Failure analysis on woven glass/epoxy composite laminates due to the effect of V-Notch and angle of fiber orientation

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ABSTRACT

Although the use of V-notch can significantly reduce the load-bearing capacity of structures, it is still widely used in engineering components due to some necessary design requirements. Despite the vast studies conducted on the effects of V-notch to composite structures, there is still a lack of studies related to the effects of the V-notch and angle variation of fiber orientation of composite laminates. Therefore, this study aims to investigate the effects of the V-notch and the variation of fiber orientation angle to the strength of Glass/Epoxy composite laminates through the failure behaviour of Glass/Epoxy composite laminates plain plate and V-notch plate under bending load. The study was conducted in two stages which comprised of numerical validation and failure analysis. For the failure analysis, a plane plate and V-notch under bending load were modelled by using ANSYS. Maximum Stress failure criterion were selected for failure prediction. The laminates were made of 24 layers woven Glass/Epoxy and the stacking sequence was $(\theta_4/0_4/-\theta_4)s$. The angle of fiber orientation, θ, was varied from 0° to 90° and failure loads for both plane plate and V-notch were determined. The trend of displacement and failure behaviour for plane plate and V-notch were compared to each other. From the results, it is found that the failure behaviour of V-notch is minimal from plane plate and was not affected by the variation of fiber orientation. This analysis and finding are important in aiding the engineers in designing a reliable V-notch on composite laminate. Therefore, it can be concluded that the current study is useful in contributing significant knowledge to better understand the failure behaviour of composite plate.

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Introduction

Notches are widely used in engineering components due to some necessary design requirements. The only drawback over the use of notch is that it significantly reduces the load-bearing capacity of structures as a result of the stress concentration in the notch vicinity [1]. The concept was first introduced by Neuber through his book, Theory of Notch Stresses [2] and studies on notches have continued and are still valid up until today. It is necessary to understand the singular characteristic stress near a notch vertex in order to evaluate the safety of a V-notched structure [3].

In order to provide the solution for V-notches with end hole, Zapplalorto [4] conducted a study In-plane and Out-plane stress field solutions for V-notches with end holes. The study concluded that although it is only approximate, the degree of accuracy of the new solution has been found to be satisfactory for engineering applications.

The study on finding the relation between strain energy release rates and generalized stress intensity factors for two-dimensional V-notches was conducted by Duan [5]. This study was done due to the past criteria which require firstly analysing the local stress or displacement distributions ahead of notches. From the results, the study managed to provide a concise formulation for the relation by using the work done by the stresses distributed along the V-notch front on displacements induced by the propagated crack at the notch tip.

Since composite structure are now common in various engineering applications such as advanced aerospace parts [6], researchers have extended the study on the effects of the notches to composite structures. The study on the behaviour of notch crack in adhesively bonded composite laminates by using numerical analysis was conducted by Bouiadjra [7] to analyze the notched effect and the behaviour of crack emanating from notches by computing the stress intensity factor at the notch crack tip. The study concluded that the sensibility of the notch characterized by its stress concentration factor is more important in the layer of the laminate which has higher mechanical resistance. Using Boron/Glass/Aluminum, Yeh [8] conducted a study to investigate the effects of a blunt notch on the strength of hybrid fiber metal laminates through experiment using static tensile test and numerical by finite element method. From the results of both approaches, the study has found an excellent agreement of maintained load-bearing capabilities on the hybrid even after the rupturing of boron fibers. Focus on the stress concentration near sharp and rounded V-notches, Savruk [9] aims to generalize of the unified approach to the problems of the theory of elasticity of orthotropic body with V-notches and to discuss of using a quasi-orthotropic model for orthotropic material when stress state depends on one parameter. The study solved the boundary value problem of semi-infinite sharp and rounded V-notches, and establishes the relationship between the stress intensity factor for sharp V-notch and normal stress at the vertex of rounded V-notch.

Based on Ressiner-Mindlin Theory, Chen [10] attempts on investigating the bending singularity orders in a V-notched composite laminate plate. From the investigation, it was found that the bending singularity orders can be determined by solving an eigenvalue problem numerically. Through the numerical investigation, it revealed that the bending singularity orders depend on the plate angle, material orientation, material anisotropy and the laminate stacking sequence.

