Compressive Failure Behaviour of Unidirectional and Woven Kevlar/Epoxy Composite Laminates under Various Angles of Fiber Orientation

Mohamad Mali, Jamaluddin Mahmud

Abstract*: Studies have shown that the angle of fiber orientation significantly affects the mechanical properties of a composite laminate. Due to this, accurate prediction of the laminate response because of the loading effect is crucial. Many investigations on the properties of composite materials have been conducted. However, there is still the lack of study related to Kevlar/Epoxy laminate. Therefore, this study aims to investigate the effect of the angle of fiber orientation to woven and unidirectional (UD) Kevlar/Epoxy laminates under compression state. The study was conducted in two stages comprising of numerical validation and failure analysis. For the failure analysis, a flat plate and flat plate with circular hole under compression were modelled using ANSYS. Two of the most common failure models, Maximum Stress Theory and Tsai-Wu Failure criteria were selected for the failure prediction. The laminates were made of 24 layers woven Kevlar/Epoxy and the stacking sequence was (θ_4/0_4/-θ_4)s. The angle of fiber orientations, θ, have been varied from 0° to 90° and failure loads for both flat plate and flat plate with circular hole were determined. The trend of displacement and failure behaviour for both types of plate were compared. The results show that the angle of fiber orientation affects significantly the trend of the displacement and failure curves of UD and woven Kevlar/Epoxy. The curves for UD and woven; flat plate and flat plate with circular hole are different and unique in nature; and thus should be treated individually. These analysis and findings are important in aiding the engineers at designing a stronger woven Kevlar/Epoxy composite laminate. Therefore, it can be concluded that the current study has contributed towards enhancing knowledge about the compressive failure behaviour of unidirectional and woven Kevlar/Epoxy composite laminates.

Keywords: Kevlar/Epoxy, Composite laminates, failure behaviour, FEA, ANSYS.

I. INTRODUCTION

Composite materials are materials that are not only superior in any form of a single material, but also have special properties which a separate component does not have [1]. This is because a composite material property is tailorable and can be designed to produce useful and superior structures. Though the development of such composite materials offers bigger variety of materials selection, they can also increase the complexity in design and analysis [2]. Fortunately, with the development of finite element (FE) model in computer software, there is an increase in studies related to analysing composite materials.

One of the studies has been conducted by Rahim et al [3] on the parametric study of failure analysis of composite laminate for the uniaxial tensile loading. The study had investigated the effect of material property, aspect ratio and number of plies in composite laminates based on its failure load using computer software finite element analysis (FEA) and the software had been proven to be capable of predicting the failures in laminated composite plates. Another study had been conducted by Samsudin & Mahmud [4] on the investigation of the effect of lamination scheme and angle variations to the displacements and failure behaviour of composite laminate. Using FEA, the research had verified that both symmetric and anti-symmetric laminates may fail at the same failure load.

To verify the obtained results from the FEA, researchers began comparing their results with the experimental results from a study conducted by Zhang et al [5] on the prediction of failure envelopes and stress-strain curves of fiber composite laminates under triaxial loads. From the study, they discovered that the predictions using Christensen's lamina failure criterion appealed to the test results for most cases. Similar approach had been conducted by Mahmud et al [6] on the study of the failure analysis of composite laminates based on the experiment-simulation integration. With a more systematic procedure and introduced validation process for FE model, Mahmud succeeded at integrating the experiments and simulations to investigate the failure behaviour of Carbon/Epoxy laminate.

Consequently, the study on the composite materials is favoured toward the comparing method. Rahimi et al [7] had conducted an evaluation of failure criteria for composite plates under the state of tension by using commercial FEA and FE programme. In this study, the results obtained from both methods are compared with the experimental values to prove that the capability of this method can simulate the failure behaviour of composite plates accurately under tension. Samsudin et al [8] had conducted a study to predict the deformation and failure analysis of symmetric and anti-symmetric Graphite/Epoxy laminate due to the variations in fiber orientations using two

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different numerical methods. With both results showing a promising outcome, the study is considered successful and it has proven that numerical approach can produce good results. Mali et al [9] had later used a similar approach to investigate the failure analysis of composite laminates under biaxial tensile load due to the variations in a lamination scheme. By using both analytical method and FEA to predict the results, Mali had first validated the models from both methods by comparing the results with past experiments. Mali had succeeded in achieving the results of the research and had proven that both methods are capable at simulating accurate failure behaviour of composite laminates under biaxial tensile loads.

