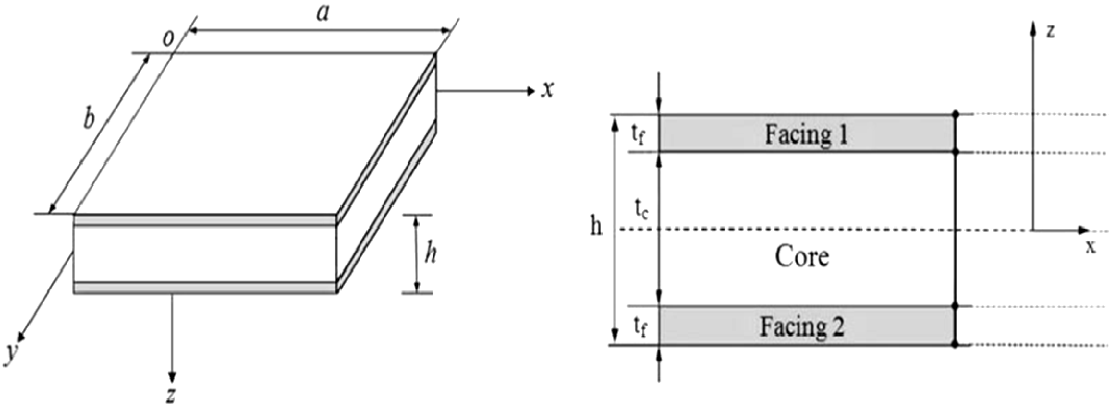

Fig. 1. Geometry details of sandwich plate (0^0 skew angle)

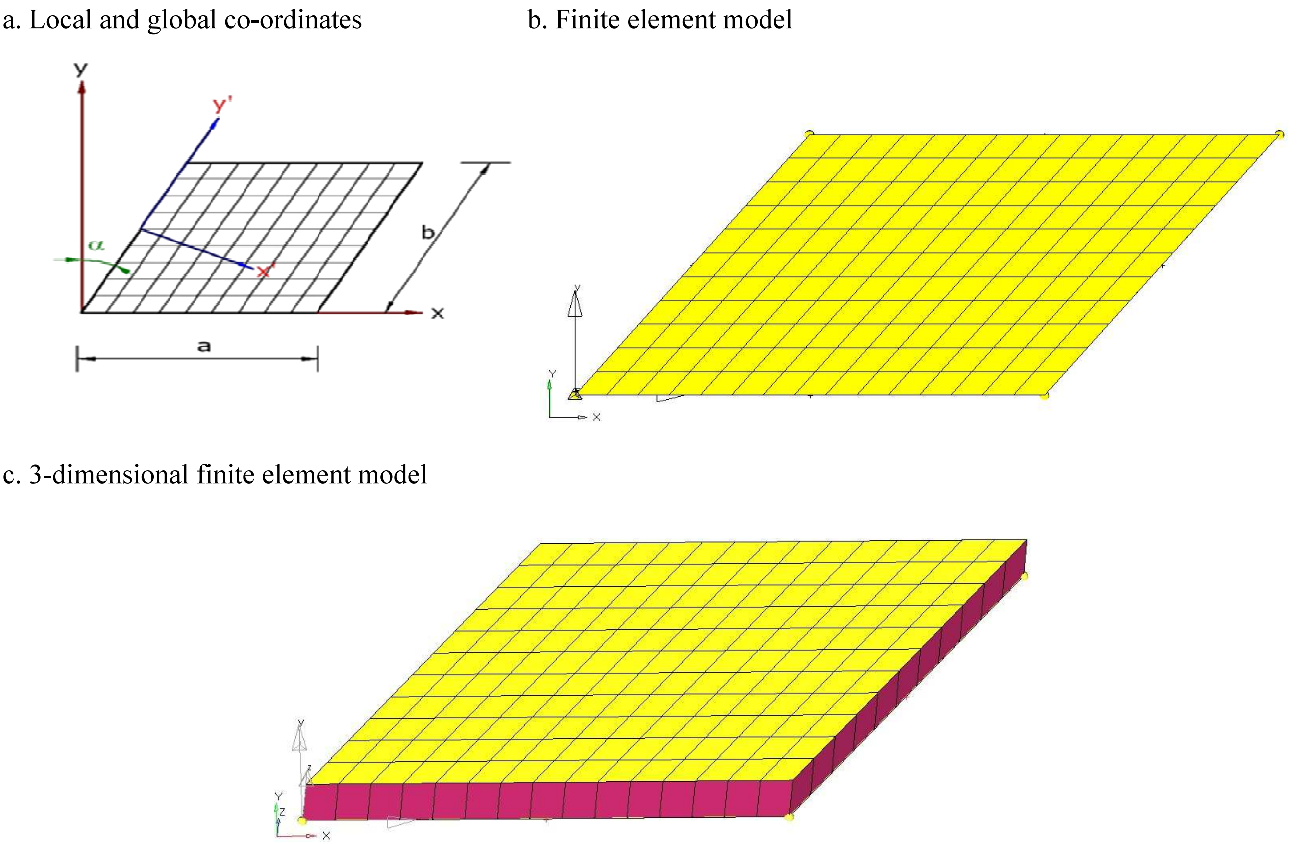

Fig. 2. Finite element mesh models of flat skew (30°) sandwich plate

TABLE 1. **Convergence study for fundamental natural frequencies [Hz] of skew sandwich plates (*a*/*b* = 1, *a*/*h* = 10, t_c/t_f = 10)**

