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The Effect Of Lamination Scheme And Angle Variations To The Displacements And Failure Behaviour Of Composite Laminate

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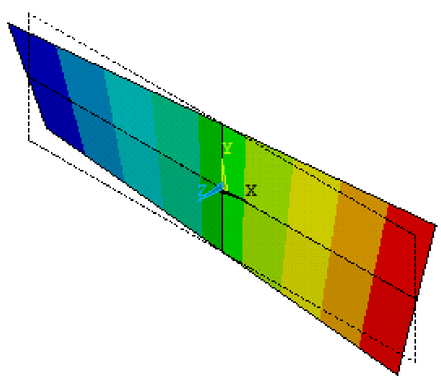
Graphical abstract



Abstract

This paper aims to investigate the effect of lamination scheme and angle variations to the displacements and failure behaviour of composite laminate. Finite element modelling and analysis of symmetric, anti-symmetric and angle-ply Graphite/ Epoxy laminate with various angles of fiber orientation subjected to uniaxial tension are performed. Maximum Stress Theory and Tsai-Wu Failure Criteria are employed to determine the failure load (failure index = 1). Prior to that, convergence analysis and numerical validation are carried out. Displacements and failure behaviour of the composite laminates (symmetric, anti-symmetric and angle ply) are analysed. The failure curves (FPF and LPF) for both theories (Maximum Stress Theory and Tsai-Wu) are plotted and found to be very close to each other. Therefore, it can be concluded that the current study is useful and significant to the displacements and failure behaviour of composite laminate.

Keywords: Composite laminate, failure analysis, deformation analysis, ANSYS

1.0 INTRODUCTION

Composite materials can be defined as a combination of perfectly bonded reinforcements into the binding materials (matrix) [1][2], which could improve the strength and the failure behaviour of the materials. By definition, failure occurs in a material when the applied load reached its threshold [3][4][5]. In analysing failure, the Maximum Stress Theory is one of the common failure criteria used in predicting composite laminate failure [6][7]. This criterion considers that the composite material fails when the stress in the principal material axes (σ_1, σ_2 and τ_{12}) exceeds the corresponding strength (X, Y and S) in that direction ($\sigma_1 > X$, $\sigma_2 > Y$ and $\tau_{12} > S$). Tsai-Wu failure criterion involves polynomial equations in predicting composite failure [8][9].

Previous study focused on predicting the first ply failure and last ply failure of composite laminates [10][11][12][13]. Nevertheless, the composite laminate displacements before the occurance of failure have not been analysed thoroughly. For example, it could be observed that the lamination schemes and variations of angle orientation could effect the displacements and failure behaviour of the symmetric, anti-symmetric and angle-ply laminate.

Therefore, this study aims to investigate the effect of lamination scheme and angle variations to the displacements and failure behaviour of composite laminate.

2.0 METHODOLOGY

Figure 1 shows the overall workflow of the current study. The failure analyses are performed for different lamination schemes (symmetric, anti-symmetric and angle-ply) and various angle of fiber orientations (0°, 10°, 20°, 30°, 40°, 45°, 50°, 60°, 70°, 80°, 90°), using two failure criteria (Maximum Stress Theory and Tsai-Wu failure criterion). There are two phases involved in order to achieve the main objectives of this study:

- Phase 1: Finite element modelling

- Phase 2: Failure analysis

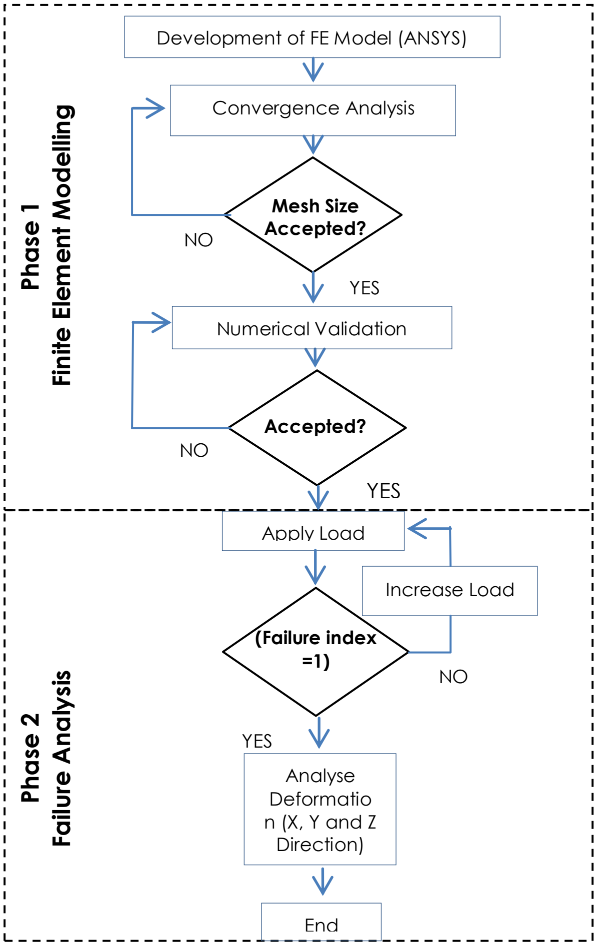


Figure 1 The overall workflow.

2.1 Convergence Analysis

Accurate meshing and mesh size are always important in finite element analyses. Using smaller mesh size could increase the accuracy of the simulated results, nevertheless it will increase the computing time and cost [3]. Convergence analysis is important and thus, this study starts with performing convergence analysis. These analyses are carried out under constant uniaxial tension (7010.5 N), using quadrilaterals element and various mapped meshing (2x2, 4x4, 8x8. 16x16, 32x32, 64x64, 128x128 and 256x256). Mesh size of 1x1 (or any odd mesh size) is not possible as the boundary condition is fully fixed at the centre of the plate.

