International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2015): 78.96 | Impact Factor (2015): 6.391

Design and Failure Analysis of a Laminated Composite Tube using Maximum Stress and Tsai-Wu Failure Criteria

Mustafa Al-Khazraji

Al-Nahrain University, College of Engineering, Iraq
M.Sc. Mechanical Engineering Design, University of Manchester, UK

Abstract: ***A composite tube made by filament winding technique was designed and analysed. The tube comprises of four layers of Carbon-Epoxy plies. The failure of the tube was investigated by varying the orientation angles of the plies forming the tube and check it against failure under axial compression and internal pressure loads,special design requirements were satisfied (direction of the twist angle). Maximum stress failure criterion was implied and the tube winding angles were chosen to be (-75^o and -39.3^o) which produce a maximum twist angle of (-12.986^o) without failure. This set of winding angle results were tested numerically using Tsai-Wu failure criterion under axial loading condition and compared to maximum stress failure criterion results. It was found that the tube failed under axial compression loadaccording to Tsai-Wu failure criterion while no failure recorded according to maximum stress failure criterion. It was concluded that the sole dependence on one criterionfor assessing composite structures is not sufficient and several criteria application might observe other modes of failure. Finally, some recommendations for tube design improvement were presented and tested such as varying the load, varying the stacking sequence of the plies and adding more plies to the composite tube.***

Keywords: Composite Tube, Winding Angles, Failure Criteria and Design Assessment

1. Introduction

Composites can be defined as multi-layer materials that comprise of multiple layers of either the same or different materials arranged in various directions. This orientation and material diversity give the composite variable mechanical properties in various directions. This diversity in the mechanical properties gives the composites an advantage over other materials in that its strength and properties can be designed to satisfy the desired application and loading conditions. (Hoppel & De Teresa, 1999)

In order to control composites properties, different ways can be utilized. One of these ways is to change the materials that form the composite, the second is to change the lay-up as well as the stacking sequence of the laminas that forming the laminate and the third is to change the orientation angle of the plies. Either using one or a combination of these techniques, the resulted composite material will have different mechanical properties. During the design stage, the design requirements can be fulfilled by following these procedures. (Khandan, et al., 2010)

Due to the properties that it can provide, composites have been widely used in various applications worldwide due to its light weight and strength properties. For instance, many kinds of composites are being used, nowadays, for the manufacturing of airplanes and pressure vessels due to its high strength and light weight. However, some drawbacks can be noticed as a result of failure of composites under certain loading conditions. (Parnas & Katirici, 2002)

Several failure criteria were proposed for assessing the likelihood of composite materials to fail under certain loads. The earliest failure criteria was "Maximum Stress Failure Criteria). This criteria predicts failure modes of composites and it is widely used criteria for predicting composites failure mode. However, this failure criteria does not take into account the interaction between shear stresses and strains. Another criteria was proposed by Tsai and Wu in 1971 and called (Tsai-Wu Failure Criteria). This criteria is more conservative than the previous criteria in predicting general composite failure. However, this criteria does not predict the modes of composite failure and, therefore, Tsai-Wu failure criteria is not popular nowadays. Other criteria exist and can be applied to assess composites failure. However, in this research, only maximum stress and Tsai-Wu criteria were implemented and compared.

In this research, a hollow composite cylinder made up of four layers subjected to axial compression and internal pressure loads separately will be analyzed. Classical laminate theory will be applied after simplifying the problem to composite laminated plate. The cylinder should withstand both loading conditions without failure. Maximum stress failure criteria will be applied to assess the likelihood of failure under axial compression and internal pressure loading conditions. All the previous aspects will be tolerated by varying the orientation angle of the laminas and the resulted stresses will be compared. In addition, the specified orientation angle should satisfy the condition that it will provide the maximum twist angle for the cylinder under axial compression load without failure. Finally, the tube was tested using Tsai-Wu criteria and the results were compared.

2. Design Specification

A cylindrical composite tube made up of four layers (thickness= 0.25mm each) of the same materialwill be analyzed using classical laminate theory and maximum stress failure criteria. The cylinder is manufactured using filament winding technique by rotating a cylindrical mandrel in various directions and winding the tape (made from UD prepreg sheet).

The layup of the cylindrical tube is [α/β/α/β] and is to be designed bywinding tapes cut from a UD (unidirectional) prepreg sheet on to a φ50mm mandrel. For the consideration ofpracticality, the range of these two winding angles will have to fall in [−75°, −30°] or [+30°,+75°] to the axis of the tube, i.e. −75°≤α≤−30° or +30°≤α≤+75°. The thickness of theprepreg is 0.25mm. The tube should be made to a length of 300mm.

