Compressive Failure Behaviour of Composite Laminates due to The Effects of Cutout Sizes and Variation in Fibre Orientations

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Preface: 2nd International Conference on Information Technology, Advanced Mechanical and Electrical Engineering (ICITAMEE) 2021

We would like to present, with great pleasure, the collection of research paper presented in the 2nd International Conference on Information Technology, Advanced Mechanical and Electrical Engineering (ICITAMEE) 2021. The ICITAMEE 2021 was held on August 25th-26th 2021, located at Universitas Muhammadiyah Yogyakarta, Bantul, Yogyakarta, Indonesia. Due to bad pandemic condition, the presenters virtually presented the papers in the ICITAMEE 2021.

The ICITAMEE 2021 gathered distinguish speakers, researchers, academicians, and industry practitioner from Indonesia and other countries to share their expertise and discuss cutting edge knowledge and research in engineering and related topics. The discussion covers the area of research interest including material, mechanical, electrical, biomedical, and informatics engineering, computer science, and technology, in order to understand in more depth of how those aspects intertwine in daily human lives.

We would like to express our appreciation and gratitude to all keynote speakers as well as all participants for the great discussions. We also thank our technical program (scientific) committee and reviewers for maintaining a good quality standard of the accepted manuscripts for publication. Some of the technical program committees are from our co-host (Universiti Teknologi MARA, Malaysia). We hope that the proceedings will serve as a valuable reference and be able to stimulate further research in related topic.

Editors,

Yessi Jusman

Hanifah Rahmi Fajrin

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Compressive Failure Behaviour of Composite Laminates due to The Effects of Cutout Sizes and Variation in Fibre Orientations

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Abstract. Composite laminates have become progressively trending due to its tailorable of material properties, thus widely used in modern structures. Nevertheless, due to the complex fiber-matrix interaction added by the existing of cutouts, it is complicated to understand the failure mechanism and deformation behaviour of composite laminates. Based on literature review, the studies on the effect of various diamond cutout sizes and fibre orientations to the composite laminates are limited but in reality, the application of diamond cutouts are found practical for many composite structures. This paper aims to study the effect of various diamond cutout size to the failure behaviour of T300/5208 Graphite/Epoxy and UD Kevlar/Epoxy with various fibre orientations under uniaxial compression. Failure analysis was conducted using the Finite Element Simulation (ANSYS) based on Maximum Stress Theory. The results show a noticeable strength difference between composite plates with and without cutout. The main finding deduced from the study is that the existing of diamond cutout shape reduces the compressive strength of Graphite/Epoxy and Kevlar/Epoxy composite laminates up to 100 and 10 times respectively. The fibre orientation has greater effect in reducing the compressive strength of the composite laminates compared to the cutout size. This information is important in designing practical composite structure where cutouts exist, and thus this study has significantly contributed new fundamental knowledge.

Keywords: Composite Laminates, Cutout Sizes, Failure Behaviour, Fibre Orientations, Compressive Test.

INTRODUCTION

The development of composite laminates which rigorously began for defence and aeronautical industries, has recently been expanded significantly towards civil and consumer use such as construction, sports equipment, automotive and household components (1). The latest generation of composite materials has great potential to meet the demand for both rapid growth of industry and change in technology (2). Since the strength of material is an important property in designing reliable structures (3), composite materials are becoming a popular option, mainly because of its tailorable properties and having high strength to weight ratio (4). Graphite/Epoxy and UD Kevlar/Epoxy commonly selected due to its popularity of excellent mechanical properties, light weight, toughness, and resistance to impact damage (5). The strength of material is a capability of the material to withstand with the applied load. Nahas et al. (3) has claimed that a material fails when the applied load reaches the limit of its load carrying capacity. Laminate failure led to permanent loss of integrity within the laminate along with degradation of stiffness and strength of the material (6).

