BUCKLING OF CARBON-FIBRE REINFORCED POLYMER COMPOSITES PERFORATED PLATES SUBJECTED TO SHEAR LOADING

By

IMAN SYAHIRAH BINTI OSMAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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Chairman : Noorfaizal bin Yidris, PhD
Faculty : Engineering

Buckling occurs when composite laminated plates are forced into shear or compression. Composite materials combine two or more components to minimize weight while preserving strength and less attention has been paid to composite plate buckling. In order to develop more efficient and lighter structures, holes are frequently required. Also, to improve reliability and performance, these structural components must be analysed with various hole shapes under in-plane loads such as shear. Although research has been done on the effect of cutouts on plate structure, little is known about shear loading on symmetrical angle plied square plates with center cutouts. As a result, the current study used a circular hole in the center of the plate with angle ply stacking and shear loading as well as to evaluate the influence of shear load directions on the behavior of symmetric angle ply CFRP laminates.

To achieve the study's objectives, an understanding of laminated square plate buckling is required, particularly under shear loads. The current work analysis is completely numerical, using FEA software. This method has been studied for use in the current study since it can save time and cost. Since the current study uses ABAQUS to complete the analysis, the method for using the software is obtained.

The results of the numerical analysis are compared to previously available theoretical data gathered through a literature study. The percentage difference used in this study must be less than 10% to be legitimate and accepted. Carbon-fiber reinforced polymers (CFRP) were chosen for the current investigation due to their material properties and common application in aerospace. This work's basic model geometry is a 200mm x 200mm square plate with no cutout. The model's central section is removed to further investigate shear buckling behavior

of laminated square plates. The type of hole analysed is circular to guarantee consistency.

The hole diameter/width ratio, d/b on perforated plates can affect the shear buckling behavior of square perforated plates. As the hole ratio d/b increases, the plate's strength decreases. The study's findings showed that composite structural parts with plate holes require special consideration. They have variable buckling capabilities depending on the shear stress and the holes. The perforated plate with a hole d/b of 0.5 exhibits the greatest decrease in critical buckling stresses, whereas the perforated plate with a hole d/b of 0.1 exhibits the least reduction in critical buckling stresses.

Additionally, the results of the analysis of plates with cutouts subjected to shear loadings can be used to guide researchers and engineers in determining the size of the hole that can be generated in their plate structure designs, notably in finite element analysis.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

LENGKOKAN KE ATAS PLAT KOMPOSIT POLIMER BERTETULANG SERAT KARBON YANG BERLUBANG DAN DIBEBANI OLEH DAYA RICIH SESATAH

Oleh

IMAN SYAHIRAH BINTI OSMAN

Januari 2022

Pengerusi : Noorfaizal bin Yidris, PhD
Fakulti : Kejuruteraan

Lengkokan berlaku apabila plat berlapis komposit dipaksa mengalami ricih atau mampatan. Bahan komposit menggabungkan dua atau lebih komponen untuk meminimumkan berat sambil mengekalkan kekuatan dan kurang perhatian diberi terhadap tekuk plat komposit. Untuk membangun struktur yang lebih cekap dan lebih ringan, lubang diperlukan. Juga, untuk meningkatkan kebolehpercayaan dan prestasi, komponen struktur ini mesti dianalisis dengan pelbagai bentuk lubang di bawah beban dalam pesawat seperti ricih. Walaupun telah dilakukan penyelidikan mengenai kesan potongan pada struktur plat, tidak banyak yang diketahui mengenai pembebanan ricih pada plat segi empat bersudut simetri dengan potongan tengah. Akibatnya, kajian semasa menggunakan lubang bulat di tengah-tengah plat dengan susunan lapisan sudut dan pembebanan ricih sesatah serta menilai pengaruh arah beban ricih sesatah ke atas tingkah laku laminat CFRP lapis sudut simetri.

Untuk mencapai objektif kajian, diperlukan pemahaman mengenai tekuk plat persegi berlapis, terutama di bawah beban ricih. Analisis kajian semasa dijalankan sepenuhnya secara berangka, menggunakan perisian FEA. Kaedah ini dikaji untuk digunakan dalam kajian semasa kerana dapat menjimatkan masa dan kos. Oleh kerana kajian semasa menggunakan ABAQUS untuk menyelesaikan analisis, kaedah untuk menggunakan perisian diperolehi.

