American Journal of Engineering Research (AJER)
e-ISSN : 2320-0847 p-ISSN : 2320-0936
Volume-02, Issue-07, pp-33-40
www.ajer.org

Research Paper Open Access

Buckling Analysis of Woven Glass Epoxy Laminated Composite Plate

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Abstract: Buckling behavior of laminated composite plates subjected to in-plane loads is an important consideration in the preliminary design of aircraft components. The sizing of many structural subcomponents of the aircraft structures is often determined by stability constraints. The objective of the current study is to understand the influence of the length-to-thickness ratio, the aspect ratio, the fiber orientation and the cut-out shapes on the buckling load for the glass epoxy laminated composite plate in clamped-free-clamped-free configuration by FE analysis using MSC.Patran/Nastran. Initially, buckling analysis was carried out on aluminum plates, both; experimentally and numerically; for the two different geometric configurations to predict the critical buckling load and the test results were compared with the FEA predictions, to check the validity of the analysis methodology. The same methodology was further followed for analyzing the buckling behavior of the composite plates. The results shows the effect of orientation of fiber, aspect ratio, cut-out shape and length-to-thickness ratio on the buckling of the glass epoxy laminated composite plate.

Keywords: *- Plate buckling, woven glass epoxy laminate, length-to-thickness ratio, aspect ratio, fiber orientation, cut-out shapes*

I. INTRODUCTION

Development of new applications using 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 their heterogeneous nature. Properties of composite arise as a function of its constituent materials, their distribution and the interaction among them and as a result an unusual combination of material properties can be obtained.

Laminated composites are gaining wider use in mechanical and aerospace applications due to their high specific stiffness and high specific strength. Fiber-reinforced composites are used extensively in the form of relatively thin plate, and consequently the load carrying capability of composite plate against buckling has been intensively considered by researchers under various loading and boundary conditions. Due to the excellent stiffness and weight characteristics, composites have been receiving more attention from engineers, scientists, and designers. During operation, the composite laminate plates are commonly subjected to compression loads that may cause buckling if overloaded. Hence their buckling behaviors are important factors in safe and reliable design of these structures.

There are few studies on optimal design of simply supported rectangular plates laminated to composite material and subjected to uniaxial compressive loading [1,5]. Numerical results are presented for optimal-design plates laminated of glass/epoxy, boron/epoxy, and carbon/epoxy composite materials. Initially, few studies were made on thin-walled structures which are having high strength coupled with the ease of manufacturing and the relative low weight. However, thin-walled structures have the characteristic of susceptibility of failure by instability or buckling. It is therefore important to the design engineer that accurate methods are available to determine the critical buckling strength [8].

A procedure for determining the buckling load of the aluminum rectangular plate is carried out where buckling loads are determined from different experiment methods and were compared with the theoretical buckling loads and also various formulation based on the first-order shear deformation theory and von-Karman-type nonlinearity to estimates the critical/buckling loads of laminated composite rectangular plates under in-plane uniaxial and biaxial loadings. Different combinations of simply supported, clamped and free boundary conditions were considered [5, 11]. Also, the influence of boundary conditions on the buckling load for rectangular plates was studied [2]. Numerical and experimental studies were conducted to investigate the effect of boundary conditions, length/thickness ratio, and ply orientation on the buckling behavior of E-glass/epoxy composite plates under in-plane compression load.

It was found that most of the studies were focused on unidirectional fiber. Industry driven woven fibers are being increasingly used in many industries. Hence more importance is give on its structural behavior. It also indicates that the interaction among stacking sequence, cutout shape and length/thickness ratio on the buckling behavior of woven fiber laminated composites are needed to investigate in more detail. The aim of performing this work is to extend the knowledge of the structural behavior of woven fabric composites subject to compressive load which is lacking. The main objective of this study is to carry out buckling analysis of symmetrically and laminated composite plates under clamped-free–clamped-free boundary condition. The effects on buckling load by cut out size, length/thickness ratio, ply orientation and cut-out shapes are investigated.

