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EXPERIMENTAL AND FINITE ELEMENT STUDIES ON FREE VIBRATION OF SKEW PLATES

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The present paper deals with the experimental studies carried out on free vibration of isotropic and laminated composite skew plates. The natural frequencies were also determined using QUAD8 finite element of MSC/NASTRAN and a comparison was made between the experimental values and the finite element solution**.** The effects of the skew angle and aspect ratio on the natural frequencies of isotropic skew plates were studied. The effects of the skew angle, aspect ratio, fiber orientation angle and laminate sequence (keeping the number of layers constant) on the natural frequencies of antisymmetric composite laminates were also studied. The experimental values of natural frequencies are in good agreement with the FE solutions. The natural frequencies are found to increase with an increase in the skew angle. The variation of natural frequencies with the aspect ratio is small and negligible both for isotropic and laminated composite skew plates.

Key words: skew plates, antisymmetric laminates, free vibration, experimental method, finite element analysis.

1. Introduction

Skew plates find a wide range of applications in civil, marine, aeronautical and mechanical engineering, the common applications being swept wings of aeroplanes, skew bridge design, ship hulls and parallelogram slabs in buildings. The exact solutions to skew plate vibration problems are mathematically difficult and hence most of the solutions available in the literature are based on approximate methods. Over the past four decades, a lot of research has been carried out on the study of vibration characteristics of skew plates. Today the skew plate problem has been widely recognised as a benchmark in the testing of a newly developed finite element.

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The earlier studies on free vibration characteristics of skew plates are those of Barton (1951), Kaul and Cadambe (1956) and Hasegawa (1957) using Rayleigh-Ritz method. Hamada (1959) applied the Lagrangian-multiplier method to obtain the fundamental frequency of rhombic skew plates. Claassen (1963) extended the work of Barton (1951) by adopting a Fourier sine series solution scheme in conjunction with the Rayleigh-Ritz method. Conway and Farnham (1965) employed the point matching method to study the free vibration of triangular, rhombic and parallelogram plates. The frequencies were calculated for different skew angles of simply supported and clamped boundary conditions. Laura and Grosson (1968) obtained fundamental frequencies of vibration for simply supported rhombic plates using conformal mapping and Galerkin's method and compared their results with those of Conway and Farnham (1965). The discrepancy has been found to increase with the skew angle.

Monforton (1968) obtained fundamental frequencies of clamped rhombic plates by using the FEM. The frequencies and mode shapes of clamped skew plates were studied by Durvasula (1969) using Galerkin's method. The deflection function was expressed as a double series of beam characteristic functions in terms of skew coordinates to satisfy the zero deflection and normal slope on all the edges. Some interesting results were obtained and compared with the results of Kaul and Cadambe (1956), Hasegawa (1957) and Conway and Farnham (1965). Thangam Babu and Reddy (1971) investigated the free vibration of orthotropic skew plates with two opposite edges simply supported and the other two edges free. Nair and Durvasula (1973) reported the frequencies of isotropic and orthotropic skew plates for the simply supported, clamped, free edge boundary condition and for a combination of the above three edge conditions. Srinivasan and Ramachandran (1975) employed a numerical method to study variations of frequencies and mode shapes of orthotropic skew plates. Kuttler and Sigillito (1980) used trial function method to solve the vibration problem of skew plates.

Mizusuwa *et al*. (1979; 1980), Mizusuwa and Kajita (1986; 1987) employed the Rayleigh-Ritz method with B-spline functions to study the effect of skew angle and location of point supports on natural frequencies of isotropic skew plates. Liew and Lam (1990) used a set of 2-D orthogonal plate functions as an admissible deflection function to study the flexural vibration of skew plates using Rayleigh-Ritz method and obtained the results for four rhombic plates with different support conditions. Bardell (1992) adopted the hierarchical finite element method to determine natural frequencies and mode shapes of isotropic skew plates. Liew and Wang (1993) employed the Rayleigh-Ritz method and obtained results for four rhombic plates with different support conditions by changing the internal support, skew angle and aspect ratio. Singh and Chakravarthy (1994) evaluated the first five frequencies for the transverse vibration of skew plates under different boundary conditions by using boundary characteristics orthogonal polynomials. McGee and Butalia (1994) studied the free vibration of thick and thin cantilever skew plates using C^0 continuous isoparametric quadrilateral elements.

Few studies on the free vibration of composite skew plates have been made. Kamal and Durvasula (1986) studied the free vibration characteristics of composite laminates using the modified shear deformation layered composite theory by employing the Rayleigh-Ritz energy approach. Malhotra *et al*. (1988) studied the rhombic orthotropic plates using a parallelogram orthotropic plate finite element for various boundary conditions and skew angles. Krishnan and Deshpande (1992) employed the DKT finite element to demonstrate the effect of fiber orientation angle, skew angle, aspect ratio and length-to-thickness ratio on the fundamental frequencies of single layer graphite/epoxy and glass/epoxy skew plates.

