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Parametric study on buckling behavior of thin laminated composite plates

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ABSTRACT

The fiber reinforced laminate composite plates, because of its outstanding mechanical properties such as high strength, high stiffness with less weight, durability, corrosion resistance, finds many engineering applications. In this work, local failure of plate alone in-between the stiffeners is taken for study. This work compares the buckling behavior of thin fiber reinforced laminate composite plates subjected to axial compression under different types of boundary conditions with different types and different angle of layups. For this purpose graphite / epoxy composite rectangular plate is used for the analysis. Further, by varying the dimension of plate, effect of the aspect ratio of the plate on the buckling strength of plate is also studied. Eigen buckling analysis of ANSYS is used for analysis.

Introduction

In many engineering structures such as columns, beams, or plates, the failure develops not only from excessive stresses but also from buckling. Only rectangular thin plates are considered in the present study. When a flat plate is subjected to low in-plane compressive loads, it remains flat and is in equilibrium condition. As the magnitude of the in-plane compressive load increases, however, the equilibrium configuration of the plate is eventually changed to a non-flat configuration and the plate becomes unstable. The magnitude of the compressive load at which the plate becomes unstable is called the “critical buckling load.”

A composite material consists of two or more materials and offers a significant weight saving in structures in view of its high strength to weight and high stiffness to weight ratios. Further, in a fibrous composite, the mechanical properties can be varied as required by suitably orienting the fibers. In such material the fibers are the main load bearing members, and the matrix, which has low modulus and high elongation, provides the necessary flexibility and also keeps the fibers in position and protect them from the environment.

Development of new applications and new composites is accelerating due to the requirement of materials with unusual combination of properties that cannot be met by conventional monolithic materials. Actually, composite materials are capable of covering this requirement in all means because of be varied as required by suitably orienting the fibers. In such material the fibers are the main load bearing members, and the matrix, which has low modulus and high elongation, provides the necessary flexibility and also keeps the fibers in position and protect them from the environment.

Literature Review

In the earlier literatures, a good amount of research was dedicated to study of buckling behavior of composite plates without cut-out. A brief review of research works carried on laminated composites under buckling load was discussed in Starnes and Rouse (1981), Kumar and Kishore (1991), Cheung et.al., (1993), Williams and Cairns (1994) and Gu and Chattopadhyay (2000). A brief review of research work carried on laminated composites under buckling load out up to 1987 was discussed in Leissa (1987). Similarly, Chamis (2006) reviewed the research and development in composite mechanics from 1965 to 2006. This review covers micromechanics, macro-mechanics failure theories, impact resistance, structural analysis, plate and panel buckling, shell buckling, progressive fracture, containment, and probabilistic composite simulation in the area of composite material research.

Uenoya and Redwood (1977) obtained critical loads for a square plate subjected to edge shear stress and containing centrally located circular holes by using the Rayleigh-Ritz method. In the work of Hirano (1979) and Muc (1988), it was concluded that the buckling resistance of rectangular composite laminate plates depends on ply orientations. Choen (1982) found the critical loads for rectangular anisotropic laminated plates by using the effect of transverse shear deformation and compared the results from three-dimensional elasticity with those of classical plate theory. Guedes Soares (1988) developed design equation for the compressive strength of unstiffened plate with initial imperfections under uniaxial compression. An exact solution to the buckling of antisymmetric angle-ply laminated plates was developed by Khdeir (1989) for various boundary conditions based on a generalized Levy type solution and results were compared with other literature works. Further, the influence of transverse shear deformation, the degree of anisotropy, number of layers, ply-angles, and by the character of the boundary conditions on buckling response characteristics of composite plates were also studied. Narita and Leissa (1990) studied buckling of simply supported symmetrically laminated rectangular plates by using Ritz method with classical plate theory. Tang and Sridharan (1990) employed finite strips in conjunction with a perturbation technique to determine the buckling strength of rectangular anisotropic composite layered plates with one pair of opposite edges simply supported. The

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results from the analysis were compared with analytical and experimental results.

