Mechanical and thermal buckling analysis of laminated composite plates

Thesis in Mechanical Engineering (15 credits)

Halmstad, May 26th, 2023
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ACKNOWLEDGEMENT

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The study of mechanical and thermal buckling analysis of laminated composite plates represents a crucial area of research with profound implications for structural design and performance. We like thanks specially to:

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- Dr. Aron Chiba, Director and Examiner of Mechanical Engineering department at Halmstad University.

Thanks & Regards,
Aswin & Roopak
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ABSTRACT

Composite laminated structures have many application fields such as aerospace, biomedical, civil, marine, transportation, and mechanical engineering because of their ease of handling, and good mechanical properties. Buckling behavior of laminated composite plates subjected to in-plane loads is an important consideration in the preliminary design of aircraft and launch vehicle components. Also, these elements may expose to high-temperature fields (while launching or re-entry) which also cause for failure due to thermal buckling. Composite laminated plates with holes and other openings are used as structural members in aerospace industry. The buckling behavior of such plates has always received much attention. In this study buckling analysis was carried out of a laminar composite plate with an elliptical hole. In the analysis, finite element method (FEM) was applied to perform parametric studies on various plates based on the shape and position of the hole. ANSYS has been used as a platform for buckling analysis.
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</tr>
<tr>
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</tr>
</tbody>
</table>
1 – INTRODUCTION

1.1 Background

Composite materials are very flexible and can operate in a broad range of applications. It is completed by integrating two materials which are reinforcement (fiber) and matrix (resin). Application fields of composite materials are continuously expanding from traditional application areas to the various engineering fields. There are a large application range of composite materials such as for electrical and electronics, buildings and public work, transportation (road, rail, marine, air and space), sports and recreation, general mechanical applications and aerospace industry. Nowadays, the application of composite materials in aerospace industry is growing up. Composite materials provide a completely high strength-to-weight ratio in addition to the capability to produce large and integrated structure. Composite materials are one such class of materials that plays a significant role in current and future aerospace parts. For instance, one component of composite materials is capable of changing ten or more conventional metal parts which may impressively reduce manufacturing time and cost. A true understanding of their structural behavior is required such as the deflections, buckling loads and modal characteristics, the through thickness distributions of stresses and strains, the large deflection behavior and of extreme importance for obtaining strong, reliable multi-layered structures, the failure characteristics.

In at least one important way, a composite must be better than the materials from which it is made—otherwise there's no point to it. Added strength is the most common reason for making a composite, sometimes, we're looking to make a material better in a different way. For example, we might need an airplane part with better fatigue resistance than we'd get from a metal, so it doesn't snap (like a paperclip) when it's repeatedly stressed and strained in flight. Or we might need an engine part that can survive at higher temperatures than an ordinary ceramic. Perhaps we need a plastic that's stiff and strong but still lightweight, or one that can carry heat and electricity better than ordinary plastic (something with improved thermal and electrical conductivity, in other words). Composites can help us in all these situations.

1.2 Aim of the study

Due to the excellent stiffness and weight characteristics, composites have been receiving more attention from engineers, scientists, and designers. During these applications the composite laminate plates are commonly subjected to compression loads that may cause buckling if overloaded. Hence, structural instability becomes a major concern in safe and reliable designs of the composite plates. So their
buckling behaviors are crucial factors in safe and reliable design of these structures. Laminated composite is often employed to replace traditional metal for the skin panels of aircraft wings and fuselage to reduce the weight of flight vehicles. In the design of composite skins for aircraft wings, one of the important issues is buckling of the panels. High-speed aircraft structural panels are subjected not only to aerodynamic loading, but also to aerodynamic heating and solar radiation heating. The temperature rise may buckle the plate and exhaust the load carrying capacity. In certain cases, the thermal load turns out to be the primary one and controls the design. Thermal gradients are built up across wall thickness. Due to boundary constraints, compressive stresses are induced by thermal loads, which may cause buckling, especially in thin-walled members.

A lot of studies were carried out on buckling analysis of laminated composite plate. Some works concentrated on the plates with circular or rectangular cut outs. But very few were concentrated on other cut out shapes. The current study focuses on the buckling analysis of laminated composite plates with other shaped hole at the center of the plate using FEM. The buckling loads were calculated for different orientations and sizes of the hole. Thermal buckling behavior of laminated composite plate is also studied. Effect of different boundary conditions, orientation and thickness on critical buckling temperature will also be analyzed in this study.

1.3 Limitations:

The major limitation we understand for this study is that we don’t have a physical prototype of the model. As it is an internal project the evaluation and analysis are carried out in Ansys software and the results are discussed further. Even though the material specifications are detailed we are not able to demonstrate a physical model of the same.

- No buckling analysis concerning ergonomic solutions
- No Cost Estimation of the cutout shape laminate
- No Practical applications of composite plate with elliptical cutout shape were detailed
- The study focuses on simple plate geometries and boundary conditions, which may not represent real-world engineering applications.
- The approaches are based on classical plate theory, which may not accurately capture the complex behavior of laminated composites. Advanced computational methods, such as finite element analysis, have partially addressed these limitations but still require further refinement.