Figure 2 shows that constant stresses generated for both symmetric laminate and anti-symmetric laminate.

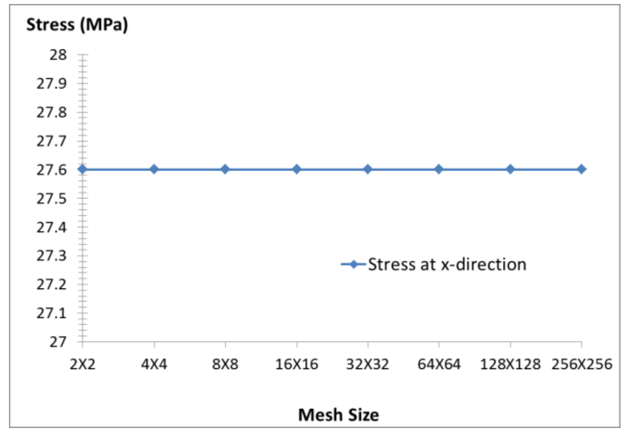


Figure 2 Computed stress (symmetric and anti-symmetric) at various fiber orientation.

Figure 3 and Figure 4 can clearly be observed that the results converge with a minimum mesh size of 2x2. Upon confident with the simulation results (based on numerical validation and convergence analysis), further analyses are carried out (failure analysis, and deformation analysis)

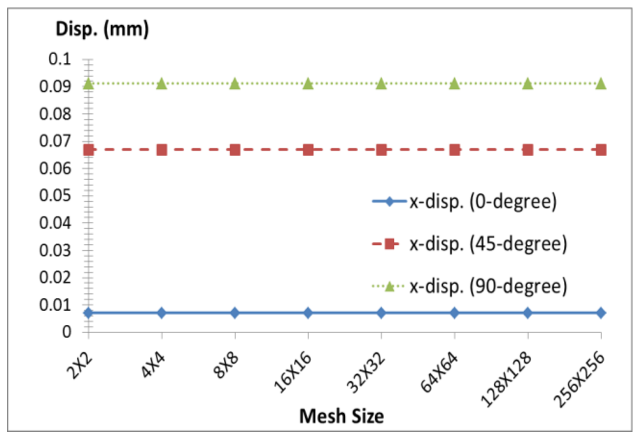


Figure 3 Displacement in x-irection for symmetric $[\theta/\theta]_T$ laminate.

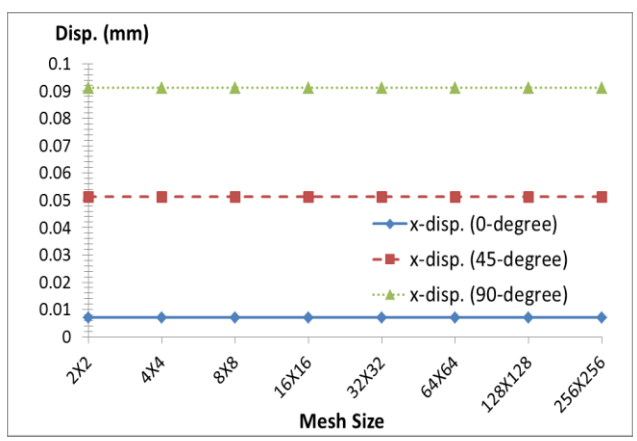


Figure 4 Displacement in x-direction for anti-symmetric $[\theta/-\theta]_T$ laminate.

2.2 Numerical Validation

The current finite-element results (ANSYS) have been validated compared to the exact solution. The plate geometry is shown in Figure 5 and the material properties are tabulated in Table 1. The results are acceptable since the error is found less than 2% (as shown in Table 2).

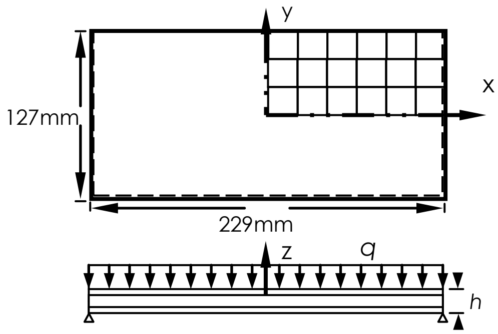


Figure 5 Geometry and computational domain for composite laminate under transverse load.

Table 1 Material properties of T300/5208 graphite/epoxy.

Properties	Values
E_1	138 GPa
E_2	10.6 GPa
G_{12}	6.46 GPa
ν_{12}	0.3
X_T	1035 MPa
X_C	1035 MPa
Y_T	27.6 MPa
Y_C	138 MPa
S	41.4 MPa

Table 2 Comparison of exact and finite-element solution, z-displacement (mm) for laminated composite plate (229mm by 127mm).

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

2.3 Failure and Deformation Analysis of Composite Laminate.

Symmetric, anti-symmetric and angle-ply composite laminate are modelled (Figure 6) under uniaxial tension consists of two layers, where the layup are symmetric $(\theta/\theta)_T$, anti-symmetric $(\theta/-\theta)_T$ and angle-ply $(0/\theta)_T$. The plate is rectangle with thickness $1.27\text{x}10^{-4}$m/ply, made of graphite-epoxy and the material and strength properties are shown in Table 3.

A finite element failure analysis procedure is carried out using commercial software (ANSYS v15.0, 2013 SAS IP, Inc.). The predictions of failure are based on available built in failure theory and failure criteria functions which are Maximum Stress Theory as shown in Eqn. (1) and Tsai-Wu as shown in Eqn. (2). The deformation behaviour is also recorded during the failure.