The carbon-epoxy prepreg to be used in the current analysis is from SP (SE 84LV/HSC/300g/400mm/37%/1 blue)of following properties:

E_1=236 GPa Young's modulus
E_2=5 GPa Shear modulus
G_{12}=2.6 GPa Poisson's ratio
ν_{12}=0.25

And the maximum failure stresses are:

$$\nu_{21} = \frac{E_2}{E_1} * \nu_{12} = 5.297 * 10^{-3}$$

$\sigma^*_{1t} = Xt = 3800$ MPa Tensile stress

$\sigma^*_{1c} = Xc = 689$ MPa Compressive stress

$\sigma^*_{2t} = Yt = 41$ MPa. Tensile stress

$\sigma^*_{2c} = Yc = 107$ MPa. Compressive stress

$\tau^*_{12} = S = 69$ MPa Shear stress

Both 25KN compressive load and 3MPa internal pressure load have to be applied independently and the resulted stresses in each lamina have to be compared with their corresponding failure stresses. The cylinder geometry is shown in figure (1).

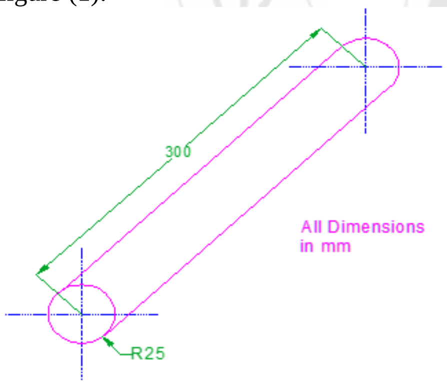


Figure 1: Schematic drawing of the composite tube showing dimensions.

In addition to the maximum stress failure criteria, the tube should achieve a maximum twist angle (ρ) under the axial compression loading (25KN) without failure. The rotational direction of the twist angle should be as shown in figure (2). In order to achieve that, the design procedure of the tube should consider the shear component of the resulted shear strains (γ_{xy}) and its direction to satisfy the design requirement of the tube.

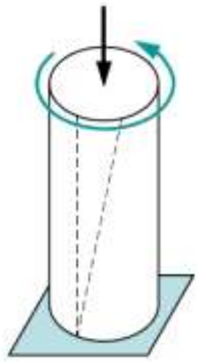


Figure 2: Required twist angle direction under axial compression load.

The design process will carried out by varying the orientation angles (α, β) of plies and comparing the resulted stresses with the maximum allowable stresses. In addition, the maximum twist angle will be calculated at each angle change and the direction of this angle will be checked. Due to the complexity and repeatability of the calculations, specific software (MATHCAD in this case) will be used to perform the calculations at each stage. All the following equations will be entered to MATHCAD in the same sequence and the results were compared.

3. Classical Laminate Theory

In order to reduce the complexity of composite material analysis, some theories were developed. One of these theories is called "classical laminate theory" which simplifies the three-dimensional problem into a two-dimensional one by making some assumptions. One of these assumptions is that used in beam theory; i.e.: the plane section assumption. Using these assumptions along with the assumption of plane stress state for every layer, the classical laminate theory can be derived. (Teng, et al., 2005)

The analysis of the tube was carried out by considering the tube to follow the classical laminate theory (the layup of the tube is α/β/α/β) because the composite tube is actually a laminated structure. Therefore, the tube can be cut to a flat plate and analyzed using classical laminate theory.

The classical laminate theory was applied by taking an infinitesimal element with a layup (α/β/α/β). Generalized stresses and strains will be calculated for this element i.e.: N_x, N_y, N_{xy}, ε_x^o, ε_y^o, γ_x^o

The values of the generalized stresses will be calculated from the loading conditions, and the generalized strains will be found using generalized stress-strain relationship.

The coordinate transformation matrix [T] was calculated using the following formulas for each combination of α and β:

$$T_\alpha = \begin{bmatrix} \cos(\alpha)^2 & \sin(\alpha)^2 & -2\cos(\alpha)\sin(\alpha) \\ \sin(\alpha)^2 & \cos(\alpha)^2 & 2\cos(\alpha)\sin(\alpha) \\ \cos(\alpha)\sin(\alpha) & -\cos(\alpha)\sin(\alpha) & (\cos(\alpha)^2 - \sin(\alpha)^2) \end{bmatrix} \quad (1)$$

$$T_\beta = \begin{bmatrix} \cos(\beta)^2 & \sin(\beta)^2 & -2\cos(\beta)\sin(\beta) \\ \sin(\beta)^2 & \cos(\beta)^2 & 2\cos(\beta)\sin(\beta) \\ \cos(\beta)\sin(\beta) & -\cos(\beta)\sin(\beta) & (\cos(\beta)^2 - \sin(\beta)^2) \end{bmatrix} \quad (2)$$