1.4 Individual responsibility and efforts during the project:
Both authors undertook and completed the thesis work evenly. As part of a challenging product development project, the authors met several times per week to discuss and work on project-related issues. Each task including data collection, report writing, and software analysis could be shared and contributed based on the individual skills and knowledge in Microsoft Word, Excel, Auto CAD Software, Finite Element Method etc. Appointments with our supervisor from Halmstad University were made when needed.

1.5 Study Environment:
The study was performed by evaluating more than 30 articles and books. The group had access to databases and literature given by the school library, as well as additional databases and Google searches such as IEEE Xplore, ScienceDirect, and ResearchGate Databases were used jointly for data collection and information gathering. Individual group members have performed works from the comfort of their respective homes, and also meet on a regular basis to share ideas and information. The software used in this thesis were CAD Software, Finite Element Method, MS Office, MS Excel Microsoft.
2 – METHOD

2.1 Alternative Methods:

Buckling analysis of laminated composite plates using an efficient C0 FE model

According to S.K. Singh and A. Chakrabarti, 2012 an efficient C0 FE model based on higher order zigzag theory can be used to analyze buckling of laminated composite plates. To avoid the difficulty of C1 continuity associated with the FE implementation of the plate theory, the first derivatives of transverse displacement were considered as independent variables in this model. The penalty parameter approach is used to correct for the C0 continuity of the current FE model in stiffness matrix calculations. The current model is particularly efficient in forecasting the buckling reactions of laminated composites, according to numerical data and compared with other available solutions.

2.2 Chosen Method

The current study focuses on the buckling analysis of laminated composite plates with elliptical shaped hole at the center of the plate using FEM. The buckling loads were calculated for different orientations and sizes of the hole. Thermal buckling

Figure 1 - Chosen Method
behavior of laminated composite plate is also studied. Effect of different boundary conditions, orientation and thickness on critical buckling temperature will also be analyzed in this study.

A sample model of the laminate plate has been created using CAD Modelling and Buckling analysis and simulation is done with ANSYS Software. Mechanical and thermal buckling can be performed by applying the boundary conditions in Finite Element Method.

2.2.1 Significance of elliptical cutout Shape

Cutouts of circular, rectangular, square, elliptical, and triangular shapes are often used in composite plates as access ports for mechanical and electrical systems, for damage inspection, as doors and windows, and to reduce overall structure weight. This study investigates the effects of elliptical cutout on the buckling behavior of carbon fiber composite plates. To investigate the effects of cutout on buckling, loaded edges are assumed to be fixed and unloaded edges are assumed to be free. Finite element analysis is also used to estimate the impact of various geometrical cutouts, orientations, and cutout positions on buckling behavior.

According to the study conducted by Ahmet Erklig and Eyüp Yeter 2012 the buckling loads of plates are decreased by increasing the fiber orientation angle. The most critical buckling load is obtained when fiber angle was used as 45°, and after this angle critical buckling load begins to increase. Also, from 0° to 45° fiber orientation angle, elliptical cutout has the highest buckling load, but after 45° circular cutouts have the highest buckling load. According to Anu George and S. Usha, 2016 Laminated composite plate with rectangular and square cutout shows a decrease in buckling load carrying capacity than plates with circular cutouts. As many studies were already performed on circular cutout shapes, we’ve decided to move on with elliptical cutout shape which is highly significant based on the above facts. Also, on considering practical application elliptical cutout shapes ensures slotting for the adjustments of bolt and nuts and makes the assembly process easier.

2.3 Software Analysis

2.3.1 CAD Modeling

Computer-aided design is one of the many tools used by engineers and designers and is used in many ways depending on the profession of the user and the type of software in question. CAD is one part of the whole digital product development (DPD) activity within the product lifecycle management (PLM) processes, and as such is used together with other tools, which are either integrated modules or stand-alone products, such as:
• Computer-aided engineering (CAE) and finite element analysis (FEA, FEM)
• Computer-aided manufacturing (CAM) including instructions to computer numerical control (CNC) machines
• Photorealistic rendering and motion simulation.
• Document management and revision control using product data management (PDM)

2.3.2 Finite Element Method

Finite element method (FEM) is a numerical method for solving a differential or integral equation. It has been applied to a number of physical problems, where the governing differential equations are available. The method essentially consists of assuming the piecewise continuous function for the solution and obtaining the parameters of the functions in a manner that reduces the error in the solution. The finite element method (FEM) (its practical application often known as finite element analysis (FEA)) is a numerical technique used for finding approximate solutions of partial differential equations (PDE) as well as of integral equations. The solution approach is based either on eliminating the differential equation completely (steady state problems), or rendering the PDE into an approximating system of ordinary differential equations, which are then numerically integrated using standard techniques such as Euler's method, Runge-Kutta, etc.