Hasil analisis berangka dibandingkan dengan data sedia ada dari kajian literatur. Perbezaan peratusan yang digunakan dalam kajian ini mestilah kurang dari 10% untuk menjadi sah dan diterima. Polimer bertetulang serat karbon (CFRP) dipilih untuk kajian semasa kerana sifat material dan aplikasi biasa dalam aeroangkasa. Geometri model asas ini adalah plat segi empat sama 200mm x

200mm tanpa potongan. Bahagian pusat model dikeluarkan untuk menyiasat dengan lebih lanjut tingkah laku tekuk ricih dari plat persegi berlapis. Jenis lubang yang dianalisis adalah bulat untuk menjamin konsistensi.

Nisbah diameter lubang/lebar, d/b pada plat berlubang boleh mempengaruhi tingkah laku lengkungan ricih pada plat berlubang persegi. Apabila nisbah lubang d/b meningkat, kekuatan plat menurun. Hasil kajian menunjukkan bahawa bahagian struktur komposit dengan lubang plat memerlukan pertimbangan khas. Mereka mempunyai keupayaan tekuk berubah-ubah bergantung pada tegangan ricih dan lubang. Plat berlubang dengan lubang d/b sebanyak 0.5 mempamerkan penurunan paling besar dalam tegasan tekuk kritikal, manakala plat berlubang dengan lubang d/b sebanyak 0.1 mempamerkan pengurangan paling sedikit dalam tegasan tekuk kritikal.

Selain itu, hasil analisis plat dengan lubang yang tertakluk kepada beban ricih boleh digunakan untuk membimbing penyelidik dan jurutera dalam menentukan saiz lubang yang boleh dijana dalam reka bentuk struktur plat mereka, terutamanya dalam analisis unsur terhingga.

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Noorfaizal bin Dato' Yidris, PhD
Associate Professor Ts.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Ezanee bin Gires, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 09 February 2023

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Signature: ______________________

Name of Chairman of Supervisory Committee: Associate Professor Dr. Noorfaizal bin Dato' Yidris

Signature: ______________________

Name of Member of Supervisory Committee: Dr. Ezanee bin Gires

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LIST OF ABBREVIATIONS

A	Area
a	Plates length
b	Plates width
BC	Boundary condition
d	Hole diameter
E	Young's Modulus
F	Force
FEA	Finite Element Analysis
FEM	Finite Element Method
G	Shear module
$\bar{N}_{xy}$	Critical shear stress
t	Plate thickness
n	Lay-up configuration
θ	Ply angle
mm	Millimeter
N	Newton
ʋ	Poisson's ratio
%	Percentage

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter summarizes the study undertaken, including the research overview, research background, issue problem statements, research objectives, research scopes, and thesis layout.

1.2 Research Overview

Composites have become significant materials due to their light weight, high specific strength, high specific stiffness, superior corrosion resistance, and great fatigue resistance, when compared to the majority of commonly used metallic alloys, such as steel and aluminium alloys.

Composite materials are also widely employed in a variety of applications, including the aircraft and aerospace industry, the automotive sector, and civil engineering (Atas et al., 2009).

The advantages and benefits of lightweight structures in areas such as aerospace and automotive have prompted engineers to work with new materials. The behavior of these materials requires extensive testing, achieved through the development of appropriate design, analysis, fabrication, and production processes. Composite materials are just one of a growing number of innovative man-made materials that may be adapted for specific applications. However, certain additional material imperfections may be observed when composite materials are used. The cutout/hole is one of these imperfections (Damghani, 2009).

The selection of materials is critical during the design cycles of aerospace components and systems. It has a significant impact on a variety of aspects of aircraft performance, from design to disposal, including structural efficiency, safety and reliability, flight performance, payload, energy consumption, disposability, recyclability, and lifecycle cost (Mouritz, 2012).

