Failure Analysis of Composite Laminates Under Biaxial Tensile Load Due To Variations in Lamination Scheme

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ABSTRACT

Due to its variability in mechanical properties and complex anisotropy behaviour, the work related to the design and analysis of composite laminates or composite structures is complicated yet crucial. At present, the analytical and finite element simulation techniques are the more preferred methods than the tedious and costly physical testing procedures. Unfortunately, even after many research works have been conducted, there is still a lack of understanding in relation to the failure behaviour of composite

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ISSN 1823-5514, eISSN2550-164X

Received for review: 2017-07-30
Accepted for publication:2017-07-24
Published:2017-12-31

laminates under the effect of biaxial load. This paper investigates the failure behaviour of fibre-reinforced composite laminates under biaxial tensile load due to variations in lamination scheme by comparing results obtained from analytical approach and finite element simulation. Failures in the laminates follow Maximum stress and Tsai-Wu criteria based on FSDT. The analytical approach was developed based on the CLT in which the computed strains, global stresses, principal stresses and displacements were used to predict the failure. The results from the finite element models were validated by comparing with the accepted published results. Three variations of lamination scheme; symmetric unidirectional-ply, cross-ply and angle-ply ($[0/0]_s$ & $[90/90]_s$, $[0/90]_s$ and $[+45/-45]_s$) were investigated. Comparison of the results obtained from the analytical and FEM were found in good agreement for all three schemes. In addition, it was found that the lamination scheme affected the failure behaviour composite laminates under the biaxial load. In conclusion, it can be concluded that the present study is useful and significant in enhancing knowledge about failure behaviour of composite laminates under biaxial tensile load.

Keywords: *Composite laminates, biaxial tensile load, analytical method, ANSYS*

Introduction

The demand of composite material has increased because of its excellent mechanical properties that can be achieved at a relatively low cost [1]. The usage of this advanced material has also expanded from defence and aeronautical industries to civil industries. As requests increases, continuous research related to the design and development of composite material or composite laminates is crucial [2].

Evaluation on failures in composite material involves various approaches [3]. Less convenient and very costly is the physical testing in comparison to the more favourable methods; the analytical technique and the finite element method (FEM) [4,5]. The analytical approach is based on the various established theories in Classical Lamination Theory (CLT). Similar to analytical approach, finite element simulation uses massive theoretical calculation, where the result can be viewed graphically or by using animation. One advantage of FEM is that it can be applied to many complex models (geometrical, material and problem complexity) compared to the analytical approach. The FEM started after the computer was introduced, utilizing special written program [6] or built-in programs in the commercial software. By utilising the computer instead of conducting a physical test to collect data, researchers have begun using computer software to conduct failure analysis on composite material [7, 8, 9].

Nevertheless, there is still lack of understanding in failure behaviour of composite laminates under the effect of biaxial tension load. Previous studies have been more focused on the failure of laminates under uniaxial tensile load [10,11,12]. Therefore, this paper investigates the failure behaviour of fibre-reinforced composite laminates under biaxial tensile load due to variations in lamination scheme by comparing results obtained from the analytical method and the finite element simulation.

Methodology

In this study, the analytical approach was conducted with the aid of Matlab computational software, (version R2013a (8.1.0.604),The MathWorks, Inc). The relevant theories of macromechanical based on CLT and Maximum stress and Tsai-Wu criteria were used to build a MATLAB programme. This programme can compute strains, global stresses, principal stresses and displacements in which these values were used to predict failure based on FSDT.

The finite element method was performed using the commercially available FE software package, (ANSYS v16.0 2014 SAS IP, Inc.) with built-in failure criteria functions. ANSYS was used owing to its simplicity, and its ability to provide all the necessary functions for structural analysis of layered composite structures. The present studies were systematically divided into three numerical stages.

Stage 1: Convergence analysis
Stage 2: Numerical validation

- Numerical validation with exact solution
- Numerical validation with analytical result

Stage 3: Failure analysis

- $[0/0]_s$&$[90/90]_s$ (Comparison with published results)
- $[0/90]_s$ Comparison between analytical and simulation results
- $[+45/-45]_s$ Comparison between analytical and simulation results

1. Convergence Analysis

Initially, in order to develop an accurate model, a convergence analysis was performed to determine the accurate minimum size of mesh to be used for the models. This process could reduce the cost of analysis and to ensure minimisation of processing time [13, 14]. Six models with six different mesh sizes (1x1, 2x2, 4x4, 8x8, 16x16 and 32x32) were simulated under the constant biaxial tension, 650N for P_x and P_y. The maximum displacements on both x-direction and y-direction were recorded.