2.3.3 ANSYS

ANSYS is a general-purpose finite element modelling package for numerically solving a wide variety of mechanical problems. The problems include static/dynamic structural analysis (both linear and non-linear), heat transfer and fluid problems, as well as acoustic and electromagnetic problems. In common, a finite element solution may be broken into the following three stages.

1. Pre-processing: defining the problem; the major steps in pre-processing are given below:
   • Define key points/lines/areas/volumes
   • Define element type and material/geometric properties
   • Mesh lines/areas/volumes as required the amount of detail required will depend on the dimensionality of the analysis (i.e., 1D, 2D, axi-symmetric, 3D)
2. Solution: assigning loads, constraints and solving; here we specify the loads (point or pressure), constraints (translational and rotational) and finally solve the resulting set of equations.

3. Post processing: further processing and viewing of the results; in this stage one may wish to see
   - Lists of nodal displacements
   - Element forces and moments
   - Deflection plots
   - Stress contour diagrams.
3 – THEORY

3.1 Summary of literature study

3.1.1 Theory of Elasticity and bending of thin plates

S.G Lekhnitskii, 1977 explains the general concepts and equation of elasticity of an isentropic body. He put forwards the concept of generalized plane strain on a homogeneous rectilinear anisotropic body. To solve problems of the distribution of stress and strain in an anisotropic body, it is necessary to proceed from the equations of the theory of elasticity that take account of the difference in elastic properties for different directions and accordingly contain more than two elastic constants.

3.1.2 Buckling of laminated composite plates

According to Osama Mohammed Elmardi Suleiman-August 2016 the effects of boundary conditions and lamination arrangements (i.e. stacking sequence and orientation of a lamina) were found to be important factors in determining a suitable exact, analytical or semi-analytical method for analyzing buckling loads on laminated plates. It was also found that the derivative order of shear deformation increases, the accuracy of stresses, strains, buckling loads, etc.

Woo-Min Kyoung, Chun-Gon Kim, Chang-Sun Hong.- 1999 studied the buckling and post buckling behavior of cross ply laminates with multiple delaminations using finite element method. The eight-node degenerated shell selected for finite element modeling. The variation of size and geometry of delamination depends upon material properties, layup angle, impact energy etc. The literature includes how the buckling load varies for through-the-width delamination and embedded delamination.

3.1.3 Finite element method

Mahmoud Yassin Osman, Osama Mohammed Elmardi Suleiman-march 2017 used Finite element method (FEM) is to obtain numerical solution of the governing differential equations. Buckling analysis of rectangular laminated plates with rectangular cross – section for various combinations of boundary conditions and aspect ratios is studied.

S S.Rajendran and D.Q.Song-1998 discussed the finite element modelling of delamination buckling of composite panels. The panel was hypothetically divided into two sub-laminates by a plane containing the delamination. Using this modeling approach, a few typical test problems were solved. The computed buckling loads
and strain energy release rate values for various test problems were presented and compared with theoretical results.

F. Cappello, D. Tumino-2005 studied the buckling and post-buckling behavior of unidirectional and cross-ply composite laminated plates with multiple delaminations. Finite elements analyses were performed, using a linear buckling model, based on the solution of the Eigen values problem, and a non-linear one, based on an incremental-iterative method. They found that both delamination length and position and stacking sequence of the plies influence the critical load of the plate.

### 3.1.4 Laminated Composite plates with cutout shapes

Anu George1, S. Usha2-2016 compares the critical buckling load of the laminated composite plate with cutout by changing the cutout shapes of the optimized fiber orientation of the laminate by numerical methods. Laminated composite plate with rectangular and square cutout shows a decrease in buckling load carrying capacity than plates with circular cutouts.

S.A.M. Ghannadpour, A. Najafi, B.Mohammadi 2006 studied the influences of a cut-out on the buckling performance of rectangular plates made of polymer matrix composites (PMC). The study was concentrated on the behavior of rectangular symmetric cross-ply laminates. Finite element analysis was also carried out to obtain the effects of cut out on the buckling behavior of these plates.

Variddhi Ungbhakorn, Pairod Singhatanadgid-2005 studied the buckling behavior of composite laminated plates with various edge support using extended Kantorovich method. A combination of simple support, clamped and free edge considered for the analysis and compared the results of extended Kantorovich method and Rayleigh–Ritz method. The thermomechanical buckling and postbuckling response of laminated composite plates is clearly one of practical importance for structures operating at elevated temperatures and thus the understanding of the thermal buckling and postbuckling response of the composite laminated plates is desirable for the design of the composite laminates subjected to high temperatures.

### 3.1.5 Thermal Buckling of laminated composite plates

R.Thangaratnam, palalinathan and J Ramachandran-1998 analyzed the buckling behavior of composite laminates for critical temperatures under thermal loads with a semiloof shell element for analysis. The critical temperatures of simply supported and clamped edge, isotropic and orthotropic square plates subjected to constant and
linearly varying temperature distributions obtained verified against the energy method based on previous literatures. They also compared the variation of critical temperatures for clamped edge simply supported boundary conditions.