Element Density	Element Type	S-S-S-S				C-C-C-C			
		Skew Angle (α°)				Skew Angle (α°)			
		0°	15°	30°	45°	0°	15°	30°	45°
Present (10 x 10)	CQUAD 4	2493.9910	2570.4620	2827.0370	3369.7240	3017.5620	3081.5220	3300.5110	3779.8480
	CQUAD 8	2519.0970	2596.4920	2856.2510	3405.9890	3052.6520	3117.3970	3339.1410	3824.8110
Present (14 x 14)	CQUAD 4	2507.1890	2584.1460	2842.3580	3388.6750	3036.2910	3100.6410	3320.9820	3803.5300
	CQUAD 8	2520.0180	2597.4460	2857.2710	3407.1300	3054.2610	3119.0140	3340.7600	3826.5090
Present (18 x 18)	CQUAD 4	2512.6310	2589.7870	2848.6990	3396.4650	3044.0390	3108.5500	3329.4870	3813.3040
	CQUAD 8	2520.3950	2597.8360	2857.7200	3407.6070	3054.9250	3119.6800	3341.4660	3827.2070
Present (22 x 22)	CQUAD 4	2515.3870	2592.6440	2851.8770	3400.4040	3047.9690	3112.5610	3333.7560	3818.2570
	CQUAD 8	2520.5860	2598.0340	2857.9010	3407.8510	3055.2610	3120.0170	3341.7770	3827.5620
Present (26 x 26)	CQUAD 4	2516.9730	2594.2880	2853.7180	3402.6670	3050.2320	3114.8710	3336.2300	3821.1070
	CQUAD 8	2520.6960	2598.1470	2858.0400	3407.9930	3055.4550	3120.2110	3341.9750	3827.7670
Present (30 x 30)	CQUAD 4	2517.9680	2595.3190	2854.8720	3404.0860	3051.6530	3116.3220	3337.7830	3822.8940
	CQUAD 8	2520.7650	2598.2180	2858.1190	3408.0820	3055.5770	3120.3330	3342.0990	3827.8960
Present (34 x 34)	CQUAD 4	2518.6340	2596.0090	2855.6660	3405.0330	3052.6030	3117.2910	3338.8520	3824.0900
	CQUAD 8	2520.8110	2598.2660	2858.1930	3408.1430	3055.6580	3120.4150	3342.2130	3827.9820
Present (38 x 38)	CQUAD 4	2519.1000	2596.4920	2856.2070	3405.6980	3053.2700	3117.9710	3339.5810	3824.9270
	CQUAD 8	2520.8430	2598.2990	2858.2300	3408.1860	3055.7150	3120.4720	3342.2710	3828.0430

Dhotre Pavan Kumar, Srinivasa C.V. [10]

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Validation

Validation of the results from the elements used in the present study is made by comparing to the available literature values. For a clamped skew sandwich plate, the material constants employed are similar to those used in [9]. The comparisons of the results shown in Table 2 are in good agreement with [13] for different layup sequences. The results obtained from the current study are higher due to exclusion of the kinematic energy of the adhesive layer in finite element modeling.

Moreover, the material constants referred to for simply supported sandwich skew plates with different layup sequences and for different skew angles, are those used by Park et al. [12]. The results displayed in Table 3 obtained by the present method are in close agreement with those values reported in literature [14].

TABLE 2. **Fundamental frequencies [Hz] of clamped laminated composite sandwich plates with orthotropic core**

Layup Sequence	**Authors**	**Mode Number**				
		1	**2**	**3**	**4**	**5**
300/300/300 /C/ 300/300/300	Yuan and Dawe [9]	708.0000	1153.0000	1423.0000	1629.0000	1999.0000
	LEE (1966) [3]	707.0000	1150.0000	1424.0000	1627.0000	1990.0000
	Present CQUAD4	**762.9000***	**1240.6000***	**1527.7000***	**1753.7000***	**2131.0000***
	Present CQUAD8	**763.6000***	**1241.9000***	**1529.9000***	**1756.7000***	**2135.0000***
00/00/00 /C/ 00/00/00	Yuan and Dawe [9]	692.3000	1191.0000	1366.0000	1720.0000	1954.0000
	LEE (1966) [3]	691.0000	1200.0000	1353.0000	1715.0000	1997.0000
	Present CQUAD4	**746.8000***	**1296.8000***	**1454.0000***	**1846.1000***	**2128.9000***
	Present CQUAD8	**747.3000***	**1298.3000***	**1455.5000***	**1850.6000***	**2132.3000***
300/-300/300 /C/ 300/-300/300	Yuan and Dawe [9]	559.1000	1001.0000	1088.0000	1484.0000	1615.0000
	LEE (1966) [3]	558.0000	997.0000	1090.0000	1478.0000	1604.0000
	Present CQUAD4	**630.7000***	**1124.0000***	**1226.8000***	**1662.4000***	**1803.8000***
	Present CQUAD8	**631.5000***	**1125.8000***	**1228.90000**	**1667.6000***	**1807.5000***
00/900/00 /C/ 00/900/00	Yuan and Dawe [9]	628.3000	1011.0000	1273.0000	1521.0000	1604.0000
	LEE (1966) [3]	628.0000	1007.0000	1272.0000	1517.0000	1593.0000
	Present CQUAD4	**709.4000***	**1137.0000***	**1433.0000***	**1708.9000***	**1794.0000***
	Present CQUAD8	**709.7000***	**1138.1000***	**1434.3000***	**1712.3000***	**1796.2000***

*Present values obtained excluding kinetic energy of adhesive layer

TABLE 3. **Fundamental frequencies [Hz] of simply supported laminated composite skew sandwich plates with orthotropic core**