II. EXPERIMENTAL STUDY

Experimental studies were carried on the following two Al-plate configurations to find out the critical buckling load:

- Rectangular Al 2024 T3 plate (300×200×1.6 mm)
- Square Al 2024 T3 plate (300×300×1.6mm)

This experimental study was carried out to validate the buckling results obtained from FEA, so that the same analysis methodology can be followed for the buckling analysis of woven fabric composite plates. The experiment comprises of an aluminum plate clamped on two longitudinal ends on an INSTRON 1341 testing machine of 50KN capacity and kept free at the other two. Then it was loaded in axial compression. Clamped boundary conditions were simulated along the top and bottom edges, restraining 50mm length and the test specimens were mounted on the testing machine through the mechanical fixtures. The top fixture was held fixed during the test whereas the bottom fixture was moved by servo hydraulic cylinder.

Figure 1: Buckling test setup and onset of buckling in rectangular aluminum plate

As the load was increased the dial gauge needle started moving and at a particular value of the load applied, there was a sudden large movement of the needle and thus the 1st mode buckling was observed. The load corresponding to this point is the critical buckling load of the plate.

The same test procedure was repeated, similarly, for the square aluminum plate and under the similar loading conditions, the dial gauge showed sudden large movement of the needle due to the large out-of-plane deformation of the plate and thus the 1st mode buckling was observed. The load vs. displacement curve was plotted and the load at which the initial part of the curve deviated from linearity was taken as the Critical buckling load.

Figure 2: Buckling test setup and onset of buckling in square aluminum plate

III. FINITE ELEMENT ANALYSIS

3.1 FE Buckling Analysis of Aluminum 2024-T3 Plates

In this study, linear static buckling analysis was carried out on both aluminum plates and for the woven fabric laminated composite plates using MSC.Patran and MSC.Nastran package to estimate critical buckling load in order to study the influence of length-to-thickness ratio, the ply orientation, cut out shape and the aspect ratio on the buckling behavior of the woven fabric laminated composite plate.

Here QUAD4 shell elements of 1 mm global edge length were used to mesh the model and the total number of elements was around 60,000 with 60500 nodes. The solution was found using Solution Sequence 105 under Buckling solution type employing the Lanczos extraction method for the 1st mode buckling i.e. for the 1st Eigen value.