Engelstad et al, (1992) presented a progressive failure analysis to investigate the post-buckling response and failure prediction of two graphite–epoxy panels loaded in axial compression. A degenerated shell element was employed and a limited property degradation model with the maximum stress criterion and a modified Tsai–Wu criterion [Tsai and Wu (1971)] was used to simulate the progressive failure process of the structure and the numerical results showed good agreement with the experimental results [Starnes and Rouse(1981)]. Kim and Hoa (1995) in their work studied theoretically, experimentally and numerically about the buckling behavior of composite plates subjected to bi-axial loading. Finite element analysis was performed considering large deflection but small strain conditions. Hu and Lin (1995) studied about the buckling resistance of rectangular composite laminate plates depends on end conditions and it was concluded that the plates with clamped boundary conditions will give higher buckling strength than other types of boundary conditions. Shrivastava and Singh (1999) studied about the buckling resistance of rectangular composite laminate plates depends aspect ratio of the plate.

Pekbey and Sayman (2006), in their work determined that the reduction in critical load for a square notched plate is more sensitive for thinner and simple plate than for clamped plate and further concluded that antisymmetric angle-ply laminates under the uniaxial compression have the best ability to resist, the optimum of which is the ([45°/–45°]n) laminate. Chen NZ and Soares (2007) developed a progressive failure analysis with use of the finite element code coupled with the Tsai–Wu criterion and a limited property degradation model to determine the post-buckling compressive strength of laminated composite plates and stiffened panels. The numerical accuracy and the computational efficiency of the progressive failure analysis were evaluated with experimental data, and other numerical results published in the references. A parametric study to investigate the effects of the stacking sequences and the lamina thickness on the post-buckling compressive strength of laminated composite plates and stiffened panels was also performed. Baltaci (2007) et.al, in their work studied about the effect of boundary conditions on buckling strength of the composite plate under uni-axial compression and it was concluded that the non-dimensional buckling load under C–C boundary condition is greater with respect to F–C and C–F boundary conditions.

Baba and Baltaci (2007) studied the influence of boundary conditions on the buckling load for rectangular plates. Boundary conditions consisting of clamped, pinned, and their combinations were considered. Numerical and experimental studies were conducted to investigate the effect of boundary conditions, length/thickness ratio, and ply orientation on the buckling behaviour of E-glass/epoxy composite plates under in-plane compression load.

Buckling analysis of the laminated composites is performed by using finite element analysis software ANSYS. Comparisons were made between the test results and predictions based on finite element analysis.

Chirica (2008) et.al, considered uni-axially in-plane loaded clamped, composite laminated quadratic plate for their numerical and experimental analysis. The imperfection is considered as the initial deformation due to the manufacturing operations: cosine shape in both of the longitudinal and transverse direction. Buckling strengths of the imperfect composite plates were determined numerically and as well as experimentally and are found to have good agreement with each other. In the study carry out by Özben (2009), the critical buckling value of fiber reinforced composite plate with different boundary conditions was calculated by analytical and finite element method. The composite deformation behavior and critical buckling values were determined according to aspect ratio of the plate dimension.

But, in this work, efforts are taken to compare the buckling behavior of thin laminate composite plate with symmetric and anti symmetric layups.

For this purpose, a graphite epoxy laminated composite plate with four laminates is taken for study. Also, a parametric study is carry out to determine the influence of aspect ratio, angle of layup, type of layup and different type of boundary conditions on the buckling strength of composite plate.

FE Modelling

Element selection

Shell99 element of ANSYS is used for all the analysis carried out in this work. This element allows up to 250 layers. If more than 250 layers are required, a user-input constitutive matrix is available. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes.

Validation of FE Model

For validating the eigen analysis used in this work, the Plate used in reference [Hu and Lin (1995)] is taken. The details of the plate and material properties are as follows.

Length = 200mm Width = 100 mm

No. of layup = 16 Thickness of laminate = 0.125 mm

Arrangement of layup $[\pm 40/90/0]_{2s}$

$E_{11} = 128 \times 10^3$ N/mm^2 $E_{22} = 11 \times 10^3$ N/mm^2

$G_{12} = 4.48 \times 10^3$ N/mm^2 $G_{13} = G_{23} = 1.53 \times 10^3$ N/mm^2

$\gamma = 0.25$

Loading and boundary conditions taken for validating FE model are shown in Fig.1.