Layup Sequence	**Authors**	**Skew Angle (α°)**			
		0°	**15°**	**30°**	**45°**
0°/90° /C/ 0°/90°	Yuan and Dawe [9]	152.5800	-	-	-
	Ajay Kumar Garg [4]	166.3086	177.6942	217.7630	310.6456
		152.2992	161.7182	194.3770	267.3398
	Voyiadjis [12]	150.9120	161.1690	195.8480	269.5720
	Present CQUAD4	**152.3300**	**163.0240**	**198.8113**	**277.4106**
	Present CQUAD8	**152.3602**	**163.0580**	**198.8503**	**277.4685**
0°/90° /C/ 90°/0°	Yuan and Dawe [9]	145.9900	-	-	-
	Ajay Kumar Garg [4]	159.8275	170.7568	209.3430	299.3778
		146.5089	155.5495	186.9801	257.5617
	Voyiadjis [12]	145.0002	155.1070	188.7120	260.1220
	Present CQUAD4	**145.6081**	**155.8880**	**190.2696**	**265.4776**
	Present CQUAD8	**145.6373**	**155.9213**	**190.3088**	**265.5364**
90°/0° /C/ 0°/90°	Yuan and Dawe [9]	159.3000	-	-	-
	Ajay Kumar Garg [4]	172.7237	184.5342	225.9660	321.4230
		158.0954	167.8775	201.7029	276.9311
	Voyiadjis [12]	156.6980	161.1840	202.9450	278.6170
	Present CQUAD4	**158.9292**	**170.0157**	**207.1453**	**289.0373**
	Present CQUAD8	**158.9602**	**170.0502**	**207.1840**	**289.0932**

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The non-dimensional frequency parameters (K_f) of simply supported five-layered symmetric laminated composite skew sandwich plates with an orthotropic core are determined using Equation (1).

$$K_f = 100\omega a\sqrt{(\rho / E_1)_f} \tag{1}$$

The material properties employed for the study are as mentioned by Chalak et al. [6]. The results are shown in Table 4, which proves the overestimation in the natural frequencies obtained by others and [15]. The overestimation is greater as the skew angle increases. The present method produces more converged and accurate results than other methods presented by other researchers.

TABLE 4. **Non dimensional frequency parameter (K_f) of simply supported laminated composite skew sandwich plates with orthotropic core**

Authors		Skew Angle (α) 0°	15°	30°	45°
Kapuria and Kulkarni [7]	ZIGT FE	9.8130	-	-	-
		9.8200	-	-	-
		9.8240	-	-	-
	3D ZIGT	9.8281	-	-	-
	ZIGT	9.8300	-	-	-
Chakrabarti and Sheikh [2]	Mesh 8x8	10.0510	-	-	-
	Mesh 12x 12	10.0520	-	-	-
	Mesh 16x16	10.0530	-	-	-
Pavan and Srinivasa [10]	TOT	12.0880	-	-	-
Chalak and Chakrabarti [7]	HOZIGT	9.8365	10.2467	11.6056	14.4349
Present CQUAD4		9.2704	9.5546	10.5191	12.5896
Present CQUAD8		9.2768	9.5612	10.5266	12.5988

In Tables 1 to 4 it is observed that the CQUAD8 element gives more accurate results than the CQUAD4 element. From now, CQUAD8 is adopted in the work.

NUMERICAL RESULTS AND DISCUSSION

The present numerical study considers a variety of parameters such as the aspect ratio, ratio of length to thickness of sandwich plates, ratio of face sheet thickness to core thickness, skew angle and the boundary conditions of sandwich skew plates. The sandwich plates were modeled with a face sheet from a graphite/epoxy composite and a core with glass reinforced epoxy (heavy-orthotropic). Two types of edge conditions are used – simply supported and clamped; also the aspect ratio was kept constant at 1 (a/b = 1) throughout the study. The results from the numerical methods are extracted by adopting material properties for further study as mentioned by Ajay et al. [4]. Different geometric parameters are used for the numerical study and the discussion is as follows.

Study on the effect of the number of layers in the face sheet (NL)

Five-layer, antisymmetric, cross-ply laminated sandwich plates with varying skew angles and numbers of layers in the face sheet for all sides simply supported and clamped edge conditions are considered. The stacking sequence and the different number of layers in the face sheet are shown in Figure 3. The ratio of core thickness to face sheet thickness (t_c/t_f = 10) and the ratio of the length to total thickness of the sandwich plate (a/h = 10) are kept constant.

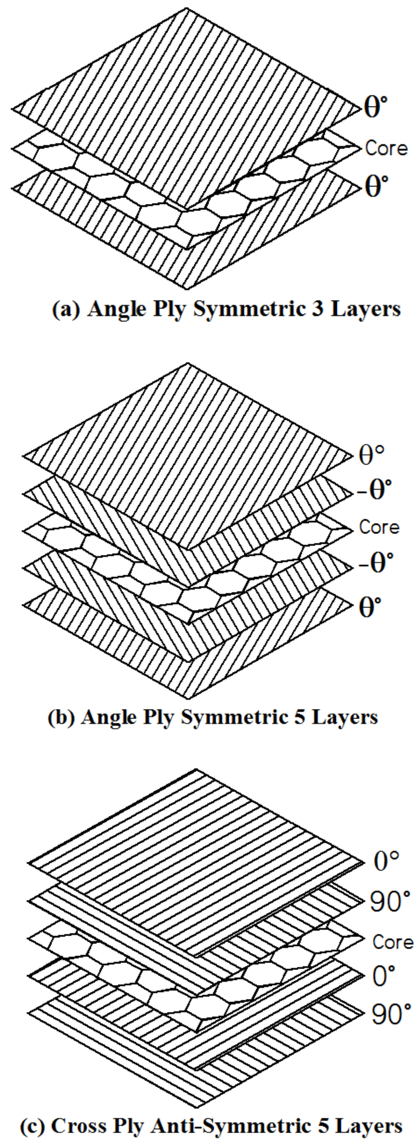

Fig. 3. Schematic representation of construction of sandwich plates with varying number of layers in face sheet and fiber angle in face sheet

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The effect of the number of layers on the fundamental frequency is studied and the results are graphically presented in Figures 4 and 5 in K_f non-dimensional form. The first five mode shapes are extracted in Table 5.

