Buckling Studies on Laminated Composite Skew Plates

C.V. Srinivasa
Department of Mechanical Engineering
GM Institute of Technology, Davangere-577006, India

Y.J. Suresh
Department of Mechanical Engineering
J.N.N. College of Engineering
Shivamogga-577204, India

W.P. Prema Kumar
Department of Civil Engineering
Nagarjuna College of Engineering & Technology
Bangalore-562110, India

ABSTRACT
This paper presents buckling studies made on skew plates using finite element. The effects of the skew angle, aspect ratio, length-to-thickness-ratio, fibre orientation angle, and numbers of layers in the laminate and laminate sequence on the critical buckling load factor (K_{cr}) of antisymmetric composite laminates have also been presented. The critical buckling load factor (K_{cr}) is found to increase with the skew angle. When the number of layers in the laminate is large, the variation of critical buckling load factor (K_{cr}) with the number of layers is not appreciable.

Keywords
Skew Plates; Antisymmetric Laminates; Buckling; Finite Element,

Nomenclature:

a	: Plate length
b	: Plate width
t	: Plate thickness
NL	: Number of layers
E	: Modulus of elasticity
E_1	: Young's modulus of the fibre in longitudinal direction
E_2	: Young's modulus of the fibre in transverse direction
G_{12}	: Shear modulus
D	: Plate bending rigidity, $Et^3/12(1-\nu^2)$
k_r	: Ratio of buckling factors
K_{cr}	: Buckling load intensity factor
α	: Skew angle
θ	: Fibre orientation angle
ν	: Poisson's ratio
ν_{12}	: Major Poisson's ratio
λ	: Eigen Value
N_x	: Stress along x-axis
σ_x	: In-plane stress along x-axis

1. INTRODUCTION
Due to light weight and high strength, the use of fibre-reinforced composite materials has increased rapidly in recent years. Application fields of composite materials are continuously expanding from traditional application areas such as military aircraft to various engineering fields such as automobiles, robotics, day to day appliances, building industry etc. The design of components made of such materials demands correct understanding of the structural behavior such as deflections, buckling loads and modal characteristics, the through-thickness distributions of stresses and strains etc including failure characteristics. The members and structures composed of laminated composite materials are usually very thin and hence more prone to buckling. Their buckling must be accounted for in the safe and reliable design of composite structures among other considerations.

The skew plates are often used in civil, marine, aeronautical and mechanical engineering applications. Complex alignment problems in bridge design arising from functional, aesthetic or structural requirements are often solved by the use of skew plates. Various other applications of skew plates can be found in ship hulls, swept wings of aero planes, parallelogram slabs in buildings etc.

Few analytical solutions are available for skew plates and that too for simple cases. When the analytical methods[1-13] have failed to provide solutions, the numerical techniques such as finite element[14-33], finite-strip element method [34], spline finite strip-method[35-36] and differential quadrature methods[37-40] have been employed successfully for the analysis of skew plates. Studies on skew composite plates available in literature are not many.

This paper deals with the determination of critical buckling load factors for isotropic and laminated composite skew plates using CQUAD4 and CQUAD8 elements of MSC/NASTRAN. The accuracy of the elements has been verified against literature values. The effects of skew angle, fibre orientation angle, number of layers in the laminate, laminate sequence and boundary conditions on the critical buckling load factor (K_{cr}) of skew plate are investigated.

2. VALIDATION AND CONVERGENCE STUDIES
In the present work classical buckling analysis is performed on isotropic and laminated skew composite plates by using MSC/NASTRAN software. CQUAD4 (four-noded plate element) and CQUAD8 (eight-noded isoparametric curved shell element) are employed in the present investigation. Numerical studies are carried out on isotropic and laminated composite skew plates with clamped/simply supported edge conditions.

In the displacement based finite element method, the boundary conditions are imposed through the displacements tangential and normal to the edges. Geometry of the skew plate with finite element mesh and global and local coordinate systems is shown in Fig. 1. *x-y* is the global orthogonal coordinate system and u, v are displacement components in the x, y directions, respectively, which are inclined to the skew edges and hence the displacement boundary conditions cannot be applied straightaway. In order to overcome this, a local coordinate system, $(x'-y')$ normal and tangential to the skew edges, respectively, becomes necessary. u', v' are the corresponding displacement components.

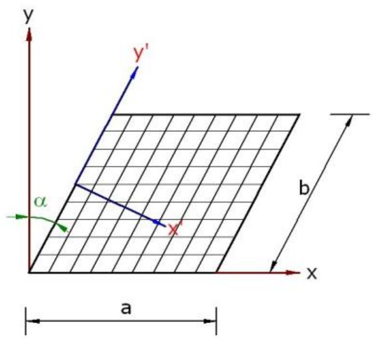

Figure 1: Geometry of the skew plate with finite element mesh showing global and local coordinate systems.

2.1 Validation check

The validation for the present elements is performed by comparing the values for critical buckling load intensity factor (K_{cr}) obtained in this work with those available in literature. The same is presented in Table 1 for simply supported(S-S-S-S) and clamped(C-C-C-C) isotropic skew plates. It can be seen from Table 1 that the results obtained using the CQUAD8 element are closer to the literature values than the results obtained using CQUAD4 element.

In a similar manner validation check is performed considering a simply supported square antisymmetric high modulus graphite/epoxy angle-ply laminates with different fibre angle (0^o to 90^o) and different number of layers while keeping the total thickness constant.

The results obtained in the present work are presented in Table 2 and compared with the results available in [41]. It is observed that there is a good agreement. From Table 2 it can be seen that CQUAD8 element yields better results when compared with the CQUAD4 element. Hence CQUAD8 element is employed in the further studies of the present work.

2.2 Convergence study

Convergence study has been undertaken to establish the number of elements required for ensuring adequate accuracy. This study has been performed on simply supported(S-S-S-S) and clamped(C-C-C-C) isotropic skew plates having aspect ratio (=a/b) of 1.0 and skew angles 0^o, 15^o, 30^o and 45^o using CQUAD4 (four-noded) and CQUAD8 (eight-noded isoparametric curved shell element) elements of MSC / NASTRAN. The convergence details are presented in Table 3.

3. PRESENT WORK – RESULTS AND DISCUSSIONS

The present work has been carried by using CSQUAD8 element of MSC/NASTRAN and based on classical buckling analysis. The material properties used are:

$E_l / E_t = 40$, $G_{lt} / E_t = 0.5$ and $\nu_{lt} = 0.25$.

The results of the present work are presented in the form of buckling load intensity factor (K_{cr}) as:

$$K_{cr} = \lambda \sigma_x \frac{b^2 t}{\pi^2 D} \text{ for isotropic and}$$

$$K_{cr} = \lambda \frac{N_x b^2}{\pi^2 E_2 t^3} \text{ for laminated skew plates}$$

3.1 Isotropic skew plates

Studies have been made on skew plates with different aspect ratios, skew angles, and length-thickness ratio with simply supported and clamped boundary conditions. The results obtained are tabulated in Table 4 in the form of buckling load intensity factor (K_{cr}).

Form table 4, it is seen that K_{cr} *decreases* as the aspect ratio (a/b) increases in the case of C-C-C-C boundary condition. For the S-S-S-S boundary condition, K_{cr} *decreases as the aspect ratio increases* up to 1.0 and thereafter the change is not considerable. It is also seen that as the skew angle (α) increases the K_{cr} also increases for constant values of a/b and a/t.

3.2 Laminated skew plates

The lamination sequences considered in the present work are: (1) antisymmetric cross-ply and (2) antisymmetric angle-ply. In both the cases the results are presented for graphite epoxy composite plates with material properties:

$E_1 = 206.91\ GPa, E_2 = 5.173\ GPa, G_{12} = 2.586\ GPa,$ and $\vartheta_{12} = 0.25$

The results are presented in terms of non-dimensional *critical buckling load factor* (K_{cr}).