Reliability helps to mitigate the risk of threatening and unexpected failures. Numerous forces and structural stresses act on an aircraft both in flight and in stationary mode. When the aircraft is stationary, the pull of gravity produces weight, which the landing gear supports. During takeoffs and landings, the landing gear absorbs the forces applied to the aircraft fuselage. Any manoeuvre that results in acceleration or deceleration increases the forces and stresses acting on the wings and fuselage during flight. Compression, shear, tension, bending, and torsion are all stresses that an aircraft's fuselage, wings, and landing gear must withstand. Each component of the wing structure absorbs these stresses and transmits them to the fuselage structure. The empennage (tail section) absorbs and transmits the same stresses to the fuselage. These stresses are referred to as loads, and the analysis of loads is referred to as a stress analysis (Vasudevan et al., 2016). Figure 1.1 illustrates the stresses acting on an aircraft (Federal Aviation Authority, 2012).

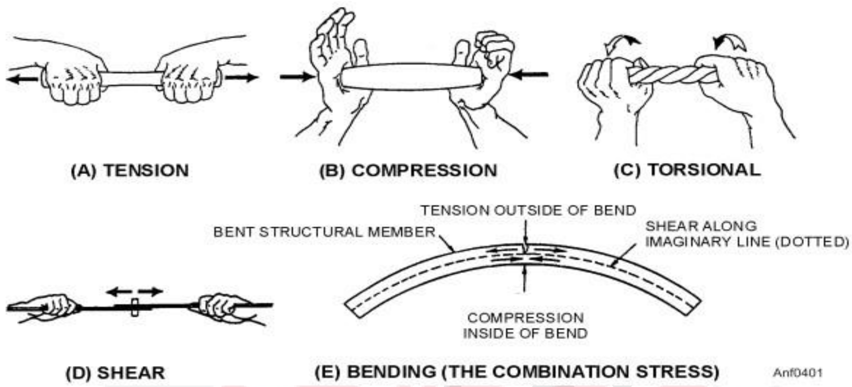

Figure 1.1 : The stresses acting on an aircraft (Federal Aviation Authority, 2012)

Therefore, the critical requirements for aerospace structural materials include physical, mechanical, and chemical properties such as high stiffness, high strength, damage tolerance and fatigue durability, high thermal stability, low density, and high resistance to oxidation and corrosion, along with commercial requirements such as cost, servicing, and manufacturability (Flower, 2012).

Practical considerations often necessitate the inclusion of a cutout in an aircraft subcomponent. Cutouts in the cover panels and wing spars of military fighter wings and commercial transport wings, for example, are required to allow for damage inspection and hydraulic line access. In certain circumstances, these structural elements are required primarily to withstand buckling. As a result, understanding buckling behavior is required in order to design them effectively (Nemeth, 1995).

1.3 Research Background

The phrase composite material means that two or several materials are combined to generate a useful third substance on a macroscopic scale. Composite materials fiber-reinforced with high stiffness-to-weight and strength-to-weight ratios have become essential in weight-sensitive applications (Jones, 1999).

A typical sheet of composite material is a "lamina" or "ply." It is an essential building block. A fiber-reinforced lamina is made up of numerous fibers in a matrix (Reddy, 2004). The use of epoxy-resin, polyester-resin, vinyl-resin as matrix in many engineering and civilian applications has increased, from aircraft fuselages to tennis racket frames. The matrix material in a composite holds the fibers together, protects them from the environment, and carries interlaminar shear. It increases a component's impact and fracture resistance (Chaudhary et al., 2020).

A "laminate" is a lamina collection layered to create the desired thickness and stiffness. For example, a unidirectional fiber-reinforced lamina can be layered to allow fibers in each lamina to be orientated in the same or other directions (Reddy, 2004).

Figure 1.2 illustrates a laminate consisting of a lamina with various fiber orientations. The stacking sequence refers to the sequence of numerous orientations of a fiber-reinforced composite layer within a laminate (Tawfik et al., 2016). Figure 1.3 illustrates fundamental building components made of fiber-reinforced composites.