Krishna Reddy and Palaninathan (1999) used a general high precision triangular bending element to study the free vibration of laminated skew plates. A consistent mass matrix in explicit form is used for the study. Singha and Ganapathi (2004) studied the large amplitude free flexural vibrations of laminated composite skew plates using the FE approach. Garg *et al.* (2006) carried out free vibration studies on isotropic, orthotropic, and layered anisotropic composite and sandwich skew laminates using the isoparametric finite element model.

Maruyama *et al*. (1983) used the real time technique of time averaged holographic interferometry to determine the natural frequencies and the corresponding mode shapes for the transverse vibrations of clamped trapezoidal plates. Clary (1975) investigated theoretically and experimentally the effect of fiber orientation on the first five flexural modes of vibration of rectangular, unidirectional, boron-epoxy panels. The agreement between theoretical and experimental frequencies was generally good, though there were large errors in some of the predictions of thinner panels. Cawley and Adams (1978) used the finite element method which included transverse shear deformation to predict the natural modes of free-free CFRP plates. Dutt and Shivanand (1978) studied the free vibration response of C-F-F-F and C-F-C-F woven carbon composite laminates using a FFT analyzer and compared with the finite element analysis solution. Chakraborty, *et al*. (2000) made studies on the free vibration response of FRP composite plates using experimental and numerical techniques. Although a number of researchers have developed several analytical and numerical methods for the determination of natural frequencies of isotropic and laminated composite laminates, few experimental studies on isotropic and laminated composite skew plate structures have been made.

2. Test specimens and experimental setup

2.1. Test specimens

In this study isotropic plates made of alumina 7075-T6 are used. The material was supplied by the Rio-Tinto Alcon, Canada (Pechiney Aluminum, France). The laminated composite plate specimens were fabricated by hand layup technique using unidirectional glass, epoxy-556 resin and the hardener (HY951) supplied by Ciba-Geigy India Ltd. The ratio of fiber to matrix by weight was taken as 1:1. The appropriate ASTM provisions were followed during the preparation of the test specimens. For each specimen, five trials were made and the average value of frequency is adopted. The materials properties of the plates are: for alumina 7075-T6, $E=71.7$ GPa, $\mu=0.33$, $\rho=2800\ kg/m^3$ and for glass-epoxy $E_1 = 38.07$ GPa, $E_2=8.1$GPa, $G12 = 3.05$ GPa, $\nu_{12}=0.22$, $\rho=2200\ kg/m^3$ and the aspect ratio was varied from *1.0* to *2.5*.

2.2. Experimental setup

The experimental set-up is shown in Fig.1. The fixture shown in Fig.1 provides clamped-edge-condition for two opposite edges in one direction and free-edge-condition for the other two opposite edges. An impact hammer was used to give the input pulse to the specimen and precautions were taken for ensuring that the stroke is normal to the surface of the plate. The first three natural frequency responses were captured by means of accelerometer placed at the geometric centre of the plate. The response signal was acquired using the FFT (Fast Fourier Transform) analyzer which was later amplified using a conditioning amplifier and then read using a high resolution signal analyzer giving on FRF (Frequency Response Function).

Fig.1. Experimental set-up.

3. Finite element solution

A finite element analysis was made for obtaining the first three natural frequencies using MSC/NASTRAN software. CQUAD8 (eight-noded isoparametric curved shell element) was employed as it yields better results compared to CQUAD4 element of the said software as revealed by the investigation reported in Srinivasa *et al*. (2012).

4. Results and discussions

The results of the present work are presented in terms of the non-dimensional frequency coefficient (K_f) defined by $K_f = \frac{\omega a^2}{\pi^2}\sqrt{\frac{\rho\, t}{D}}$ for isotropic plates and by $K_f = \omega a^2 \sqrt{\frac{\rho_l}{E_t\, t^3}}$ for laminated composite plates.

4.1. Isotropic skew plates

The thickness of the isotropic skew plates is taken as *2.0 mm*. The aspect ratio is varied from *1.0* to *2.5* and the skew angle from 0^o to 45^o. Table 1 and Fig.2 show the variation of the non-dimensional frequency coefficient with the aspect ratio and skew angle. The variation of the non-dimensional frequency coefficient (Experimental and FE solution) with the aspect ratio is very small. The non-dimensional frequency coefficient (Experimental and FE solution) increases monotonically with an increase in the skew angle. The experimental values of the frequency coefficient are in very good agreement with FE solutions. The first three mode shapes obtained by FEA are shown in Fig.3 for the aspect ratio = *1.0*.

Table 1. Non-dimensional frequency coefficients for isotropic skew plates.

Aspect ratio (a/b)	Mode number	Non-dimensional frequency coefficients (K_f)							
		Skew angle (α)							
		0^O		15^O		30^O		45^O	
		Exp	FEM	Exp	FEM	Exp	FEM	Exp	FEM
1.0	1	2.978	3.102	3.216	3.265	3.732	3.822	4.946	5.066
	2	3.518	3.665	3.735	3.792	4.133	4.233	5.136	5.260
	3	5.795	6.036	6.123	6.216	6.708	6.870	8.383	8.585
1.5	1	3.028	3.080	3.185	3.241	3.548	3.711	4.833	4.761
	2	4.169	4.241	4.313	4.388	4.587	4.798	5.832	5.779
	3	8.343	8.487	8.817	8.970	9.519	9.957	11.483	11.361
2.0	1	3.001	3.071	3.151	3.206	3.538	3.602	4.342	4.418
	2	4.825	4.939	5.000	5.087	5.433	5.532	6.484	6.596
	3	8.270	8.465	8.747	8.898	9.998	10.180	12.554	12.771
2.5	1	3.006	3.064	3.130	3.181	3.417	3.512	4.052	4.150
	2	5.591	5.699	5.764	5.858	6.168	6.339	7.331	7.508
	3	8.281	8.442	8.709	8.850	9.749	10.019	11.972	12.260