Other than a comparison study, another purpose of the research was to compare between the two materials in terms of property. Kumar & Kalam [10] had conducted a study on design, analysis and comparison between the conventional materials with composite material of the leaf springs and they had discovered that the composite material leaf spring have a lesser stress compared to the steel leaf spring. The study on the effect of a woven and a UD fiber structure for the mechanical properties of the polyester composite reinforced kenaf was conducted by Ratim et al [11] in order to investigate the strength difference in terms of fiber structure. The study had concluded that the highest tensile strength had been achieved by woven structures instead of the UD structures.

Despite the vast study in the analysis of composite materials, there are still the lack of information related to Kevlar/Epoxy especially in comparison between the woven structure and the UD structure thus the behaviour of the properties is still not well understood. Hence, the objective of the research was to analyse the displacements and failure behaviours of woven and UD Kevlar/Epoxy composite laminates under compression state using finite element (FE) software ANSYS.

II. METHODOLOGY

This was a continuation study on the failure analysis of woven Kevlar/Epoxy composite laminates under the compression state due to the variations in a fiber orientation. Using similar approaches, the present study was conducted in two numerical stages:

Stage 1: Numerical Validation

Stage 2: Displacement and Failure Analysis

A. Stage 1: Numerical Validation

The use of FE software was important to reduce the cost and to avoid tedious experiment [7]. However, to ensure the obtained result was valid, numerical validation was required as practiced by some past researchers [6], [9]. Present models have been validated through result comparisons with the exact solutions from a past study [12], presented in Table- I. The results obtain from the FE software used for this study was valid since the error had been found to be less than 2%.

Table- I: Comparison of present model with exact solutions

Lamination Scheme	UDL (Pa)	Exact Solution (mm)	Present (mm)	Error (%)
[0/90/0/90]	689.5	0.00340	0.00338	0.59
[0/90/90/0]	689.5	0.00582	0.00579	0.52
[45/-45/45/-45]	689.5	0.00276	0.00274	0.72
[15/-15/15/-15]	689.5	0.00639	0.00636	0.43
[45/-45]	689.5	0.04066	0.04029	0.91
[15/-15]	689.5	0.06610	0.06576	1.42

B. Stage 2: Displacement and Failure Analysis

The prediction of failures was based on the available built-in failure theory and failure criteria functions, Maximum Stress and Tsai-Wu criteria. The deformation behaviour of plate had also been recorded. Fig. 1 shows the overall workflow of the present study.

Model of composites in the shape of rectangular flat plates and rectangular flat plate with discarded circular hole (D = 0.03 meter) were developed as in Fig. 2. The model was made out of 24 laminates with symmetry ($\theta_4/0_4/\text{-}\theta_4$)s layup (where θ = 0° to 90°). The model with thickness of 0.13333 mm had been applied with compression forces to study the effect of circular hole and angle of lamination scheme towards the deformation and fracture/failure of the first-ply and last-ply of the woven Kevlar/Epoxy and UD Kevlar/Epoxy composite laminates.

The material and strength properties of woven and UD Kevlar/Epoxy is shown in Table- II. A FE failure analysis procedure was carried out by using commercial software (ANSYS v18.1, 2018 SAS IP, Inc.).

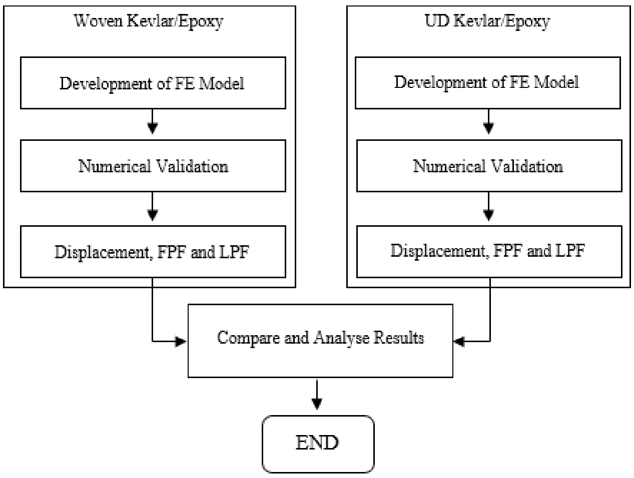

Fig. 1. The process flow of failure analysis of composite laminates

Table- II: Material properties of woven Kevlar/Epoxy [13] and UD Kelvar/Epoxy [14]