W J Chen, P D Lin and L W Chen-1990 analyzed the buckling behavior of composite laminates subjected uniform and non-uniform temperature rise. Analysis includes the variation of critical temperature with different lamination angle, modulus ratio, plate aspect ratio, and boundary constraints and found that thermal buckling load is significantly influenced by lamination angle, modulus ratio, plate aspect ratio and the type of temperature distribution.

3.2 Laminated Composites

In materials science, a composite laminate is an assembly of layers of fibrous composite materials which can be joined to provide required engineering properties, including in-plane stiffness, bending stiffness, strength, and coefficient of thermal expansion. The individual layers consist of high-modulus, high-strength fibers in a polymeric, metallic, or ceramic matrix material. Typical fibers used include cellulose, graphite, glass, boron, and silicon carbide, and some matrix materials are epoxies, polyimides, aluminum, titanium, and alumina. Layers of different materials may be used, resulting in a hybrid laminate. The individual layers generally are orthotropic (that is, with principal properties in orthogonal directions) or transversely isotropic (with isotropic properties in the transverse plane) with the laminate then exhibiting anisotropic (with variable direction of principal properties), orthotropic, or quasi-isotropic properties. Quasi-isotropic laminates exhibit isotropic (that is, independent of direction) in plane response but are not restricted to isotropic out-of-plane (bending) response. Depending upon the stacking sequence of the individual layers, the laminate may exhibit coupling between in plane and out-of-plane response. An example of bending-stretching coupling is the presence of curvature developing as a result of in-plane loading. When a fiber reinforced composite consists of several layers with different fiber orientations, it is called multilayer (angle-ply) composite

3.2.1 Theoretical Formulation

The buckling of a plate involves two planes, namely, xz, yz and two boundary conditions on each edge of the plate. The basic difference between plate and column lies in the buckling characteristics. The column, once it buckles, cannot resist any additional axial load. Thus, the critical load of the column is also its failure load. On the other hand, a plate, since it is invariably supported at the edges, continues to resist the additional axial load even after the primary buckling load is reached and does not fail even when the load reaches a value 10-15 times the buckling load.
The load transfer mechanism in a single fiber embedded in matrix is explained by J.N. Reddy. The stiffness and strength of fibrous composites come from fibers which are stiffer and stronger than the same material in bulk form. The matrix material keeps the fibers together, acts as a load-transfer medium between fibers, and protects fibers from being exposed to the environment.

3.2.2 Buckling Behavior of Laminated Composite Plate

In laminated composites, failure of one layer does not necessarily imply failure of the entire laminate; the laminate may, in fact, be capable of sustaining higher loads despite a significant change in stiffness. An analogy to this phenomenon is the ability of an in-plane loaded plate to carry loads higher than the buckling load, but at an increase in the amount of deformation per unit of load (a decreased stiffness) as in fig 2 and 3.

Figure 2 - Load-deformation behavior of plate

Figure 3 - Load-deformation behavior of laminate
All strength theories for composite materials depend on the strength in the principal material directions, which likely do not coincide with principal stress direction. Therefore, the strength of each lamina in a laminate must be assessed in a co-ordinate system that is likely different from those of its neighboring laminae. This co-ordinate mismatch is but one of the complications that characterizes even a macroscopic strength theory. The main factors that are peculiar to laminate strength analysis are:

- Laminae strength
- Laminae stiffnesses
- Laminae coefficient of thermal expansion
- Laminae orientation
- Laminae thickness
- Stacking sequence

3.2.3 Theory of Bending of Thin Plates

According to S.G Lekhnitskii, 1977 A rectangular plate of constant thickness made of homogeneous material with anisotropy of the general kind is deformed by forces distributed over the sides; in each element of the edge having a height equal to the thickness of the plate the forces reduce to bending and twisting moments that do not vary along the length of the side.

on the other two sides (per unit length). Assuming that the external forces vary across the thickness of the plate according to a linear law, we obtain the same distribution of stress as in the corresponding isotropic plate (thin slab):

\[
\begin{align*}
\sigma_x &= \frac{12 M_1}{h^3} z, \\
\sigma_y &= \frac{12 M_2}{h^3} z, \\
\tau_{xy} &= \frac{12 H}{h^3} z, \\
\sigma_z &= \tau_{yz} = \tau_{xz} = 0.
\end{align*}
\]

The components of strain are found from Eqs, and the projections of displacement from these components. Suppose, for definiteness, that an element of the middle surface at the center of the plate is fixed. The conditions for the displacements at are then

\[
\begin{align*}
u &= w = \frac{\partial w}{\partial x} = \frac{\partial w}{\partial y} = \frac{\partial u}{\partial x} = \frac{\partial u}{\partial y} = 0.
\end{align*}
\]
3.3 SOLSH190 Element Description

SOLSH190 is used for simulating shell structures with a wide range of thickness (from thin to moderately thick). The element possesses the continuum solid element topology and features eight-node connectivity with three degrees of freedom at each node: translations in the nodal x, y, and z directions and has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. SOLSH190 is used for layered applications such as modelling laminated shells or sandwich construction. Accuracy in modelling composite shells is governed by the first order shear deformation theory (also known as Mindlin-Reissner shell theory). SOLSH190 elements perform adequately for sandwich composites with material properties and geometries similar to those used in the aerospace industry, provided care is taken to apply the correct boundary conditions when using SOLSH190 elements (Biswajit Banerjee, 2011).