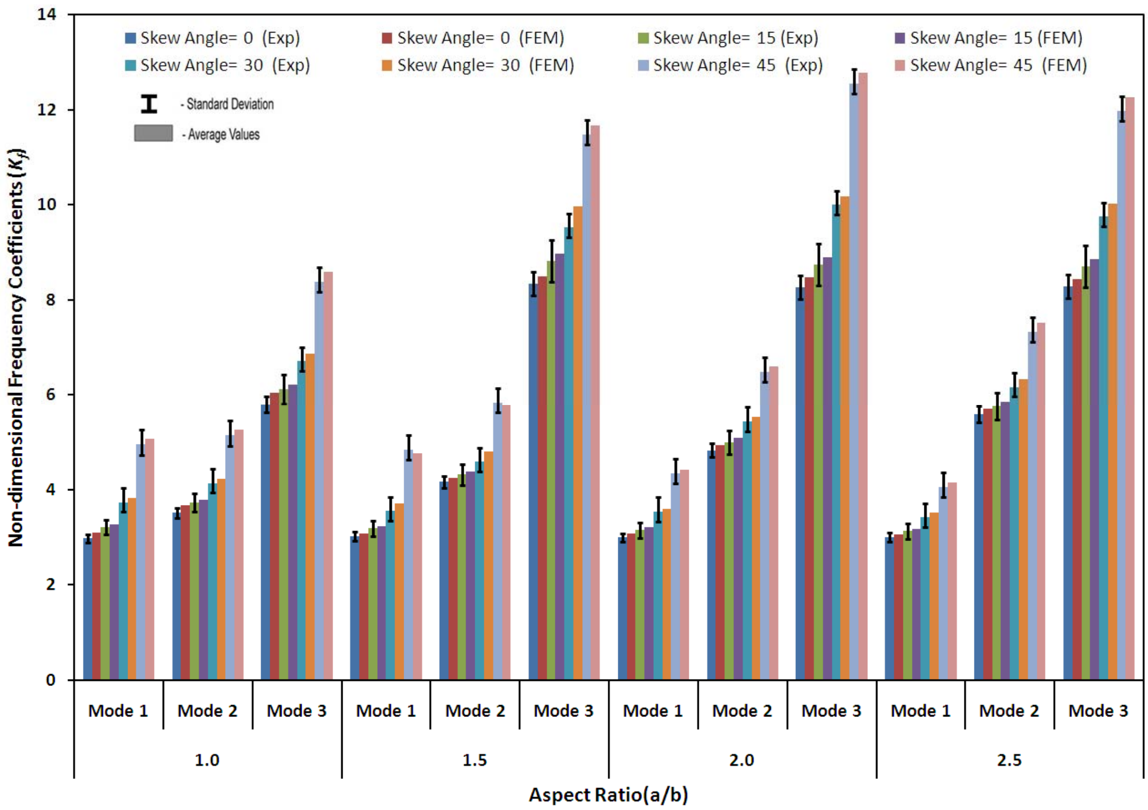

Fig.2. Variations of K_f with aspect ratio (a/b) for isotropic skew plates.