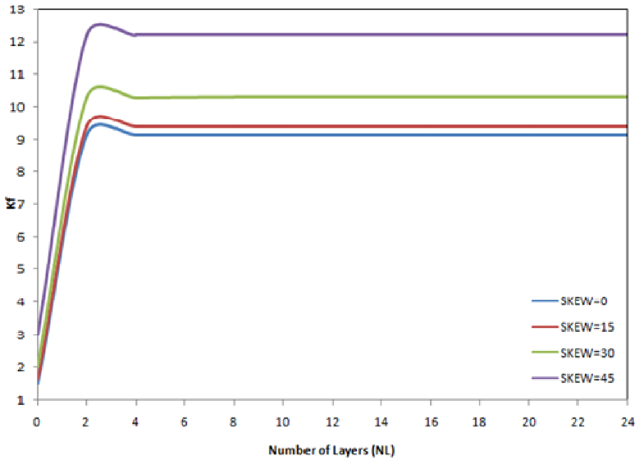


Fig. 4. K_f values for laminated simply supported antisymmetric cross-ply (0°/90°/C/0°/90°) skew sandwich plates

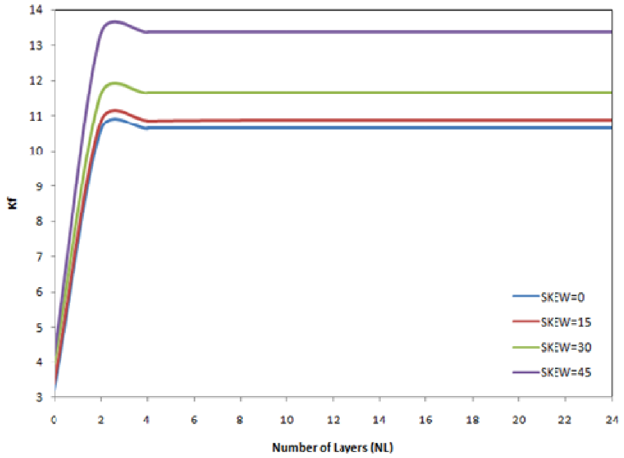
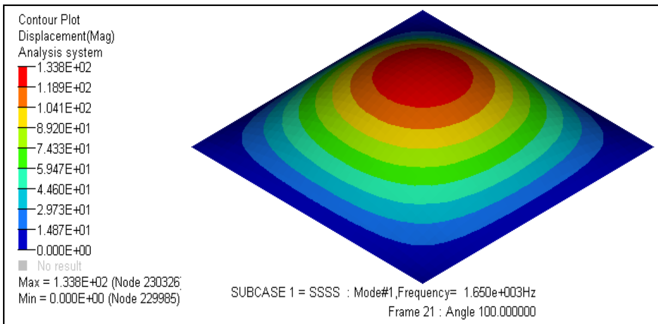


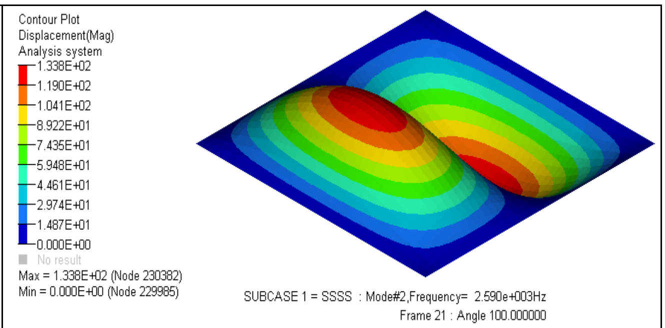
Fig. 5. K_f values for laminated clamped antisymmetric (0°/90°/C/0°/90°) cross-ply skew sandwich plates

As the number of layers in the face sheet is increased, K_f initially increases up to four layers, after that the change is constant or negligible. An increase in the skew angle of the sandwich results in an increase in the K_f value. The K_f value is higher for the all sides clamped condition than all sides simply supported.

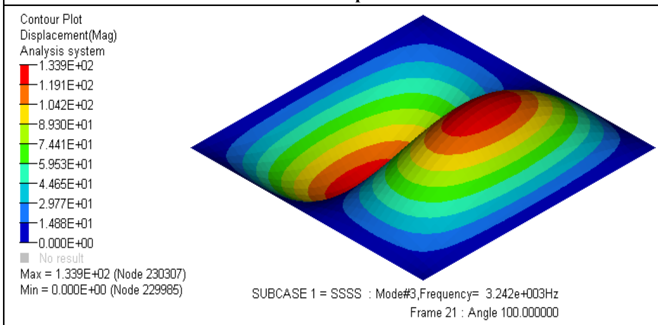
TABLE 5. **Mode shapes of antisymmetric five-layer (0°/90°/C/0°/90°) skew sandwich plates**



