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DEFORMATION AND FAILURE ANALYSIS OF SYMMETRIC AND ANTI-SYMMETRIC GRAPHITE/EPOXY LAMINATE DUE TO VARIATIONS IN FIBER ORIENTATION

Azizul Hakim Samsudin, Ahmad Kamil Hussain and Jamaluddin Mahmud
Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia
E-Mail: azizulhakimsamsudin@gmail.com

ABSTRACT

This paper aims to simulate and analyse the failure behaviour, deformation behaviour and mode of failure of composite laminate using the built-in failure criteria function provided by ANSYS. Finite element modelling and analysis of symmetric and anti-symmetric 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, numerical validation and convergence analysis are carried out. The failure loads (First ply failure, FPF and last ply failure, LPF loads) and corresponding stresses (σ_x, σ_y and τ_{xy}) predicted from the finite element simulation using ANSYS are then transformed to determine the principal stresses (σ_1, σ_2 and τ_{12}) using a MATLAB programme, specifically developed for stress transformation computation. Principal stresses are then used to determine the modes of failure (fiber failure, matrix failure or shear stress) of each layer corresponding to specific angle of fiber orientation. The failure curves (FPF and LPF) for both laminates (symmetric and anti-symmetric) and 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 in enhancing knowledge about the failure behaviour, deformation behaviour and mode of failure of composite laminate.

Keywords: ccomposite laminate, deformation analysis, failure analysis, ANSYS.

INTRODUCTION

Composite materials are increasingly used in the construction of mechanical, aerospace, marine and automotive structures since they offer improved material properties and high strength-to-weight ratio. The other main advantage is that its stiffness and strength can be tailored to specific design loads. The capability of composite structure to withstand critical loading can be evaluated either by physical testing or any advance computational method.

Experimental approach (physical tests) required to establish strength characteristics of composite materials are complex, tedious and expensive. This is because to come up with an accurate assessment of a lamina design requires many repetitive tests and sufficient number of samples to cater changes in material properties, lamination scheme, and loading conditions.

Therefore the idea of failure theory has been introduced to predict the strength of a composite materials (Khashaba *et al*., 2013), (Liu and Zheng, 2010), (Taha and Shrive, 2006). Theoretically, determining the desired strength of composite laminate has involved complex computational method and highly mathematical implementation. Thus to avoid this, the current usual preferred analytical tool is the finite element (FE) implementation using commercial software (Zhang and Yang, 2009).

Predicting tool is important, driven by the observation that extensive tests on composite structures are extremely expensive (Nahas, 1986). This is because to come up with an accurate assessment of a lamina design requires many repetitive calculations due to changes in loading conditions, material properties, and laminate geometry (Rahimi *et al*., 2012).

In developing the FE model of composite laminates, scientists or engineers use programming languages, computational tools and algorithms to create codes that run efficiently on high performance computers (Tay *et al*., 2008). Moreover, at present there are digital computers and software packages that could perform laminate analysis that can satisfy various computational requirements for solution.

In terms of lamination theories, First-order shear deformation theory (FSDT) has been employed to establish finite element models for many research pertaining to laminate analysis (Zhang and Yang, 2009), (Vallejo and Tarefder, 2011), (Gupta, *et al*., 2013), (Wang *et al*., 2013), (Sen and Sayman, 2011). Moreover, commercial FE software (ANSYS) has adapted FSDT and an example of study includes Din *et al*. (2014). The use of finite element analysis in predicting the deformation of laminated composites requires further research to provide an acceptable accuracy when compared with experimental results. Due to that, Higher-order Shear Deformation Theory (HSDT) has also been developed and it improves the earlier assumption applied in FSDT for more accurate deformation (Khorsandnia *et al*., 2014), (Hou *et al*., 2014), (Cárdenas *et al*., 2013). Though, HSDT requires more complicated mathematical expression and thus makes programming more difficult. At present HSDT is not available commonly in ANSYS.

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Failure occurs in a material when the applied load reached its threshold. For composite laminate failure in any one layer does not imply failure of other layers in other directions. Therefore it is important to study the behaviour of composite laminate after failure (progressive failure) that occurred in a lamina with the ply by ply approach which considered as bonded layers (Nahas, 1986).