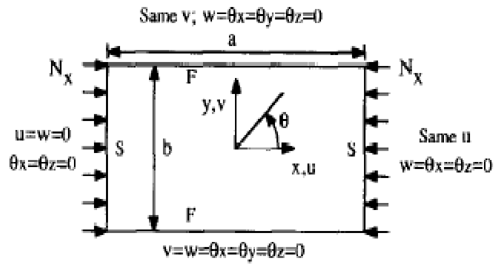


Fig. 1. Loading and boundary condition applied for validation of FE model

The mode shape obtained and comparison of buckling strength values are shown in Fig.2 and Table 1 respectively. Thus the selection of element and accuracy of the solutions are proved.

Table 1. Comparison of buckling strength

Mode shape	Buckling Strength (N)		
	[Hu and Lin (1995)]	Present work	% Difference
1	24100	24792	2.8

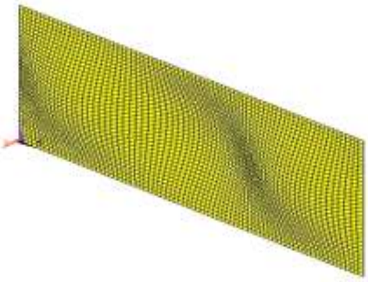
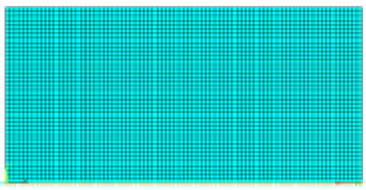


Fig. 2. First eigen model shape obtained for validation of FE model

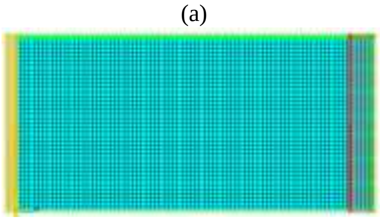
But, details of the plate and material properties considered for this study [Ozben (2009)] are as follows.

Length (L) : 250, 275 and 300 mm.
Width (W) : 150 mm.
Thickness of laminate (t) : 0.125 mm.
Angle of layup (θ) : 0, 15, 30 and 45^0
No. of layers : 4
Laminate type considered : Symmetric $(0/\theta)_s$ and Anti-symmetric $(0/\theta)_{as}$

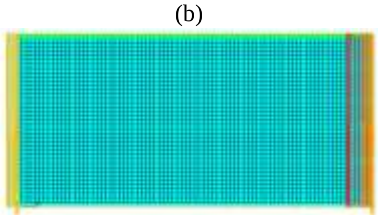
$E_{11} = 128\text{x}10^3$ N/mm^2 $E_{22} = 11\text{x}10^3$ N/mm^2
$G_{12} = 4.48\text{ x}10^3$ N/mm^2 $G_{13} = G_{23} = 1.53\text{ x}10^3$ N/mm^2
$\gamma = 0.25$



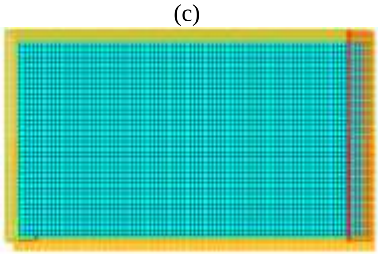
(a)



(b)



(c)



(d)

Fig. 3. FE model of plate with loading and (a) SSSS, (b) CSSS, (c) CCSS, (d) CCCC loading and boundary conditions

Results and Discussions

In this work, efforts are taken to study about the effects of parameters such as, aspect ratio, angle of layup, types of layup and boundary conditions on buckling strength of rectangular thin composite plates with four lamina laminate. The aspect ratio (L/W) of the plate is varied as 1.666, 1.843 and 2, keeping plate width (W) as 250mm. The angle of layup (θ) is varied as 0^0, 15^0, 30^0 and 45^0. The two patterns of layups are considered for analysis are symmetric $[0/\theta]_s$ and anti-symmetric $[0/\theta]_{as}$ layup. Four types of boundary conditions namely SSSS, CSSS, CCSS, CCCC, where S refers to simply supported boundary conditions and C refers to clamped boundary conditions.