	Woven	UD		Woven	UD
E_1	26180 MPa	33500 MPa	X_T	420 MPa	358 MPa
$E_2 = E_3$	26180 MPa	8000 MPa	X_C	150 MPa	260 MPa
$\upsilon_{12} = \upsilon_{13}$	0.11	0.35	Y_T	420 MPa	21 MPa
υ_{23}	0.11	0.33	Y_C	150 MPa	130 MPa
$G_{12} = G_{13}$	1533 MPa	2260 MPa	$S_1 = S_3$	106 MPa	44 MPa
G_{23}	1533 MPa	3000 MPa	S_2	106 MPa	34 MPa

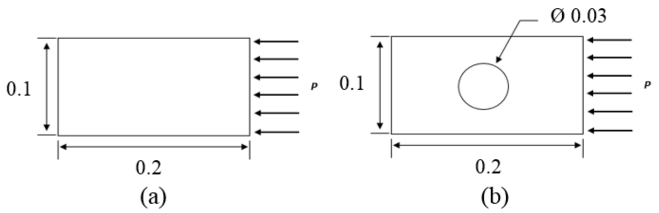

Fig. 2. Model of (a) Flat plate and (b) Flat plate with circular hole

III. RESULT AND DISCUSSION

A. Woven and UD Kevlar/Epoxy (for Flat Plate)

The deformation results for woven and UD Kevlar/Epoxy flat plate is illustrated in Fig. 3. From the figure, it can be found that there are not many differences in terms of deformation between the woven and the UD Kevlar/Epoxy composite laminates. Most displacement occurred towards the x-direction due to the equal direction compression force applied and maximum displacement was at a 45-degree point. Almost the same displacement occurred at the y-direction and both materials showed no displacement at the z-direction. At the y-direction, the results are almost similar except for the slightly higher displacement range on the UD Kevlar/Epoxy before the 45-degree point. At the x direction, the woven and UD Kevlar/Epoxy were in parallel with the woven Kevlar/Epoxy result and was higher than the UD Kevlar/Epoxy results until it reached the 45-degree point. After that point, the woven Kevlar/Epoxy gradually decreased back to form a symmetrical line while the UD Kevlar/Epoxy line was almost straight up to the 90-degree point. It had been discovered that the maximum displacement occurring in the woven Kevlar/Epoxy for flat plate was at the 45-degree point and the minimum displacement was at 0 and 90-degree point. For UD Kevlar/Epoxy, the minimum displacement had occurred at 0-degree and had increased gradually towards the 50-degree point before the displacement results became parallel towards the 90-degree point.

The failure curves for woven and UD Kevlar/Epoxy flat plate has been presented in Fig. 4. From the graph, all the lines showed the same pattern with maximum point in both at 0 and 90-degree. Compared to UD, the woven Kevlar/Epoxy curves is in symmetry with the lowest failure load resulting at the 45-degree point. The results in FPF and LPF for woven Kevlar/Epoxy that have been found by using the Maximum stress and Tsai-Wu failure criteria when they are close to each other at all the angle of the fiber orientation. This proves that woven Kevlar/Epoxy failure behaviour is easier to predict compared to the UD Kevlar/Epoxy composite flat plate. For the strength properties, it can be found that results from UD Kevlar/Epoxy are much greater than the woven Kevlar/Epoxy. Compared to woven, there is always a gap in between FPF and LPF for UD Kevlar/Epoxy. This shows that the UD Kevlar/Epoxy is much more affected by the fiber orientation compare to woven Kevlar/Epoxy composite laminates.