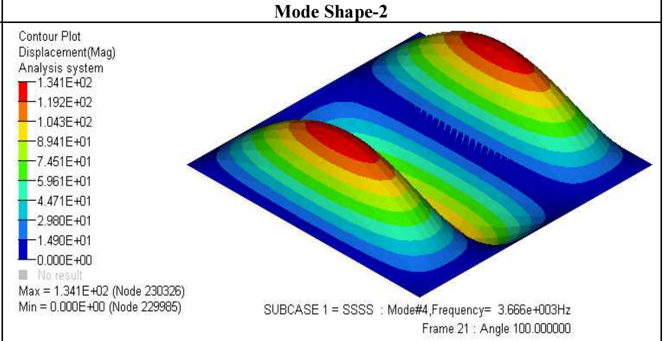
Mode Shape-1



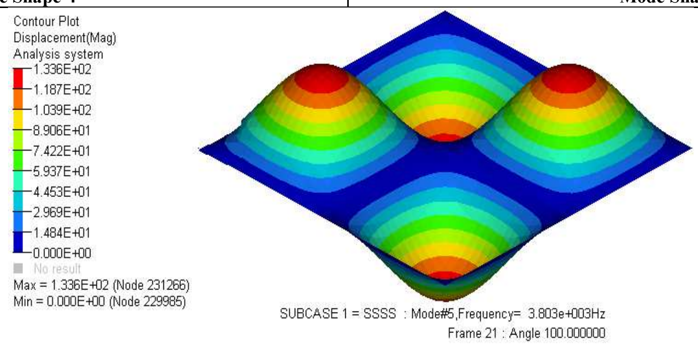
Mode Shape-2



Mode Shape-4



Mode Shape-4



Mode Shape-5

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Effect of the ratio of core thickness to face sheet thickness (t_c/t_f)

The fundamental frequencies are obtained for antisymmetric cross-ply, five-layer sandwich plates with simply supported and clamped boundary conditions by varying skew angle ($\alpha°$) and ratio (t_c/t_f). Ratio (a/h = 10) is kept constant. The K_f values are graphically presented in Figures 6 and 7. As ratio t_c/t_f is increased, the K_f value decreases considerably for a given skew angle. Furthermore, as the skew angle is increased, the K_f value increases for a given t_c/t_f ratio. The K_f value is higher for the all sides clamped condition than all sides simply supported.

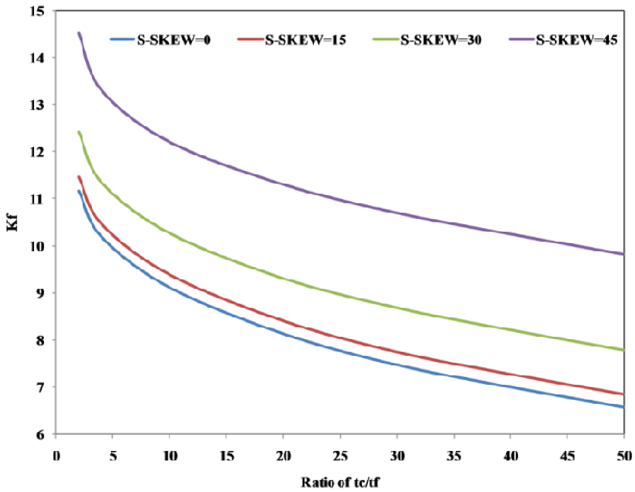

Fig. 6. K_f v/s values of t_c/t_f ratio for laminated simply supported antisymmetric cross-ply (0°/90°/C/0°/90°) skew sandwich plates

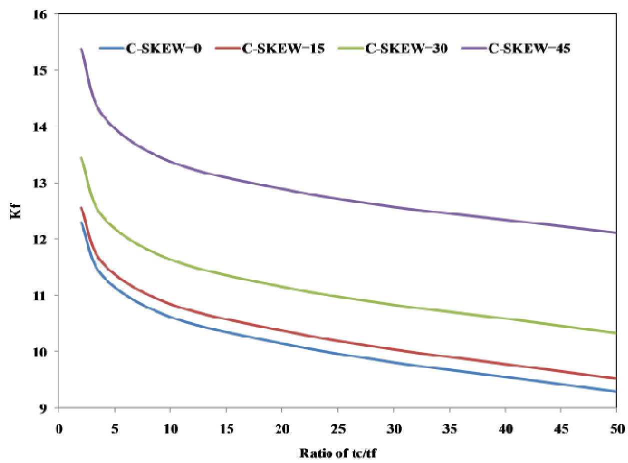

Fig. 7. K_f v/s values of t_c/t_f ratio for laminated clamped antisymmetric cross-ply (0°/90°/C/0°/90°) skew sandwich plates

Effect of a/h ratio

The aspect ratio (a/b = 1) and the (t_c/t_f= 10) ratio are kept constant, only ratio a/h is varied. The results are obtained for antisymmetric cross-ply; five-layer simply supported and clamped boundary conditions for different skew angles. The K_f values are graphically presented in Figures 8 and 9. From the graph, it is evident that the K_f value decreases considerably when an increase in ratio (a/h) is made for a given skew angle. Furthermore, when skew angle is increased K_f increases for a given a/h ratio. It is always observed that K_f is higher for the all sides clamped condition than all sides simply supported.

Effect of laminate sequence

A symmetric angle-ply laminated skew sandwich plate is considered for the analysis. The aspect ratios (a/b = 1), (a/h = 10) and (t_c/t_f = 10) are kept constant, only the skew angle and fiber angle are varied. Both simply supported and clamped edge conditions are incorporated.