Despite the quite number of studies on the effects of V-notch to composite structures, there is still a lack of studies related to the effects of the V-notch and the angle variation of fiber orientation of the composite laminates. To overcome the discrepancy, this study aims to investigate the effects of the V-notch and the variation of fiber orientation angle to the strength of Glass/Epoxy composite laminates through the failure behaviour of Glass/Epoxy composite laminates plain plate and V-notch plate under bending load.

In this paper, a finite element analysis (FEA) is conducted and presented for studying the displacement, first ply failure (FPF) and last ply failure (LPF) of composite laminates. The accuracy of the proposed finite element implementation and model is validated through the comparison of the present finite element result with those reported in the literature.

Methodology

The present work adopts and adapts finite element modeling and simulation in investigating the displacement, FPF and LPF of composite laminates using commercially available finite element software, ANSYS (ANSYS v18.1, 2018 SAS IP, Inc.). The study was executed in two numerical stages:
Stage 1: Numerical Validation
Stage 2: Displacement and Failure Analysis

Stage 1: Numerical Validation

The use of FE software is important to reduce cost and avoid tedious experiments [11]. However, to ensure the obtained result is valid, numerical validation is required as practiced by some past researchers [12, 13]. Present model has been validated through results comparison with the exact solution from past studies [14], presented in Table 1. The results obtain from the FE software used for this study is valid since the error is found less than 2%.

Table 1: 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

Stage 2: Displacement and Failure Analysis

Model of composite in the shape of rectangular flat plate and flat plate with v-notch were developed as in Figure 1. The model is made of 24 laminates with symmetry $(\theta_4/0_4/-\theta_4)s$ layup (where $\theta = 0°$ to $90°$). The model with thickness of 0.0055555 mm (0.133333 mm per ply) is applied with bending load to study the effect of v-notch and angle of lamination scheme toward the displacement and fracture/failure of the first-ply and last-ply of the woven Glass/Epoxy composite laminates. The material and strength properties of woven Glass/Epoxy is shown in Table 2. A FE failure analysis procedure is carried out using commercial software.

Table 2: Material properties of woven Glass/Epoxy [15]

	Woven		Woven
E_1	21500 MPa	X_T	452.37 MPa
$E_2 = E_3$	21500 MPa	X_C	312.69 MPa
$v_{12} = v_{13} = v_{23}$	0.11	Y_T	452.37 MPa
$G_{12} = G_{23} = G_{13}$	3420 MPa	Y_C	312.69 MPa
		S	69.76 MPa

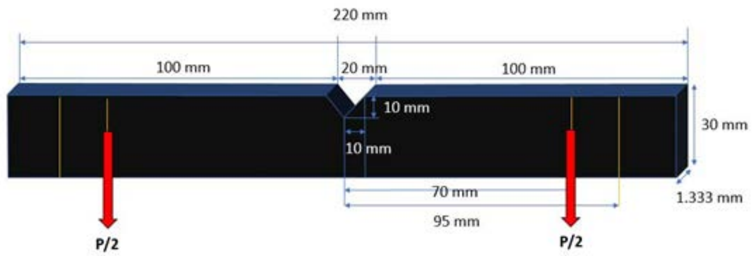

Figure 1: V-notch plate geometry

Results and Discussion

Displacement Results

Displacement results on both model plain plate and V-notch plate is recorded and plotted as in Figure 2. From the figure, it is clear that the displacement that occurs on the V-notch plate is greater compared to plain plate. Highest displacement point is recorded at point 45 degree and lowest displacement point is at 0 and 90 degrees on the y direction for both plates. The displacement in y direction is greater than the x and z direction is due to the applied bending load. The similar pattern in all curves shows that the fiber orientation in the laminates does not affect the displacement on the both models.