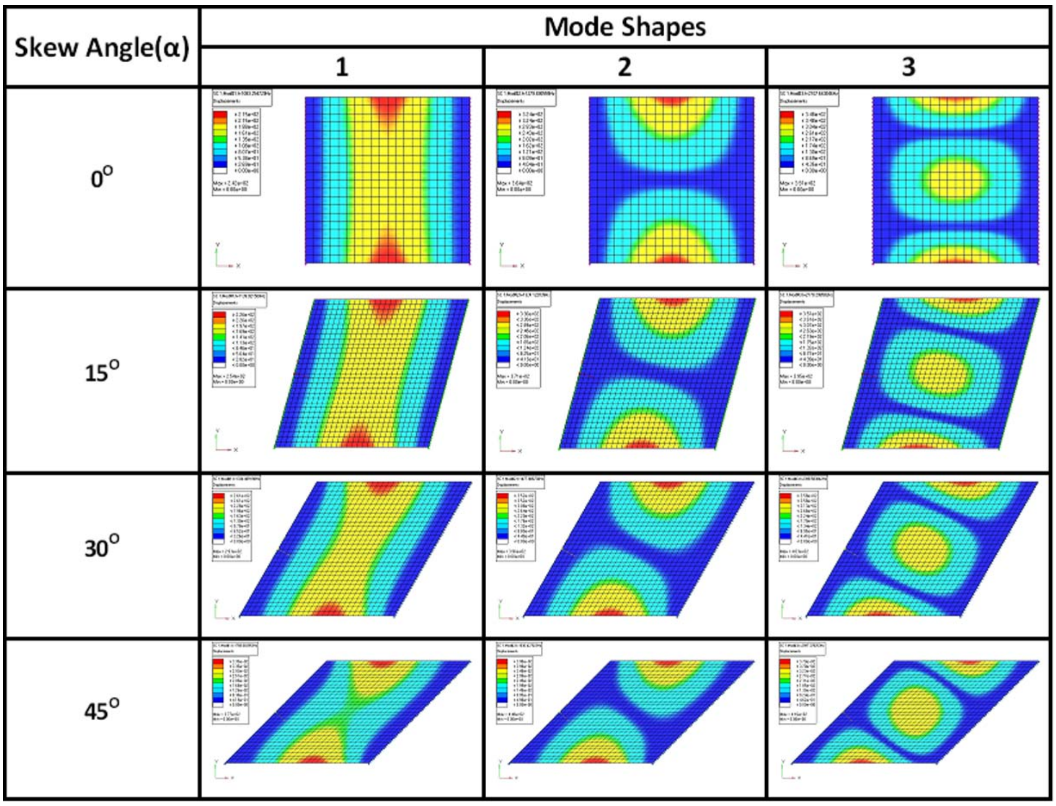

Fig.3. Mode shapes for isotropic skew plates.

4.2. Laminated composite skew plates

The total thickness of the laminate is maintained constant at *2 mm*, the number of layers being 20. The aspect ratio is varied from *1.0* to *2.5* and the skew angle from 0^o to 45^o. Tables 2 through 5, Figs 4 through 7 show the variation of the non-dimensional frequency coefficient with the aspect ratio and stacking sequence for various values of the skew angle equal to *0*, *15*, *30* and *45* degrees, respectively. The stacking sequences of the laminates considered are: antisymmetric cross-ply $0^o/90^o$, antisymmetric angle ply 0^o, antisymmetric angle ply 90^o and antisymmetric angle ply $\pm 45^o$. It is seen that the variation of the first natural frequencies with the aspect ratio is small and negligible for practical purposes. Other parameters being same, antisymmetric angle-ply *0* yields the highest value for the natural frequencies and antisymmetric angle-ply *90* yields the lowest value. The natural frequencies for the other layups lie inbetween the above two extreme values. The natural frequencies increase in magnitude with an increase in the skew angle. The first three mode shapes obtained by FEA are shown in Fig.8 for antisymmetric cross-ply laminates for the aspect ratio *=1.0*.

Table 2. Non-dimensional frequencies of laminated composite skew plate (skew-0^o).

Antisymmetric laminate sequence	Mode number	Non-dimensional frequency coefficients (K_f)							
		Aspect ratio (a/b)							
		1.0		*1.5*		*2.0*		*2.5*	
		Exp	FEM	Exp	FEM	Exp	FEM	Exp	FEM
Angle ply 0^o	*1*	*15.304*	*15.617*	*15.180*	*15.649*	*14.983*	*15.607*	*14.824*	*15.604*
	2	*15.990*	*16.316*	*16.683*	*17.199*	*17.536*	*18.267*	*18.613*	*19.593*
	3	*19.435*	*19.832*	*26.194*	*27.004*	*36.684*	*38.213*	*40.859*	*43.010*
Angle ply $\pm 45^o$	*1*	*9.454*	*9.647*	*9.260*	*9.547*	*9.039*	*9.416*	*8.855*	*9.321*
	2	*12.851*	*13.114*	*15.880*	*16.371*	*19.119*	*19.916*	*22.488*	*23.671*
	3	*22.684*	*23.147*	*25.673*	*26.467*	*25.069*	*26.114*	*24.548*	*25.840*
Angle ply 90^o	*1*	*7.055*	*7.199*	*6.996*	*7.213*	*6.905*	*7.193*	*6.831*	*7.191*
	2	*8.448*	*8.620*	*9.818*	*10.121*	*11.356*	*11.830*	*13.021*	*13.707*
	3	*19.399*	*19.795*	*19.283*	*19.879*	*19.031*	*19.824*	*18.827*	*19.818*
Cross-ply $0^o/90^o$	*1*	*11.901*	*12.144*	*11.805*	*12.170*	*11.654*	*12.139*	*11.530*	*12.137*
	2	*12.777*	*13.038*	*13.686*	*14.109*	*14.784*	*15.400*	*16.090*	*16.937*
	3	*19.420*	*19.817*	*32.410*	*33.412*	*32.120*	*33.458*	*31.780*	*33.452*

Table 3. Non-dimensional frequencies of laminated composite skew plate (skew-*15°*).