The geometry, node locations, and the element coordinate system for this element are shown in fig below.
Because of the different hole dimensions and angles, the different models and mesh structures has been made. Sample mesh structure, boundary conditions and loading of the model for the analysis are illustrated in fig 5

### 3.4 Thermal Load (Uniform Temperature Profile Heating)

Uniform temperature loading case is used for the analysis. fig 6 explains the method of uniform temperature profile heating.

Temperature load of 1°C is chosen as input to all nodes of the finite-element model so that the eigen value calculated from ANSYS will give the buckling temperature $T_c$, namely & $T_c = \lambda c \times 1 = \lambda c$

Where $\lambda c$ is the eigen value which multiplies the applied temperature to give critical buckling temperature.

Critical buckling temperatures for different orientation of ellipse and for different values of $c/a$ were found in this study. The variation of critical buckling temperature with increasing plate thickness also studied.
4 - RESULTS AND DISCUSSIONS:

4.1 Model and Material Properties

In this study, the effects of elliptical hole on the buckling load of laminated composite plates have been studied numerically. The composite plate was considered as a square with dimensions of (a*a) 120 mm * 120 mm. The thickness of plate is 1.6 mm. Nonetheless, the cut-out shape was assumed an elliptical hole (c/b) 30mm/60mm centered in the square plate in this work. The hole was also positioned according to α angle rotated about z-axis as 0°, 15°, 30°, 45°, 60°, 75° and 90°. The diameters of the major and minor axes’ dimensions of ellipse are represented by b and c respectively. In other words, the width is b and height is c. The parameters b and c are changed according to selected ratios; hence the eccentricity of the ellipse is also varied. Fig 7 shows the geometry of the model.

Figure 7 - Geometry of the model

For the analysis material properties of graphite/epoxy laminate (CU-125NS) is used. Table 1 shows the material properties of graphite/epoxy laminate.

Table 1 - Material properties of graphite/epoxy laminate (CU-125NS)

<table>
<thead>
<tr>
<th>E₁</th>
<th>E₂, E₃</th>
<th>G₁₂, G₁₃</th>
<th>G₂₃</th>
<th>ν₁₂, ν₁₃</th>
<th>ν₂₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>134.5 GPa</td>
<td>9.6GPa</td>
<td>4.8GPa</td>
<td>3.2GPa</td>
<td>.31</td>
<td>.52</td>
</tr>
</tbody>
</table>

Briefly, buckling analysis was performed for various elliptical holes in terms of created different models. Four different composite plates based on stacking sequences namely cross-ply [0/90]S and angle-ply [15/-75]S, [30/-60]S, [45/-45]S
were analyzed. Consequently, four different composite plates based on stacking sequences have been analyzed. In this manner, the effects of orientations of laminated composite plates on the buckling loads were also analyzed.

![Sample mesh and boundary conditions](image)

*Figure 8 - Sample mesh and boundary conditions*

In this boundary condition, all degree of freedoms is constraint in one edge. The adjacent sides kept free. In the opposite side, displacement in the direction of X and Z are constraint and load applied in Y direction. The boundary conditions are shown in figure 8.

### 4.2 THERMAL BUCKLING ANALYSIS

#### 4.2.1 Model and Boundary Conditions

Model used for thermal analysis is same as used for the mechanical buckling analysis. Square plate with dimensions of \((a \times a) 120 \text{ mm} \times 120 \text{ mm}\) and thickness of plate is 1.6 mm with elliptical hole. Material properties of graphite epoxy composite (CU-125NS) is used whose thermal expansion coefficients are

\[
\alpha_1 = 21.6 \times 10^{-6} / \text{C}; \alpha_2 = 0.18 \times 10^{-6} / \text{C}
\]

The element used for thermal analysis is SOLSH190.

Two types of boundary conditions are used for the analysis. 4 sides fixed condition and 2 sides fixed and 2 sides free. The boundary conditions used for the analysis is shown in figure 9 and 10.
Since the selected element has only three degree of freedom on nodes, they are translational in X, Y and in Z direction, no need to consider the rotational degree of freedom.

Figure 9 - Two sides fixed and two sides free boundary condition

In 2 sides fixed and 2 sides free condition, two opposite sides are kept fixed and other two sides are kept free. The displacement in all direction is constraint in fixed sides. In 4 sides fixed condition, displacement in all direction is constraint in all sides. For fixed edge $U_x = U_y = U_z = 0$

Figure 10 - Four sides fixed boundary condition
4.3 MECHANICAL BUCKLING ANALYSIS RESULTS

This study mainly focused on the variation of buckling load with the change in orientation of elliptical hole at the center of the composite laminated plate. Also, the variation of buckling load with c/a (ratio of minor diameter to the edge length of the plate) also studied. The results are shown in the following sections.