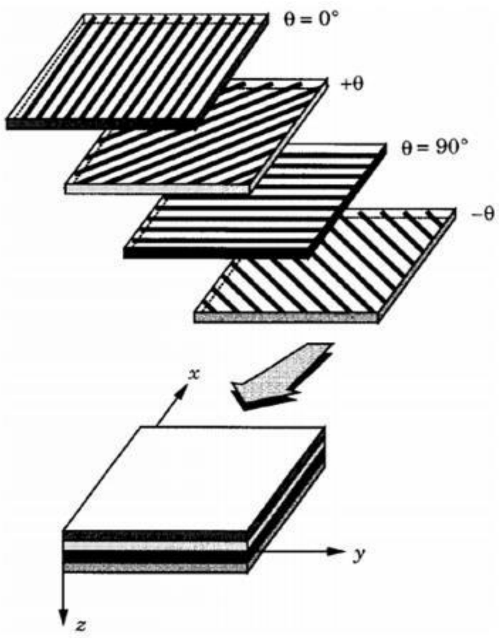

Figure 1.2 : A laminate constructed from lamina with varying fiber orientations (Reddy, 2004)

Fibers + matrix + coupling agent or surface coating for fibers + fillers and other additives

↓

Lamina

(thin layer or ply)

↓

Laminate

(a multi-layered stack that has been consolidated)

Figure 1.3 : Fundamental building components made of fiber-reinforced composites (Mallick, 2007)

As seen in Figure 1.4, a standard laminate orientation code is employed to assure industry standards.

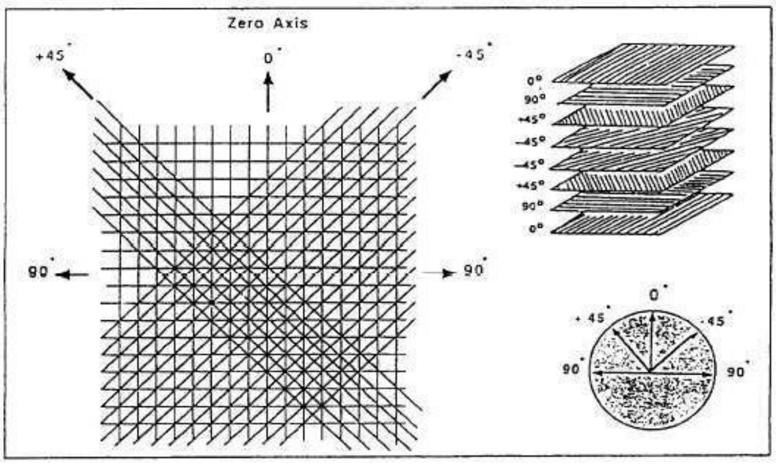

Figure 1.4 : A standard laminate orientation code (Luca, 2017)

Fiber-composite laminate materials have become increasingly popular due to their light weight and high strength. Compressive forces typically cause buckling of composite laminate plates in service. As a result, structural instability is a fundamental consideration in the design of composite plates. Most investigations on the stability of fiber-composite laminate plates have used rectangular plates (Pascal, 1978), (Hirano, 1979), (Rhodes et al., 1984), (Leissa, 1985), (Muc, 1988), (Nemeth, 1988), (Hu & Lin, 1995) and (Vellaichamy et al., 1990). According to the previous studies, there are numerous studies on the buckling analysis of fiber reinforced composites subjected to compression loading that used rectangular plates. Also, less attention has been dedicated to shear-loaded square plates.

Since 1969, when boron fiber-reinforced epoxy skins for F-14 horizontal stabilizers were introduced, the use of fiber-reinforced polymers has steadily increased. Carbon fiber-reinforced epoxy has become the dominant material in many fuselage, wing, and empennage components since the 1970s. Table 1.1 shows an early use in military aircraft of fiber-reinforced polymers (Riggs, 1984).

Table 1.1 : Early use in military aircraft of fiber-reinforced polymers

Types of Aircraft	Components of Aircraft	Material Used	Weight Savings Compared to Metal Components (%)
F-11	Wing fairings	Carbon fiber-epoxy	19
F-14	Horizontal stabilizer box	Boron fiber-epoxy	19
F-16	Fin leading edge and ertical fin box	Carbon fiber-epoxy	23
F-15	Rudder, fin, and stabilizer	Boron fiber-epoxy	25
AV-8B	Fuselage, flaps, ailerons and wing skins	Carbon fiber-epoxy	25
F/A-18	Tail boxes, wing skins	Carbon fiber-epoxy	35

(Riggs, 1984)

Based on the table given, the combination of carbon-fiber epoxy reduces the weight of the aircraft compared to metal components.