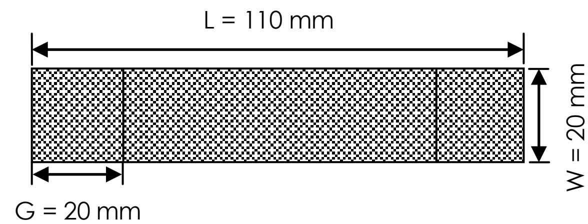


Figure 6 Uniaxial tension model.

Table 3 Material properties for T300/5208 [5].

Properties	Values
E_1	132.4 GPa
$E_2 = E_3$	10.76 GPa
$G_{12} = G_{13}$	5.65 GPa
G_{23}	3.38 GPa
$\nu_{12} = \nu_{13}$	0.24
ν_{23}	0.49
Ply thickness, h_i	0.127mm/ply

$$\sigma_1 = X_t \text{ or } X_c, \quad \sigma_2 = Y_t \text{ or } Y_c, \quad \tau_{12} = S \qquad \text{(Eq. 1)}$$

$$F_1\sigma_1 + F_2\sigma_2 + F_6\tau_{12} + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + 2F_{12}\sigma_1\sigma_2 + F_{66}\tau_{12}^2 \geq 1 \qquad \text{(Eq. 2)}$$

3.0 RESULTS AND DISCUSSION

Results in Figure 7 and Figure 8 show the laminate strength decreases when the fibers are orientated from 0° to 90 °. Figure 7 shows the failure curves for various lamination scheme (angle-ply, symmetric and anti-symmetric) of Maximum Stress Theory. Each lamination scheme displays different shape of failure curves but still decrease in laminate strength with the increase of the angle variations. For the angle-ply, the stress (MPa) between the first ply failure (FPF) curve and last ply failure (LPF) curve are different in value compared to the symmetric and anti-symmetric laminate scheme where the first ply failure and last ply failure curves of this two lamination schemes lies on the same value of stress (MPa). The highest failure curves which contribute the highest applied stress before the composite laminate failed lies on angle-ply LPF curve and the graph is non-linear. The second highest failure curve also lies on angle-ply lamination scheme but for first ply failure curve and similarly the graph is non-linear. While the lowest stress (MPa) value lies on symmetric lamination scheme. Anti-symmetric lamination scheme lies between angle-ply(FPF) and symmetric (FPF & LPF).

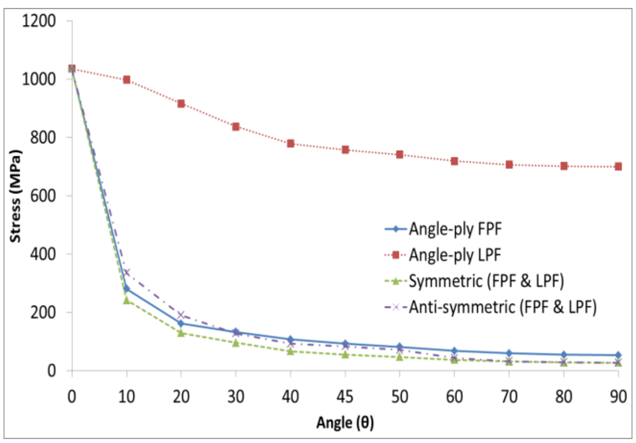


Figure 7 Failure curves for various lamination scheme (Maximum Stress Theory)

Figure 8 shows the failure curves for various lamination scheme (angle-ply, symmetric and anti-symmetric) based on Tsai-Wu criterion. Tsai-Wu criterion demonstrates different shape of failure curves but still decrease in laminate strength with the increase of the angle variations. Tsai-Wu criterion also show different stress (MPa) for first ply failure curve and last ply failure curve of angle-ply lamination scheme while the other two lamination scheme (symmetric and anti-symmetric), the first and last ply failure curves lies on the same value of stress (MPa). Compared to Maximum Stress Theory, Tsai-Wu criterion also predict that the highest failure curve lies on angle-ply LPF curve while the lowest stress (MPa) value before the lamination fail lies on symmetric lamination scheme.

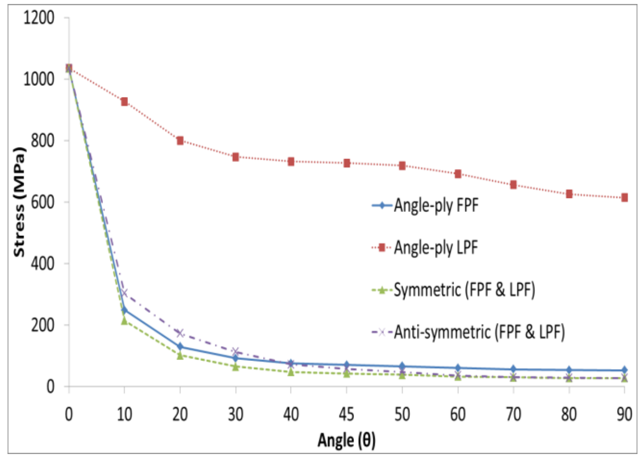


Figure 8 Failure curves for various lamination scheme (Tsai-Wu criterion)

Figure 9 shows the displacement curves in x-direction during failure as predicted by Maximum Stress Theory. It could be observed that the maximum displacement in x-direction occurs at the angle, θ = 0° at the failure load. This is due that the fibre direction parallels to the direction of the load applied. While the least displaced plate occur at angle 90 ° since the fibre direction perpendicular to the x-axis (global axis) which also perpendicular to the load applied. This makes the plate easier to break. This situation only occur to the symmetric, anti-symmetric and angle-ply FPF. While angle-ply LPF have the increasing displacement in x-direction with the increasing value of angle variations (0° to 90 °). Therefore, the highest displacement predicted by Maximum Stress Theory occurs at angle-ply LPF at angle 90 °. While the lowest predicted displacement occurs on angle-ply FPF at angle 90 °.