2. Numerical Validation

Numerical Validation with Exact Solution

For the Stage 2 process, a T300/5208 Graphite/Epoxy model with the geometry (Figure 1) and material properties (Table 1) was developed. The finite element simulation (ANSYS) model was validated using the results from the exact solution [15].

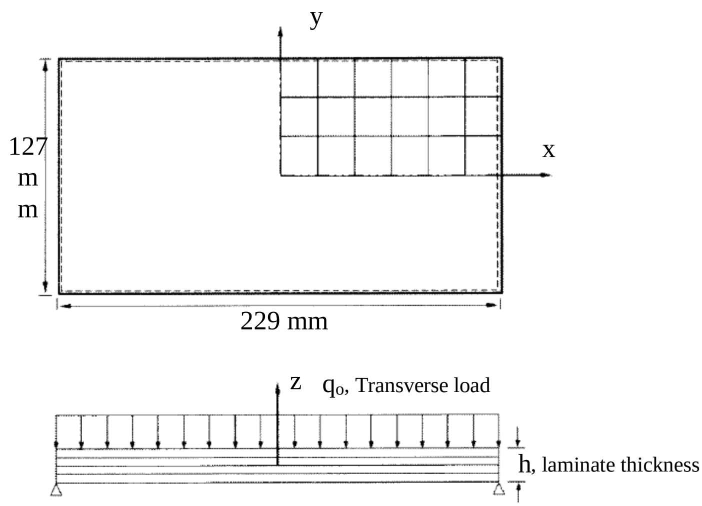

Figure 1: Geometry, computational domain and boundary conditions for composite laminate

Table 1: Material properties of T300/5208 Graphite/Epoxy [13]

Properties	Values	Properties	Values
E_1	138 GPa	X_T	1035 MPa
$E_2 = E_3$	10.6 GPa	X_C	1035 MPa
G_{12}	6.46 GPa	Y_T	27.6 MPa
υ_{12}	0.3	Y_C	138 MPa
		S	41.4 MPa

Numerical Validation with Analytical Result

Models with stacking sequence $[\theta_4/0_4/\theta_4]_s$ and variations in fibre orientation (θ = 0^o - 90^o) were simulated using finite element approach to predict the maximum displacement for both x-direction and y-direction under uniaxial tension load. The geometry and the material properties used for this model are shown in Figure 2 and Table 1. For this analysis, the MATLAB results were compared with the analytical approach for various ply arrangements.

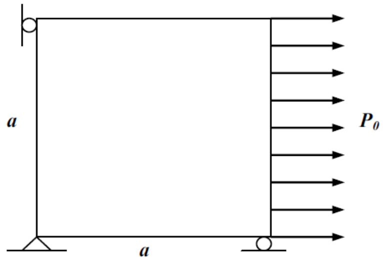

Figure 2: Model under uniaxial load

Table 1: Material properties for T300/5208 [16]

Properties	Values	Properties	Values
E_1	53.78 GPa	X_T	1035 MPa
$E_2 = E_3$	17.93 GPa	X_C	1035 MPa
G_{12}	8.62 GPa	Y_T	27.6 MPa
υ_{12}	0.25	Y_C	138 MPa
		S	41.4 MPa

3. Failure Analyses

Symmetric composite laminates were modelled with biaxial tension loads and boundary condition as shown in Figure 3. The model are squares with length, a = 0.02 m and the thickness of each lamina, h_i = 5 x 10^{-4} m. Three stacking sequences, $[0/0]_s$& $[90/90]_s$, $[0/90]_s$ and $[+45/-45]_s$, were analysed separately in this study. The material properties for the models are shown in Table 2.