4.3.1 Variation of Buckling Load for Various Composite Layup with Change in Ellipse Angle α

<table>
<thead>
<tr>
<th>b/a; c/a</th>
<th>Ellipse angle ‘α’</th>
<th>Buckling Load (MPa) for different composite lay up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>[0/90]s</td>
</tr>
<tr>
<td>0.5; 0°</td>
<td>74.25</td>
<td>70.22917</td>
</tr>
<tr>
<td>0.15 15°</td>
<td>76.5625</td>
<td>75.63021</td>
</tr>
<tr>
<td></td>
<td>81.46875</td>
<td>74.41146</td>
</tr>
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<td></td>
<td>89.70313</td>
<td>86.78646</td>
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<td></td>
<td>95.625</td>
<td>93.34375</td>
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<td>99.79688</td>
<td>92.74479</td>
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<td>0.5; 0°</td>
<td>65.26563</td>
<td>61.03646</td>
</tr>
<tr>
<td>0.3 15°</td>
<td>72.16146</td>
<td>64.79167</td>
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<td></td>
<td>72.38021</td>
<td>67.92188</td>
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<td>67.64063</td>
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<td>74.35417</td>
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<tr>
<td></td>
<td>76.40625</td>
<td>72.51563</td>
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<tr>
<td></td>
<td>76.72396</td>
<td>73.38542</td>
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<tr>
<td>0.5; 0°</td>
<td>63.22917</td>
<td>59.55729</td>
</tr>
<tr>
<td>0.45 15°</td>
<td>64.47396</td>
<td>60.75521</td>
</tr>
<tr>
<td></td>
<td>65.56771</td>
<td>58.54167</td>
</tr>
<tr>
<td></td>
<td>68.10417</td>
<td>60.76563</td>
</tr>
<tr>
<td></td>
<td>65.36458</td>
<td>61.63021</td>
</tr>
<tr>
<td></td>
<td>65.52083</td>
<td>61.25</td>
</tr>
<tr>
<td></td>
<td>64.71875</td>
<td>60.24479</td>
</tr>
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</table>
Here the ellipse angle is changed for different composite layups, taking one at a time and the buckling load is calculated by linear Eigen value buckling analysis. Table 2 gives the critical buckling loads obtained for different orientation and for different lay-ups.

Using the above values of buckling load, the following three graphs were plotted. fig 11 shows the variation of buckling load with change in ellipse angle $\alpha$ for different lay-ups when $b/a= 0.3$ and $c/a= 0.15$.

**Figure 11 - Variation of buckling load with change in ellipse angle for different composite layups (when $b/a=0.5$ and $c/a=0.15$)**

**Figure 12 - Variation of buckling load with change in ellipse angle for different composite layups (when $b/a=0.5$ and $c/a=0.3$)**
The figure 11 shows that the buckling load increases when the value of ellipse angle increases. The maximum buckling load obtained for an ellipse angle $\alpha=90^0$.

The effect of ellipse angle on buckling load when $b/a=0.5$ and $c/a=0.3$ is shown in fig 12. Similarly, the variation when $b/a=0.5$ and $c/a=0.45$ is shown in fig 13.

In fig 12, $c/a$ ratio used is 0.3 and $b/a$ is 0.5. Here also the trend of variation in buckling load with ellipse angle is similar to the figure 11. But the rate of increase in variation is less in fig 12 compared to fig 11.

Fig 13 shows the variation in buckling load with ellipse angle when $b/a=0.5$ and $c/a=0.45$. As $c/a$ ratio reaches the value 0.45, the variation is very less compared to the cases when $c/a=.15$ and $c/a=.3$. From these three figures it’s clear that the variation of critical buckling temperature decreases as the value of $c/a$ increases.

In fig 11, 12 and 13, the maximum buckling load is for cross ply laminate $[0^0/90^0]_S$ followed by angle ply $[15^0/-75^0]_S$, $[30^0/-60^0]_S$ and minimum buckling load is for $[45^0/-45^0]$. So, from the analysis it is clear that cross ply laminate is stronger, and weakest is $[45^0/-45^0]$ among the analyzed laminates.

**Figure 13 - Variation of buckling load with change in ellipse angle for different composite layups (when $b/a=0/5$ and $c/a=0.45$)**
4.3.2 Effect of ‘c/a’ ratio on buckling load

The variation of buckling load with minor axis, keeping major axis as a constant is also studied. The ratio of minor axis(c) to the edge length (a) is used for the study. The variation plotted in fig 14 is for an ellipse angle 45°. The fig 14 shows that the rate of variation of buckling load decreases as the value of c/a increases.

![Variation of Buckling load with c/a ratio (α=45°)](image)

The buckling load shows decreasing behavior as the value of c/a increases. When c/a crosses the value 0.35 the decreasing rate of buckling load is less. When the minor axis is close to the value of major axis, the variation in buckling load with the orientation of ellipse is less.