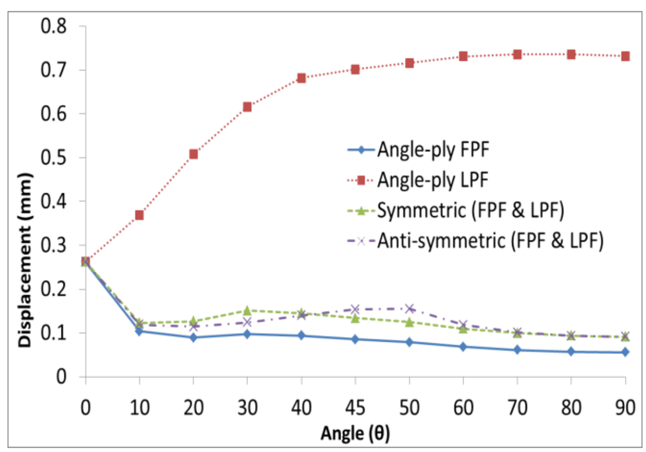


Figure 9 Displacement curves at FPF and LPF loads in the x-direction (Maximum Stress Theory)

It goes the same for Tsai-Wu criterion as shown in Figure 10, the displacement curves predicted by this criterion shows the same trend compared to Maximum Stress Theory (Figure 9) where the angle-ply LPF have the increasing displacement in x-direction with the increase value of angle variations (0° to 90°). There was a sharp increase in displacement (x-direction) from angle 0° to 60° for angle-ply LPF where it reached its peak at angle 60°. Tsai-Wu criterion similarly predicts that angle-ply FPF deformed the least at x-direction where bottomed out at angle 90°. From the observation in Figure 9 and Figure 10, it can be concluded that Tsai-Wu criterion predicts a smoother curve than Maximum Stress Theory for deformation in x-direction, thus proving that the interaction terms between the stresses (σ_x and σ_y) in Tsai-Wu criterion are significant.

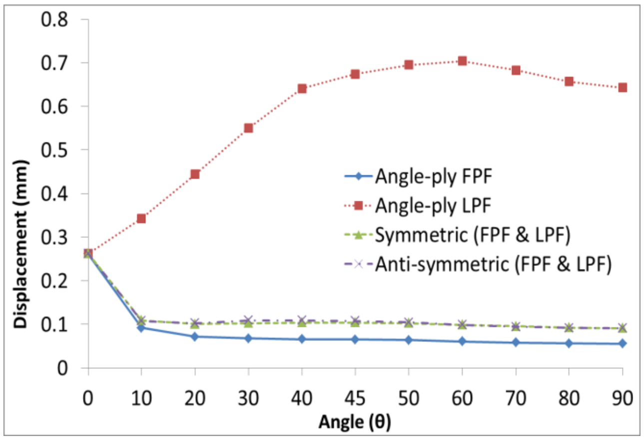


Figure 10 Displacement curves at FPF and LPF loads in the x-direction (Tsai-Wu criterion).

For displacement in y-direction (Figure 11) show that Maximum Stress Theory predicts the highest displacement curves occur at angle-ply LPF at angle 30°. While the lowest diplaced curves befall in y-direction occur at the same angle which is 90 ° at three different lamination scheme; symmetric, anti-symmetric and angle-ply FPF.

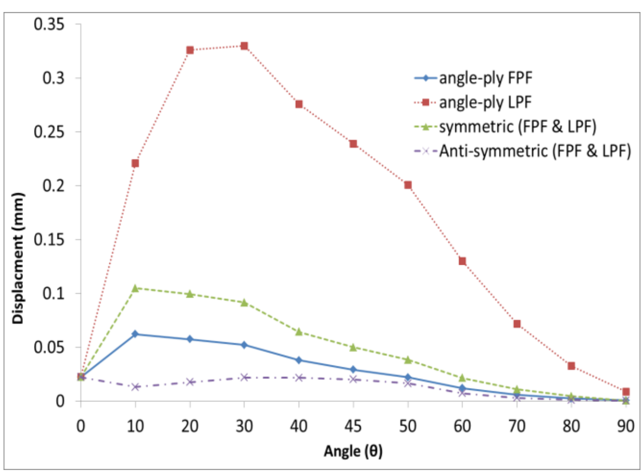


Figure 11 Displacement curves at FPF and LPF loads in the y-direction (Maximum Stress Theory).

Tsai-Wu criterion as shown in Figure 12 predicts the displacement curves for y-direction. Compared with Maximum Stress Theory (Figure 11), the trend of the displacement curves is similar with Tsai-Wu criterion where it reached its peak at angle 30° angle-ply LPF lamination scheme. Then displacement plummeted, dropping dramatically between angle 30° and 90°. While the lowest displacement curves predicted by Tsai-Wu criterion occur at angle 90° where it bottomed out at three different lamination scheme; symmetric, anti-symmetric and angle-ply FPF. By comparing between Maximum Stress Theory (Figure 11) and Tsai-Wu criterion (Figure 12), it could be observed that Maximum Stress Theory predicts the highest displacement curves occur at angle 30° angle-ply LPF lamination scheme.