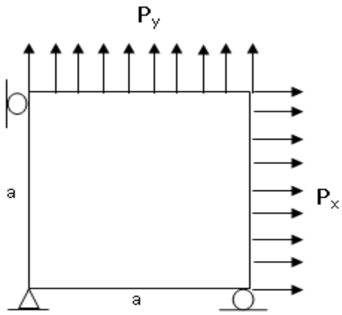

Figure 3: Biaxial tension model

Table 2: Material property for fibre-reinforced composite laminates [17]

Properties	Values	Properties	Values
E_1	45.6GPa	X_T	1280 MPa
$E_2 = E_3$	16.2GPa	X_C	800 MPa
G_{12}	5.83 GPa	Y_T	40 MPa
υ_{12}	0.278	Y_C	145 MPa
		S	724 MPa

Failure results were obtained using both the finite element and analytical approaches. Governed by the Maximum stress and Tsai-Wu failure criteria given in Equation 1 and Equation 2, each model was simulated biaxial load of various increments maintaining fixed ratio ($\sigma_x/\sigma_y = 1$). First ply failure (FPF) and last ply failure (LPF) were recorded for this study.

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

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

Result And Discussion

1. Convergence Analysis

Figure 4 and Figure 5 showcase the maximum displacements in x-direction and y-direction in relation to various mesh sizes, respectively for $(0/0)_s$ and $(90/90)_s$ laminates. It can be clearly observed that the mesh sizes have no effect on the displacement values. Hence, the mesh size 1x1 was chosen in the present study in order to reduce the modelling and processing time to generate results.

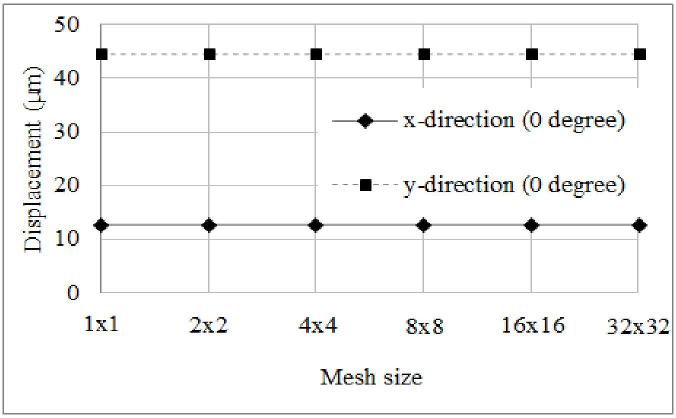

Figure 4: Displacement in x-direction and y-direction for **(0/0)**$_s$ laminate.

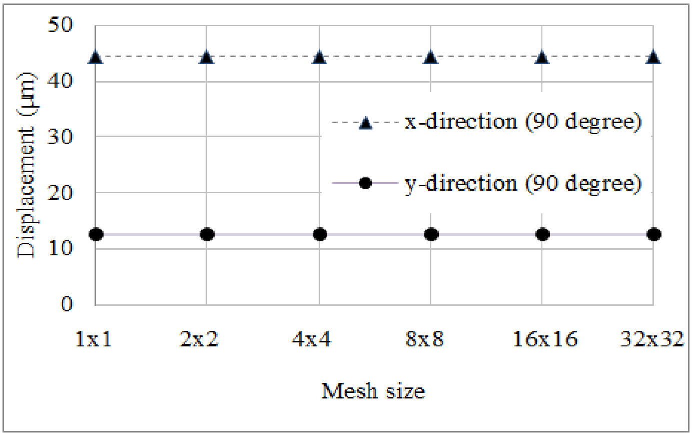

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Figure 5: Displacement in x-direction and y-direction for (90/90)$_s$ laminate

2. Numerical Validation

1. Numerical Validation with Exact Solution

The results from the exact solution and FEM were compared and tabulated in Table 2. The percentage errors of their differences were calculated and the errors were less than 2%. These relatively small errors indicate that both methods are reliable enough to be used for these laminate orientations and the transverse loading type.

Table 2: Comparison between exact solution and finite element simulation results for composite plate under transverse load

Lamination Orientation	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	0.51

2. Numerical Validation with Analytical Result

Results from both finite element and analytical approaches are tabulated in Table 4 and the graphically presented in Figure 6. Both methods are comparable with error ranging from 0% to 1.9% (below 2%) for both x-direction and y-direction in relation to the angles of the lamination scheme.