4.3.3 Variation of buckling load with c/b ratio

The variation of buckling load with c/b ratio (minor axis to major axis) is calculated for a cross ply laminate [0/90]S. When c/b=1, the hole become circular. The area of the ellipse is maintained constant (π*30*60) and major and minor axis is varied for different c/a ratios. The buckling load is calculated for different c/a ratio (0.2, 0.4, 0.6, 0.8 and 1) for constant ellipse angle 0°. The variation of buckling load with c/b ratio is shown in fig 15.

Table 3 - Buckling loads for different c/a ratio

<table>
<thead>
<tr>
<th>c/b ratio</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckling load (MPa)</td>
<td>60.51563</td>
<td>116.3177</td>
<td>128.8802</td>
<td>139.724</td>
<td>128.8802</td>
</tr>
</tbody>
</table>
The fig 15 shows that as c/b ratio increases, the value of buckling load increases. Thus, as the elliptical hole transforms into circle, it withstands higher buckling load. The maximum buckling load is for maximum when c/b=1, ie, when ellipse becomes perfectly circle. The rate of increase in buckling load is very high, when the value of c/b increases from 0.2 to 0.4.

4.3.4 Mode Shapes Mechanical Buckling:

The mode shapes of buckling can be plotted using ANSYS. Buckling mode shapes of composite laminate plate [45/-45]S (When b/a=0.5 and c/a=0.35) are shown in fig 16 a,b,c,d and e.
4.4 Thermal buckling analysis results

Thermal buckling analysis has been carried out with two different boundary conditions. Four sides fixed condition and two sides fixed and two sides free condition.

4.4.1 Four sides fixed condition

In this boundary condition the variation of critical buckling temperature with the orientation of ellipse, increasing thickness and increasing diameter have been analyzed.
4.4.1.1 Variation of critical buckling temperature with the orientation

The variation of critical buckling temperature with the orientation of ellipse (α) is calculated for cross ply and angle ply laminates. The critical buckling temperatures for different orientation of ellipse are given in table 4.

Table 4 - Variation of buckling temperature with ellipse angle for different lay-ups.

<table>
<thead>
<tr>
<th>Ellipse angle</th>
<th>Buckling temperatures for different lay-ups (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[0/90]s</td>
</tr>
<tr>
<td>0°</td>
<td>39.74</td>
</tr>
<tr>
<td>15°</td>
<td>39.42</td>
</tr>
<tr>
<td>30°</td>
<td>38.87</td>
</tr>
<tr>
<td>45°</td>
<td>39.81</td>
</tr>
<tr>
<td>60°</td>
<td>38.11</td>
</tr>
<tr>
<td>75°</td>
<td>38.13</td>
</tr>
<tr>
<td>90°</td>
<td>39.68</td>
</tr>
</tbody>
</table>

Fig 17 shows the variation of buckling temperature with ellipse angle for different lay-ups.

The fig 17 shows that the variation of buckling temperature with ellipse angle is very less in four sides fixed condition. The variation is in the order of 2 °C - 4°C. Also the buckling temperature for different lay-ups is almost similar.
4.4.1.2 Mode shapes

The fig 18 a,b,c,d,e represents the buckling mode shapes of 4 sides fixed plate with elliptical hole at the center.

Figure 18 - Mode shapes for buckling of 4 sides fixed plate.
4.4.2 Two Sides Fixed and Two Sides Free

In this analysis two opposite sides kept fixed and other two sides kept free. Uniform temperature distribution is used as thermal load. Here also variation of buckling temperature with ellipse angle are analyzed.

4.4.2.1 Variation of buckling temperature with ellipse angle (α)

The variation of buckling temperature with the orientation of elliptical hole for different lay-ups is given in table 5 and the values plotted are shown in fig 19.

Table 5 - Variation of buckling temperature with ellipse angle for different lay-ups in two sides fixed and two sides free boundary condition

<table>
<thead>
<tr>
<th>Ellipse angle</th>
<th>Buckling temperatures for different lay-ups (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[0/90]_s</td>
</tr>
<tr>
<td>0°</td>
<td>32.3</td>
</tr>
<tr>
<td>15°</td>
<td>32.16</td>
</tr>
<tr>
<td>30°</td>
<td>28.66</td>
</tr>
<tr>
<td>45°</td>
<td>25.35</td>
</tr>
<tr>
<td>60°</td>
<td>26.34</td>
</tr>
<tr>
<td>75°</td>
<td>30.2</td>
</tr>
<tr>
<td>90°</td>
<td>29.13</td>
</tr>
</tbody>
</table>

In the above figure buckling temperature variation with ellipse angle is shown. Buckling temperature decreases as the value of ellipse angle increases. But the change is very less and response of each lay-up shows different response in variation of buckling load.
5 – CONCLUSION