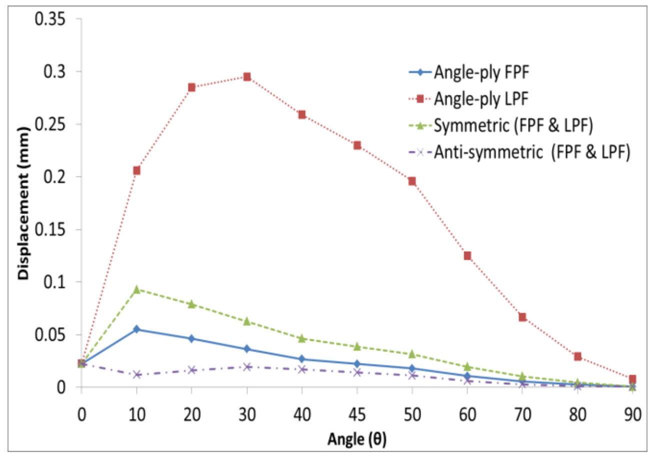


Figure 12 Displacement curves at FPF and LPF loads in the y-direction (Tsai-Wu criterion).

Displacement curves in z-direction as shown in Figure 13 predicted by the Maximum Stress Theory. Angle-ply LPF, angle-ply FPF and anti-symmetric displacement curves increased sharply between angle 0° and 10° and then plummeted, dropping dramatically between angle 10° and 90°. At angle 90°, Maximum Stress Theroy predicts that displacement curves in z-direction reached its lowest deformation. While displacement curves reached its peak at angle 10° anti-symmetric lamination scheme. While the second highest displacement occur at angle 10° angle-ply LPF follows with angle-ply FPF lamination scheme. For symmetric lamination scheme, the displacement in z-direction is too small and it seems to remain constant as shown in the Figure 13.

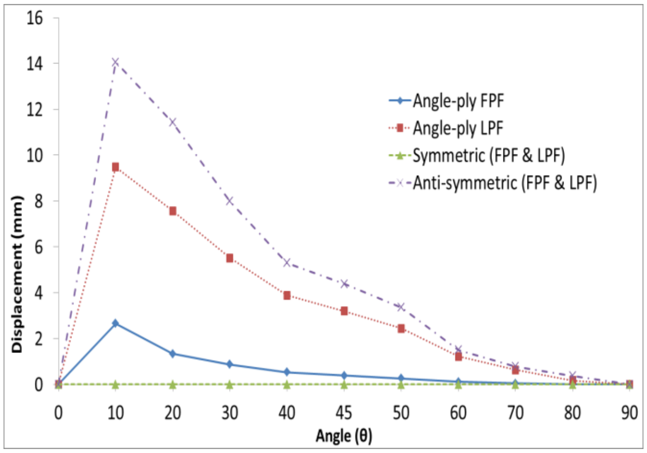


Figure 13 Displacement curves at FPF and LPF loads in the z-direction (Maximum Stress Theory).

The trend of the displacement curves of Tsai-Wu criterion (Figure 14) and Maximum Stress Theory (Figure 13) were the identical. It goes the same with Tsai-Wu criterion (Figure 14) where angle-ply LPF, angle-ply FPF and anti-symmetric displacement curves increased sharply between angle 0° and 10° and then plunged, dropping dramatically between angle 10° and 90°. At angle 90°, Tsai-Wu criterion similarly predicts that displacement curves in z-direction reached its lowest deformation. Displacement curves reached a peak at angle 10° anti-symmetric lamination scheme. Whereas the second highest displacement curves occur at angle 10° angle-ply LPF follows with angle-ply FPF lamination scheme. For symmetric lamination scheme, likewise Tsai-Wu criterion predict that the displacement curves in z-direction is too small and it seems to remain constant as displayed in the Figure 14.

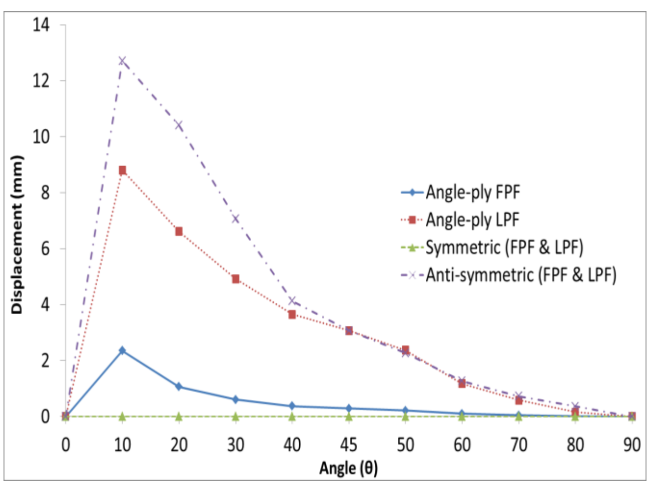


Figure 14 Displacement curves at FPF and LPF loads in the z-direction (Tsai-Wu criterion).

Results in Figure 15 demonstrate the displacement curves at FPF for angle-ply laminate in the x-, y- and z-directions. It shows that displacement in z-direction increases significantly from 0° to 10° and then plummets, drops and hits the bottom at angle 90°. The other two directions (x and y) show only small displacements compared to the z-direction. It can be concluded that for angle-ply FPF, Maximum Stress Theory predicts higher displacements in the z-direction compared to x- and y-directions.