Antisymmetric laminate sequence	Mode number	Non-dimensional frequency coefficients (K_f)							
		Aspect ratio (*a/b*)							
		1.0		*1.5*		*2.0*		*2.5*	
		Exp	FEM	Exp	FEM	Exp	FEM	Exp	FEM
Angle ply *0°*	*1*	*15.346*	*15.821*	*15.350*	*15.990*	*14.997*	*15.787*	*14.495*	*15.420*
	2	*16.103*	*16.602*	*16.502*	*17.190*	*17.739*	*18.672*	*18.852*	*20.056*
	3	*19.876*	*20.491*	*26.997*	*28.122*	*37.684*	*39.668*	*40.917*	*43.528*
Angle ply ±*45°*	*1*	*10.235*	*10.552*	*9.688*	*10.092*	*9.498*	*9.998*	*9.253*	*9.844*
	2	*13.044*	*13.447*	*16.013*	*16.680*	*18.952*	*19.949*	*22.047*	*23.455*
	3	*22.592*	*23.291*	*26.898*	*28.019*	*27.056*	*28.479*	*25.625*	*27.260*
Angle ply *90°*	*1*	*7.368*	*7.596*	*7.253*	*7.556*	*7.107*	*7.481*	*6.976*	*7.421*
	2	*8.909*	*9.184*	*10.238*	*10.664*	*11.722*	*12.339*	*13.660*	*14.532*
	3	*18.957*	*19.544*	*20.157*	*20.996*	*19.726*	*20.765*	*19.583*	*20.833*
Cross-ply *0°/90°*	*1*	*12.032*	*12.404*	*12.099*	*12.603*	*11.740*	*12.358*	*11.480*	*12.212*
	2	*13.092*	*13.497*	*14.051*	*14.636*	*15.159*	*15.957*	*17.075*	*18.165*
	3	*20.156*	*20.779*	*31.759*	*33.082*	*32.392*	*34.097*	*32.422*	*34.492*

Table 4. Non-dimensional frequencies of laminated composite skew plate (skew-*35°*).

Antisymmetric laminate sequence	Mode number	Non-dimensional frequency coefficients (K_f)							
		Aspect ratio (*a/b*)							
		1.0		*1.5*		*2.0*		*2.5*	
		Exp	FEM	Exp	FEM	Exp	FEM	Exp	FEM
Angle ply *0°*	*1*	*16.014*	*16.595*	*15.812*	*16.557*	*15.543*	*16.448*	*15.314*	*16.379*
	2	*16.999*	*17.616*	*17.909*	*18.753*	*18.955*	*20.058*	*20.203*	*21.608*
	3	*21.958*	*22.755*	*30.296*	*31.723*	*41.246*	*43.646*	*42.345*	*45.289*
Angle ply ±*45°*	*1*	*12.972*	*13.442*	*12.003*	*12.569*	*11.117*	*11.764*	*10.461*	*11.188*
	2	*14.369*	*14.890*	*16.867*	*17.662*	*19.881*	*21.038*	*22.708*	*24.286*
	3	*23.764*	*24.626*	*33.427*	*35.002*	*33.081*	*35.006*	*32.189*	*34.426*
Angle ply *90°*	*1*	*8.892*	*9.214*	*8.474*	*8.873*	*8.079*	*8.549*	*7.780*	*8.321*
	2	*10.655*	*11.042*	*11.900*	*12.461*	*13.312*	*14.087*	*14.902*	*15.938*
	3	*20.408*	*21.149*	*23.573*	*24.683*	*22.761*	*24.085*	*22.164*	*23.705*
Cross-ply *0°/90°*	*1*	*13.020*	*13.492*	*12.778*	*13.380*	*12.488*	*13.215*	*12.242*	*13.093*
	2	*14.555*	*15.082*	*15.690*	*16.429*	*16.832*	*17.811*	*18.175*	*19.439*
	3	*23.111*	*23.949*	*34.105*	*35.712*	*34.522*	*36.531*	*33.954*	*36.314*

Table 5. Non-dimensional frequencies of laminated composite skew plate (skew-45^o).

Antisymmetric laminate sequence	Mode number	Non-dimensional frequency coefficients (K_f)							
		Aspect ratio (a/b)							
		1.0		1.5		2.0		2.5	
		Exp	FEM	Exp	FEM	Exp	FEM	Exp	FEM
Angle ply 0^o	1	18.149	18.711	17.719	18.457	17.593	18.137	17.515	17.872
	2	19.284	20.087	20.491	21.570	21.794	23.186	23.288	25.040
	3	26.964	28.087	37.360	39.327	46.893	49.887	46.186	49.662
Angle ply $\pm 45^o$	1	17.949	18.697	16.312	17.171	14.077	14.975	12.561	13.506
	2	18.365	19.130	19.842	20.886	23.149	24.627	26.238	28.213
	3	28.674	29.869	37.477	39.449	43.781	46.576	40.812	43.884
Angle ply 90^o	1	13.011	13.554	11.513	12.119	10.253	10.907	9.411	10.119
	2	14.626	15.235	15.792	16.623	17.033	18.121	18.577	19.976
	3	25.705	26.776	30.856	32.480	29.319	31.190	27.562	29.636
Cross-ply $0^o/90^o$	1	16.062	16.731	15.304	16.109	14.547	15.475	13.928	14.976
	2	17.989	18.739	19.401	20.422	20.551	21.863	21.952	23.604
	3	29.705	30.943	39.355	41.427	40.157	42.721	38.893	41.820