Laminated composite structures develop local failures such as matrix cracks, fibre breakage fibre matrix and ply delamination under normal operating conditions, which are termed as damage (Gupta, *et al*., 2013), (Wang *et al*., 2013). All of those could occur in any ply in the laminate and the weakest which fails first is considered as the first ply failure (FPF). These effect cause permanent loss of integrity within the laminate and result in loss of stiffness and strength of the material. The failure will further propagate to the next weakest plies available until it finally leads to the total rupture when the last ply fails (Nahas, 1986). While the first ply failure analysis often overlooks the consequence of individual failure, determination of last ply failure (LPF) depends greatly on it.

In terms of failure criterion, Maximum Stress Theory is one of the famous failure criteria employed in predicting composite laminate failure (Sun *et al*., 1996), (Pedro, 2002). Maximum Stress Theory considers that the composite fails when the stress in the principal material axes (σ_1, σ_2 and τ_{12}) exceeds the corresponding strength in that direction (exceeds the respective allowable). It is simple and direct way to predict failure of composites and no interaction between the stresses acting on the lamina is considered. Failure will occur when any one of the stress components fails.

Another commonly employed is the Tsai-Wu failure criterion, where it involves polynomial composite laminate in predicting composite failure. However, Tsai-Wu cannot identify modes of failure (fiber failure, matrix failure and shear stress) compared to interactive failure criteria, such as the Maximum Stress Theory (Nahas, 1986), (Rahimi *et al*., 2012). In general, due to its form, the Tsai-Wu failure criterion could identify an element failure (Padhi *et al*., 1998).

Previous study focused on predicting the first ply failure and last ply failure of composite laminates (Rahimi *et al*., 2012). Nevertheless, the deformation behaviour and mode of failure have not been analysed thoroughly, although the deformation behaviour and mode of failure of composite laminates are indeed very interesting phenomena. For example, for a two-layer laminate, the deformation behaviour could be different for both symmetric and anti-symmetric laminate under variations of fiber angle orientation and this phenomenon has not been thoroughly investigated.

Therefore, this study aims to predict the failure behaviour, deformation behaviour and mode of failure of two-layer symmetric and anti-symmetric graphite/epoxy laminate under uniaxial tension due to variations of fiber angle orientation.

METHODOLOGY

In order to achieve the main objectives of this study, the current study is carried out in four main stages:

Stage 1: Numerical validation and convergence analysis
Stage 2: Failure analysis
Stage 3: Deformation analysis
Stage 4: Mode of failure analysis.

Figure-1 shows the overall workflow of the current study. The workflow repeated with different variations in angle (0°, 10°, 20°, 30°, 40°, 45°, 50°, 60°, 70°, 80°, 90°) and using two failure criteria (Maximum Stress Theory and Tsai-Wu).

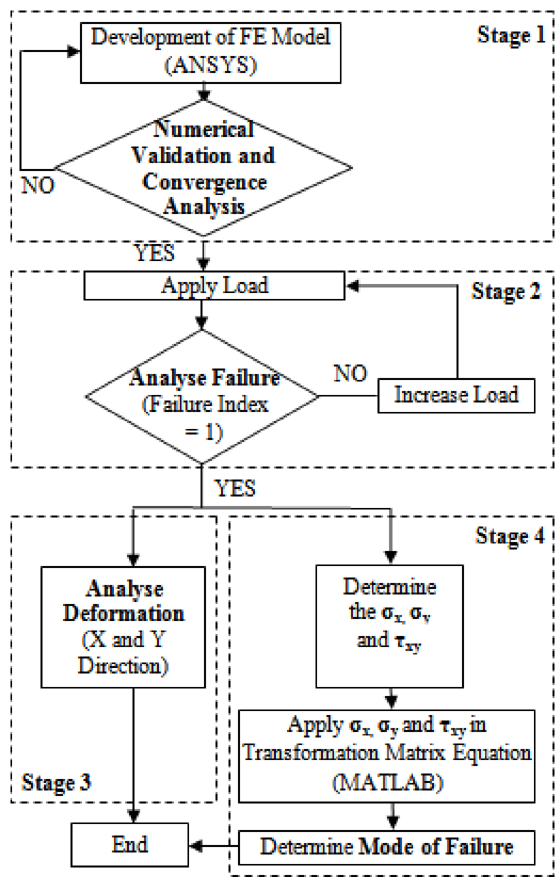

Figure-1. The process flow of failure and deformation analysis of composite laminate.