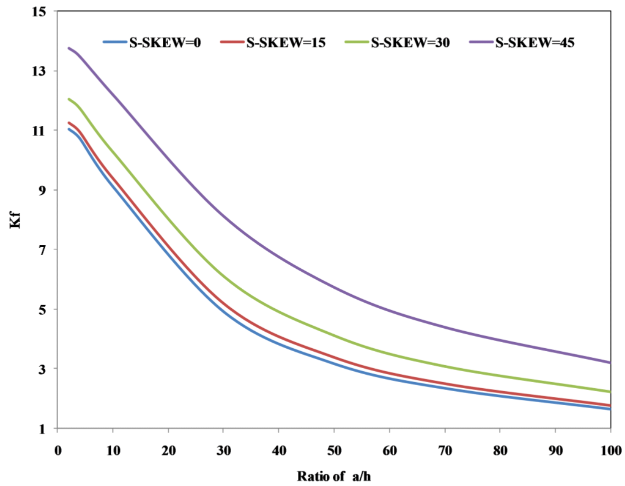

Fig. 8. K_f v/s values of a/h ratio for laminated simply supported antisymmetric cross-ply (0°/90°/C/0°/90°) skew sandwich plates

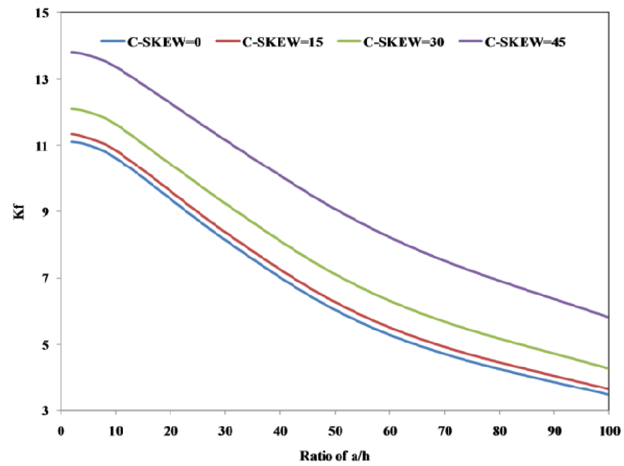

Fig. 9. K_f v/s values of a/h ratio for laminated clamped antisymmetric cross-ply (0°/90°/C/0°/90°) skew sandwich plates

Symmetric three-layer angle ply skew sandwich plates

The results are obtained for symmetric three-layer simply supported and clamped boundary conditions. The K_f values are graphically presented in Figures 10 and 11.

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Moreover, the first five mode shapes for a simply supported sandwich plate are presented in Table 6. It can be seen from the graph, for the 0° skew angle, that the K_f increases with an increase in the fiber angle value.

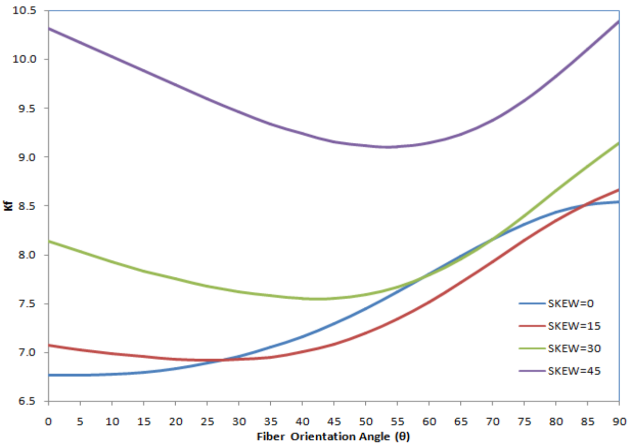


Fig. 10. K_f values for laminated simply supported symmetric (θ°/C/θ°) angle-ply skew sandwich plates

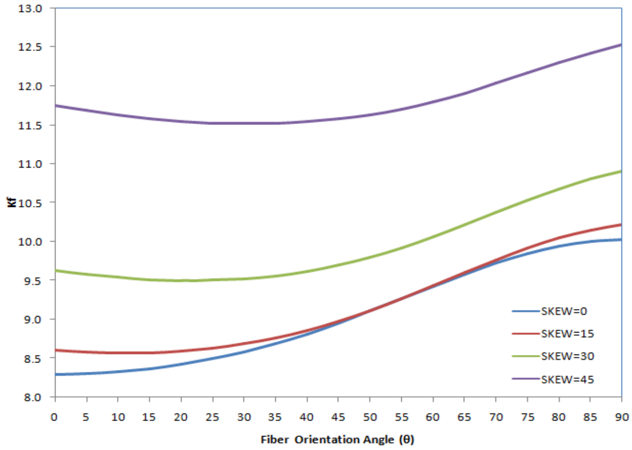
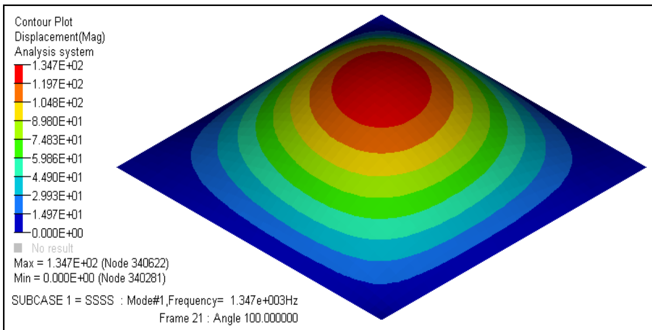


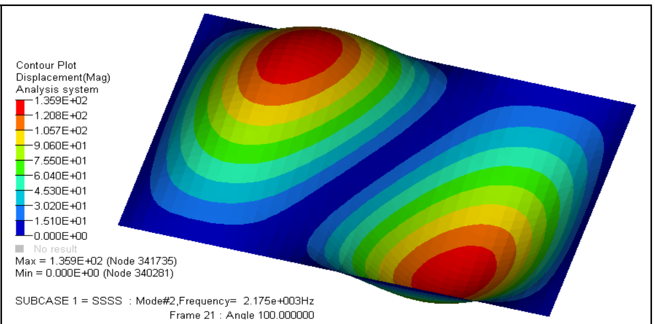
Fig. 11. K_f values for laminated clamped symmetric (θ°/C/θ°) angle-ply skew sandwich plates

When the fiber angle is increased for skew angles 15°, 30° and 45°, the K_f value initially decreases and then increases.The K_f value is higher for the all sides clamped condition than all sides simply.