3.2.1 Antisymmetric cross-ply skew laminates

The variation of critical buckling load factor (K_{cr}) with respect to skew angle(α), fibre orientation angle (θ) and number of layers(NL) for graphite/epoxy antisymmetric cross-ply skew laminates are presented in Figs. 2 and 3 for simply supported and clamped boundary conditions respectively. From Figs. 3 and 4 it is seen that, as the skew angle increases K_{cr} increases for a given number of layers. For a given skew angle, it is also seen that K_{cr} increases initially up to NL = 4 and remains constant thereafter irrespective of the skew angle.

3.2.2 Antisymmetric angle-ply skew laminates

a) Simply supported boundary condition

The variations of buckling load intensity factor (K_{cr}) with skew angle (α), fibre orientation angle (θ) and number of layers (NL) for antisymmetric angle-ply skew laminates under S-S-S-S boundary conditions are presented in Figs. 4-7. For NL=2, K_{cr} initially decreases with fibre orientation angle and later varies as shown in Figures 4-7. For NL≥4 and for all the skew angles, K_{cr} increases and reaches a maximum at about θ=57.5^o,47^o,48^o and 50^o, for skew angles = 0^o,15^o,30^o and 45^orespectively. The increase in K_{cr} beyond NL= 10 is not appreciable in all the cases. The ratio of buckling factors K_r is defined as $K_r = \left[(K_{cr})_{\theta=90^0} / (K_{cr})_{\theta=0^0} \right]$. The values of K_r for various skew angles are presented in Table 5. It is seen that K_r decreases as the skew angle increases.

b) Clamped Boundary Condition

For antisymmetric angle-ply skew plates of α=0^o,15^o,30^o and 45^o , the variations of K_{cr} with θ and NL are presented in Figs. 8-11. For zero skew angle, maximum value of K_{cr} occurs when fibre angle is zero and K_{cr} varies as shown in Figure 8. For skew angle = 15 degrees also, maximum value of K_{cr} occurs when fibre angle is zero and K_{cr} varies as shown in Fig 9. For skew angles of 30 and 45 degrees, K_{cr} initially increases with fibre angle up to about 45 degrees and later decrease as shown in Fig. 10 and 11. The increase in K_{cr} with NL for a given fibre angle for NL greater than 10 is not appreciable. Figs. 12-15 show sets of contour plots for the typical buckling mode shapes for isotropic and Anti-symmetric Angle-Ply laminated skew plates with simply supported and clamped edge conditions. The K_r values for various skew angles (α) are presented in Table 5.

4. CONCLUSIONS

The present investigation deals with buckling of composite skew plates, the parameters considered being skew angle, aspect ratio, lamination sequence, fibre orientation angle, number of layers and boundary conditions. It is seen that CQUAD8 element of MSC/NASTRAN yields better results when compared with CQUAD4 element. The said elements have been validated against literature values. It is seen that the buckling load of a skew plate increases as the skew angle increases. The buckling load also increases with the increase in number of layers in the laminate keeping total thickness constant up to about 10 layers, beyond which the increase is not substantial. The boundary condition has a significant effect on the buckling load.

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6. REFERENCES

1. Asthon, J.E.1969. Stability of clamped skew plates under combined loads. Journal of Applied Mechanics. 139-140.
2. Durvasula, S.1970. Buckling of clamped skew plates. AIAA Journal. 8(1).178-181.
3. Prabhu, M.S.S., and Durvasula, S. 1972. Stability of clamped skew plates. Applied Science research. 26. 255-271.
4. Srinivasan, R.S., and Ramachandran, S.V. 1976. Stability of generally orthotropic skew plate. Journal of the Engineering Mechanics Division. 102(EM3). 569-572.
5. Kennedy, J.B., and Prabhakara, M.K. 1978. Buckling of simply supported orthotropic skew plates. Aeronautical Quarterly. 161-174.
6. Mizusawa, T., Kajita, T., and Naruoka, M. 1980. Buckling of skew plates structures using B-spline functions. International Journal for Numerical Methods in Engineering.15. 87-96.
7. Kamal, K., and Durvasula, S. 1991. A continuum solution to the problems of composite laminate analysis. Defense Science Journal. 41(1). 69-77.
8. Kitipornchai, S., Xiang, Y., Wang, C.M., and Liew, K.M. 1993. Buckling of thick skew plates. International Journal for Numerical Methods in Engineering. 36.1299-1310.
9. York, C.B., and Williams, F.W. 1995. Buckling analysis of skew plate assemblies: Classical plate theory results incorporating lagrangian multipliers. Computers and Structures. 56(4).625-635.
10. Jaunky, N., Norman, F. Knight Jr., and Ambur, D.R. 1995. Buckling of arbitrary quadrilateral anisotropic plates. AIAA Journal. 2414-2417.
11. Wang, S. 1997. Buckling of thin skew fibre-reinforced composite laminates. Thin Walled Structures. 28(1).21-41.
12. Azhari, M., Shahidi, A.R., and Saadatpour, M.M. 2004. Post local buckling of skew and trapezoidal plates" Advances in Structural Engineering. 7(1).61-70.
13. Pannok, C., and Singhatanadgid, P. 2006. Buckling analysis of composite laminate rectangular and skew plates with various edge support conditions. The 20th Conference of Mechanical Engineering Network of Thailand .18-20.
14. Fried, I., and Schmitt, K. 1972. Numerical results from the application of gradient iterative techniques to the finite element vibration and stability analysis of skew plates. Aeronautical Journal. 76. 166–169.
15. Bucco, D., and Mazumdar, J. 1984. Buckling analysis of plates of arbitrary shape. Journal of Australian mathematical society. Serial B26. 77-91.
16. Lee, Y.J., Lin, H.J, and Lin, C.C. 1989. Buckling analysis of composite laminates. Composite Structures. 12.133-148.
17. Liao, C.L., and Lee, Z.Y. 1993. Elastic stability of skew laminated composite plates subjected to biaxial follower forces. International Journal for Numerical Methods in Engineering. 36. 1825-1847.
18. Krishna Reddy, A.R., and Palaninathan, R. 1995. Buckling of laminated skew plates. Thin Walled Structures. 22 .241-259.
19. Wang, S. 1997. Buckling analysis of skew fibre-reinforced composite laminates based on first-order shear deformation theory" Composite Structures. 37(1).5-19.
20. Sarath Babu, C., and Kant, T. 1999. Two shear deformable finite element models for buckling analysis of skew fibre-reinforced composite and sandwich panels. Composite Structures. 46(2).115-124.
21. Hu, H.T., and Tzeng, W.L. 2000. Buckling analysis of skew laminate plates subjected to uniaxial inplane loads. Thin-Walled Structures. 38. 53-77.
22. Kant, T. and Babu, C.S. 2000. Thermal buckling analysis of skew fibre-reinforced composite and sandwich plates using shear deformable finite element models. Composite Structures.49. 77-85.
23. Huyton, P., and York, C.B. 2001. Buckling of skew plates with continuity or rotational edge restraint. Journal of Aerospace Engineering. 92-101.
24. Singha, M.K, Ramachandra, L.S., and Bandyopadhyay, J.N. 2001. Thermal post buckling analysis of laminated composite plates. Composite Structures.54. 453-458.
25. Singha, M.K., Ramachandra L.S., and Bandyopadhyay, J.N. 2001. Stability and strength of composite skew plates under thermo mechanical loads. AIAA Journal. 39(8). 1618-1623.
26. Huyton, P., and York, C.B. 2002. Buckling of skew plates with planform taper. AIAA Journal. 1572-1581.
27. Ganapathi, M., Prakash, T., and Sundararajan, N. 2006. Influence of functionally graded material on buckling of skew plates under mechanical loads. Journal of Engineering Mechanics. 132(8). 902-905.