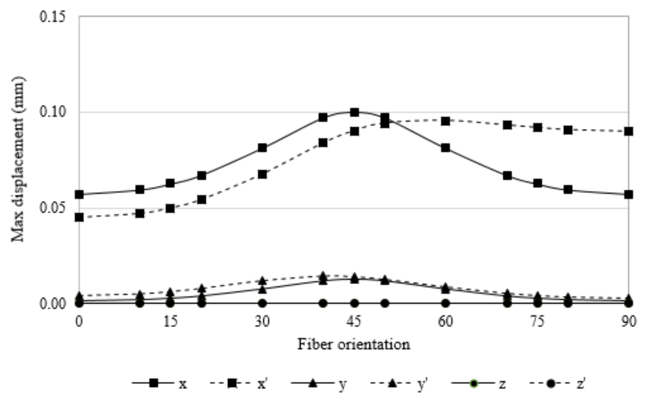

Fig. 3.Woven UD Kevlar/epoxy displacement curves (for Flat plate)

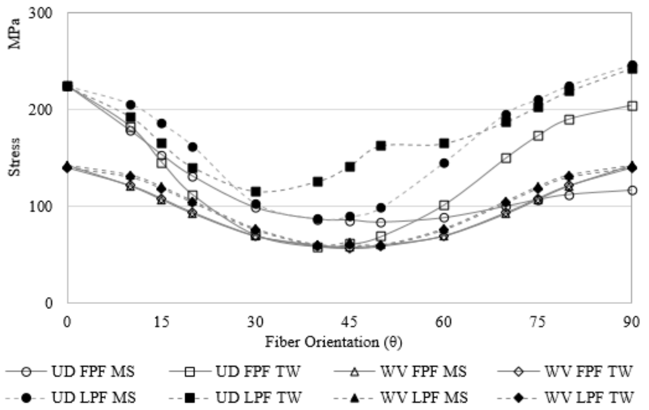

Fig. 4. FPF and LPF curves (for Flat plate using Tsai-Wu and Maximum stress)

B. Woven and UD Kevlar/Epoxy (for Flat Plate with Circular Hole)

The deformation results for woven and UD Kevlar/Epoxy flat plate has been illustrated in Fig. 5. From the figure, it is clear that there is a different in deformation occurring in the woven and UD structures.

Similar to the previous results, the woven Kevlar/Epoxy displacement in both x and y directions are symmetry where the maximum displacement occurred at 0 and 90-degree point. At the point of 45-degree, the displacement was recorded contrary to the flat plate, UD Kevlar/Epoxy maximum displacement for x and y-direction had occurred at 0-degree and gradually decreased towards the 90-degree point. The displacement line partially decreased as the angle of fiber orientation increased. No displacement occurred at the z-direction for both woven and UD Kevlar/Epoxy flat plate with circular hole. Overall the variation of lamination scheme does not affect the displacement for both woven and UD Kevlar/Epoxy flat plate with circular hole.

FPF and LPF for woven and UD Kevlar/Epoxy composite laminate results are illustrated in Fig. 6. From the figure, the woven Kevlar/Epoxy results produced a symmetrical line and the UD Kevlar/Epoxy had produced a climbing line. From point 0 to 50-degree, the woven Kevlar/Epoxy FPF and LPF results are found to be higher than the UD Kevlar/Epoxy results. However, after the 60-degree point, UD Kevlar/Epoxy FPF and LPF have exceeded the results of the woven Kevlar/Epoxy.

Other similarities with the previous results are in good agreements of the failure criteria used, Maximum stress and Tsai-Wu in most of the angle of the fiber orientation. A plain line result for the woven Kevlar/Epoxy flat plate shows that the results are not affected much by the variation of the angle orientation. As for the UD Kevlar/Epoxy flat plate with circular hole, the results between Maximum stress and Tsai-Wu are close compare to the flat plate especially on the FPF results. The curves show a steady increase in result of the FPF and the LPF along with the increase in the number of angle of the fiber orientation.