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The ideal approach to analyse the failure of composite materials is by conducting physical tests. The data obtained regarding to this approach can be considered as accurate and valid. However, physical tests are tedious, costly and time consuming as it requires numerous repetitive tests for various parameters and loading conditions. Latterly with the development of computer, researchers start exploring alternatives such as employing numerical methods to perform the failure analysis (1). In numerical approaches, the idea of failure theory is implemented in order to estimate the strength of laminated composite through advanced computational method using finite element analysis which are preferable for researchers in predicting the failure of composite laminate (7).

Rahimi et. al., (5) had performed failure analysis under uniaxial tension on woven Kevlar/Epoxy laminate using analytical and finite element method. The results of first-ply failure and last-ply failure were determined and compared between the two methods. M. Mali et. al. (8) studied the effects of the V-notch and the variation of fibre orientation angle to the strength of Glass/Epoxy composite laminates. The failure behaviour of plain plate and V-notch plate laminate were analysed under bending load. B. M. İçten et. al. (9) has conducted failure analysis both numerically and experimentally on woven Kevlar/Epoxy pin joints under tensile load. Failure mode and failure load of composite plates were determined by using Hashin, Hoffman and Maximum Stress criteria. For laminated composite with cutout,

M. Mali et. al. (10) studied the effects of the angle of fibre orientation to woven Kevlar/Epoxy laminates under a compression state on a flat plate with circular hole.

To fully understand the property of composite laminates, failure behaviour of this material should be well analysed (11), especially for marine, aerospace and racing applications. Practically, there is a need for different type of cutout shapes and sizes on the composite laminated structure to accommodate bolts, nuts, rivet and others. The presence of cutouts is inevitable, but their presence is clearly reducing load carrying capacity and strength (12).

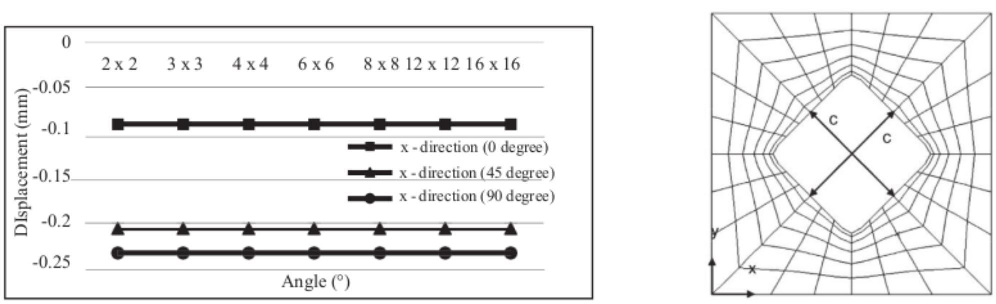
Despite there are a lot of studies that have been carried out such as a study conducted by Abu Talib et al. (13)on the failure analysis of cutouts shapes, there still have a limitation and lack of studies on the effect of various diamond cutout sizes related to Graphite/Epoxy and Kevlar/Epoxy. Thus, the behaviour of these properties is not fully understandable. This paper aims to study the effect of diamond cutout to the failure behaviour of T300/5208 Graphite/Epoxy and UD Kevlar/Epoxy composite laminates with various fibre orientations under uniaxial compression. Failure analysis is conducted by using the finite element method (FEM) with Maximum Stress Theory as the failure criteria. This study helps to provide a proper selection of Graphite/Epoxy and Kevlar/Epoxy with suitable cutout to prevent future problems such as delamination and cracking of laminate.

METHODOLOGY

Stage 1: Mesh Convergence Analysis

The study began with performing the convergence analysis as it is very crucial. The significant part in conducting the finite element process is to perform accurate meshing and determining the mesh size. The simulated result will be more accurate as the mesh size decreased. Nonetheless, the smaller the mesh size used, the computing time and the cost will be increase (4). Various mapped meshing (2x2, 3x3, 4x4, 6x6, 8x8, 16x16) with quadrilateral elements under constant uniaxial compression, 80000 N for Graphite/Epoxy with no cutout were analysed. Figure 1.a) can be observed that the results for Graphite/Epoxy converge with a minimum mesh size of 2x2.