Table 4: Comparison between analytical results and finite element simulation results for composite laminates under uniaxial load

θ°	Load (N)	Analytical		Simulation (ANSYS)		Error	
		x (m)	y (m)	x (m)	y (m)	x %	y %
0	650	3.60E-05	1.06E-05	3.53E-05	1.06E-05	1.9	0.0
15	650	4.00E-05	2.80E-05	3.97E-05	2.97E-05	0.8	6.1

30	650	5.80E-05	6.00E-05	5.77E-05	5.93E-05	0.5	1.2
45	650	8.00E-05	5.40E-05	7.95E-05	5.34E-05	0.6	1.1
60	650	8.80E-05	2.60E-05	8.89E-05	2.64E-05	1.0	1.5
75	650	9.20E-05	8.62E-06	9.11E-05	8.62E-06	1.0	0.0
90	650	9.20E-05	3.04E-06	9.14E-05	3.04E-06	0.6	0.1

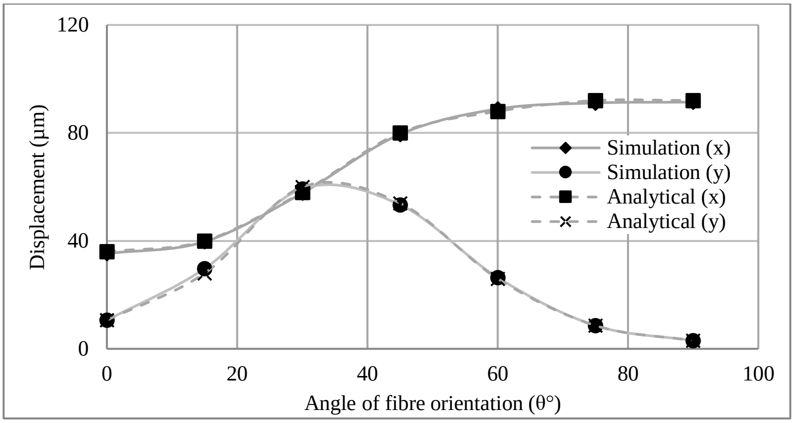

Figure 6: Comparison results on maximum displacement using simulation (ANSYS) and analytical approach

3. Failure Analyses

1. $[0/0]_s$ & $[90/90]_s$ (Comparison with past published results)

The first case for failure analysis subjected to biaxial load was conducted using two models of symmetric unidirectional-ply, $[0/0]_s$ & $[90/90]_s$. Results obtained from the finite element (ANSYS) and the analytical approach were plotted and presented in Figures 7 and 8. Failure envelopes from the past published results [17] are also shown as well. In Figure 7 the curves represents failure using the maximum stress criterion while Figure 8 displays the failure curves using Tsai-Wu criterion.

Both figures have clearly shown that the models have failed at the material's maximum tensile strength of 1280 MPa. It was found that results obtained from the finite element and the analytical approaches were in agreement with results obtained by past published results. Hence, it can be concluded that both approaches are valid and capable of producing reliable data for composite material analysis.

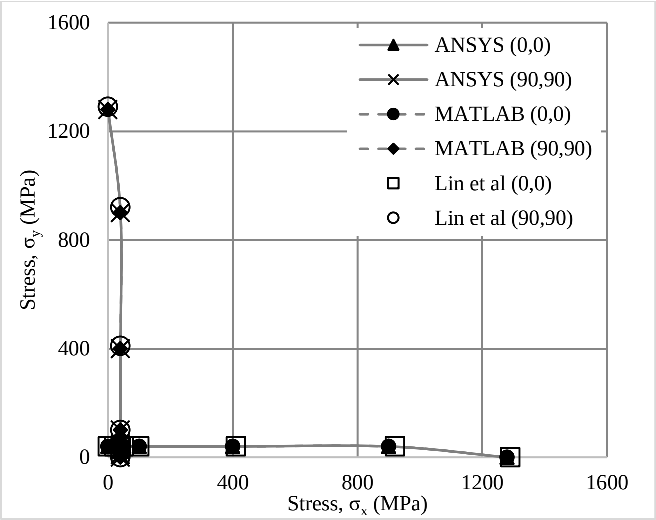

Figure7: Failure envelopes for numerical validation using Maximum stress criterion