SSSS Boundary conditions

(a) Symmetric layup

Table 2 and Fig. 4show the effect of aspect ratio and angle of layup on buckling strength of thin laminated composite plate having symmetric layup with SSSS boundary conditions.

Table 2. Effect of L/W and θ on buckling strength of thin composite plate having symmetric layup with SSSS boundary conditions.

Aspect ratio (L / W)	Buckling strength (N) for angle of layup (θ)			
	0^0	15^0	30^0	45^0
1.666	68.759	70.643	77.579	85.107
1.843	67.674	69.442	76.927	85.834
2	68.329	69.925	77.959	88.352

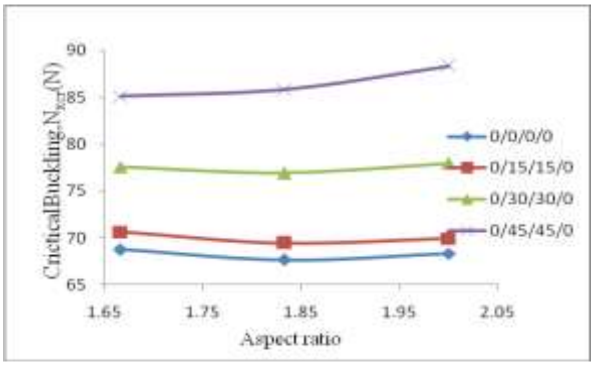


Fig.4. Effect of L/W and θ on buckling strength of thin composite plate having symmetric layup with SSSS boundary conditions.

It can be seen that as the aspect ratio of the plate increases buckling strength increases by very meager amount. For example highest deviation noticed at 45° is only 3.81%. But, this increase in buckling strength for increase in aspect ratio decreases as the angle of layup decreases.

As the angle of inclination of layup increases from 0°to 45° the increase in buckling strength is 23.78%. Hence it can be concluded that for same size of plate as the angle of layup increases buckling strength of the plate increases.

(b) Anti-symmetric layup

Table 3 and Fig. 5 show the effect of aspect ratio and angle of layup on buckling strength of thin laminated composite plate having anti-symmetric layup with SSSS boundary conditions.

Table 3. Effect of L/W and θ on buckling strength of thin composite plate having anti-symmetric layup with SSSS boundary conditions.

Aspect ratio (L / W)	Buckling strength (N) for angle of layup (θ)			
	0^0	15^0	30^0	45^0
1.666	68.759	75.547	92.935	110.08
1.843	67.674	75.057	94.452	112.16
2	68.329	76.118	97.223	114.87

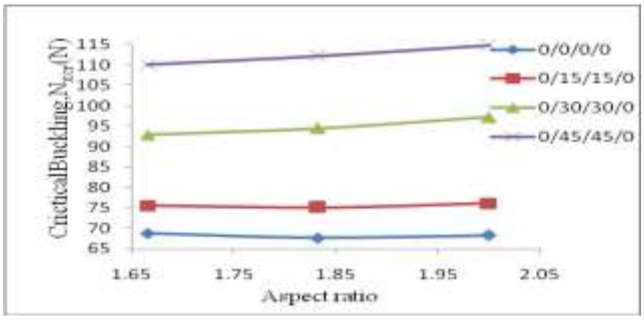


Fig. 5. Effect of L/W and θ on buckling strength of thin composite plate having anti-symmetric layup with SSSS boundary conditions.

Here also, it can be seen that as the aspect ratio of plate increases buckling strength increases by very meager amount. For example, highest deviation is noticed at 45° between aspect ratio 1.666 to 2 is only 4.94%. Further, for a particular aspect ratio, as the angle of layup increases the buckling strength of the plate increases. For example, this increases in buckling strength is 60% at L/W =1.666 and 64.14% at L/W = 2. From Figs. 4 & 5 and it is vividly seen that buckling strength of anti symmetric layup is higher than that of the corresponding symmetric layup. For example, for L/W = 2, θ=45°, the anti symmetric layup shows higher buckling strength than symmetric layup by 26.29% and the same at l/W=1.666 by 29.34%.