In the case of laminate with cutout, the convergence of results has been obtained for finite element mesh 144 elements and corroborate with the results obtained by Dinesh Kumar (14). Schematic of finite element mesh for composite laminate with cutout shape is shown in Figure 1.b).



a) b)

FIGURE 1. Displacement in x-direction for a) Graphite/Epoxy with no cutout and b) with cutout symmetric $[\theta_4/0_4/-\theta_4]_s$ laminate.

Stage 2: Numerical Validation

Models with stacking sequence [θ4/04/-θ4]s and variations in fibre orientation (θ = 0° - 90°) were simulated using finite element approach to predict the maximum displacement for both x-direction and y-direction under uniaxial compression load. The geometry and the material properties of Kevlar/Epoxy used for this model are shown in Figure 2 and Table 2 respectively. For this analysis, the simulation results using ANSYS were compared with the analytical approach using MATLAB for various ply arrangements. Table 1 has proven that the result is good since the error is less than 2%.

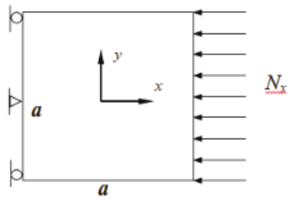


FIGURE 2. The modelling of geometry under uniaxial compression.

TABLE 1. Comparison between analytical results and finite element simulation results.

Angle	Load	Analytical		Simulation (ANSYS)		Error	
$\theta\theta^{00}$	(N)	x (m)	y (m)	x (m)	y (m)	x (%)	y (%)
0	-50000	9.868E-05	1.678E-05	9.870E-05	1.680E-05	0.02	0.14
10	-50000	1.042E-04	3.019E-05	1.040E-04	3.020E-05	0.21	0.02
15	-50000	1.127E-04	4.661E-05	1.130E-04	4.660E-05	0.31	0.03
20	-50000	1.269E-04	6.789E-05	1.270E-04	6.790E-05	0.07	0.02
30	-50000	1.746E-04	1.075E-04	1.750E-04	1.070E-04	0.21	0.43
40	-50000	2.265E-04	1.082E-04	2.260E-04	1.080E-04	0.20	0.22
45	-50000	2.434E-04	9.385E-05	2.430E-04	9.380E-05	0.15	0.05
50	-50000	2.534E-04	7.588E-05	2.530E-04	7.590E-05	0.14	0.02
60	-50000	2.600E-04	4.276E-05	2.600E-04	4.280E-05	0.01	0.08
70	-50000	2.594E-04	2.043E-05	2.590E-04	2.040E-05	0.16	0.16
75	-50000	2.585E-04	1.325E-05	2.590E-04	1.330E-05	0.18	0.36
80	-50000	2.577E-04	8.354E-06	2.580E-04	8.350E-06	0.10	0.05
90	-50000	2.570E-04	4.578E-06	2.570E-04	4.580E-06	0.02	0.05

Stage 3: Failure Analysis

Properties of the material of Graphite/Epoxy with volume fraction 60% and Kevlar/Epoxy of each lamina are presented in Table 2. The plate is in rectangular shape as shown in Figure 2; thus, the length of the plate, a is 0.279 m, which is equal to the width of the plate. The thickness of the plate, h, is 1.86 x 10^{-3} m and having an aspect ratio (S = a/h) of 150. Therefore, the cross-sectional area (A = ah) is 0.51894 x 10^{-3} m^2. The composite laminates consist of 24 layers, where the layup studied is $(\theta_4/0_4/-\theta_4)_s$. The composite laminates with and without central cutouts of a specific shapes which is diamond cutout sizes are analysed. Three cutout sizes of areas designated as A_1, A_2 and A_3 (as shown in Table 3) have been considered to observe the effect of cutout shape on the failure behaviours of the laminate under uniaxial compressive loading.

TABLE 2. Material Properties for T300/5208 Graphite/Epoxy (14) and Uni-Directional Kevlar/Epoxy (15).

