Failure analysis of woven kevlar/epoxy composite laminates under compression due to variations in fiber orientation

M Mali, A K Hussain, M A Muzafar, A F M Zainol and J Mahmud*

Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor Malaysia

*jm@uitm.edu.my

Abstract. Studies have shown that the angle of fiber orientation significantly affects the mechanical properties of a composite laminate. Although investigations on the properties of the composite material have been conducted, there is still a lack of studies related to Kevlar/Epoxy laminate. Therefore, this study aims to investigate the effects of the angle of fiber orientation to woven Kevlar/Epoxy laminates under a compression state. The study was conducted in two stages comprising of numerical validation and failure analysis. 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/0/-θ)ₘ. The angle of fiber orientation, θ, was 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 type of plates were compared. From the results, it is found that the effects of the fiber angle on the plate with circular hole are more significant than the flat. Therefore, it can be reasoned that the current study is useful in contributing significant knowledge to better understand the failure behaviour of composite plate.

1. Introduction

Composite material is a material with properties that can be tailored to meet higher anticipations such as the extreme environment of outer space [1]. Researchers such as Abd-Ali et al. [2] and Mali et al. [3], had proven this by altering the angle of fiber orientation in a composite laminate; thus, discovering that various strengths can be achieved. Hashimoto et al. [4] conducted an investigation of tensile strength of discontinuous carbon fiber/polypropylene composite with distribution of fiber orientation. The investigation proposed the layer-wise technique to predict the discontinuous fiber reinforced composites tensile strength and simple micromechanical analysis. The investigation concluded that the rule of mixture is efficient for qualitative prediction of strength and acknowledged the accuracy depends on the fiber orientation distribution in composites. Retnam et al. [5] also studied on the effects of fiber orientation on mechanical properties of hybrid bamboo/glass fiber polymer composites. In the study, the mechanical properties of composites is tested by tensile test, flexural test and impact test before the result was analyzed using SEM. The study reveals that the hybridization of the composites increases the mechanical properties by increasing the bonding strength between the fiber and polyester resin.

Due to its versatility, Kevlar is one of the chosen advance materials for aircrafts [6]. In line with the interest, researchers start conducting studies in this composite material. The study in influence of cut-out hole on multilayer Kevlar/epoxy composite laminated plates was conducted by Talib et al. [7] to investigate the variety of orientation angles of Kevlar fiber. The study was executed by experimental
followed by simulation using AUTODYN under ANSYS-12.1 software. From the results, it was observed that the hole and fiber angle orientation has affected the Kevlar/epoxy composite strength and stiffness. Nilakantan and Gillespie Jr. [8] also conducted a study of plain woven Kevlar fabrics on the effect of yarn sizing, pullout rate and fabric pre-tension. The finding in this study demonstrated the potential for strategic tailoring of the yarn sizing and yarn surface characteristics to optimize the fabric ballistic impact performance.

Despite the vast studies on the properties of composite materials, there is still a lack of studies related to Kevlar/epoxy laminates; thus, the behaviour of these properties is still not well understood. Hence, the objective of this paper is to investigate the effects of the angle of fiber orientation to woven Kevlar/Epoxy laminates under compression state using finite element (FE) software ANSYS.

2. Methodology
The present study was conducted in two numerical stages.

Stage 1 : Numerical Validation
Stage 2 : Displacement and Failure Analysis

2.1. Stage 1: Numerical Validation
The use of FE software was important to reduce the cost and to avoid the tedious experimentations [9]. Researchers like Jiang and Blahous [10] started using computer applications to analyze the tension value and to calculate the stress data for their study. However, to ensure the obtained result was valid, numerical validation was required as practiced by some past researchers [3, 11]. Present model has been validated through results comparison with the exact solution from the past studies [12], presented in table 1. The results obtained from the FE software used for this study is valid since the error was found to be less than 2%.

| Lamination Scheme | UDL (Pa) | Exact Solution (mm) | Present (mm) | Error (%) |
|-------------------|---------|---------------------|--------------|-----------|
| [0/90/0/90]       | 689.5   | 0.00340             | 0.00338      | 0.59      |
| [0/90/0/90/0]     | 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      |

2.2. Stage 2: Displacement and Failure Analysis
The failure prediction were based on an available built-in Maximum stress and Tsai-Wu failure theory and failure criteria functions. The displacement of the plate had also been recorded. Figure 1 shows the overall present study workflow. The work was repeated with different variations in angles (θ = 0° to 90°) and by using Maximum stress criterion and Tsai-Wu failure criterion to identify the first ply failure (FPF) and last ply failure (LPF).
Figure 1. The failure analysis flow of composite laminates.