The buckling response of a graphite epoxy composite laminated square plate with centered elliptical hole is investigated in this study. Both mechanical buckling and thermal buckling analysis has been done. In mechanical buckling analysis, the elliptical hole is positioned according to various angles from $\alpha=0^\circ$ to $90^\circ$. Additionally, the effect of ‘$c/a$’ and ‘$c/b$’ on buckling loads are calculated. Models were created by using AutoCAD 3D software and solution is done with FEM using ANSYS. From the present study, the following conclusions can be made. Firstly, the magnitudes of buckling loads are decreased by increasing $c/a$ ratio. This means that as the size of the hole increases the strength of the plate decreases. The increasing of hole positioned angle cause to decrease of buckling loads. The cross ply $[0/90]_S$ composite laminate plates are stronger than other angle ply ($[15/-75]_S$, $[30/-60]_S$, $[45/-45]_S$) laminated plates. Meanwhile, the $[45^\circ/-45^\circ]_S$ laminated plate is observed as the weakest angle-ply plate.

In thermal buckling analysis, two types of boundary conditions are used. Four sides fixed condition and the other is two sides fixed and two sides free condition. In 4 sides fixed case critical buckling is higher compared to the two sides fixed and two sides free boundary condition.

5.1 Future scope

Experimental analysis can be performed to validate the results obtained. Buckling analysis of laminated composite plates with different boundary conditions, materials and cut outs can be carried out. Delamination effect and post buckling behavior of laminated composite plate, thermal buckling analysis with different thermal loads can be studied.
6 – CRITICAL REVIEW

6.1 The Environment

The mechanical and thermal buckling of laminated composite plates can have several environmental impacts. These impacts arise from the consequences of buckling failures, as well as the manufacturing, maintenance, and repair processes associated with laminated composite structures. Here are some key environmental impacts to consider.

- **Material Waste and Resource Consumption:** Buckling failures can lead to structural damage and the need for repairs or replacements. This results in increased material waste, as damaged composite plates may need to be discarded.
- **Energy Inefficiency and Increased Emissions:** Buckling failures may compromise the structural integrity of composite plates, leading to increased energy consumption and emissions during operation.
- **Increased Maintenance and Repair Requirements:** Mechanical and thermal buckling can increase the frequency and complexity of maintenance and repair activities. This entails additional resource consumption, energy use, and emissions associated with maintenance operations.

Mitigation Strategies:

- **Design Optimization:** Implementing design optimization techniques can enhance the structural integrity and reduce the likelihood of buckling. This includes optimizing ply orientations, stacking sequences, and incorporating reinforcement structures to improve load-bearing capabilities.
- **Alternative Materials:** Exploring alternative materials with improved mechanical and thermal properties can help mitigate buckling issues. For example, the development of sustainable composite materials or the use of bio-based and recyclable composites can reduce environmental impacts.
- **Sustainable Manufacturing Processes:** Employing sustainable manufacturing practices, such as reducing energy consumption, minimizing waste generation, and utilizing renewable energy sources, can lessen the environmental footprint associated with composite plate production.
- **Efficient Maintenance and Repair:** Implementing efficient and sustainable maintenance and repair strategies can minimize resource consumption and waste generation. This includes regular inspections, early detection of buckling issues, and employing repair techniques that prioritize durability and longevity.
6.2 Ethical

Safety and Risk to Human Life: Buckling failures in critical structures, such as aerospace or transportation components, can pose significant risks to human life. The ethical responsibility lies in ensuring the safety of individuals who rely on the integrity of composite structures.
Proper design, testing, and maintenance procedures must be followed to minimize the risk of buckling failures and protect the well-being of users and stakeholders.

Economic Implications: Buckling failures can result in substantial economic losses. These failures can lead to expensive repairs, replacement costs, downtime, and potential liabilities for manufacturers, operators, and owners of composite structures.
Ethical concerns arise regarding the economic impact on stakeholders, including businesses, investors, employees, and customers who rely on the functionality and reliability of the composite plates.

Product Quality and Consumer Trust: Buckling failures can undermine consumer trust in products that incorporate laminated composite plates. If composite structures fail prematurely or exhibit poor performance, it raises ethical concerns related to product quality and the trustworthiness of manufacturers.
Ensuring the integrity and reliability of composite plates through rigorous quality control measures and adherence to industry standards is essential for maintaining consumer confidence.

6.3 Economical

Repair and Replacement Costs: Buckling failures in laminated composite plates can lead to the need for repairs or replacements. This incurs additional costs for materials, labor, and equipment required to restore or replace the damaged components. The extent of the buckling damage, accessibility of the affected areas, and complexity of repairs can significantly influence the associated costs.
- Downtime and Productivity Loss: When buckling failures occur in critical structures, such as in transportation or industrial applications, it can result in operational downtime.
- Liability and Legal Costs: Buckling failures that result in accidents, injuries, or damage to property can lead to legal liabilities
- Reputational Damage: Buckling failures and subsequent incidents can damage the reputation of companies and organizations associated with the affected composite structures. This can result in a loss of customer trust, reduced demand for products or services, and potential loss of business opportunities.
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APPENDIX

ANSYS program for mechanical buckling analysis
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/PREP7
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Simulation - Thermal Buckling analysis