CSSS Boundary conditions

(a) Symmetric layup

Table 4 and Fig. 6 show the effect of aspect ratio and angle of layup on buckling strength of thin laminated composite plate having symmetric plate with CSSS boundary conditions applied i.e., reaction edge of the plate is clamped.

Table 4. Effect of L/W and θ on buckling strength of thin composite plate having symmetric layup with CSSS boundary conditions.

Aspect ratio (L / W)	Buckling strength (N) for angle of layup (θ)			
	0^0	15^0	30^0	45^0
1.666	101.64	102.82	112.89	129.35
1.843	102.94	107.18	117.66	137.45
2	111.82	114.58	120.76	136.08

From Fig.6, it can be seen that as the aspect ratio of the plate increases buckling strength increases by very meager amount. For example, the deviation in buckling strength noticed at 45^0, between aspect ratio 1.666 to 2 is only 4.94%. But, for particular aspect ratio as the angle of layup increase, buckling strength of the plate also increases. For example, at L/W =1.666, for variation of angle of layup from 0^0 to 45^0, the increase in buckling strength is 27.26%.

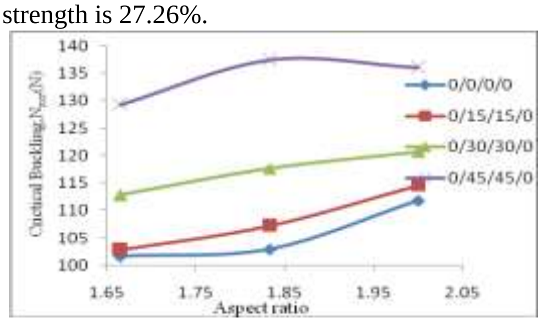


Fig. 6. Effect of L/W and θ on buckling strength of thin composite plate having symmetric layup with CSSS boundary conditions.

(b) Anti-symmetric layup

Table 5 and Fig. 7 show the effect of aspect ratio and angle of layup on buckling strength of thin laminated composite plate having anti-symmetric layup with CSSS boundary conditions.

Table 5. Effect of L/W and θ on buckling strength of thin composite plate having anti-symmetric layup with CSSS boundary conditions.

Aspect ratio (L / W)	Buckling strength (N) for angle of layup (θ)			
	0^0	15^0	30^0	45^0
1.666	101.64	109.31	135.78	152.89
1.843	102.94	114.36	137.14	145.65
2	111.82	117.88	131.87	141.98

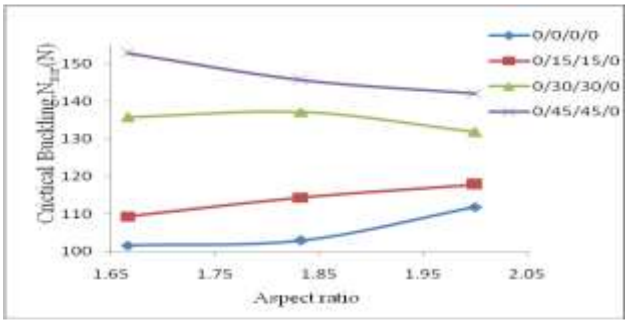


Fig. 7. Effect of L/W and θ on buckling strength of thin composite plate having anti-symmetric layup with CSSS boundary conditions.

Here also, from Fig. 7, it can be noted generally that for variation in the aspect ratio of plate, variation in buckling strength very meager. In case of θ = 0^0 and 15^0, the buckling strength meagerly increases with increases in aspect ratio But, for θ =30^0 and 45^0 buckling strength meagerly decreases as the aspect ratio increases.

From Fig .7, further it can be noted that as the angle of layup increases, the buckling strength increases generally. But here, this effect is more dominant at lower aspect ratio (i.e., L/W =1.666) than at higher aspect ratio.

From Figs 6 & 7, it can be clearly noted that buckling strength of anti symmetric layup is higher than that of the corresponding symmetric layup. For example at L/W = 2, θ=45^0, the anti symmetric layup shows higher buckling strength by 23.97% and the same at L/W =1.666 by 18.19%.