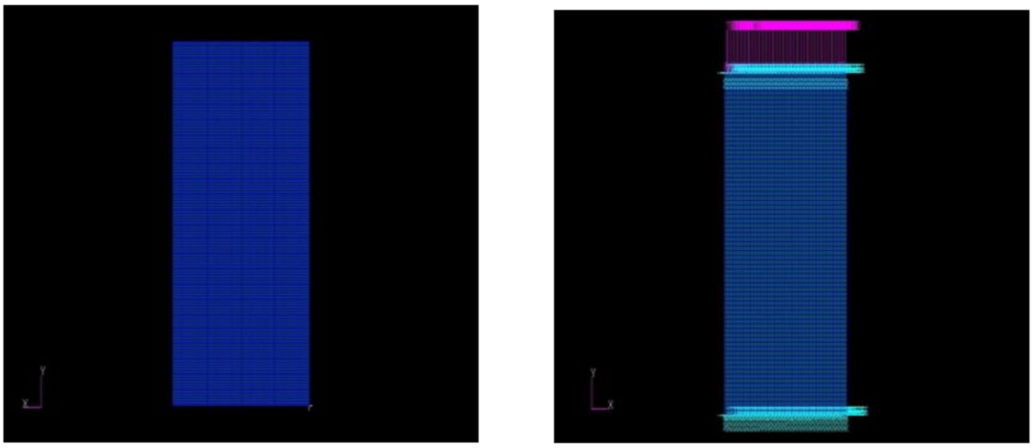


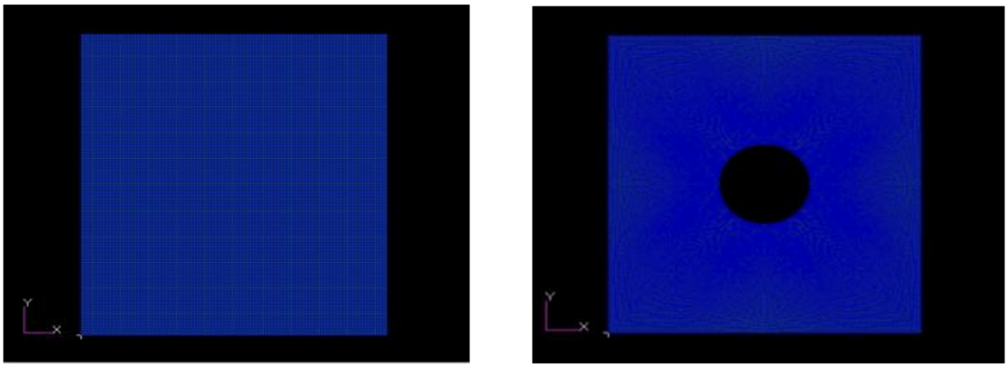
Figure 3: FE model and Boundary conditions applied for the square aluminum plate

3.2 FE Buckling Analysis of Composite Plates

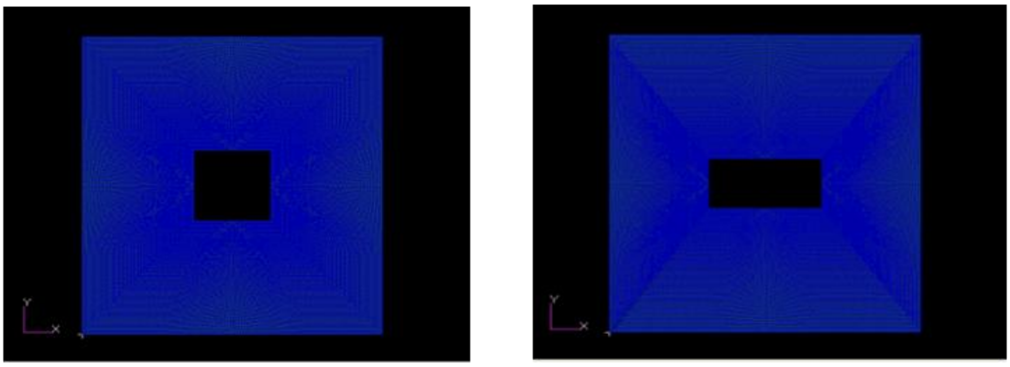
Following the validity for the correctness of the methodology used for the analysis of the aluminum plate, the same procedure was followed for the analysis of the composite plates. The mechanical properties of the analyzed specimens were $E_{11} = 7700$ N/mm^2, $E_{22} = 7700$ N/mm^2, $\nu = 0.12$ and $G_{12} = 2810$ N/mm^2.

The widths of the plates were kept constant while varying the lengths so as to study the effect of aspect ratio on the buckling behavior. Also the thicknesses were varied for the same lengths of the plates so as to study the effect of length-to-thickness ratio. Since woven fabric composite plates were considered for the analysis, the orientation of the fiber which was initially kept 0° was then changed to the 30°/-30° alignment and to 45°/-45°, in order to study the effect of fiber orientation as well.

The analysis was carried out considering the plate to be two-dimensional orthotropic laminate and the composite to be laminated. Also the loading the plate was carried along the fiber direction in the FE analysis. Also, in order to study the effect of the cut-out shapes on buckling behavior, three different cut-out shapes, namely, circular, square, and rectangular were analyzed for $[0]_{12}$ plates keeping the cut-out area constant as 962 mm^2.



a. Without cut-out b. Circular cut-out



c. Square cut-out d. Rectangular cut-out

Figure 4: FE model of composite plates with different cut-out shapes

IV. RESULT AND DISCUSSION

4.1 Buckling Results for Aluminum 2024-T3 plates

The experimental analysis of the two aluminum plates yielded the load vs. displacement curve with the displacement on the x- axis and the load on the y-axis. That critical buckling load point was determined from the intersection of two tangents drawn from the pre-buckling and post-buckling regions. From the graph shown in the Figure- 5, it can be seen that for the rectangular aluminum plate, the load becomes constant at 2.26 kN. This represents the 1st mode buckling of the specimen after which the plate is considered failed. Since the thickness of the plate is very small, the plate shows a large deflection for small increment in the load.