28. Hsuan-The, Hu. Chia-Hao Yang, and Fu-Ming Lin. 2006. Buckling analyses of composite skew plates with material nonlinearity. Composites: Part B.37. 26-36.

29. Partha, Dey, and Singha, M.K. 2006. Dynamic stability analysis of composite skew plates subjected to periodic in-plane load. Thin-walled structures. 44.937-942.

30. Chakrabarti, A., and Sheikh, A.H. 2007. Buckling of laminated sandwich plates using an efficient plate model. International Shipbuilding Progress. 54.63-81.

31. Prakash, T., Singha, M.K., and Ganapathi, M. 2008. Thermal post buckling analyses of FGM skew plates. Engineering Structures. 30. 22–32.

32. Civalek, O. 2007. Free vibration and buckling analyses of composite plates with straight-sided quadrilateral domain based on DSC approach. Finite Elements in Analysis and Design. 43.1013-1022.

33. Rupesh, D., and Singha, M.K. 2009. Influence of corner stresses on the stability characteristics of composite skew plates. International Journal of Non-Linear Mechanics. 44. 138- 146.

34. Thangam Babu, P.V., and Reddy, D.V. 1978. Stability analysis of skew orthotropic plates by the finite strip method. Computers and Structures. 8. 599-607.

35. Tham, L.G., and Szeto, H.Y. 1990. Buckling analysis of arbitrarily shaped plates by spline finite strip method. Computers and Structures. 36(4).729-735.

36. Mizusawa, T., and Kajita, T. 1986. Vibration and buckling analysis of skew plates with edges elastically restrained against rotation. Computers and Structures. 22(6).987-994.

37. Darvizeh, M., Darvizeh, A, and Sharma, C.B. 2002. Buckling analysis of composite plate using differential quadrature method. Steel and Composite Structures. 2(2). 99-122.

38. Wang, X., Tan, M., and Zhou, Y. 2003. Buckling analyses of anisotropic plates and isotropic skew plates by the new version differential quadrature method. Thin-Walled Structures. 41. 15-29.

39. Karami, G., Ali Shahpari, S., and Malekzadeh, P. 2003. DQM analysis of skewed and trapezoidal laminated plates. Composite Structures.59.393-402.

40. Civalek, O. 2004. Application of differential quadrature (DQ) and harmonic differential quadrature (HDQ) for buckling analysis of thin isotropic plates and elastic columns. Engineering Structures.26. 171–186.

41. Jones, R.M. 1975. Mechanics of Composite Materials. New York: McGraw-Hill.

Table 1: Buckling load factor (K_{cr}) for isotropic skew plates (a/b=1, a/t =100)

Aspect ratio	Authors	Method	S-S-S-S				C-C-C-C			
			Skew Angle (α)				Skew Angle (α)			
			0°	15°	30°	45°	0°	15°	30°	45°
0.5	Durvasula [2]	Rayleigh-Ritz	-	7.070	10.400	21.400	-	21.600	30.400	55.300
	Mizusawa[6]	Rayleigh-Ritz	6.250	7.000	10.020	19.300	19.340	-	-	54.940
	C.B. York[9]	Lagrangian Multiplier	-	-	-	-	-	21.600	30.600	54.700
	Fried et al.[14]	Finite Element	6.251	6.980	9.940	19.420	19.320	21.400	31.000	55.950
	Huyton [26]	Finite Element		6.970	9.870	18.900	-	21.500	30.200	54.100
	Present	CQUAD4	6.201	6.855	9.895	18.951	19.293	21.176	30.354	55.505
		CQUAD8	6.218	6.908	10.000	19.252	19.301	21.330	30.308	55.453
1.0	Durvasula[2]	Rayleigh-Ritz	4.000	4.480	6.410	12.300	10.000	10.900	13.580	20.400
	Kennedy [5]	Double-Fourier	4.000	4.330	5.530	8.470	-	-	-	-
	Mizusawa [6]	Rayleigh-Ritz	4.000	4.410	6.030	10.220	10.070	-	-	20.050
	C.B York[9]	Lagrangian Multiplier	4.000	4.740	7.630	13.540	10.070	10.850	13.580	20.210
	Jaunky[10]	Rayleigh-Ritz	-	4.400	-	-	-	10.800		-
	S. Wang[11]	B-Spline Rayleigh-Ritz	-	4.395	5.896	10.103	-	10.834	13.538	20.122
	S.Kitiporchai et al.[8]	Pb-2 Rayleigh-Ritz	4.000	4.393	5.897	10.103	10.073	10.834	13.537	20.111
	Tham [35]	Spline finite strip	4.000	4.400	5.930	10.360	10.080	10.840	13.600	20.760
	Fried et al.[14]	Finite Element	4.000	4.400	5.910	10.220	10.060	10.800	13.500	20.080
	A.R.K. Reddy [18]	Finite Element	4.000	4.320	5.550	8.640	10.080	10.760	13.640	20.620
	C.S. Babu, [20]	Finite Element	4.000	-	5.920	10.230	10.070	-	13.538	20.123
	Huyton [23]	Finite Element	-	4.390	5.850	9.670	-	10.800	13.500	20.100
	R. Daripa et al.[33]	Finite Element	4.000	-	5.856	10.291	10.064	-	15.009	26.506
	X. Wang et al.[38]	DQM	4.000	4.390	5.830	9.390	10.070	10.830	13.540	21.100
	Omer Civalek[40]	DQM	4.030	-	-	-	9.960	10.900	13.490	20.350
		HDQM	4.010	-	-	-	10.060	10.820	13.520	21.010
	Present	CQUAD4	3.919	4.306	5.761	9.526	9.854	10.690	13.503	20.092
		CQUAD8	4.000	4.355	5.875	9.954	10.000	10.775	13.537	20.105
1.5	Durvasula [2]	Rayleigh-Ritz	-	-	-	-	-	8.971	11.160	17.100
	Prabhu [3]	Rayleigh-Ritz	-	4.770	6.370	10.900	-	8.970	11.200	17.100
	Kennedy[5]	Double-Fourier	-	4.620	5.580	7.890	-	-	-	-
	Mizusawa [6]	Spline Strip	-	4.700	6.030	9.640	-	-	-	-
	C.B York[9]	Lagrangian Multiplier	-	-	-	-	-	8.960	11.000	16.300

	Fried et al.[10]	Finite Element	-	4.680	4.770	12.300	-	8.910	11.000	16.300
	Huyton [26]	Finite Element	-	4.680	5.890	8.950	-	8.930	11.000	16.200
	Present	CQUAD4	4.256	4.640	5.955	9.076	8.217	8.887	11.175	16.498
		CQUAD8	4.270	4.648	5.865	9.139	8.237	8.897	11.074	16.340
2.0	Prabhu [3]	Rayleigh-Ritz	-	4.330	6.030	10.300	-	8.700	10.500	15.700
	Kennedy [5]	Double-Fourier	-	4.270	5.200	7.680	-	-	-	-
	Mizusawa [6]	Spline Strip Method	-	4.360	5.730	9.340	-	-	-	-
	C.B York[9]	Lagrangian Multiplier	-	-	-	-	-	8.410	10.300	15.200
	Huyton [26]	Finite Element	-	4.340	5.590	8.800	-	8.390	10.300	15.100
	Present	CQUAD4	3.885	4.271	5.596	8.855	7.683	8.327	10.326	15.350
		CQUAD8	3.903	4.313	5.605	8.871	7.693	8.373	10.292	15.200
2.5	Present	CQUAD4	4.000	4.410	5.542	8.541	7.273	8.101	9.992	15.016
		CQUAD8	4.007	4.418	5.543	8.498	7.290	8.109	9.954	14.763

Table 2: Buckling load factor (K_{cr}) for simply supported square antisymmetric angle-ply laminates