The composite usage on commercial aircraft started with some selective, secondary structural components constructed of high-strength carbon fiber reinforced epoxy. The Airbus A320, which was launched in 1988, was the first commercial aircraft to operate with an all-composite tail, including a vertical stabilizer, horizontal stabilizer, and tail cone. The composite used in the Airbus A380, which debuted in 2006, is shown schematically in Figure 1.5. Approximately 25% of its weight is made up of composites.

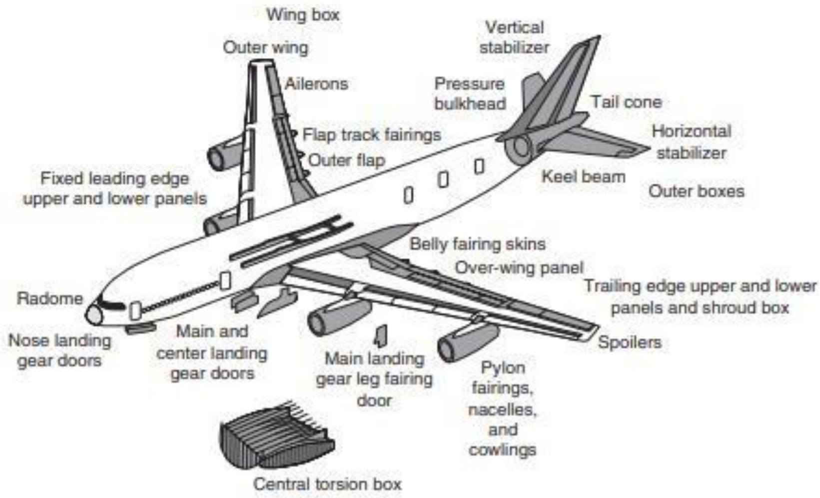

Figure 1.5 : The Airbus A380 incorporates fiber-reinforced composites (Mallick, 2007)

Two concerns are considered when designing structures: first, the structure's strength, which is defined as its capacity to support a specified load without exceeding allowable stress; and second, the structure's capacity to support a specified load without undergoing unacceptable excess deformations. Due to the complexity of the structures of isotropic materials, these procedures are considerably simpler than those for anisotropic materials. Due to features like high specific stiffness and strength, anisotropic composites are critical in the design and construction of spacecraft, maritime vehicles, and sporting items. With the growing demand for lighter and stronger buildings, the search for ways to fully utilize the features of advanced composite materials has continued (Akbulut et al., 2010).

Numerous challenges and concerns with the use of composite require attention. Prediction of buckling loads is a critical topic. Numerous research articles on plate buckling analysis can be found in the literature.

By virtue of mid-plane symmetry, symmetrically laminated angle ply composite plates prevent strength reducing bending-stretching effects. In-plane loads frequently cause buckling of these plates. (Walker, 2010).

Due to the high cost of fuel and materials, reducing excessive weight is a major design goal in both the space and aircraft industries. Eliminating weights made components lighter while maintaining structural integrity. Making holes and cutouts is a common way to reduce unnecessary weight (Yeh et al., 2007).

The basic geometries used in this study to investigate the buckling performance of the square plate are depicted in Figure 1.6. Throughout the study, the thickness of each ply is kept constant at 0.125 mm. The geometry is then transformed into a perforated plate design by removing the circular center portion of the plates. Then, the size of the square plate's centrally circular cutout is varied according to the aspect ratio d/b of 0.1, 0.2, 0.3, 0.4, and 0.5.