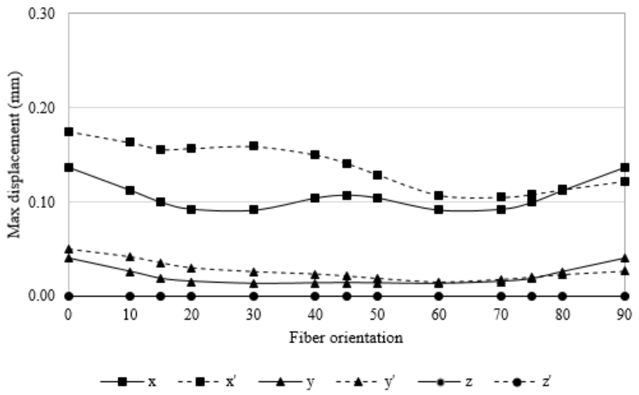

Fig. 5. Woven UD Kevlar/epoxy displacement curves (for Flat plate with circular hole)

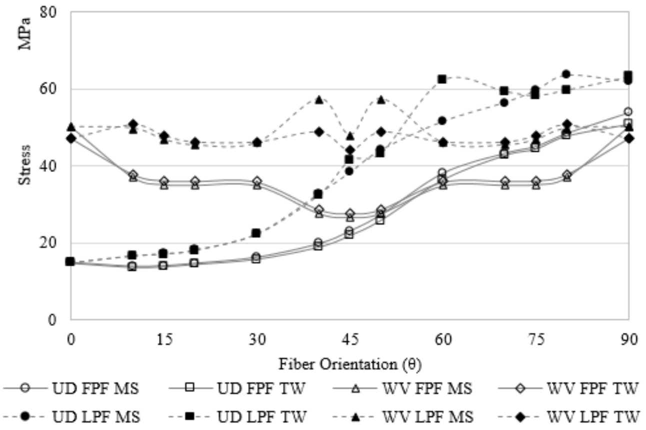

Fig. 6.FPF and LPF curves (for Flat plate with circular hole using Tsai-Wu and Maximum stress)

IV. CONCLUSION

This paper has presented and discussed in comparison of the effect of the fiber orientation angle with a flat plate and a flat plate with circular hole made of woven and UD Kevlar/Epoxy laminates under compression state. The result shows a significant different in the deformation and the failure behaviour for both woven and UD, flat plate and flat plate with circular hole in every angle of the variation. The main findings that can be deduced from this investigation are;

- On the flat plate displacement, the woven Kevlar/Epoxy is more affected compared to the UD Kevlar/Epoxy.
- Strength against compression force for the UD Kevlar/Epoxy is found to be higher than the strength of woven Kevlar/Epoxy. However, the UD strength can decrease significantly due to the variation of the composite lamination scheme. As for woven, even though the variation does affect the strength, it does not decrease as much as the UD strength.
- For the failure analysis on the flat plate with circular hole, the woven Kevlar/Epoxy strength towards the compression force is not affect much by the variation of angle of orientation but for the UD Kevlar/Epoxy, the variation of angle of orientation does affect significantly towards the strength.

Therefore, it can be concluded that the current study has contributed towards enhancing knowledge about the compressive failure behaviour of unidirectional and woven Kevlar/Epoxy composite laminates.

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Mohamad Mali currently pursuing PhD in Mechanical Engineering at the Universiti Teknologi MARA (UiTM) Shah Alam. He has graduated with a Master in Science (MSc by research) Mechanical Engineering degree from Universiti Teknologi MARA Shah Alam in July 2018, a Bachelor of Engineering (Hons.) Mechanical degree from Universiti Teknologi MARA Shah Alam in October 2011 and a Diploma in Mechanical Engineering from Universiti Teknologi MARA Shah Alam in October 2001. Mohamad Mali also has working experience for 10 years as Technician in various industrial field such as oil and gas and manufacturing before he pursued his bachelor's degree study. After graduated, he work as Maintenance Engineer for 3 years in heavy automotive industry which covers maintaining the facilities such as Cooling Tower System and Air Conditioning System, and Production Machines such as Shearing/Cutting, Drilling, Eye Rolling, Punching, Milling, and Finger Press Machine before he desire for a career change as Mechanical Design Engineer in 2013. His last experience is in administrative work as Assistant Manager in Education industry. His current areas of research interest focus on Engineering Mechanics and Composite materials.

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