CCSS Boundary conditions

(a) Symmetric layup

Table 6 and Fig. 8show the effect of aspect ratio and angle of layup on buckling strength of thin laminated composite plate having symmetric plate with CCSS boundary conditions applied. i.e., both loading and reaction edges of the plate are clamped.

Table 6. Effect of L/W and θ on buckling strength of thin composite plate having symmetric layup with CCSS boundary conditions.

Aspect ratio (L / W)	Buckling strength (N) for angle of layup (θ)			
	0^0	15^0	30^0	45^0
1.666	159.09	159.76	170.94	185.97
1.843	155.57	157.32	162.76	173.74
2	145.85	146.82	154.1	166.7

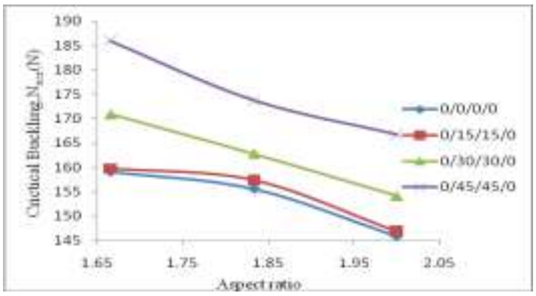


Fig. 8. Effect of L/W and θ on buckling strength of thin composite plate having symmetric layup with CCSS boundary conditions.

From Fig.8, it can be seen that as the aspect ratio of the plate increases buckling strength decreases meagerly. For example, the highest deviation in buckling strength is noticed at 45^0 is only 10.37%. For a particular aspect ratio, as the angle of layup increases from 0^0 to 45^0 the increase in buckling strength is 16% at L/W =1.666 and 14.29% at L/W = 2.

(b) Anti-symmetric layup

Table 7 and Fig. 9 show the effect of aspect ratio and angle of layup on buckling strength of thin laminated composite plate having anti-symmetric layup with CCSS boundary conditions.

Table 7. Effect of L/W and θ on buckling strength of thin composite plate having anti-symmetric layup with CCSS boundary conditions.

Aspect ratio (L / W)	Buckling strength (N) for angle of layup (θ)			
	0^0	15^0	30^0	45^0
1.666	159.09	165.54	174.39	186.09
1.843	153.57	156.11	166.68	184.99
2	145.85	148.01	163.25	187.96

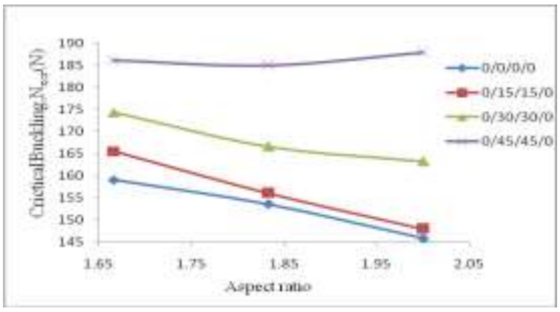


Fig. 9. Effect of L/W and θ on buckling strength of thin composite plate having anti-symmetric layup with CCSS boundary conditions.

From Fig. 9, it can be seen that as the aspect ratio of plate increase in buckling strength decreases meagerly for θ = 0^0, 15^0 and 30^0, but for θ =45^0 increase meagerly.

Further, for a particular aspect ratio, as the angle of layup increases from 0^0 to 45^0 the increases in buckling strength is 16.48% at L/W =1.666 and 28.02% at L/W = 2.

From Figs. 8 & 9, it is clearly noticed that buckling strength of anti-symmetric layup is higher than that of the corresponding symmetric layup.

For example L/W = 2, θ=45^0, the anti- symmetric layup shows higher buckling strength by 12.7% at L/W = 2 and 18.19% at L/W =1.666.

CCCC Boundary conditions

Symmetric layup

Table 8 and Fig. 10 show the effect of aspect ratio and angle of layup on buckling strength of thin laminated composite plate having symmetric layup with CCCC boundary conditions.

Table 8. Effect of L/W and θ on buckling strength of thin composite plate having symmetric layup with CCCC boundary conditions.