Fibre Angle (θ)	Number of Layers(NL)=2			Number of Layers(NL)=4			Number of Layers(NL)=6		
	Jones [41]	Present		Jones [41]	Present		Jones [41]	Present	
		CQUAD8	CQUAD4		CQUAD8	CQUAD4		CQUAD8	CQUAD4
0^o	35.830	35.794	36.278	35.830	35.794	36.278	35.830	35.794	36.278
15^o	21.730	21.244	18.813	38.250	38.212	37.077	41.310	41.260	40.440
30^o	20.440	20.282	17.963	49.820	49.745	44.794	55.270	54.873	49.741
45^o	21.710	21.307	19.459	56.088	55.369	50.110	62.460	61.229	55.766
60^o	19.390	19.026	18.309	45.434	44.632	42.816	50.257	50.108	47.330
75^o	14.750	14.230	11.864	22.075	21.834	21.684	23.772	23.592	23.495
90^o	13.132	13.120	13.304	13.132	13.120	13.304	13.132	13.120	13.304

Table 3: Convergence study for critical buckling load factor (K_{cr}) for isotropic skew plates (a/b=1, a/t =100)

AUTHOURS		S-S-S-S				C-C-C-C			
		Skew Angle (α)				**Skew Angle (α)**			
		0^o	**15^o**	**30^o**	**45^o**	**0^o**	**15^o**	**30^o**	**45^o**
PRESENT(10X10)	CQUAD4	3.88367	4.23849	5.87595	9.86936	9.81578	10.63164	14.11902	22.15015
	CQUAD8	**3.89261**	**4.31278**	**5.94400**	**10.42590**	**9.92290**	**10.69692**	**13.56186**	**20.31567**
PRESENT(16X16)	CQUAD4	3.89397	4.26779	5.82424	9.66743	9.82829	10.64395	13.66898	20.68959
	CQUAD8	**3.93365**	**4.33351**	**5.90512**	**10.19285**	**9.95524**	**10.72935**	**13.54038**	**20.13942**
PRESENT(20X20)	CQUAD4	3.90051	4.28019	5.81254	9.61615	9.82533	10.65699	13.59211	20.40574
	CQUAD8	**3.95017**	**4.34035**	**5.89368**	**10.11547**	**9.96691**	**10.74050**	**13.53961**	**20.11848**
PRESENT(24X24)	CQUAD4	3.90579	4.28884	5.80575	9.58566	9.83000	10.67263	13.55697	20.26772
	CQUAD8	**3.96456**	**4.34504**	**5.87832**	**10.06318**	**9.97533**	**10.75809**	**13.53783**	**20.11086**
PRESENT(28X28)	CQUAD4	3.91188	4.29752	5.79748	9.54917	9.83945	10.67539	13.52709	20.14447
	CQUAD8	**3.97914**	**4.34994**	**5.88657**	**9.99591**	**9.98458**	**10.76590**	**13.53751**	**20.10619**
PRESENT(32X32)	CQUAD4	3.91643	4.30313	5.77451	9.53662	9.84826	10.68409	13.51988	20.11370
	CQUAD8	**3.98239**	**4.35338**	**5.87574**	**9.97271**	**9.99144**	**10.77131**	**13.53744**	**20.10545**
PRESENT(36X36)	CQUAD4	3.91887	4.30583	5.76157	9.52614	9.85341	10.69007	13.50351	20.09231
	CQUAD8	**3.99411**	**4.35516**	**5.87555**	**9.95378**	**9.99515**	**10.77411**	**13.53743**	**20.10507**
PRESENT(40X40)	CQUAD4	3.91920	4.30590	5.76141	9.52600	9.85381	10.69007	13.50321	20.09221
	CQUAD8	**3.99491**	**4.35525**	**5.87545**	**9.95370**	**9.99565**	**10.77491**	**13.53733**	**20.10500**

Table 4: Buckling load factor (K_{cr}) for simply supported and clamped isotropic skew plates

a/b	a/t	Critical Buckling Load Factor (K_{cr})							
		Skew Angle(α)							
		0°	15°	30°	45°	0°	15°	30°	45°
		S-S-S-S				C-C-C-C			
0.5	1000	6.24300	6.90854	10.90285	19.25284	19.33735	21.33031	31.30785	55.45420
	500	6.24153	6.90853	10.90284	19.25282	19.33624	21.33021	31.19782	55.45416
	100	6.21827	6.90837	10.00000	19.25237	19.30125	21.32979	30.39761	55.29885
	50	6.17953	6.90829	9.90260	19.25217	19.19446	21.32959	30.30741	55.25184
	20	6.01605	6.90814	9.90214	19.25283	18.48196	21.31031	30.30732	55.25116
1.0	1000	4.06280	4.35628	5.92473	10.09187	10.09467	10.78441	13.54032	20.37596
	500	4.05974	4.35626	5.92472	10.09183	10.06244	10.78237	13.54026	20.37587
	100	3.99491	4.35590	5.87545	9.52600	9.99656	10.77491	13.54021	20.09820
	50	3.92852	4.35306	5.86174	9.51599	9.91666	10.74880	13.54004	19.98427
	20	3.62550	4.34954	5.84074	9.51216	8.96877	10.74023	13.53970	19.97652
1.5	1000	4.33439	4.64968	5.86553	9.14131	8.34911	8.89853	11.07385	16.34463
	500	4.32975	4.64965	5.86550	9.14041	8.34574	8.89748	11.07377	16.34363
	100	4.27046	4.64829	5.86548	9.13863	8.23728	8.89682	11.07361	16.33984
	50	4.16086	4.64766	5.86492	9.13132	7.93138	8.89674	11.07287	16.33465
	20	3.62900	4.64566	5.86469	9.13102	6.30770	8.89665	11.07187	16.33366
2.0	1000	3.99336	4.31322	5.60839	8.87174	7.86503	8.37329	10.29185	15.20065
	500	3.98701	4.31318	5.60727	8.87154	7.85951	8.37320	10.29163	15.20052
	100	3.90313	4.31313	5.60548	8.87144	7.69252	8.37310	10.29160	15.20032
	50	3.73166	4.31303	5.60440	8.87125	7.22295	8.37305	10.29127	15.20017
	20	2.95039	4.31296	5.60430	8.87103	4.88892	8.37300	10.29087	15.20002
2.5	1000	4.12690	4.41827	5.54375	8.49841	7.56990	8.10933	9.95432	14.76392
	500	4.11909	4.41821	5.54367	8.49830	7.56130	8.10922	9.95415	14.76325
	100	4.00722	4.41818	5.54327	8.49813	7.29029	8.10915	9.95405	14.76295
	50	3.76290	4.41817	5.54325	8.49810	6.55570	8.10913	9.95383	14.76282
	20	2.60227	4.41809	5.54317	8.49805	3.93707	8.10905	9.95332	14.76263

Table 5: K_r Values for Graphite/Epoxy anti-symmetric angle-ply laminated skew plates

Boundary Conditions	Skew Angle (α)			
	0°	15°	30°	45°
S-S-S-S	0.366	0.433	0.537	0.669
C-C-C-C	0.213	0.228	0.277	0.373