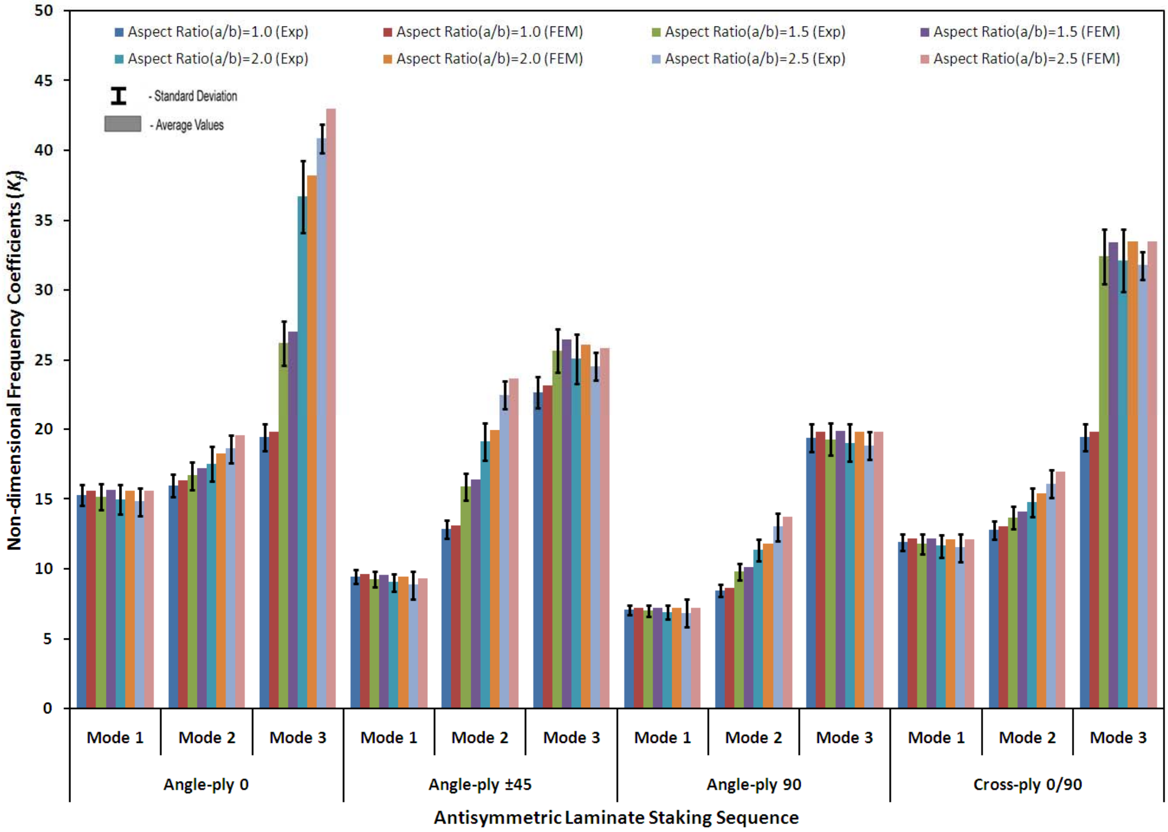

Fig.4. Variations of K_f with the aspect ratio (a/b) and laminate stacking sequence for laminated composite skew plates ($\alpha=0^o$).