T300/5208 Graphite/Epoxy				Uni-Directional Kevlar/Epoxy			
Elastic Parameter		Strength Data		Elastic Parameter		Strength Data	
E_1	132.58 GPa	X_T	1520 MPa	E_1	76 GPa	X_T	1380 MPa
$E_2 = E_3$	10.8 GPa	X_C	1700 MPa	$E_2 = E_3$	5.5 GPa	X_C	276 MPa
$\nu_{12} = \nu_{13}$	0.24	Y_T	43.8 MPa	ν_{123}	0.34	Y_T	28 MPa
ν_{23}	0.49	Y_C	43.8 MPa	G_{12}	2.1 GPa	Y_C	138 MPa
$G_{12}=G_{13}$	5.7 GPa	S	86.9 MPa			S	44 MPa
G_{23}	3.4 Gpa						

TABLE 3. Details of cutout shapes and their dimension (14).

Cutout Shape	Cutout size			
		A_1	A_2	A_3
Diamond	Ratio, c/a	0.140	0.280	0.420
	Length, c (m)	0.03906	0.07812	0.11718

A finite element failure analysis has been conducted using numerical software (ANSYS). Figure 3 shows the overall flow of failure analysis in ANSYS. The failure behaviour is based on the available built-in failure theories and failure criterion, which are Maximum Stress Theory. Maximum Stress Theory was employed to determine the failure load (failure index = 1). The failure criteria of X_t, X_c, Y_t, Y_c and S were included. The failure index of the composite laminates must be 1 or greater. Otherwise, the load must be increased continuously until the plate fails.

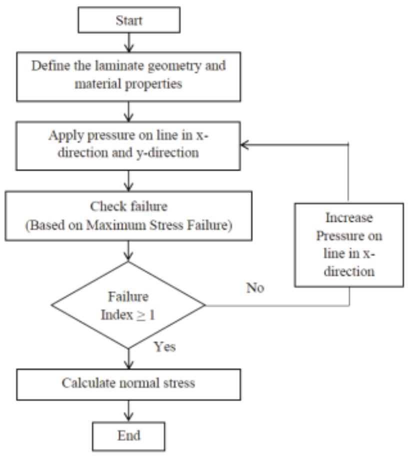


FIGURE 3. Overall Flow of Failure Analysis (ANSYS).

RESULT AND DISCUSSION

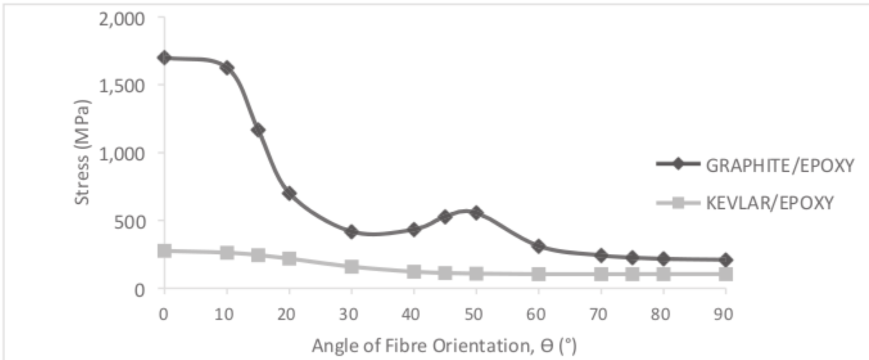
Failure results on every model tested are plotted. Figure 4.a) and Figure 4.b) shows the failure curves of composite laminates with no cutout and with cutout shapes, respectively. The findings found that the existing of diamond cutout affects the value of stress generated. The stress of Graphite/Epoxy at the angle 0° for Figure 4.a) is 1700 MPa and for Figure 4.b) at cutout size A2 is 10 MPa. The comparison from both graph shows that the compressive strength of Graphite/Epoxy's plate with no cutout is reduced up to 100 times due to the existing of the diamond cutout. However, for Kevlar/Epoxy, the stress generated at angle 0° for Figure 4.a) is 276 MPa and for Figure

4.b) at cutout size A2 is 30 MPa. The compressive strength of plate with no cutout is reduced up to 10 times.