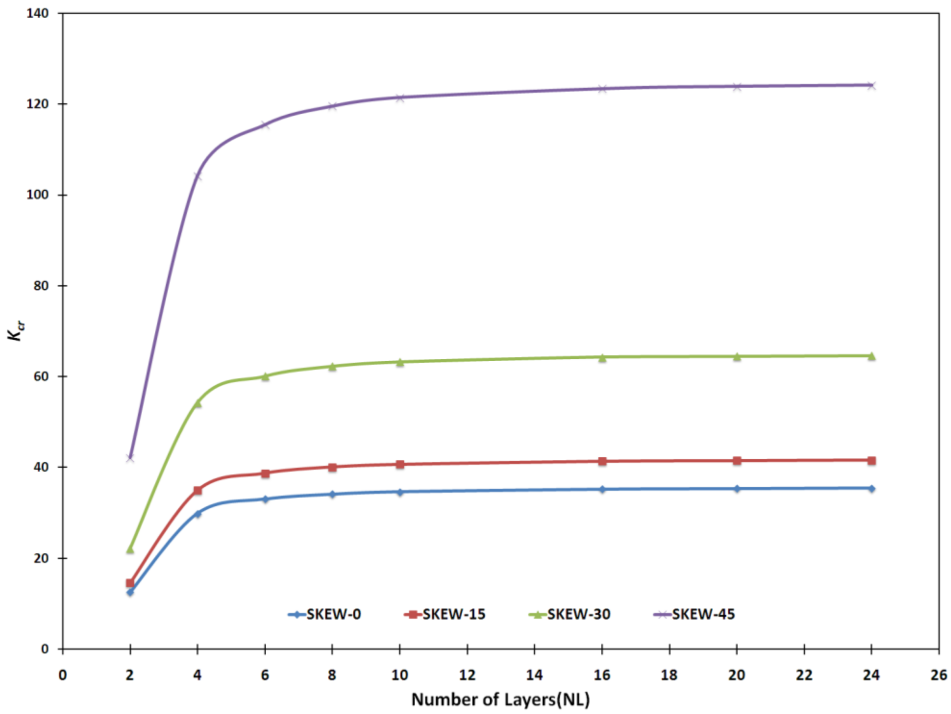

Figure 2: Critical buckling load parameter for simply supported anti-symmetric cross-ply laminated skew plates.

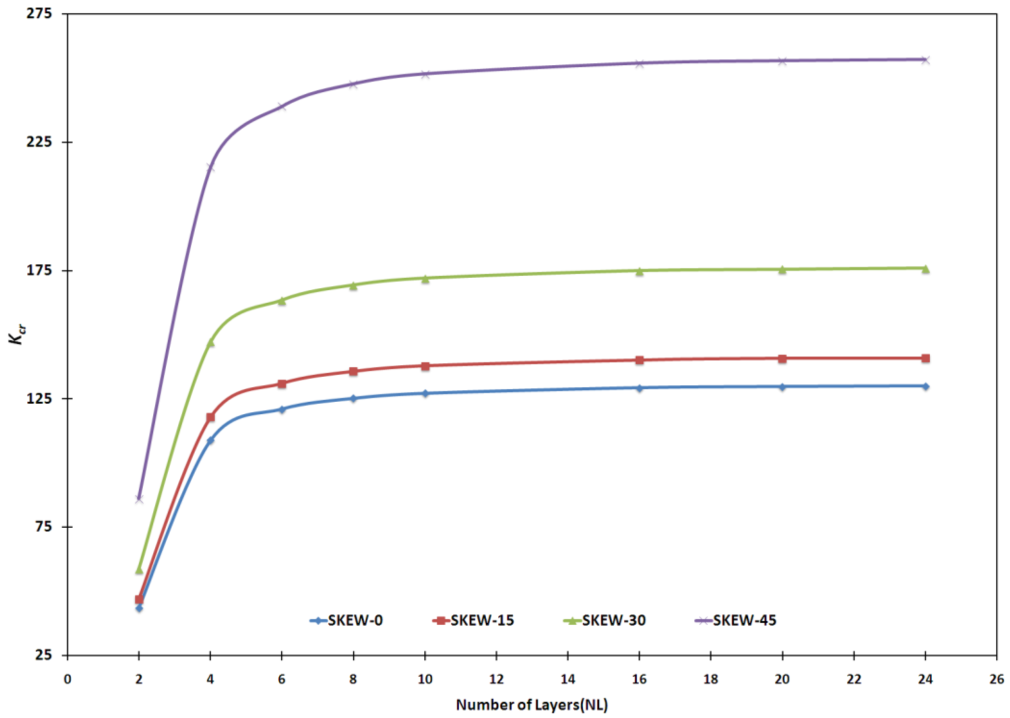

Figure 3: Critical buckling load parameter for clamped anti-symmetric cross-ply laminated skew plates.

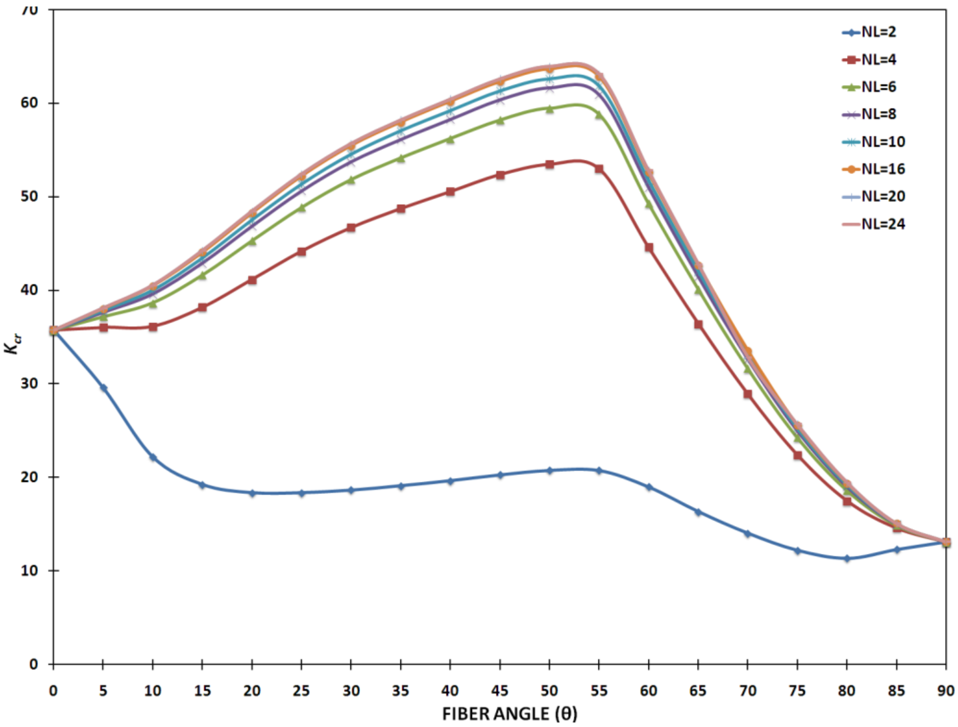

Figure 4: Critical buckling load parameter for simply supported anti-symmetric angle-ply laminated skew plates (Skew-0).

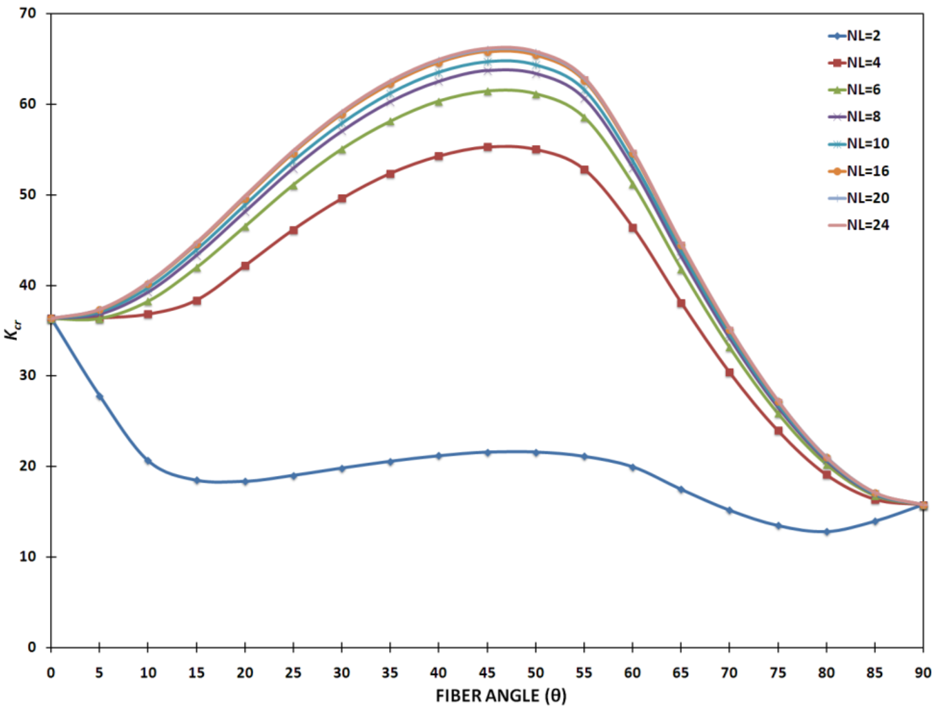

Figure 5: Critical buckling load parameter for simply supported anti-symmetric angle-ply laminated skew plates (Skew-15).