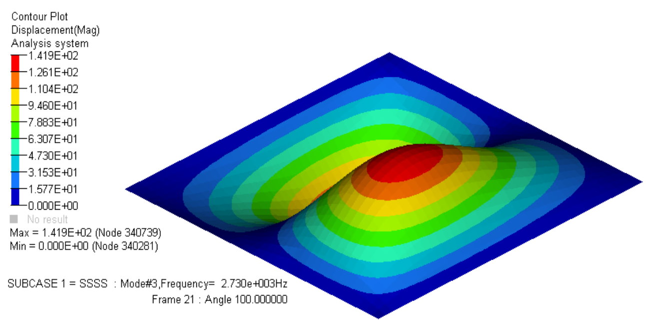
TABLE 6. **Mode shapes of antisymmetric five-layer (θ°/C/θ°) skew sandwich plates**



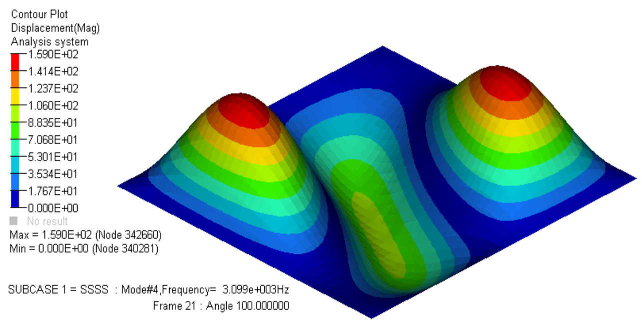
Mode Shape-1



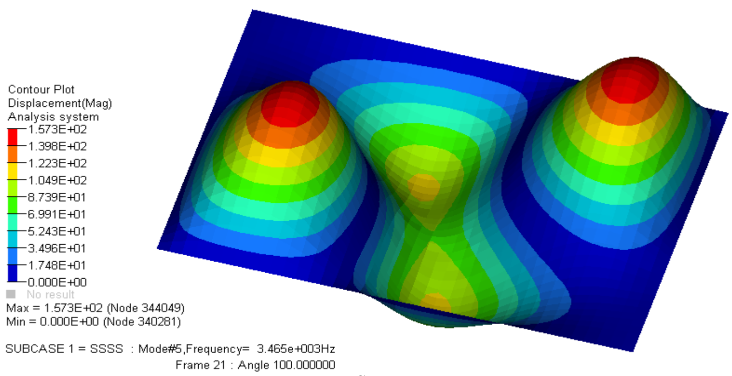
Mode Shape-2



Mode Shape-3



Mode Shape-4



Mode Shape-5

Symmetric five-layer angle-ply skew sandwich plates

The results are obtained for symmetric five-layer simply supported and clamped boundary conditions. The K_f values are graphically presented in Figures 12 and 13. First, five fundamental mode shapes are presented in Table 7.

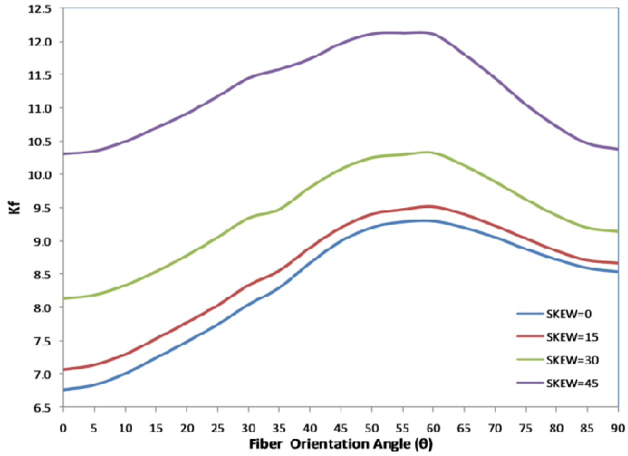


Fig. 12. K_f values for laminated simply supported symmetric (θ°/–θ°/C/–θ°/θ°) angle-ply skew sandwich plates

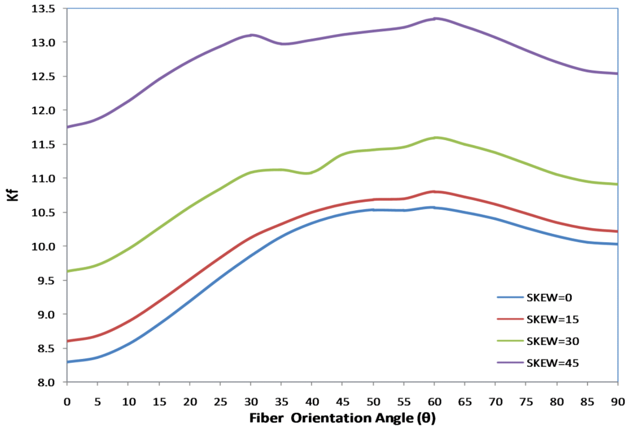
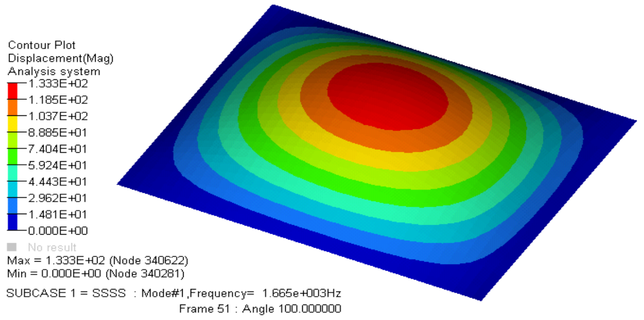