Also, the FE analysis result for the buckled shape of the rectangular aluminum plate is shown in the Figure 6. It is observed that the critical buckling load for the rectangular specimen is determined as 2.52 kN.

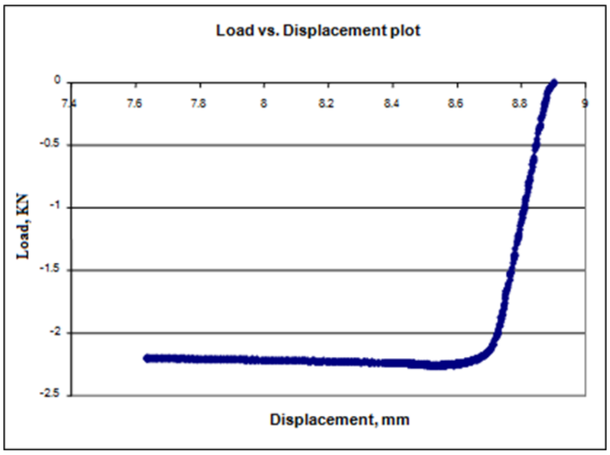


Figure 5: Load vs. out-of-plane displacement graph for rectangular aluminum plate

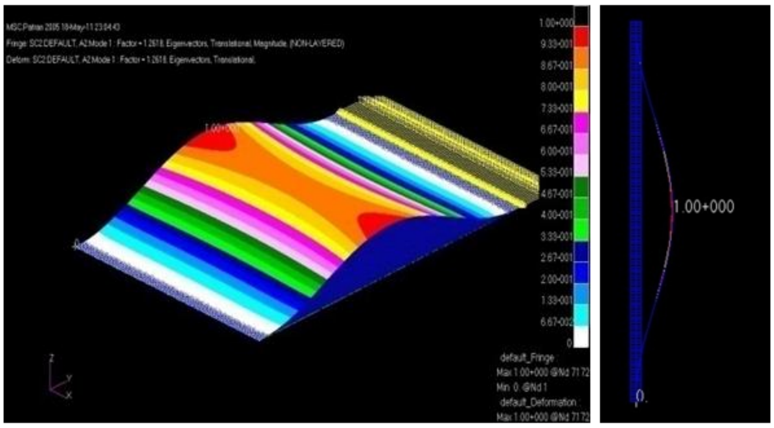


Figure 6: Buckled shape of the rectangular aluminum plate

Similarly, the load vs. out-of-plane displacement for square aluminum plate is shown in the figure-7. From the graph, it can be observed that the 1st mode buckling load is 2.87 kN.

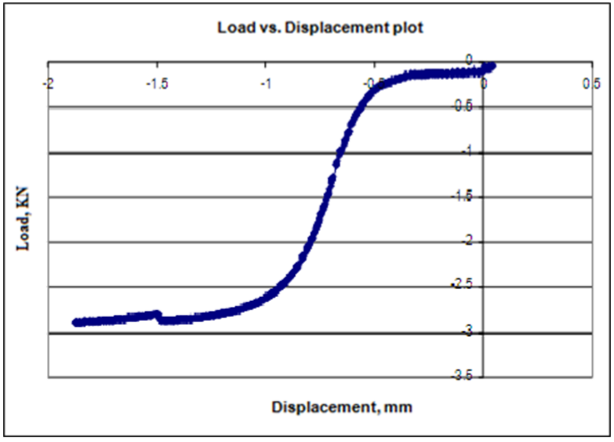


Figure 7: Load vs. out-of-plane displacement graph for square aluminum plate

The FE analysis result for the buckled shapes of the square aluminum plate is shown in the figure 8. It is observed that the critical buckling load for the square specimen is determined as 3.24 kN.