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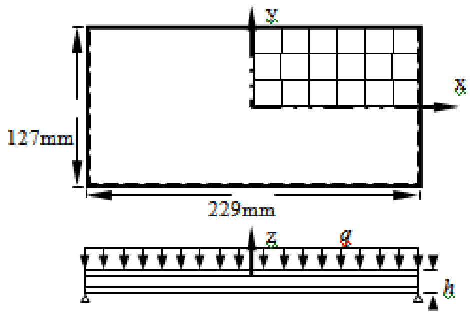

Figure-2. Geometry and computational domain for composite laminate under transverse load.

Numerical Validation

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

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

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

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

Convergence Analysis

A major bottleneck in the finite element process is that of mesh size. Smaller the mesh size, the higher the accuracy of the predicted results but it will increased the computing time (Liu *et al*., 2011). This justify that convergence analysis is important. Thus, this study starts with convergence analysis. These analyses are done using mapped meshing (2x2, 4x4, 8x8. 16x16, 32x32, 64x64, 128x128 and 256x256) with quadrilaterals element under constant uniaxial tension (7010.5 N). 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-3 shows that constant stresses are generated for both symmetric laminate and anti-symmetric laminate.

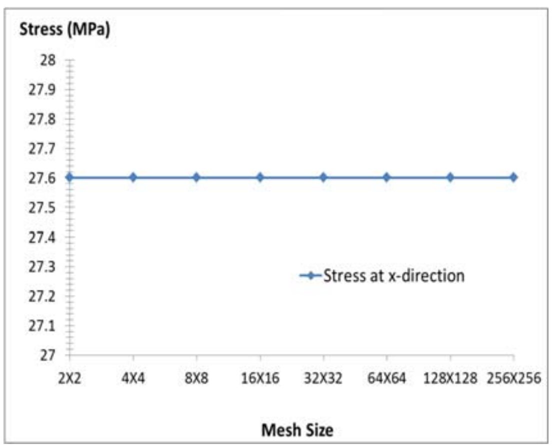

Figure-3. Computed stress (symmetric and anti-symmetric) at various fiber orientation.

It can be observed clearly in Figure-4 and Figure-5 that the results converge with a minimum mesh size of 2x2. Upon proven of the simulation results (based on numerical validation and convergence analysis), further

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analyses are carried out (failure analysis, deformation analysis and mode of failure analysis).

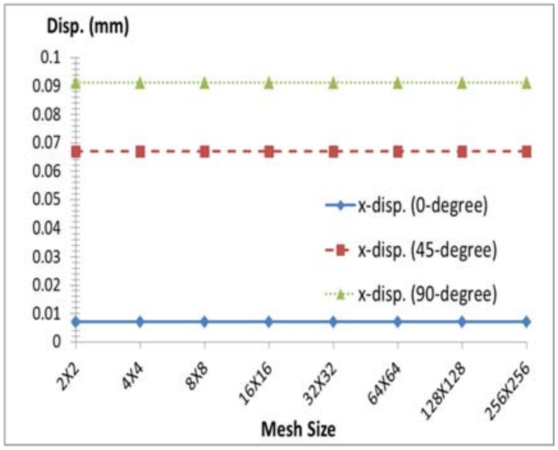

Figure-4. Displacement in x-direction for symmetric $[\theta/\theta]_T$ laminate.

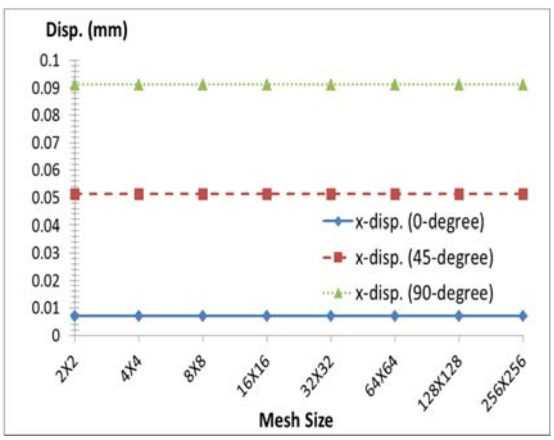

Figure-5. Displacement in x-direction for anti-symmetric $[\theta/-\theta]_T$ laminate.