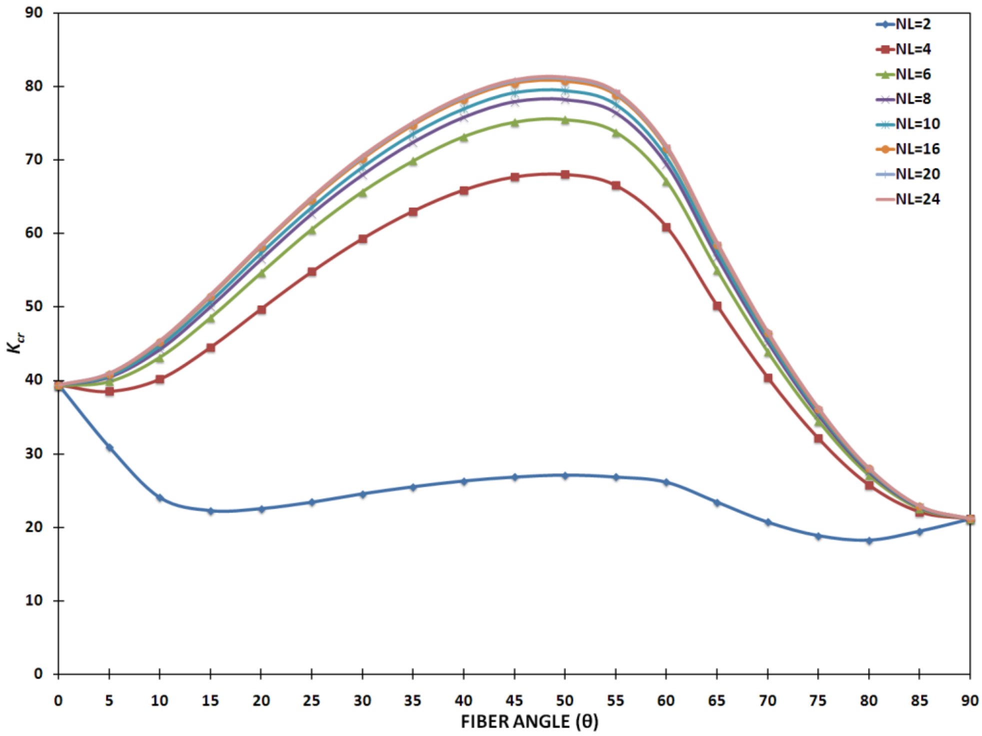

Figure 6: Critical buckling load parameter for simply supported anti-symmetric angle-ply laminated skew plates (Skew-30).

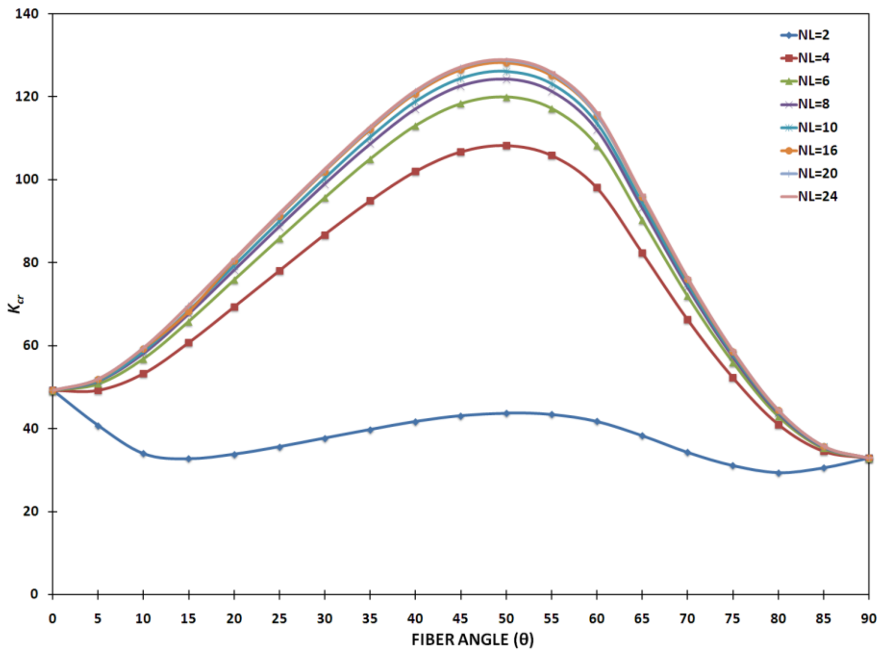

Figure 7: Critical buckling load parameter for simply supported anti-symmetric angle-ply laminated skew plates (Skew-45).

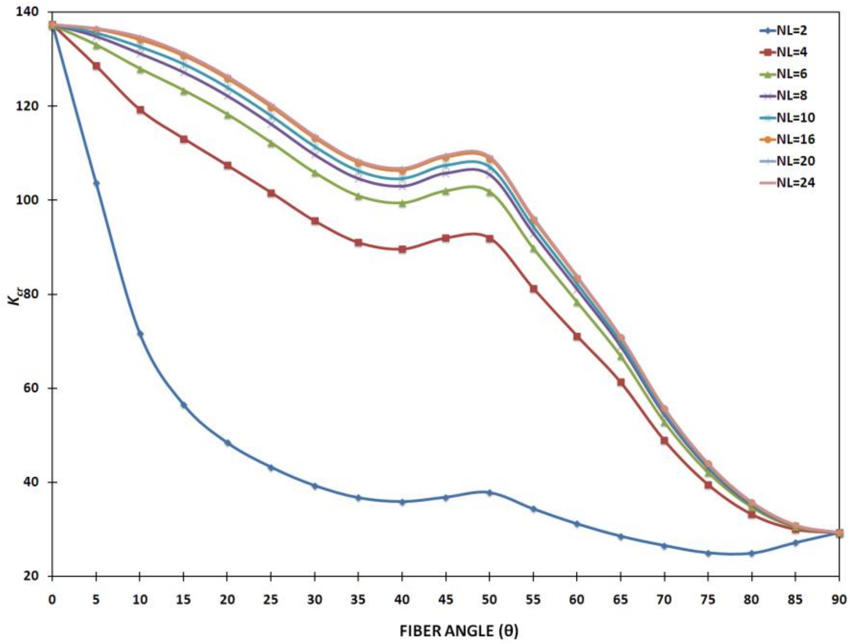

Figure 8: Critical buckling load parameter for clamped anti-symmetric angle-ply laminated skew plates (Skew-0).