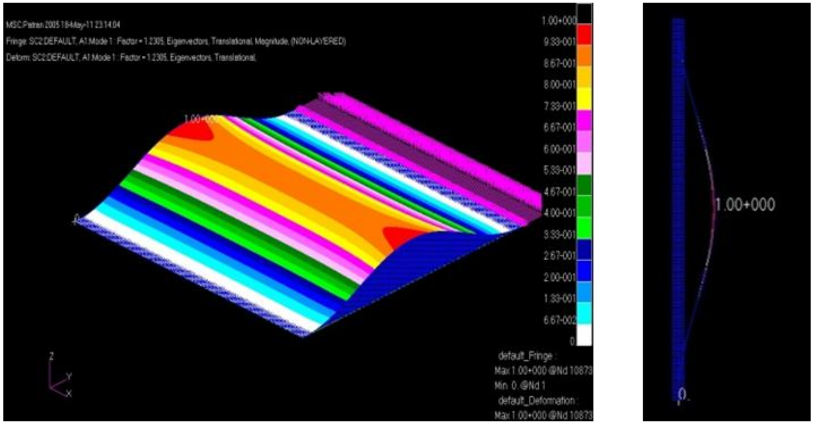


Figure 8: Buckled shape of the square aluminum plate

Table I: Buckling Results for Aluminum Plates

Plate Type	Length (mm)	Width (mm)	Thickness (mm)	Expt P_{cr} (KN)	FE Pcr (KN)
Rectangle	300	200	1.6	2.24	2.52
Square	300	300	1.6	2.52	3.24

4.2 Buckling Results for Composite Plates

The laminated composite plates were analyzed for determining the critical buckling load. The effect of length-to-thickness ratio, aspect ratio, fiber orientation and cut-out shapes on the buckling load for the woven glass epoxy laminated composite plate is studied.

4.2.1 Effect of Length-to-Thickness (a/t) ratio on Buckling Load

In this study the thickness of the plate was increased by increasing number of layers as shown in the figure 9. Here the length-to-thickness ratio was varied between 33.77 and 98.48. We can observe that the numerical results show that the variation in buckling load is very sensitive to the thickness and the buckling load decreases with increase in length to thickness ratio.

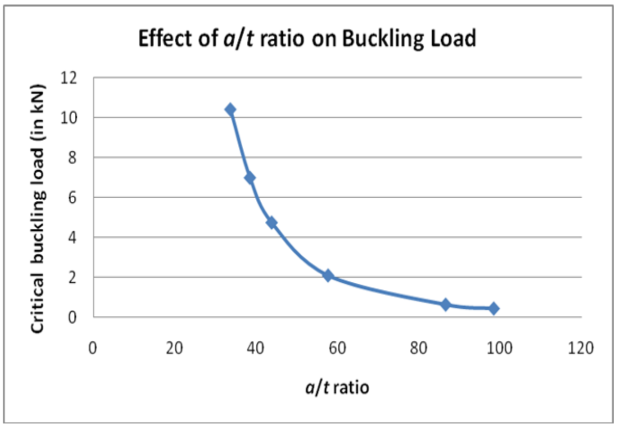


Figure 9: Buckling load vs. length-to-thickness (a/t) ratio

4.2.2 Effect of Aspect (a/b) ratio on Buckling Load

In this study, the laminated plates were evaluated at three different aspect ratios. The buckling load decreases continuously with increasing aspect ratio but the rate of decrease is not uniform It is observed that buckling load was maximum for aspect ratio 1.08 and minimum for aspect ratio 1.67. The aspect ratio and buckling load was plotted along x- and *y*- axis as shown in figure 10. From the graph, it is observed that the buckling load is decreases with the increase in the aspect ratio.