Failure and Deformation Analysis of Composite Laminate

Symmetric and anti-symmetric composite plates are modelled as shown in Figure-6 under uniaxial tension. The laminate is made of two layer, and for this study two lamination schemes are analysed, where the layup are symmetry $(\theta/\theta)_T$ and anti-symmetry $(\theta/-\theta)_T$. The plate is rectangle, with a thickness of $1.27\text{x}10^{-4}$m/ply and made of graphite-epoxy. 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 (equation 1) and Tsai-Wu (equation 2). The deformation behaviour is also recorded during the failure.

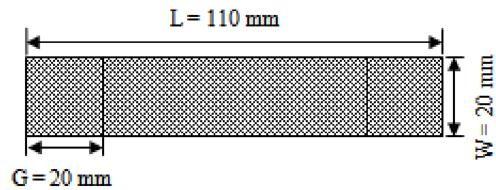

Figure-6. Uniaxial tension model.

Table-3. Material properties for T300/5208 (J.N. Reddy *et al.*, 1987).

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

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

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

Mode of Failure Analysis

Since the stresses predicted using ANSYS are computed for global axis ($\sigma_{x,}$ σ_y and τ_{xy}), a programme based on transformation matrix equation is developed using MATLAB (v8.1.0.604, R2013a, The MathWorks, Inc.) to determine the principal stresses ($\sigma_{1,}$ σ_2 and τ_{12}) for every angle. The used of stress transformation equation (equation 3) in order to determine the principal stresses. Principle stresses are then used to categorize each of the angles in failure mode based on theoretical calculation (fiber failure, matrix failure or shear failure).

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} \cos^2\theta & \sin^2\theta & -2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & 2\sin\theta\cos\theta \\ \sin\theta\cos\theta & -\sin\theta\cos\theta & \cos^2\theta - \sin^2\theta \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \qquad (3)$$

RESULTS

In general, the results show that the laminate strength decreases when the fibers are orientated from 0° to 90 °. From the results shown in Figure-7 (symmetric laminate), it could be observed that there is no significant difference of the failure curves between Tsai-Wu and Maximum Stress Theory, except between angle 10° until 60° fiber orientation. The failure curves for the 60° to 90° orientation are almost similar. Comparing between the failure curves of Maximum Stress Theory and Tsai-Wu, it is found that failure curves of shear stress (mode of failure - Table-4) shows different value of stresses while at the fibre failure and matrix failure does not shows any different.

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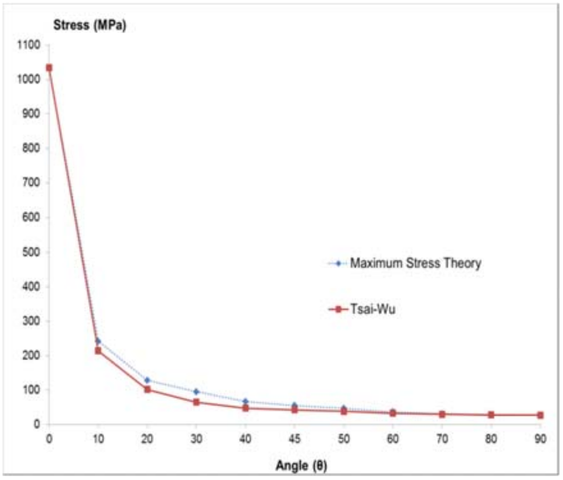

Figure-7. Failure curves for symmetric $[\theta/\theta]_T$ laminate (Maximum Stress Theory and Tsai-Wu).

Results for symmetric laminate (Figure-8) show the deformation behaviour (x-directions) during failure as predicted by Maximum Stress Theory and Tsai-wu. Displacement in x-direction shows that Maximum Stress Theory predicts higher displacement than Tsai-wu but at angle 0° and 90° the displacement are the same. At angle 0°, the plate deformed the longest since the fibre direction parallel to the x-axis (global axis) which also the direction of load being applied. While the less deformed 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.