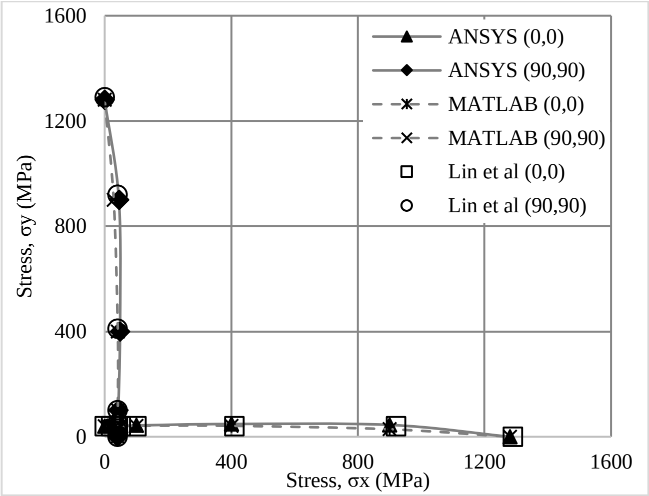

Figure 8: Failure envelopes for numerical validation using Tsai-Wu criterion

2. $[0/90]_s$ (Comparison between analytical and simulation results)

Figures 9 and 10 illustrate the failure analyses based on maximum stress criterion and Tsai-Wu criterion, respectively. Both the ANSYS and Matlab results were presented. Since perfect bonding was considered, failures for this study were only identified by the stacking ply sequences.

It was found that the ply that failed first (FPF) was in the same orientation (or closely aligned) with the applied load direction while the ply that was in the transverse direction was the ply that failed last (LPF). From the figures, both FPF and LPF curves intercepted at one point. The state of the stresses was equal on both directions and all plies were predicted to fail simultaneously. As expected both analytical and simulation results predicted similar outcomes using Maximum stress as failure criterion. The results also indicated that both analysis methods were in good agreement. Previous study by Tolson and Zabaras [18] also reported similar trend of FPF graphs even though they used different composite materials but identical symmetric cross-ply orientation.

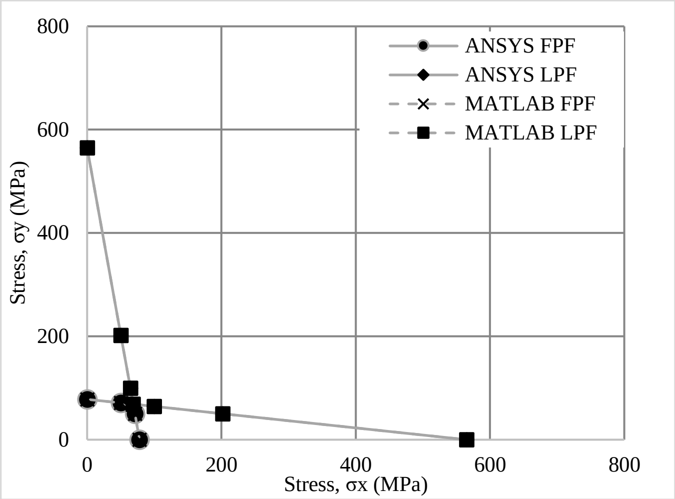

Figure 9: Failure curves for $[0/90]_s$ (Maximum stress criterion)

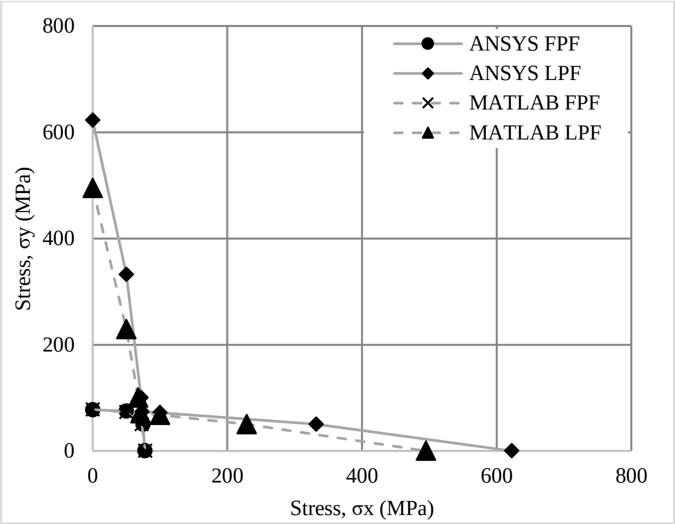

Figure 10: Failure curves for $[0/90]_s$ (Tsai-Wu criterion)

3. $[+45/-45]_s$ (Comparison between analytical and simulation results)

Figures 11 and 12 illustrate the failure envelopes (FPF and LPF) of composite laminates with symmetric angle-ply stacking sequence $[+45/-45]_s$ subjected to biaxial loading. Maximum stress and Tsai-Wu failure criteria were used. The failure envelopes were plotted to show the stresses subjected to longitudinal and transverse tensile loading (σ_x-σ_y).