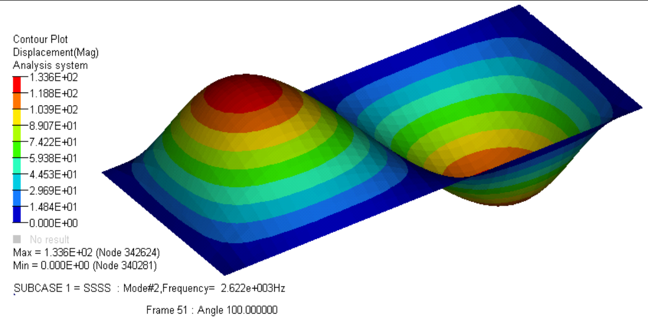
Fig. 13. K_f values for laminated clamped symmetric (θ°/–θ°/C/–θ°/θ°) angle-ply skew sandwich plates

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°, then decreases for simply supported, and 50° for clamped boundary conditions. When the skew angle is increased, the K_f value also increases for a given fiber angle. K_f is higher for the all sides clamped condition than all sides simply supported.

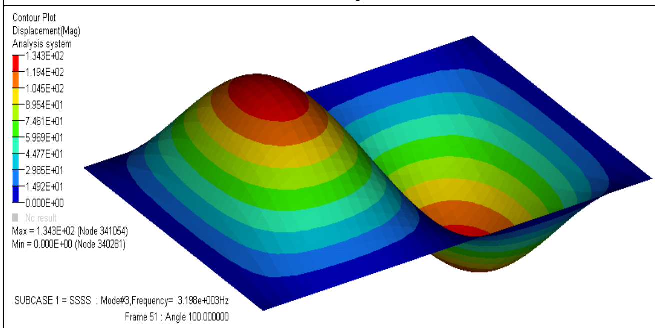
TABLE 7. **Mode shapes of symmetric five-layer (θ°/–θ°/C/–θ°/θ°) skew sandwich plates**



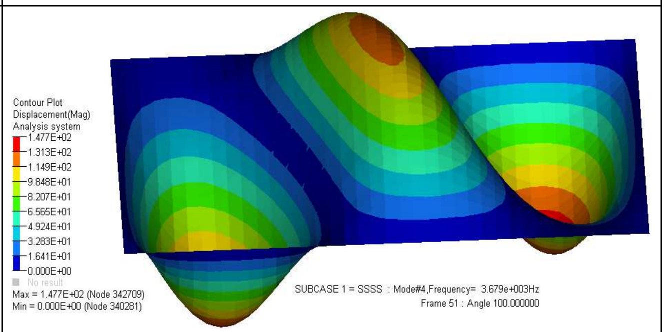
Mode Shape-1



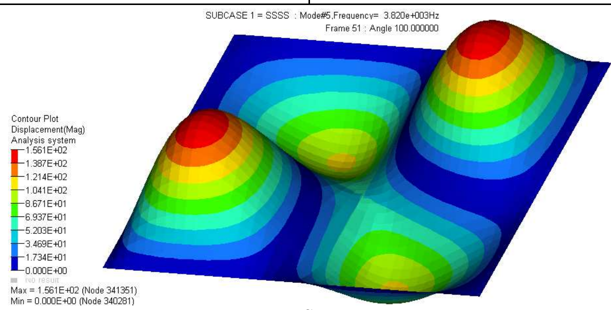
Mode Shape-2



Mode Shape-3



Mode Shape-4



Mode Shape-5

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CONCLUSIONS

Graphite fiber reinforced epoxy composite as the face sheet and glass fiber reinforced epoxy as the core material were configured for the skew sandwich plate. The free vibration study of laminated skew sandwich plates was conducted by the finite element method in conjunction with both simply supported and clamped edge conditions. The convergence study was made to find the optimum mesh size. Then, the results obtained by the present method were validated against literature values. Both CQUAD4 and CQUAD8 elements have good agreement with the available literature results. Nonetheless, the CQUAD8 element yields more accurate results than CQUAD4.

The CQUAD8 element was adopted for further numerical study. The effect of different geometric parameters, edge conditions, skew angles, ratio (a/h), ratio (t_c/t_f) on skew sandwich plates was evaluated. An increase in the K_f value was observed when the number of layers in the face sheet is increased. K_f initially increases up to 4 layers, after that the change is constant or negligible. When the skew angle was increased, K_f increases for the given tc/t$_f$ and a/h ratios. As the t_c/t_f and a/h ratios increased the K_f value decreases considerably for the given skew angle. For the three-layer symmetric laminated composite sandwich, the K_f value initially decreases then increases. What is more, for the five-layer symmetric it increases then decreases. A higher K_f value is observed for the all sides clamped condition than all sides simply supported.

Finally, future work can focus on conducting experimental studies to confirm the finite element results obtained by the present method. The present study may be extended with some more geometric parameters and edge conditions to simulate practically any conditions.

Acknowledgments

The authors would like to thank the Management and Principal of the GM Institute of Technology, Davangere, Karnataka, for the kind encouragement and constant support provided.

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