Aspect ratio (L / W)	Buckling strength in (N) for angle of layup(θ)			
	0^0	15^0	30^0	45^0
1.666	221.49	225.11	227.73	235.68
1.843	212.86	217.69	220.68	226.49
2	208.68	215.29	217.09	220.77

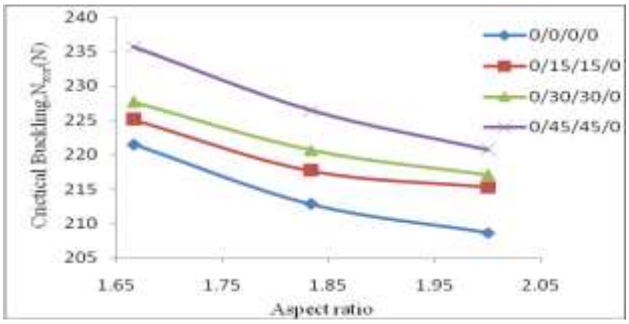


Fig. 10. Effect of L/W and θ on buckling strength of thin composite plate having symmetric layup with CCCC boundary conditions

From this figure, it can be seen that as the aspect ratio of the plate increases, buckling strength decreases. For example, this deviation at θ = 45^0 is only 7.5%. Further, as the angle of layup increases from 0^0 to 45^0 the increase in buckling strength is 7% at L/W =1.666 and 5% at L/W = 2.

(b) Anti-symmetric layup

Table 9 and Fig. 11 show the effect of aspect ratio and angle of layup on buckling strength of thin laminated composite plate having anti symmetric layup with CCCC boundary conditions.

Table 9. Effect of L/W and θ on buckling strength of thin composite plate having anti-symmetric layup with CCCC boundary conditions.

Aspect ratio L / W	Buckling strength in (N) for angle of layup (θ)			
	0^0	15^0	30^0	45^0
1.666	221.49	232.11	240.28	255.07
1.843	212.86	222.69	232.35	246.21
2	208.68	218.29	225.29	240.32

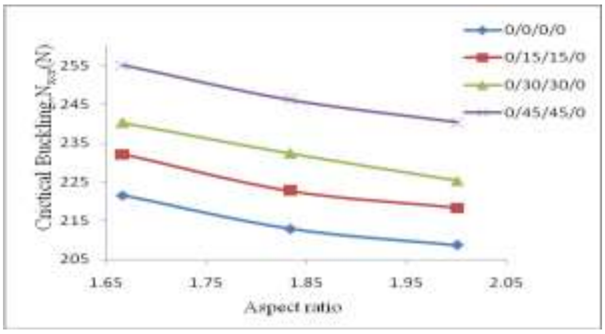


Fig. 11. Effect of L/W and θ on buckling strength of thin composite plate having anti-symmetric layup with CCCC boundary conditions.

From this figure, it can be seen that as the aspect ratio of plate increases in buckling strength decreases for all layup, As the angle of inclination of layup from 0° to 45°, the increases in buckling strength is 12.36% at L/W =1.666 and 13.198% at L/W = 2. From Fig. 10 &11it is clearly noticed that buckling strength of anti symmetric layup is higher than that of the corresponding symmetric layup. For example L/W = 2, θ=45°, the anti-symmetric layup shows higher buckling strength by 8.85% at L/W = 2 and 2.73% at L/W =1.666. Comparing Figs.4-11, it can be clearly observed that the buckling strength of anti-symmetric plate is higher than that of the symmetric plate at all angle of layup and at all aspect ratio. And it is also clear that the plate with clamped boundary conditions (CCCC) having anti-symmetric layup shows higher buckling strength compared to all other cases considered.

Conclusions

The following conclusions are derived from the eigen analysis of composite plate taken for study.

1. The effect of aspect ratio on buckling strength of the plate is meager compared to the effect of angle of layup.
2. As the angle of layup increases from 0° to 45° buckling strength increases considerably.
3. Among the cases considered, anti-symmetric layup with clamped boundary conditions (CCCC) shows highest buckling strength than the other types of boundary conditions considered in this analysis.
4. Among the cases considered, symmetric layup with simply supported boundary conditions (SSSS) shows lowest buckling strength than the other types of boundary conditions considered in this analysis.
5. In general, anti-symmetric layup arrangement gives higher buckling strength than symmetric layup arrangement of laminates.

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