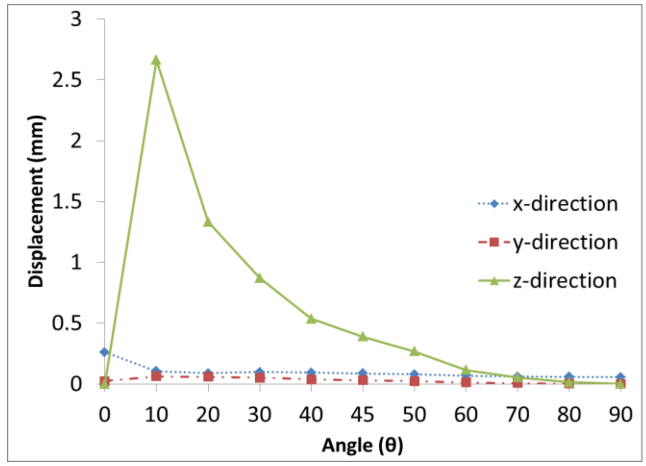


Figure 15 Displacement curves at FPF load for angle-ply laminate (Maximum Stress Theory).

As shown in Figure 16, it shows the displacement curves at LPF for angle-ply lamination scheme at x-, y- and z-directions. Similar with the prediction earlier by the FPF angle-ply lamination scheme (Figure 15), displacement curves in z-direction increased sharply from angle 0° to 10° and then plummeted, dropping and hit a bottom at angle 90°. Besides that, the other two directions (x- and y-directions) indicates small changes in displacements behaviour compared to z-direction. Comparing between this two failure crieterion (Maximum Stress Theory and Tsai-Wu), it shows that Maximum Stress Theory predicts the highest displaced curve at z-direction.

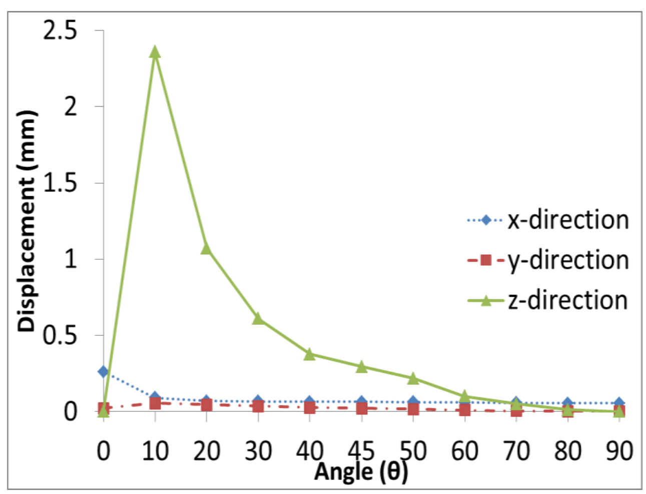


Figure 16 Displacemet curves at FPF load for angle-ply laminate (Tsai-Wu criterion).

The trend of the displacement curves between FPF and LPF are unchanged. The different between FPF and LPF is the value of stress (MPa) that failed the composite plate. Figure 17 illustrates the displacement curves at LPF for angle-ply lamination scheme in x-, y- and z-directions (Maximum Stress Theory). Still, the displacement curves in z-direction rocketed and reached at peak angle 90° and plunged, descend from angle 10° to 90°. However, the displaced curves a bit different from Maximum Stress Theory since Tsai-Wu criterion predicts steady increase in displaced curves at x-direction. Whereas displacement curves in y-direction shows small change from angle 0° to 90°.

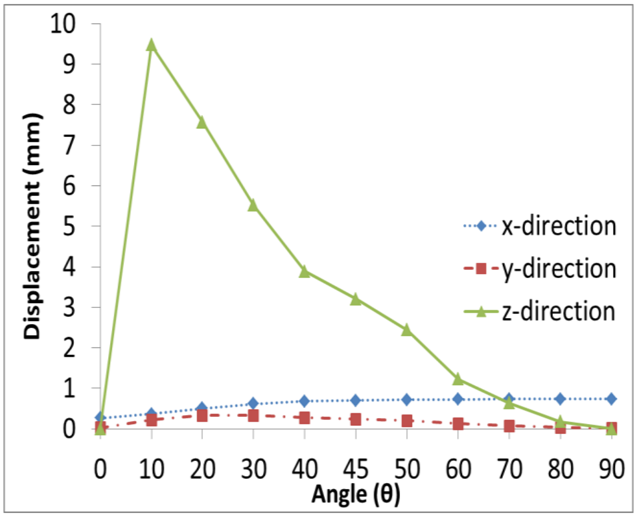


Figure 17 Displacement curves at LPF load for angle-ply laminate (Maximum Stress Theory).

Figure 18 displays the displacement curves at LPF for angle-ply lamination scheme (Tsai-Wu criterion) at x-, y- and z-directions. Similar with the prediction earlier by the Maximum Stress Theory (Figure 17), displacement curves in z-direction increased sharply from angle 0° to 10° and then plummeted, dropping and hit a bottom at angle 90°. Besides that, at x-direction, the displacement curves increase gradually from angle 0° to 90°. Unlike in y-direction, the displacement curves show small change in displacement. Comparing this two failure criteria (Maximum Stress Theory and Tsai-Wu criterion), it shows that Maximum Stress Theory predict the highest deformation at z-direction. This can be concluded that for angle-ply lamination scheme, the displacement behaviour that effect in composite laminate with angle variations predicted by Maximum Stress Theory and Tsai-Wu criterion only effected more to the displacement curves at z-direction rather than x- and y-directions.