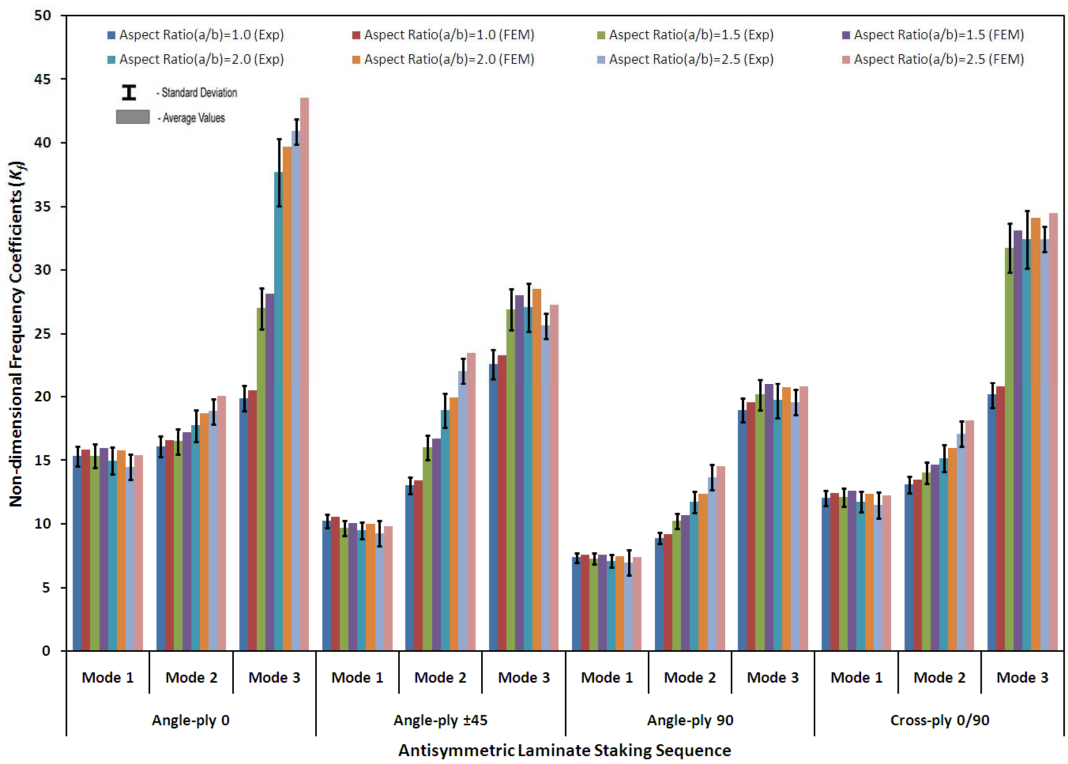

Fig.5. Variations of K_f with the aspect ratio (a/b) and laminate stacking sequence for laminated composite skew plates ($\alpha=15^o$).

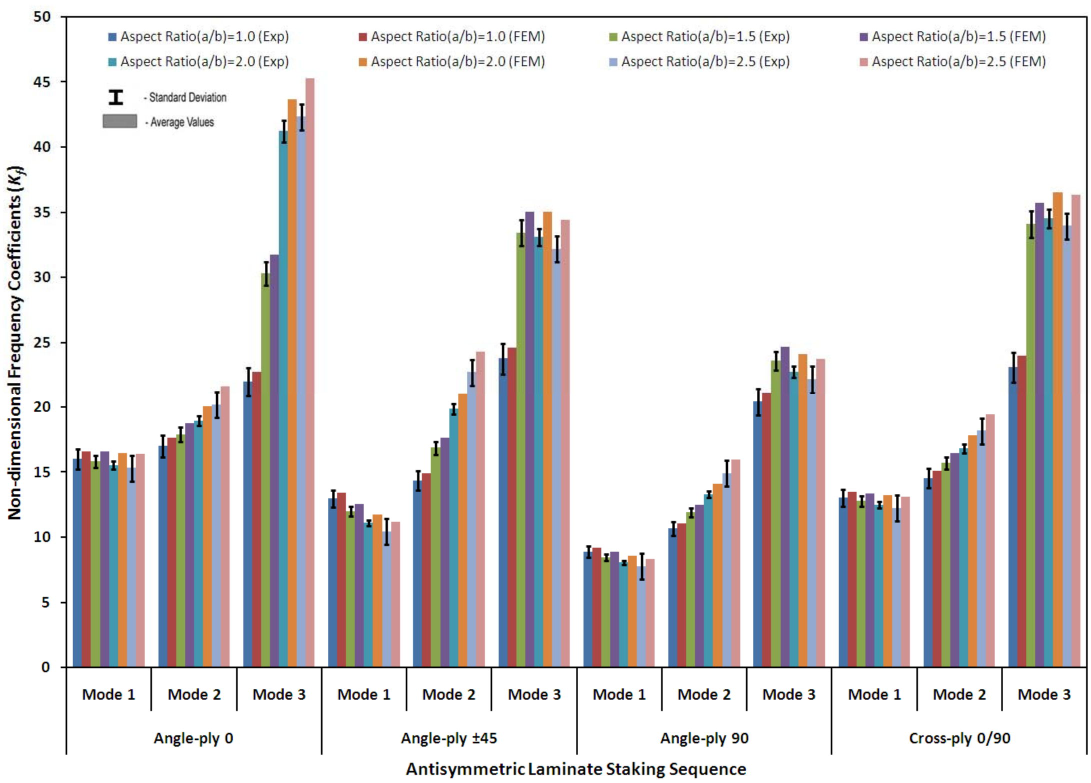

Fig.6. Variations of K_f with the aspect ratio (a/b) and laminate stacking sequence for laminated composite skew plates ($\alpha=30^o$).