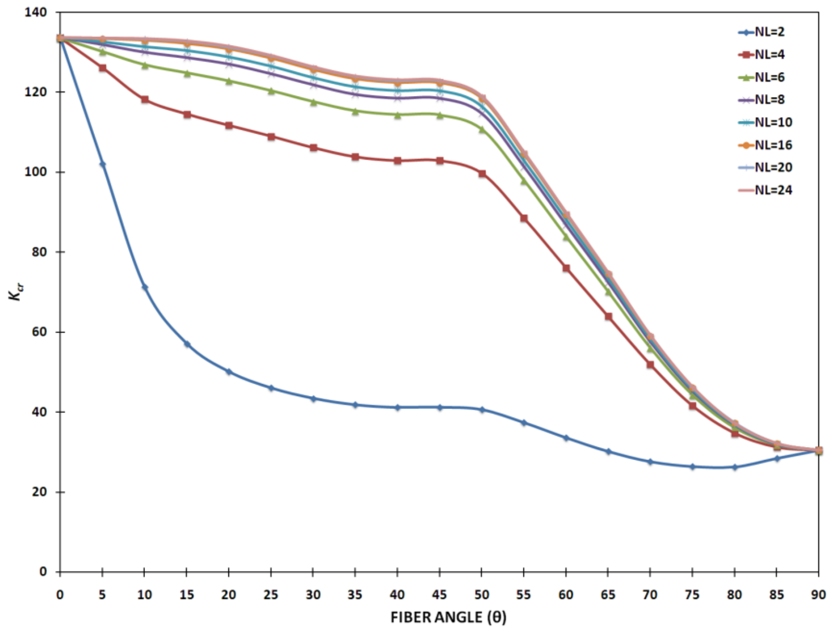

Figure 9: Critical buckling load parameter for clamped anti-symmetric angle-ply laminated skew plates (Skew-15).

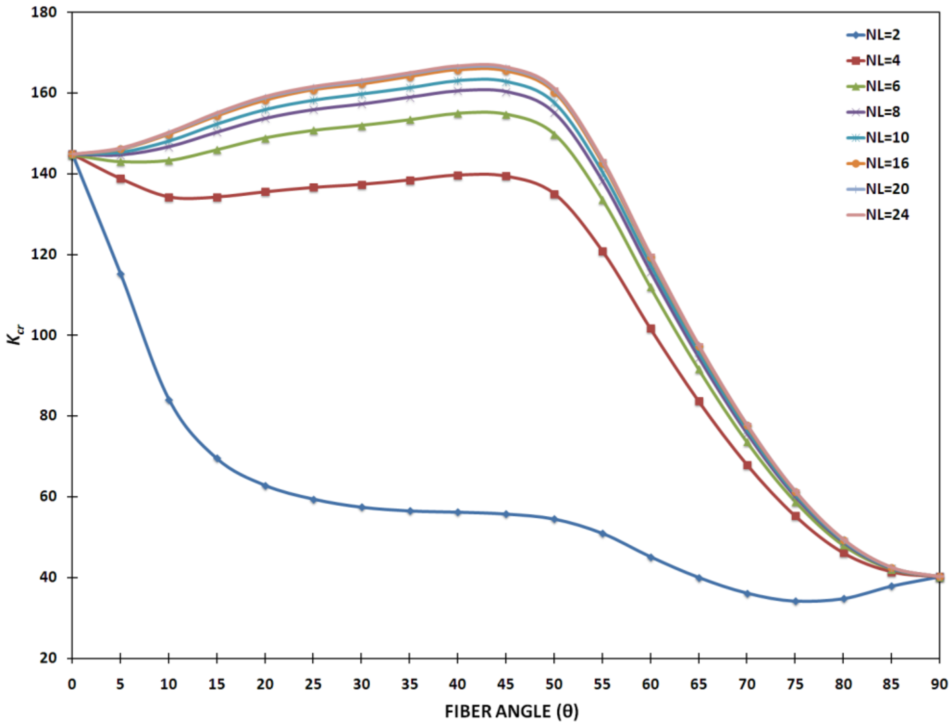

Figure 10: Critical buckling load parameter for clamped anti-symmetric angle-ply laminated skew plates (Skew-30).

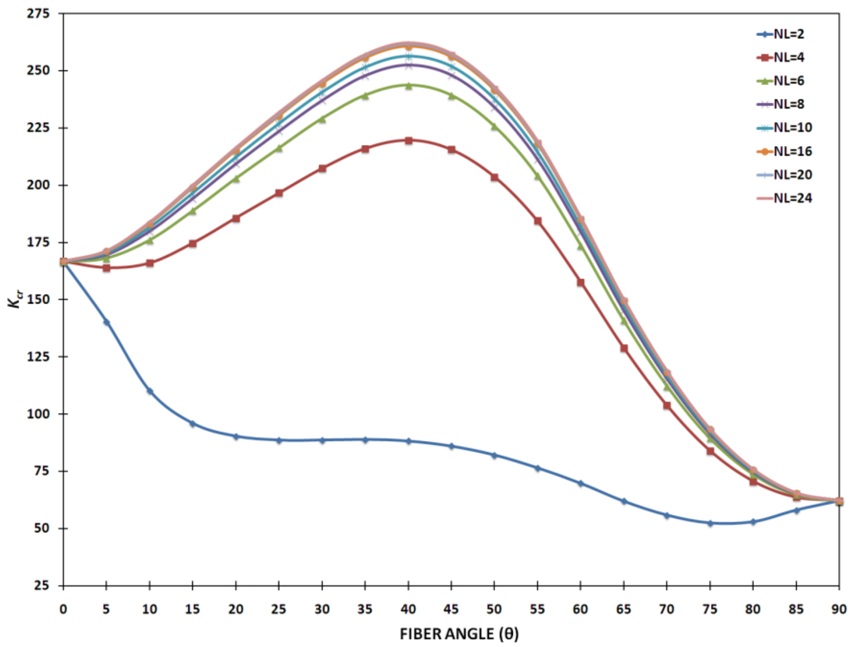

Figure 11: Critical buckling load parameter for clamped anti-symmetric angle-ply laminated skew plates (Skew-45).

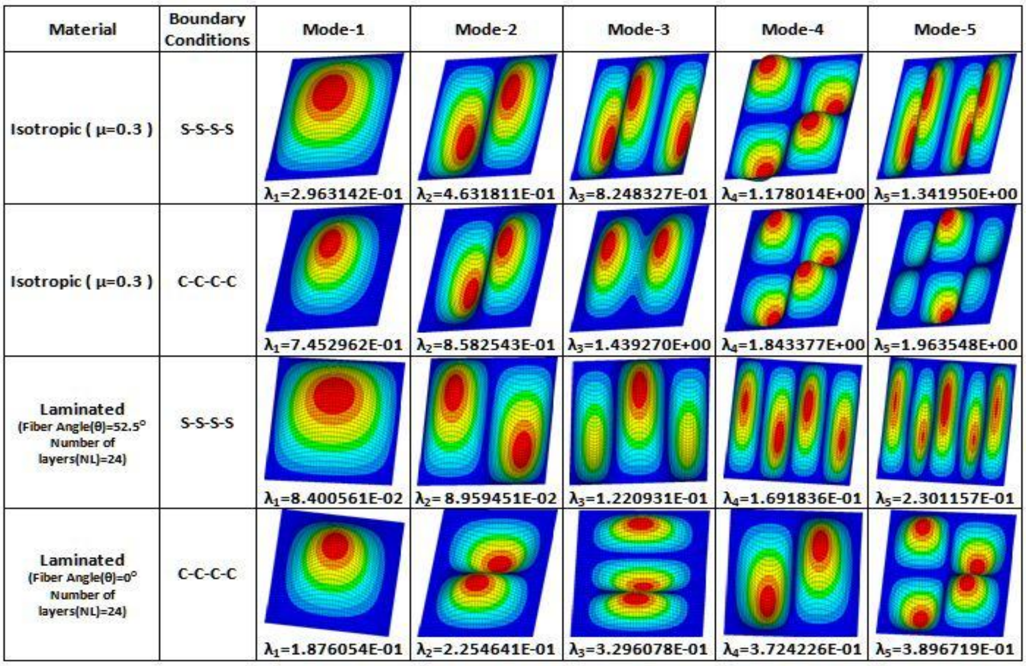

Figure 12: Buckling mode contour plots for isotropic and anti-symmetric angle-ply laminated square plates (Skew-0).