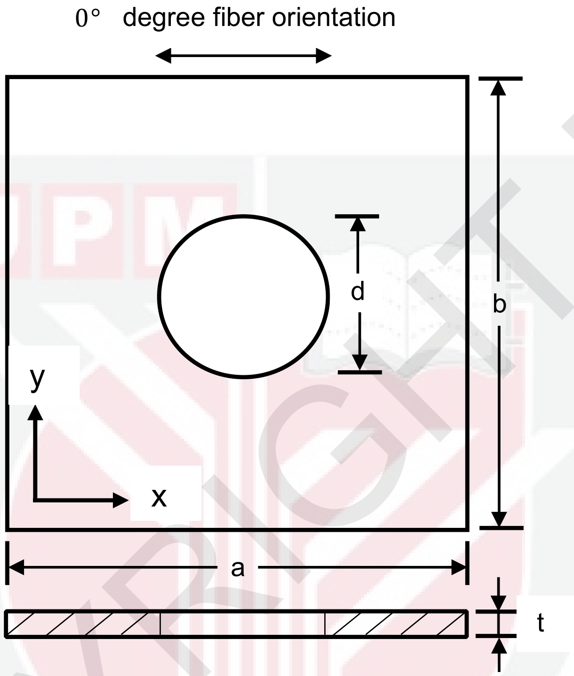

Figure 1.6 : Basic geometries of square plate with cutout

A set of simulations was conducted using fourteen different material configurations:

$[0°]_4$, $[0°]_8$, $[(15°/-15°)]_s$, $[(15°/-15°)_2]_s$, $[(30°/-30°)]_s$, $[(30°/-30°)_2]_s$, $[(45°/-45°)]_s$, $[(45°/-45°)_2]_s$, $[(60°/-60°)]_s$, $[(60°/-60°)_2]_s$, $[(75°/-75°)]_s$, $[(75°/-75°)_2]_s$, $[(90°/-90°)]_s$, $[(90°/-90°)_2]_s$ laminated composite plates with cutout.

This study takes account of the influence of circular cutouts on the buckling performance of composite plates in angle-ply laminates. Also, in this study, the effects of the circular cutout size on the buckling behavior of carbon-epoxy laminated composite plates are also included in different aspect ratios. Additionally, a finite element analysis was used to determine the influence of cutout on the buckling behavior of these plates. The present model is being verified and validated by comparing the obtained findings to those obtained from the reference (Loughlan, 2019) using the same geometrical parameters and material parameters as in the references. The boundary conditions are also as given (Loughlan, 2019). The laminated plates are constructed from high-strength carbon-epoxy ply sheets with a ply thickness of 0.125mm. The properties of the ply material applied in the calculations are as follows: $E_1 = 140.0\ kN/mm^2$, $E_2 = 10.0\ kN/mm^2$, and $G_{12} = 5.0\ kN/mm^2$ (Loughlan, 2019).

1.4 Problem Statements

Composite materials are widely employed in a variety of industries, including aerospace, marine, automotive, civil, and commercial equipment, as well as medical and recreational equipment. The growing use of composite materials is a result of their advanced material properties. Numerous studies have been conducted to identify the properties of a composite material; nonetheless, there are some areas that remain unexplored, particularly those involving the material's behavior. Another method for reducing weight, while also increasing stability, reliability, and accessibility, is to incorporate cutout/hole structures in the development of a product. During their use, these structures will be subjected to tensile and compressive loading, and it is critical for the engineer to identify the material's safe operating design and condition. It is also critical to determine the cause of a failure or fracture in a composite material. (Zahari et al., 2012)

Leonhard Euler investigated the column buckling problem for the first time in 1757. Numerous efforts have been undertaken since then to improve the buckling capacity of thin columns, owing to their relevance in aeronautical, structural, mechanical, and a variety of other sectors of engineering. When it comes to safety engineering design, buckling analysis has become a key factor since the real stress at the site of failure is considerably lower than the material's ability to sustain imposed loads (Goel et al., 2021). A study of buckling resistance is required since buckling is frequently a critical factor in column design (Nugroho & Bahtiar, 2021).

In composite structures, cutouts are frequently used. These are incorporated into structural components to allow for ventilation and, on occasion, to help lighten the structure. Cutouts are required in aircraft components (such as the wing spar and ribs) for access, electric and fuel lines, inspection, or to decrease the total weight of the aircraft. The panels are subjected to a variety of stresses and stress combinations as a result of the structure's various loads.

Excessive in-plane loads can cause panels to buckle, and in these cases, the buckling strength of the panels is used as the strength criterion. To create lighter, more efficient structures, however, the reserve strength of panels beyond buckling must be utilized. Thus, in order to design laminated panels efficiently, it is desirable to have a complete understanding of their buckling, postbuckling, failure characteristics, and overall strength (Jain & Kumar, 2004).

For numerical analysis of the structure, the finite element method has been applied. FEM is a computational method for solving linear and nonlinear transient engineering challenges (Moaveni, 2011). Additionally, FEM may be used to forecast the failure and behavior of physical systems in a virtual domain (Maropoulos & Ceglarek, 2010).