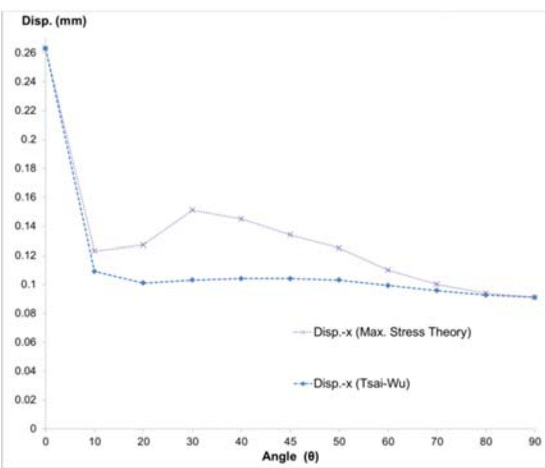

Figure-8. Displacement (x-direction) curves for symmetric $[\theta/\theta]_T$ laminate (Maximum Stress Theory and Tsai-Wu).

It goes the same with displacement in y-direction where Maximum Stress Theory predicts more displacement than Tsai-Wu and also at angle 0° and 90° the displacement are the same. For both Maximum Stress Theory and Tsai-Wu predicts the highest displacement occur at angle 10° while the lowest displacement predicted at angle 90°.

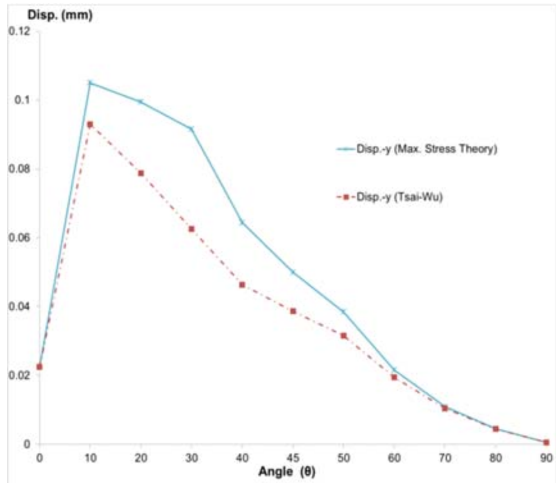

Figure-9. Displacement (y-direction) curves for symmetric $[\theta/\theta]_T$ laminate (Maximum Stress Theory and Tsai-Wu).

From the observation in Figure-8 and Figure-9, it can be concluded that Tsai-Wu predicts a smoother curve than Maximum Stress Theory, thus proving that the interaction terms between the stresses (σ_x and σ_y) are significant. For symmetric laminate, the failure predicted at the same stress since the fiber orientation for both layers are the same.

Table-4 (symmetric laminate) shows the range of angle between the modes of failure (referring to principal stresses σ_1, σ_2 and τ_{12}) obtained using MATLAB programme based on stress transformation equation. It shows that fiber failure occur between angle 0° to 2° while the remaining is shear stress (3° to 33°) and matrix failure (34° to 90°). It could clearly be observed that symmetric laminate extent and shear under uniaxial tension.

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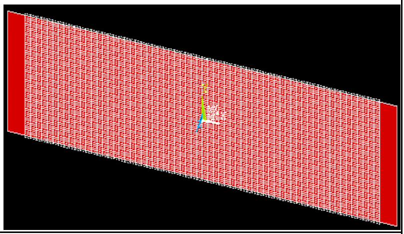
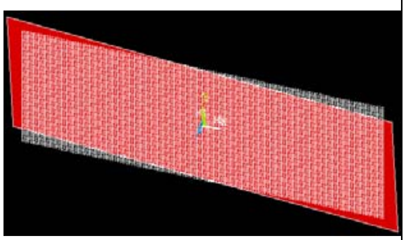
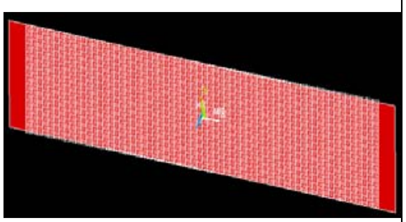
Table-4. Mode of failure for symmetric $[\theta/\theta]_T$ laminate.