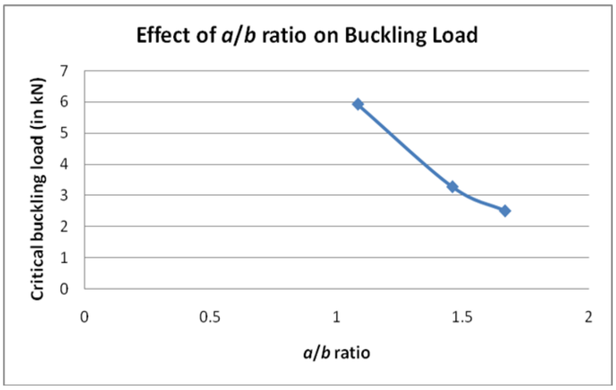


Figure 10: Buckling load vs. aspect (a/b) ratio

4.2.3 Effect of Fiber Orientation on Buckling Load

In this study the buckling load of composite plates with different fiber orientation was determined. The result shows the decreasing trend of the buckling load with increase in the fiber orientation. The maximum buckling load occurred for 0° fiber orientation. The variation of buckling load with fiber orientation is shown in figure 11. From the figure, it is observed that with the increase in fiber orientation, the buckling load decreases.

4.4.4 Effect of Cut-out Shapes on Buckling Load

In this section, in order to understand the effects of circular, square and rectangular shaped cut-outs on buckling load, plates with these cut-out shapes of equal areas were considered. From the Table 2, it can be observed buckling load generally decreases with the presence of cut-out. The plate with rectangular cut-out gives the least buckling load of 7.23 kN and for the one with the circular cut-out, the highest buckling load was observed with 7.89 kN.

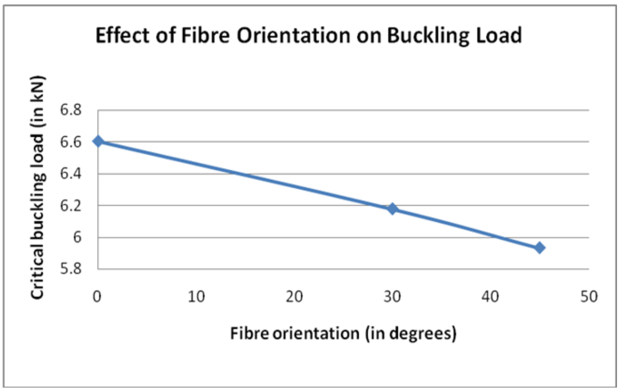
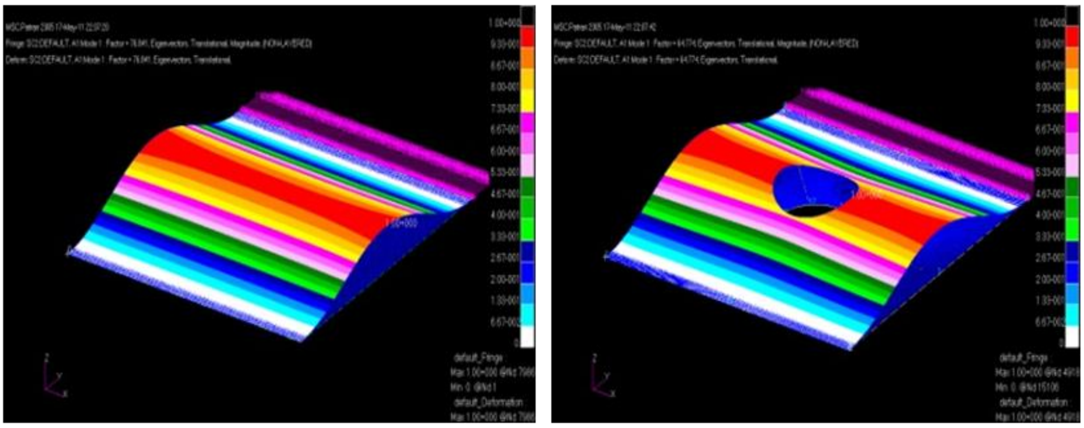
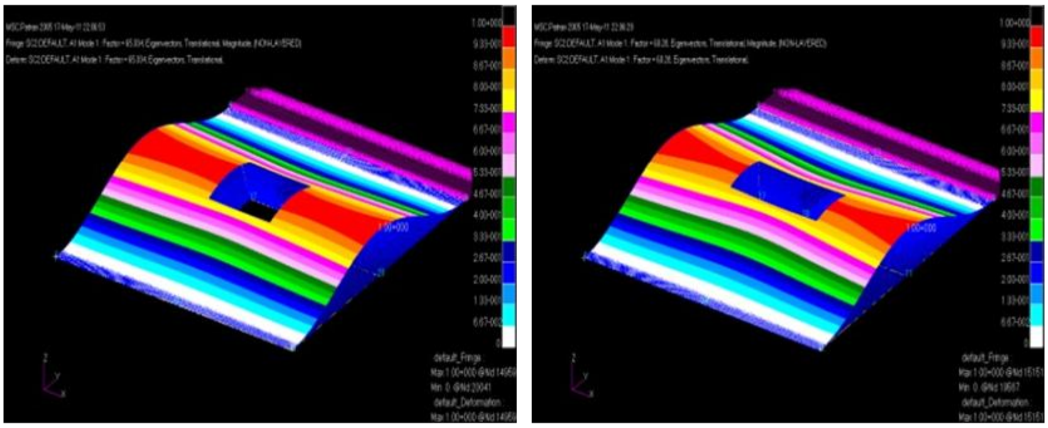