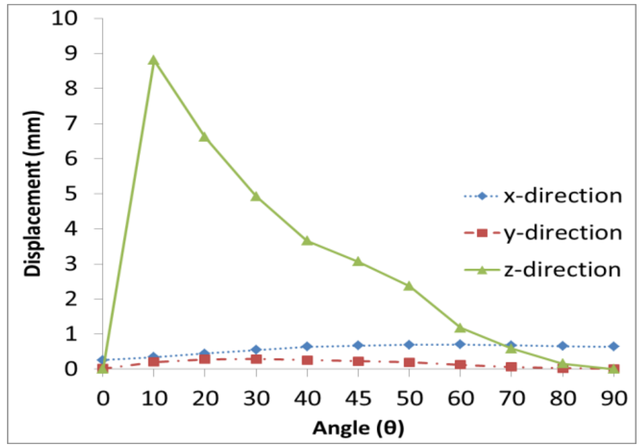


Figure 18 Displacement curves at LPF load for angle-ply laminate (Tsai-Wu criterion).

Result in Figure 19 shows the displacement curves for symmetric lamination scheme (Maximum Stress Theory) in x-, y- and z-directions. It shows that displacement curves at y-direction rose steadily from 0° to 10° and then fell gradually, dropping and hit a bottom at angle 90°. Different in displacement curves at z-direction, it can be concluded that there is no change in displacement curves at z-direction since only small change predicted by Maximum Stress Theory. However, in x-direction, the displacement reached its peak at angle 0° and then gradually descend towards angle 10°. Maximum Stress Theory indicates inconsistent displacement curves since the displacement curves increase gradually from angle 10° to 30° and then fall steadily from angle 30° to 90°.

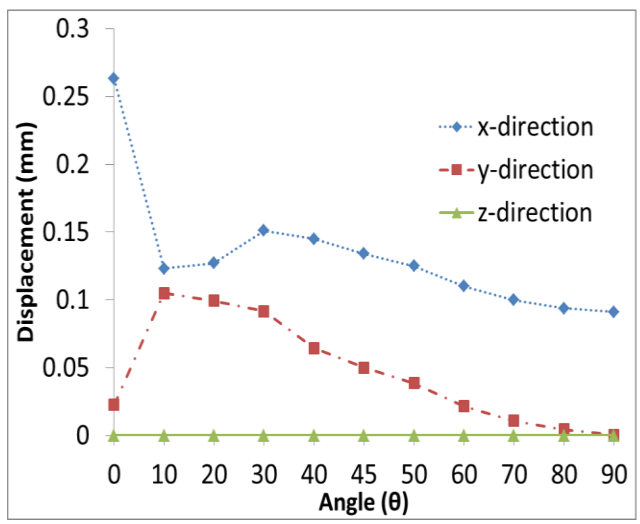


Figure 19 Displacement curves for symmetric laminate (Maximum Stress Theory).

While Figure 20 shows the displacement curves predicted by Tsai-Wu criterion for symmetric laminate in the x-, y- and z-directions. Similar to the earlier prediction using the Maximum Stress Theory (Figure 19), displacement curves in the y-direction increases steadily from angle 0° to 10° and then declines gradually, drops and hits the bottom at angle 90°. Likewise, as predicted by Maximum Stress Theory (Figure 19), it can be concluded that there is no significant change in displacement curves at z-direction since Tsai-Wu criterion predicts very minor change. For the x-direction, the displacement curves reaches its peak at angle 0° and then gradually decreases at angle 10°. The displacement curves are inconsistent since the displacement fell gradually from angle 10° to 20°, but increase steadily from angle 20° to 50° before it gradually drop from angle 50° to 90° . Comparing these two failure criteria (Maximum Stress Theory and Tsai-Wu failure criterion), it shows that both Maximum Stress Theory and Tsai-Wu criterion predicts the same highest displacement at angle 0° in x-direction. This can be concluded that for angle-ply laminate, the displacement behaviour that affects with respect to angle variations only affects the displacement curves in x- and y-directions rather than z-direction (as predicted by both Maximum Stress Theory and Tsai-Wu criterion).

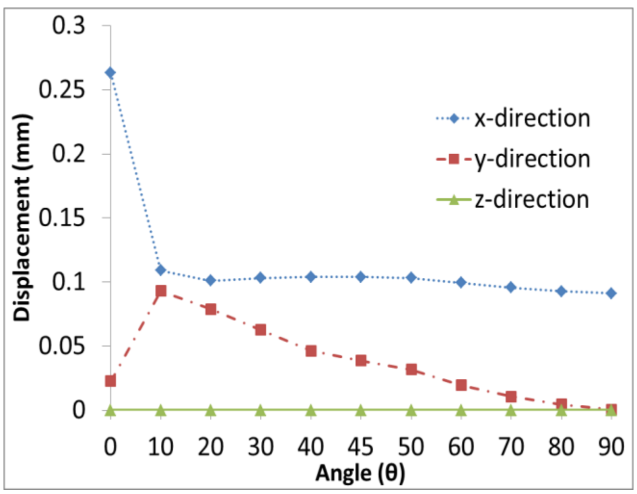


Figure 20 Displacement curves for symmetric laminate (Tsai-Wu criterion).

Figure 21 shows the displacement curves for anti-symmetric laminate (Maximum Stress Theory) in the x-, y- and z-directions. It shows that there is no change in displacement in the x- and y-directions, while displacement curves at z-direction increases significantly from 0° and reaches the peak at angle 10°. However, the displacement curves then plummets, drops and hits the bottom at angle 90°. From the observation, Maximum Stress Theory predicts more deformation at z-direction than x- and y-directions for the anti-symmetric laminate.