Modes of failure / Angle (°)	Isometric View
Fiber Failure (X_T) (0° to 2°)	
Shear Failure (S) (3° to 33°)	
Matrix Failure (Y_T) (34° to 90°)	

For anti-symmetric laminate (Figure-10), it could be observed that there is no significant difference of the failure curves between Tsai-Wu and Maximum Stress Theory, except between angle 10° until 70° fiber orientation. The failure curves for the 70° to 90° orientation are almost similar. Comparing between the failure curves of Maximum Stress Theory and Tsai-Wu, it is found that failure curves of shear stress (mode of failure - Table-5) shows different value of stresses while at the fibre failure and matrix failure does not shows any different. For anti-symmetric laminate, the failure predicted at the same stress since there is no different between angle positive and negative fibre orientation.

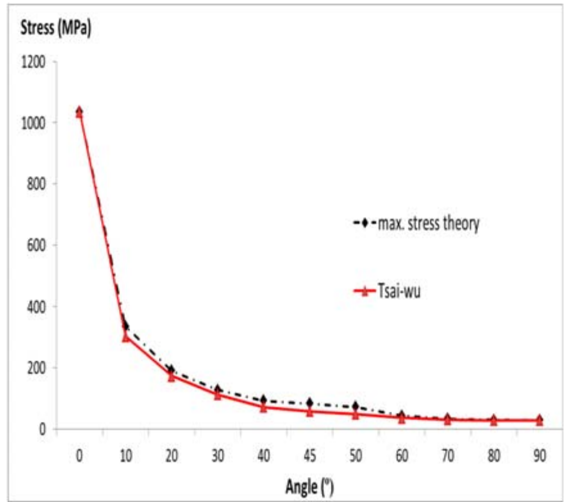


Figure-10. Failure curves for anti-symmetric $[\theta/-\theta]_T$ laminate (Maximum Stress Theory and Tsai-Wu).

Figure-11 shows the deformation behaviour (x-directions) during failure as predicted by Maximum Stress Theory and Tsai-wu. Displacement in x-direction shows that Maximum Stress Theory predicts higher displacement than Tsai-wu but at angle 0° and 90° the displacement are the same.

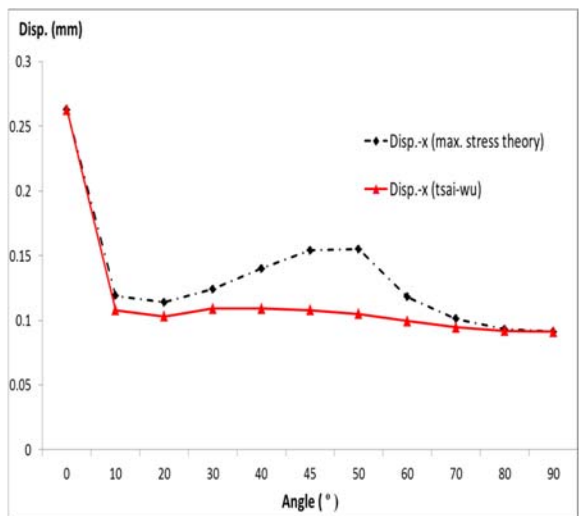


Figure-11. Displacement (x-direction) curves for anti-symmetric $[\theta/\theta]_T$ laminate (Maximum Stress Theory and Tsai-Wu).

Figure-12 shows the deformation behaviour (y-directions) during failure as predicted by Maximum Stress Theory and Tsai-wu. Displacement in x-direction shows that Maximum Stress Theory predicts higher displacement than Tsai-wu but at angle 0° and 90° the displacement are the same.

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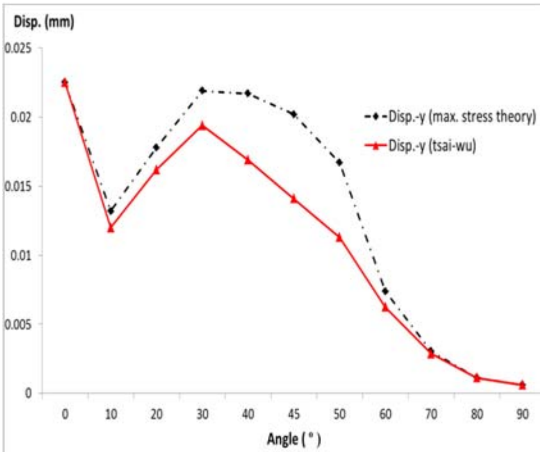


Figure-12. Displacement (y-direction) curves for anti-symmetric [θ/-θ]$_T$ laminate (Maximum Stress Theory and Tsai-Wu).