According to the above mentioned literature study, sufficient research exists to demonstrate the effect of cutout on the buckling response of laminated composite plates. The majority of researchers use FEM since it is one of the best tools for dealing with complex geometry. The FEM has been effectively used for a wide variety of problems, including fluid–structure interaction, thermochemical, thermomechanical, thermo-chemomechanical, biomedical engineering, ferroelectric, piezoelectric, and electromagnetics (Baccouch, 2021).

Additionally, the research on the effect of hole plates under shear loads was chosen due to the lack of information found in the literature about the influence of symmetrically laminated angle ply composite plates with cutout under shear force. This demonstrates that the shear buckling of fiber reinforced composites with cutouts has received little consideration. As a result, this study decides to investigate the effects of symmetrically laminated angle ply composite plates with cutout subjected to shear loads using the FEM approach.

1.5 Objectives of the Research

The primary goal of this research is to determine the effect of hole/cutout diameter and fiber orientation on the buckling behavior of carbon-epoxy laminated composite square plates under simple-supported boundary conditions with circular holes when subjected to in-plane shear loading. Apart from the primary objective, numerous secondary objectives are associated with the primary objective of this research, such as:

1) To analyze the buckling behavior of a symmetrically laminated angle ply composite plate with a circular hole and without a circular hole under shear loading.
2) To evaluate the influence of shear load directions on the behavior of symmetric angle ply CFRP laminates.
3) To investigate the effects of hole in different sizes on the shear buckling behavior of symmetric angle ply CFRP laminates.

1.6 Research Scopes

To accomplish the study's aims, an understanding of the fundamental buckling concept of laminated square plates is done, particularly when subjected to shear loadings. The current work analysis uses solely a numerical method, namely finite element analysis (FEA) software. This strategy is being investigated for use in the current study since it can expedite the process of obtaining data and save cost. Due to the fact that the current study employs finite element analysis (FEA) software, namely ABAQUS, to perform the analysis, the method for using the software is acquired since the software that has been used by previous work, Loughlan (2019) was finite strip method.

To determine the most appropriate material for the present study, a literature search is undertaken on the contents which will be used throughout the study. The study's materials were chosen based on their qualities and their widespread use in modern industries. The features of materials that are in demand in today's sectors include light weight and high strength. As a result, the optimum material for the current study has been chosen to be carbon-fiber reinforced polymers (CFRP) due to its material qualities and common application in the aerospace industry.

Additionally, the square plate with no cutout is used as the basic model geometry in this work. The square plate is 200mm x 200mm in size without perforations. The shear buckling study is performed on a square plate with no cutout using the finite element tool, ABAQUS. The numerical analysis results are verified and validated by comparing them to previously published theoretical data collected through a literature study. To ensure that the analysis's results are valid and acceptable, the percentage difference used in this study must be less than 10%.

Meanwhile, the detailed investigation of the shear buckling behavior of laminated square plates is continued by eliminating the model's center section. To ensure consistency throughout the investigation, the type of hole analysed is circular in shape. The current study considers five different hole sizes, namely hole ratios d/b of 0.1, 0.2, 0.3, 0.4, and 0.5.

Finally, the findings from all of the investigations undertaken for this study are reviewed and discussed in order to better understand the buckling behavior of laminated square plates with circular holes under shear loadings. Lastly, the study's findings are summarized and recommendations for further research are made.

1.7 Thesis Layout

This thesis is divided into five chapters, the contents of which are as follows:

- Chapter 1: Introduction

This chapter reviewed the study on the buckling of composite perforated plates under shear loading in general.

- Chapter 2: Literature Review

This chapter provides a literature review that was conducted based on a previous study and published paper on the shear buckling of laminated plates with and without cutouts.

- Chapter 3: Methodology

This chapter describes the methods used in the research, which included the use of Finite Element Analysis software.

- Chapter 4: Results and Discussions

This chapter discusses the findings of research on the shear buckling performance of laminated plates with and without cutouts, as well as the verification and validation of numerical data produced.

- Chapter 5: Conclusions and Recommendations

This chapter concludes the study with a complete conclusion based on the research findings and some recommendations for future work.

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