Figure 11: Buckling load vs. fiber orientation



a. Without cut-out b. Circular cut-out



c. Square cut-out d. Rectangular cut-out

Figure 12: Buckling behavior of composite plates with different cut-out shapes

Table II: Critical buckling loads for the various cut-out shapes

Sl. no.	**Cut-out shapes**	**Length, *a* (in mm)**	**Width, *b* (in mm)**	**Thickness, *t* (in mm)**	**Critical buckling load, P_{cr} (in kN)**
1	No cut-out	130	120	3.7	9.221
2	Circular	130	120	3.7	7.899
3	Square	130	120	3.7	7.804
4	Rectangular	130	120	3.7	7.234

V. CONCLUSION

This study considers the buckling response of rectangular laminated composite plates with clamped-free-clamped-free boundary conditions. For this, a linear buckling analysis was initially carried out on aluminum plates of two different configurations to estimate critical buckling load and the predicted FE results were verified with the results obtained from the buckling tests conducted. Further, the same analysis methodology was followed to estimate the critical buckling load for various woven fabric laminated composite plates to study the influence of length-to-thickness ratio, the aspect ratio, the ply orientation and the cut-out shapes on its buckling behavior. From the present experimental and numerical studies, the following conclusions are the following conclusions may be drawn based on the results obtained in this investigation made:

1. It was noted that variations in length-to-thickness ratio affects the critical buckling load. The buckling load decreases as the *a*/*t* ratio increases. The rate of decrease of buckling load is not uniform with the rate of increase of *a*/*t* ratio.
2. As the aspect ratio increases, the critical buckling load of the plate decreases. When the aspect ratio changed from 1.0 to 1.7. The rate of change of buckling load with *a*/*b* ratio is almost uniform.
3. It was seen that the different fiber orientation angles affected the critical buckling load adversely. With the increase in the fiber angle, the buckling load decreased. The plate with $[0]_8$ layup had the highest buckling load and the plate with $[45]_8$ layup had the least.
4. The reduction of the buckling load due to the presence of a cut-out is found to be significant. It is noted that the presence of cut-out lowers the buckling load and it varies with the cut-out shape. The plate with circular cut-out yielded to the greatest critical buckling load while the rectangular cut-out failed for the lowest buckling load.

VI. ACKNOWLEDGEMENTS

The satisfaction and euphoria that accompany the successful completion of any task would be incomplete without the mention of the people hose constant guidance and encouragement aided in its completion. The authors would like to express the voice of gratitude and respect to all who had directly or indirectly supported for carrying out this study.

The authors would like to thank and acknowledge Mr. Shyam Chetty, Director, and Dr. Satish Chandra, Head, STTD, CSIR-National Aerospace Laboratories, Bangalore, India for their support and encouragement during this work. Also sincere thanks are acknowledged to The Principal, K.S. Institute of Technology, Bangalore for the support. Special thanks are acknowledged to The Head of the Department, Department of Mechanical Engineering, and KSIT for his overwhelming support & encouragement.

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