Figure-13 shows the deformation behaviour (z-directions) during failure as predicted by Maximum Stress Theory and Tsai-wu. Displacement in x-direction shows that Maximum Stress Theory predicts higher displacement than Tsai-wu but at angle 0° and 90° the displacement are the same.

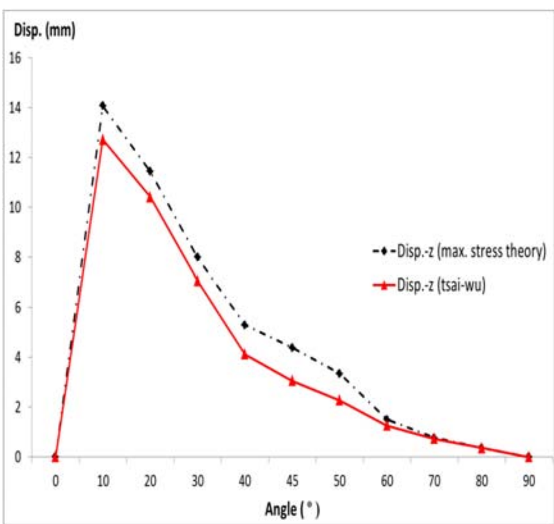
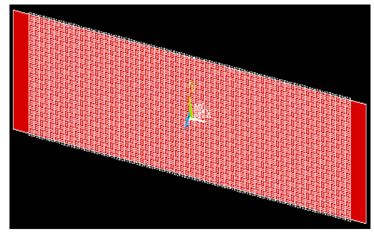
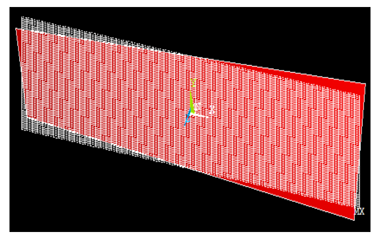
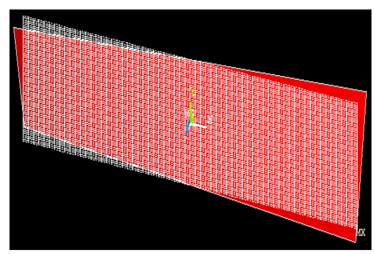


Figure-13. Displacement (z-direction) curves for anti-symmetric [θ/-θ]$_T$ laminate (Maximum Stress Theory and Tsai-Wu).

Table-5 shows the range of angle between the modes of failure (referring to principal stresses σ_1, σ_2 and τ_{12}) obtained using MATLAB programme based on stress transformation equation. It shows that fiber failure occur between angle 0° to 2° while the remaining is shear stress (3° to 48°) and matrix failure (49° to 90°). The simulation results clearly show that anti-symmetric laminate experience twisting deformation under uniaxial tension.

Table-5. Mode of failure for anti-symmetric [θ/-θ]$_T$ laminate.

Modes of Failure / Angle (°)	Isometric View
Fibre Failure (X_T) (0° to 2°)	
Shear Failure (S) (3° to 48°)	
Matrix Failure (Y_T) (49° to 90°)	

CONCLUSIONS

This paper presented the application of numerical analysis using commercial software (ANSYS) and MATLAB programme to predict the failure of composite laminates under uniaxial tension, to predict the deformation behaviour of the composite laminate during failure and finally to determine the mode of failure due to variations in angle of fiber orientation.

The results of the study prove that the main objective of the research to predict the failure curves and deformation behaviour of composite laminate using a novel approach has been achieved successfully. Modes of failure on each angle variations are also predicted.

The observation for symmetric and anti-symmetric shows that for symmetric laminate experience elongation while anti-symmetric laminate experience twisting deformation under uniaxial tension. This is a very interesting phenomena, where by just varying the fiber orientation, a two layer composite laminates could either extend, shear or twist. Also, both symmetric and anti-symmetric laminates fails at the same stress for each of the fiber orientation. Therefore, first ply failure and last ply failure occur at the same stress where it coincide.

Thus, it can be concluded that the current study is useful and contributes significant knowledge to the failure behaviour of composite laminate.

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