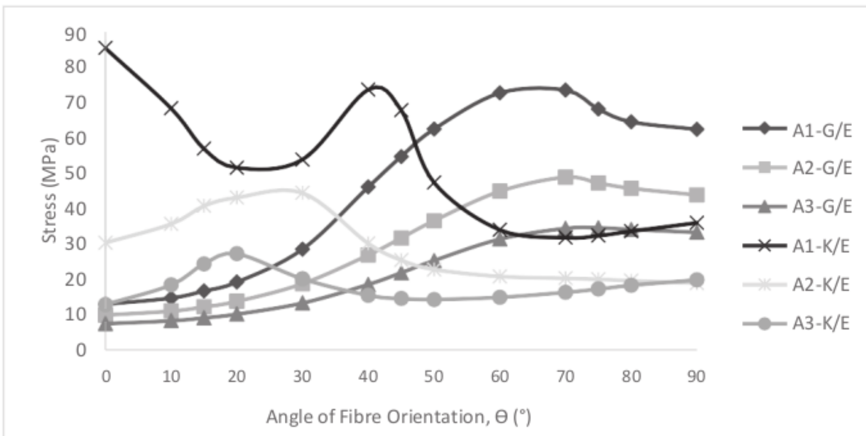
Besides, the failure curves of plate with no cutout for both materials show a small increment on the stress generated. Failure curves found that the strength of Graphite/Epoxy without cutout is affected with the increase of fibre orientation. The look alike down-trend is found from past study using different type of composite material (16). However, the flat curves on Kevlar/Epoxy prove that it is not much affected by the change of fibre orientation. The plate without cutout shows the strength of Graphite/Epoxy is higher than Kevlar/Epoxy since the value of stress is higher. Moreover, the compressive strength of Graphite/Epoxy towards the model with cutout is affected with the increase of fibre orientation. The pattern graphs out of three cutout sizes show similar trend, whereby the stress is gradually increased when the angle of fibre orientation increased. This up-trend pattern is similar with past study results on the composite plates with cutout plates under compressive loading (17), (18). For Kevlar/Epoxy's plate with cutout show that the graph is fluctuated. From A1-K/E, the stress decreased between the angle of 0° to 20°, then it is slightly rose till the angle of 40° and drop again till the angle of 70°. The highest stress for A_1-G/E is 74 MPa at angle 70°, however, for A1-K/E is found at the angle 40° which is 73 MPa. The different of the highest stress between both materials are almost similar.

From Figure 4, both can be concluded that Graphite/Epoxy and Kevlar/Epoxy strength are also affected by the cutout sizes. The results for all three sizes of cutouts are somehow different to each other. The gap in between A_1,

A_2 and A_3 are not too large. The A_1 is the smallest cutout size, and A_3 is the largest cutout size. However, the findings found that A_1 generates highest stress compared to A_2 and A_3 for both materials, where the stress at the angle 90° of A1-G/E is 62 MPa, the stress of A2-G/E is 44 MPa and the stress of A3-G/E is 33 MPa. The graph shows the bigger the cutout sizes, the higher the chances of the plate tend to fail as the value of stress increases.



a)



b)

FIGURE 4. Failure curves of Graphite/Epoxy and Kevlar/Epoxy with a) no cutout, and b) cutout sizes

CONCLUSION

This paper has presented and discussed about the effect of various diamond cutouts sizes and angle of fibre orientation to the failure behaviour of Graphite/Epoxy and Kevlar/Epoxy laminated composite plates. The results shown a noticeable difference of laminate strength between plates with and without diamond cutout. The main finding deduced from the study is that the existing of diamond cutout shape reduces the compressive strength of Graphite/Epoxy and Kevlar/Epoxy composite laminates up to 100 and 10 times respectively. The fibre orientation has greater effect in reducing the compressive strength of the composite laminates compared to the cutout size. In conclusion, this study has provided knowledge which is important for designing practical composite structure where cutouts exist.

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