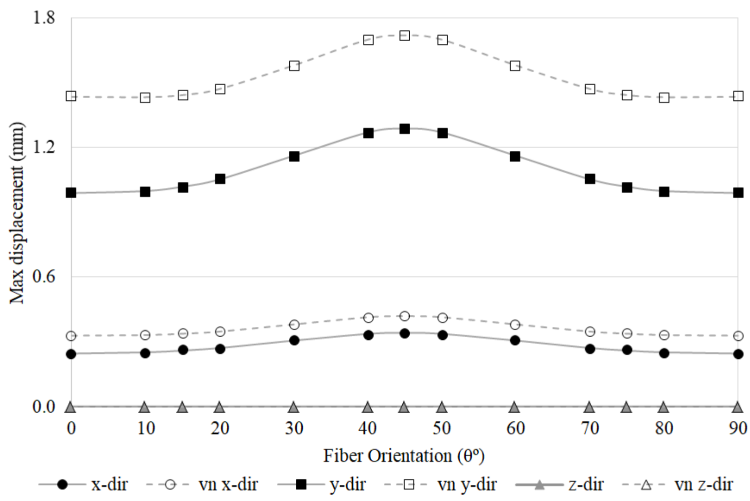

Figure 2: Displacement curves for plane plate and V-notch of woven Glass/Epoxy

Failure Analysis

FPF and LPF for woven Glass/Epoxy composite laminates plain plate and V-notch plate are illustrated in Figure 3. Similar to the displacement, curves for FPF and LPF also result in symmetrical curves. From the figure, it is clear that the FPF and LPF for plain plate are greater than the FPF and LPF for V-notch plate. For plain plate, the highest FPF and LPF recorded are in between point 40 and 50 degrees. The steeply climb before fall after reaching 50 degree point exhibiting the significant impact on the FPF and LPF results for plain plate toward the fiber orientation angle. Unlike the plain plate, FPF and LPF for V-notch plate almost remain constant especially on the FPF curve. The highest FPF recorded is at 15 and 75 degrees and for LPF is at 20 and 70 degrees. Only slight increase of the FPF and LPF from point 0 to 20 degrees before level and start to slightly decrease at point 70 to 90 degrees. This proves that the fiber orientation angle only gives small impacts towards the FPF and LPF of V-notch plate.

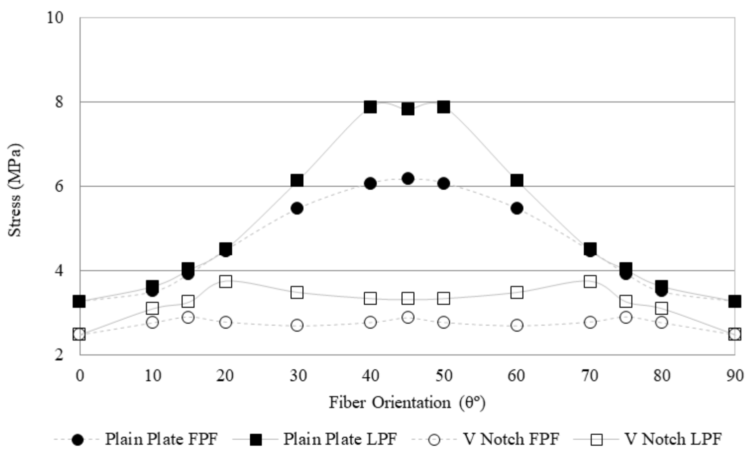

Figure 3: FPF and LPF for plane plate and V-notch of Woven Glass/Epoxy

Conclusion

This paper has presented and discussed on the comparisons on the effect of V-notch and fiber orientation angle to a flat plate made of woven Glass/Epoxy laminates under bending load. The results show significant differences on the displacement and failure behaviour in between the plain plate and V-notch results. The main findings that can be deduced from this investigation are;

- The displacement occur on the V-notch is higher than the plain plate but a similar effect was recorded for both plates towards the angle of fiber orientation.
- FPF and LPF for plain plate is greater than the FPF and LPF for V-notch has proven the disadvantages of using V-notch as it significantly reduces the load-bearing capacity of the structure.
- FPF and LPF for plane plate are significantly affected by the angle of fiber orientation where the plate is recorded to be most weak at point 0 and 90 degrees and strongest in between point 40 to 50 degrees.
- FPF and LPF for V-notch however are only slightly affected by the angle of fiber orientation.

Therefore, it can be concluded that the current study is useful in contributing significant knowledge to better understanding in the failure behaviour of composite plate.

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