Models 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 figure 2. The model was made with 24 laminates with symmetry (θd/0d−θs)s layup (where θ = 0° to 90°). The model with thickness of 0.1333 mm was applied with compression force to study the effects of circular hole and angle of lamination scheme toward the displacement and the first-ply and last-ply fracture/failure of the woven Kevlar/epoxy composite laminates.

The material and strength properties of woven Kevlar/epoxy is shown in table 2. A FE failure analysis procedure was carried out using commercial software (ANSYS v18.1, 2018 SAS IP, Inc.)

|        |        |        |        |
|--------|--------|--------|--------|
| $E_1 = E_2 = E_3$ | 26180 MPa | $X_T = Y_T$ | 420 MPa |
| $v_{12} = v_{13} = v_{23}$ | 0.11 | $X_C = Y_C$ | 150 MPa |
| $G_{12} = G_{13} = G_{23}$ | 1533 MPa | $S$ | 106 MPa |

Table 2. Material properties of Kevlar/epoxy composites [13].
3. Results and Discussion

3.1. Flat plate

The deformation results for the flat plate has been presented in figure 3 in the direction of deformation occurred. From the figure, it is clear that largest displacements occurred in the x direction. The curves illustrate the highest maximum displacement in x and y directions which occurred at the angle of 45 degree. The lowest displacement point was found at 0 and 90 degrees on both x and y directions. No displacement was recorded on the z direction. The compression force was applied in x direction thus, resulting larger displacement in the x direction compared to y direction.

The results of FPF and LPF has been obtained by using Maximum stress and Tsai-Wu failure criteria has been tabulated and shown in figure 4. From the graph, it was found that the curve patterns are symmetrical with a small gap difference in between FPF and LPF. The highest recorded stress was at the angle of 0 and 90 degrees for both FPF and LPF. The results decreased proportionally towards the 45 degree mark and increased back proportionally until it reaches 90 degrees. It was also found that the results from both Maximum stress and Tsai-Wu were in good agreement for this test.

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

Figure 3. Flat plate displacement graph.
3.2. Flat plate with circular hole
The deformation results for flat plate with circular hole has been recorded and presented in figure 5. From the figure, the deformation curves for flat plate with circular hole is symmetrical but incompatible compared to flat plate curves. The maximum displacement occurred in x and y direction at the angle of 0 and 90 degrees. The curve in x direction was found to increase again after 30 degree until it reaches 45 degree. In y direction, only some displacement occurred and no displacement was recorded in the z direction.

Using Maximum stress and Tsai-Wu failure criteria, graph from the results of FPF and LPF on the flat plate with circular hole is presented in figure 6. Similar to previous results, a symmetrical line was formed. Unlike the curves from the flat plate, the line shows a gap in between FPF and LPF results. The result from Maximum stress and Tsai-Wu failure criteria however was found to be closer to each other except for the results on the LPF at 40 and 50 degrees. For the flat plate with circular hole, it has been observed that the FPF and LPF occurred on the alternate ply in between $\theta$, ply and -$\theta$, ply. From the analysis, it was found that the effects of the fiber angle on the plate with circular hole were more significant than the flat. The result tallying with the results from past studies indicates that the material removal from the plate has reduced its strength [10]. Thus, it has been proven that the analysis and findings were important in aiding the engineers in designing a reliable woven Kevlar/Epoxy composite laminates.

Figure 4. FPF and LPF for Flat plate (Tsai-Wu and Maximum Stress).
4. Conclusions
This paper has presented and discussed about the effects of fiber orientation angle to a flat plate and flat plate with circular hole made of woven Kevlar/Epoxy laminates under the compression state. The result shows a significant difference in the deformation and failure behaviour for both flat plate and flat plate with circular hole in every angle variation.

The main findings that can be deduced from this investigation are for both flat plate and flat plate with circular hole, the main deformation occurs when the shortening of the plate in the direction of the force is applied. Different deformation recorded on every angle of orientation tested shows that the fiber orientation angle does affect the deformation of woven Kevlar/Epoxy laminates. On the flat plate, it is found to be the strongest at $\theta = 0$ and 90 degree due to the resistance from direction of fiber orientation.
towards the compression force (discussion). The strength gradually decreases along with the angle of fiber orientation, at the angle of 45-degree layup, flat plate is found to be at its lowest strength. On the other hand, the variation in fiber orientation has no significant effect on the strength of the woven Kevlar/Epoxy flat plate with circular hole. The gap between the FPF and LPF curves for the flat plate with circular hole is found to be bigger compared to the regular flat plate. The results from Maximum stress and Tsai-Wu failure criteria is found to be close proving the good agreement to each other.

Therefore, it can be concluded that the current study is useful in contributing significantly knowledge to further understand the failure behavior of a composite plate.

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