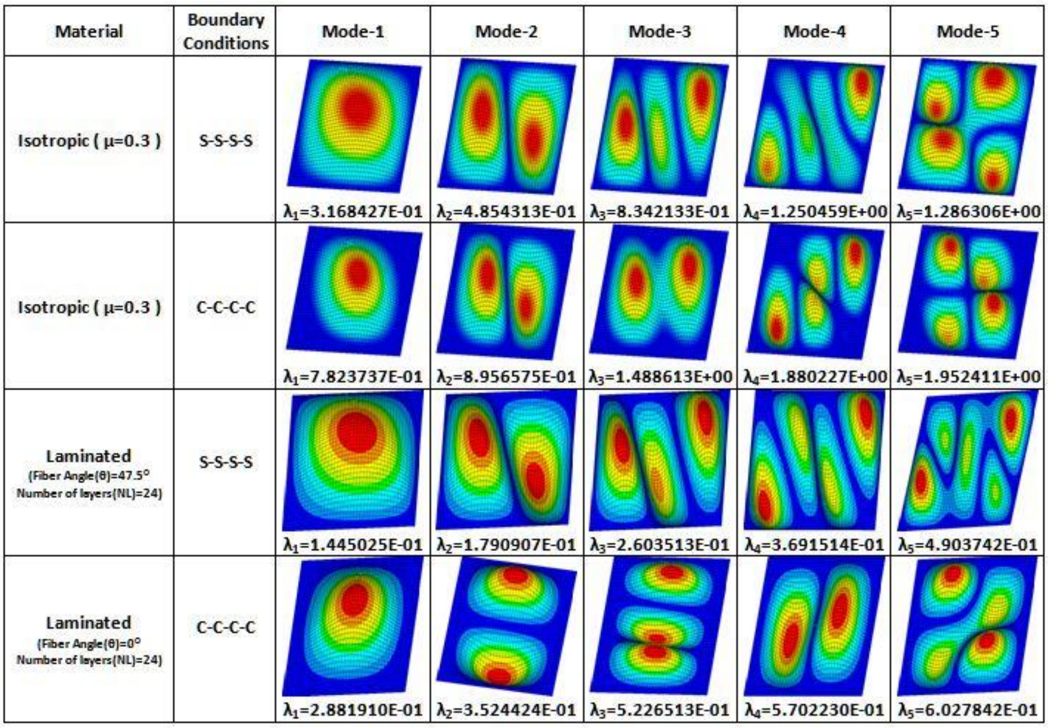

Figure 13: Buckling mode contour plots for isotropic and anti-symmetric angle-ply laminated skew plates (Skew-15).

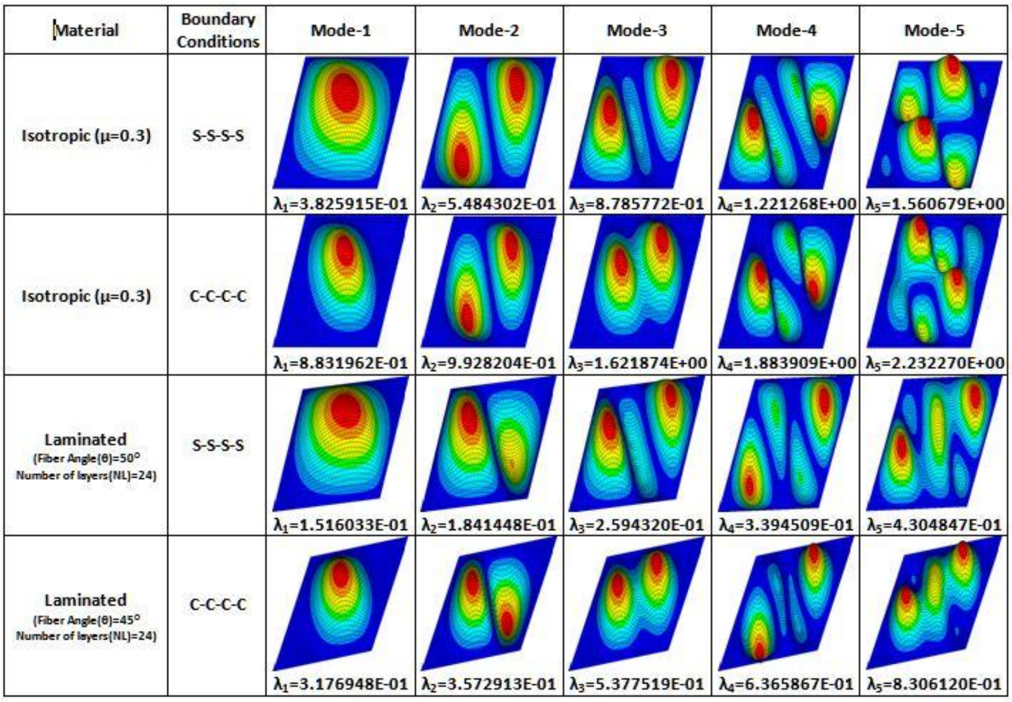

Figure 14: Buckling mode contour plots for isotropic and anti-symmetric angle-ply laminated skew plates (Skew-30).

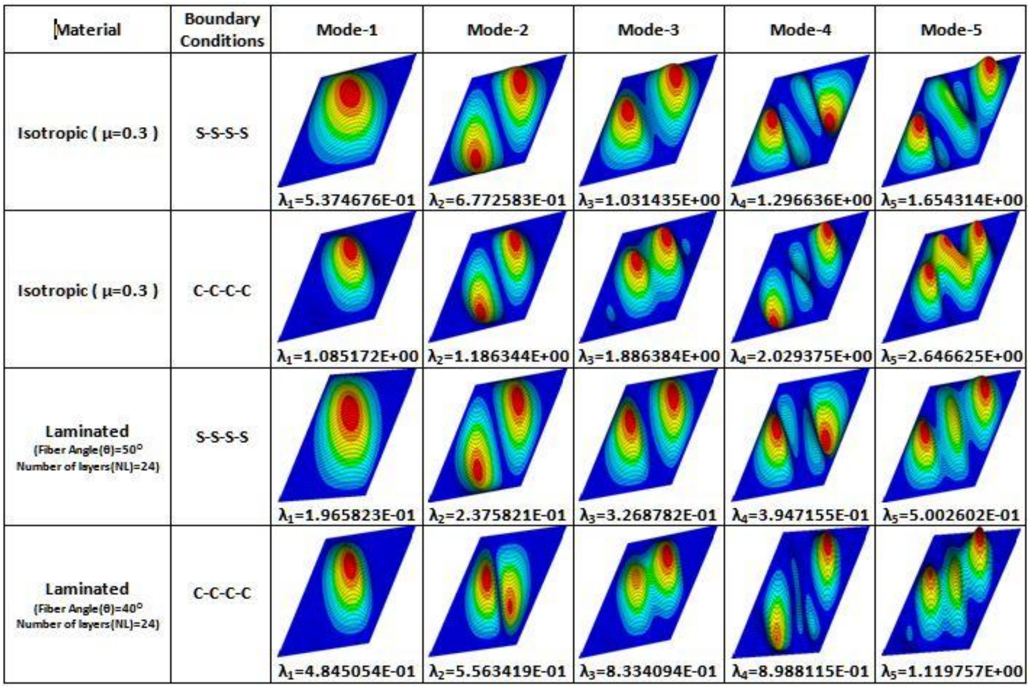

Figure 15: Buckling mode contour plots for isotropic and anti-symmetric angle-ply laminated skew plates (Skew-45).