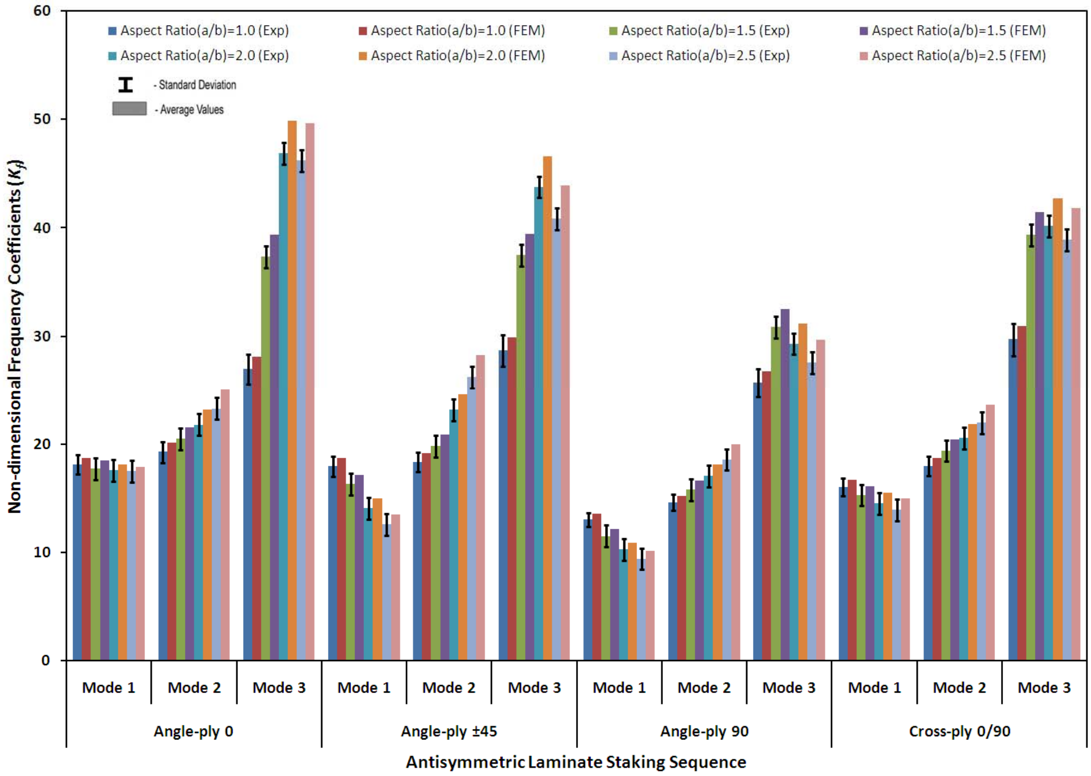

Fig.7. Variations of K_f with the aspect ratio (a/b) and laminate stacking sequence for laminated composite skew plates (α=45^o).

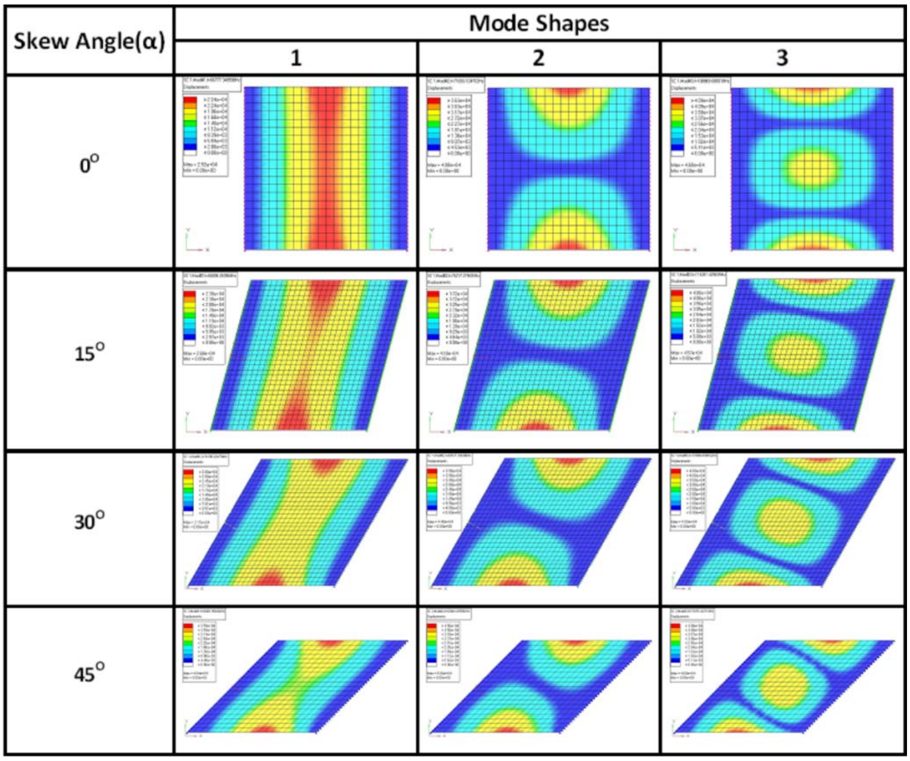

Fig.8. Mode shapes for laminated composite skew plates ($a/b=1.0$, $NL=20$, antisymmetric cross-ply laminates).

5. Conclusions

The following conclusions are made based on the above study.

- The experimental values of the natural frequencies agree well with the FE solutions both in the case of isotropic and laminated composite skew plates.
- The variation of natural frequencies with the aspect ratio is small and negligible both in the case of isotropic and laminated composite skew plates.
- The natural frequencies increase with an increase in the skew angle, the increase being considerable in the case of isotropic skew plates and small for laminated composite skew plates.
- This study sheds more light on free vibration characteristics of laminated composite skew plates in particular.

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Nomenclature

a – plate length
b – plate width
D – flexural rigidity of isotropic plate, $Et^3/12(1-\mu^2)$
E – modulus of elasticity of the material of isotropic plate
E_l – Young's modulus of the lamina in the longitudinal direction
E_t – Young's modulus of the lamina in the transverse direction
G_{lt} – in-plane shear modulus of the lamina
K_f – non-dimensional frequency coefficient
NL – number of layers in the laminate
t – plate thickness
α – skew angle of the plate
θ – fiber orientation angle of the lamina
μ – Poisson's ratio of isotropic plate
ν_{lt} – major Poisson's ratio of the lamina
ρ – mass density of the material of the plate
ρ_1 – mass density per unit area
ω – natural angular frequency of plate

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