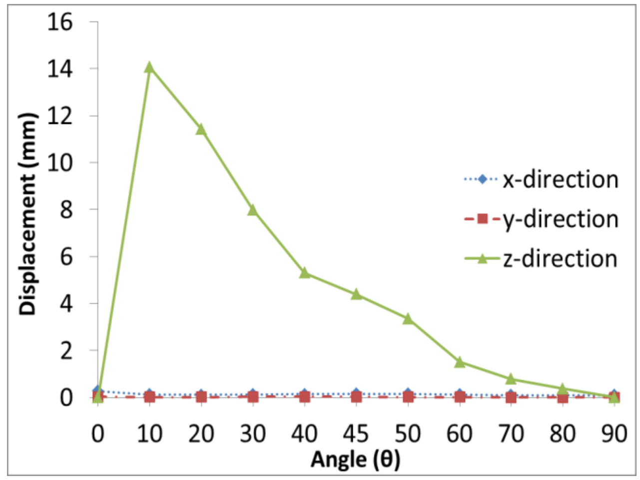


Figure 21 Displacement curves for anti-symmetric laminate (Maximum Stress Theory).

Figure 22 shows the displacement curves for anti-symmetric laminate based on Tsai-Wu criterion in the x-, y- and z-directions. Similar to the prediction based on Maximum Stress Theory (Figure 21), displacement curves at z-direction increases sharply from angle 0° to 10° and then plunges, drops and hits the bottom at angle 90°. It also shows that the other two directions (x and y) predict only small change in displacements compared to the z-direction. Comparing these two failure crieteria (Maximum Stress Theory and Tsai-Wu failure criterion), it indicates that Maximum Stress Theory predict the higher deformation at z-direction.

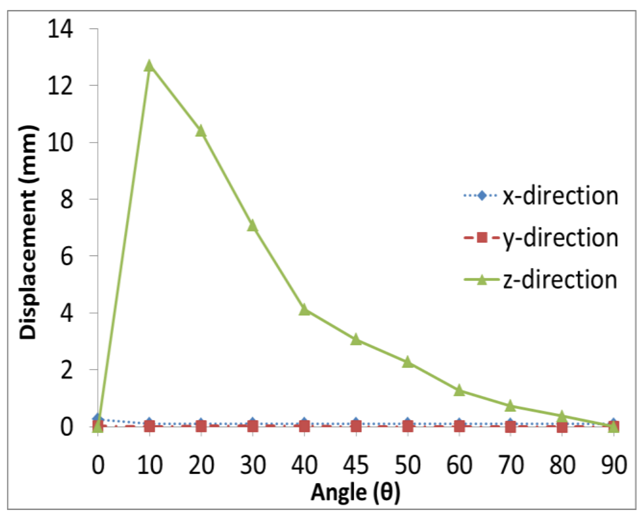


Figure 22 Displacement curves for anti-symmetric laminate (Tsai-Wu criterion).

4.0 CONCLUSION

This paper presents the application of numerical analysis using commercial software (ANSYS) to predict the failure of composite laminates under uniaxial tension and to predict the displacement behaviour of the composite laminate before failure. The results of the study prove that the main objective of the research has been achieved successfully. The findings show that both symmetric and anti-symmetric laminates fail at the same failure load and thus both FPF and LFP curves coincide repectively. In general, it can be concluded that the current study is useful and has contributed significant knowledge to better understand the displacements and failure behaviour of composite plate.

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References

[1] Deborah, D. L. and Chung. 2010. *Composite Material.* Springer.

[2] Krishan, K. C. 2012. *Composite Materials.* Springer.

[3] Liu, P. F. and Zheng, J. Y. 2010. Recent Developments on Damage Modeling and Finite Element Analysis for Composite Laminates: A Review. *Material and Design*. 31: 3825-3834.

[4] Mahmud, J., Ismail, A. F. and Pervez, T. 2005. Employing a Failure Criterion With Interaction Terms to Simulate The Progressive Failure of Carbon-Epoxy Laminate. *IEM Journal, The Institution of Engineers (IEM) Malaysia*. 66(2): 6-14.

[5] Reddy, J. N. and Pandey, A. K. 1987. A First Ply Failure Analysis of Composite Laminate. *Computer and Structures*. 25(3): 371-393.

[6] Sun, C. T., Quinn B. J., Tao, J. and Oplinger, D. W. 1996. Comparative Evaluation of Failure Analysis Methods for Composite Laminates. *Office of Aviation Research Washington. D.C.*. 1-133.

[7] Pedro, P. C. 2002. Failure Criteria for Fibre-Reinforced Polymer Composites. *Departamento de Engenharia*. 1-13.

[8] Nahas, M. N. 1986. Survey of Failure And Post-Failure Theories of Laminated Fiber-Reinforced Composites. *Journal of Composites Technology & Research*. 8: 138-153.

[9] Padhi, G. S., Shenoi, R. A., Moy, S. S. J. and Hawkins, G. L. 1998. *Progressive Failure And Ultimate Collapse of Laminated Composite Plates in Bending*. 40: 277-291.

[10] Rahimi, N., Musa, M. A., Hussain, K. and Mahmud, J. 2012. Finite Element Implementations to Predict The Failure of Composite Laminate Under Uniaxial Tension. *Advanced Materials Research*. 499: 20-24.

[11] Akavci, S. S., Yerli, H. R. and Dogan, A. 2007. The First Order Shear Deformation Theory for Symmetrically Laminated Composite Plates. *Science*. 32(2): 341-348.

[12] Rahimi, N., Hussain, A. K., Meon, M. S. and Mahmud, J. 2012. Capability Assesment of Finite Element Software in Predicting The Last Ply Failure of Composites Laminate. *Procedia Engineering*. 41: 1647-1653.

[13] Rahimi, N., Rahim, M. A., Hussain, A. K. and Mahmud, J. 2012. Evaluation of Failure Criteria for Composite Plates Under Tension. *IEEE Symposium on Humanities, Science and Engineering Research*. 849-854.