Using Maximum stress criterion, a straight symmetrical pattern was observed. However a slight curving pattern was formed using Tsai-Wu criterion. This could be due to the interaction between stresses in Tsai-Wu criterion. It can be also be pointed out that the curves formed by FPF and LPF were overlapped for both failure criteria and both ANSYS and Matlab results. This may be due to the same laminates strength or resistance on all plies under the applied biaxial load.

In addition, the model failed at below material's tensile strength. It was under the assumption that there was perfect bonding and equal distribution of strength on each plies. Both Figures 11 and 12 indicates that the results obtained from finite element are in a good agreement with analytical results.

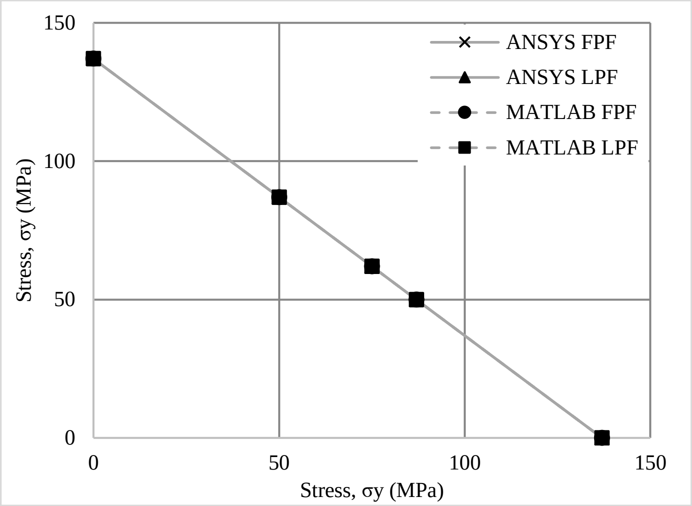

Figure 11: Failure curves for $[+45/-45]_s$ (Maximum stress criterion)

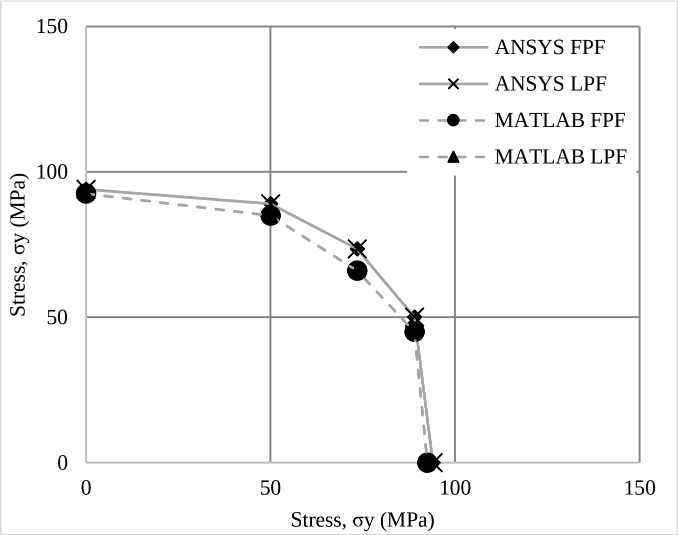

Figure 12: Failure curves for $[+45/-45]_s$ (Tsai-Wu criterion)

Conclusion

The main objective of the present study was to investigate and to report the failure behaviour of composite laminates under biaxial tensile load. The results obtained from both analytical and finite element simulation methods were found to be in agreement to each other. Therefore, any of these methods can be accepted as an alternative analysis to physical testing to accurately predict the failure behaviour for various lamination schemes. All in all, it can be concluded that this study has enhanced the knowledge pertaining to the failure behaviour of composite laminates under biaxial tensile.

Acknowledgement

This work is supported by Universiti Teknologi MARA and Ministry of Higher Education (MOHE) Malaysia under the Fundamental Research Grant Scheme (grant no 600 – RMI/FRGS 5/3 (80/2014)).

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