Then the stiffness matrix [Q] was found using:

$$Q = \begin{bmatrix} \frac{E_1}{1-(\nu_{12}\nu_{21})} & \frac{\nu_{12}E_2}{1-(\nu_{12}\nu_{21})} & 0 \\ \frac{\nu_{21}E_1}{1-(\nu_{12}\nu_{21})} & \frac{E_2}{1-(\nu_{12}\nu_{21})} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \quad (3)$$

And this stiffness matrix [Q] was converted using the following formulas for α and β and the transpose of the transformation matrices:

$$Q_\alpha = T_\alpha Q T_\alpha^T \text{and} Q_\beta = T_\beta Q T_\beta^T \quad (4, 5)$$

And calculating the extensional stiffness matrix [A]which depends on the material properties and the composite layup using the formula:

$$A = (2Q_\alpha * 0.25 * 10^{-3}) + (2Q_\beta * 0.25 * 10^{-3}) (6)$$

4. The First Loading Condition (Axial Compression)

In this case, an axial compressive load (P) with a magnitude of (25KN) will be applied to one end of the laminate and the other end will be considered to be fixed. This means that only the membrane force (N_x) will be considered and all the other components are zero (N_y= N_{xy}=0) i.e.:

$$N_x = \frac{P}{2\pi r} \quad (7)$$

Where ($2\pi r$) is the perimeter of the tube, P is the applied load and N_x is the resultant membrane force acting on the tube.

5. The Second Loading Condition (Internal Pressure)

In this case, the tube will be assumed to have close ends and an internal pressure (q) with a magnitude of (3MPa) will be applied to the inner surface of the tube. The generalized stresses in this case will comprise of two components (N_x, N_y) while (N_{xy}=0) because no shear force will act on the cross section of the tube under this loading condition. The generalized stresses will be calculated as follows: (Xia, et al., 2001)

$$N_x = \frac{1}{2} q.r \quad (8)$$

$$N_y = q.r \quad (9)$$

The bending deformation will be assumed to be very small (~0) therefore:

$$\{\kappa\}=0 \quad (10)$$

So that the generalized stresses will be calculated for each loading condition as follows:

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon^\circ \\ \kappa \end{Bmatrix} \quad (11)$$

$$\{N\}= [A]\{\varepsilon^\circ\} \quad (12)$$

The strains in the global coordinate system for each layer will be equal to the generalized strains because it has been assumed that no bending deformation exist (equation 10). Therefore:

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_x{}^o \\ \varepsilon_y{}^o \\ \gamma_{xy}{}^o \end{Bmatrix} + z \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_x{}^o \\ \varepsilon_y{}^o \\ \gamma_{xy}{}^o \end{Bmatrix} = \{\varepsilon^o\} \quad (13)$$

And the coordinate transformation matrix [T] will be applied to obtain the strain components in the material's principal axis:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = [T]^T\{\varepsilon^o\} = [T]^T \begin{Bmatrix} \varepsilon_x{}^o \\ \varepsilon_y{}^o \\ \gamma_{xy}{}^o \end{Bmatrix} \quad (14)$$

Then the stresses in the material's principal axis will be calculated as follows using the stiffness matrix [Q]:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_{12} \end{Bmatrix} = [Q] \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} \quad (15)$$

6. Application of Maximum Stress Failure Criterion:

Failure of the composites has been studied extensively and various theories and formulas have been developed to assess the likelihood of failure of the composite materials. Various scenarios can be identified for the failure of the composite structures because composites have different material properties in different directions. Most of the recently available methods for assessing the likelihood of the composite structure to fail are based on macroscopic behavior instead of microscopic failure of the composites.

One of earliest and most common failure criteria is called "Maximum Stress Failure Criterion" which relates the stresses in the material's principal axis and the stresses that will lead to failure. It has the following conditions:

$$\frac{\sigma_i}{\sigma_{it}^*} \leq 1 \text{if} \sigma_i \geq 0 \text{ or} \frac{|\sigma_i|}{\sigma_{ic}^*} \leq 1 \text{if} \sigma_i \leq 0 \text{i=1,2,3}$$

$$\frac{|\tau_i|}{\tau_i^*} \leq 1 \text{i=23, 13, 12} \quad (16)$$

If any of the above conditions is violated, the material will fail and the stress which will cause failure can be easily identified.

Although the accuracy of this failure criteria is not high, maximum stress failure criteria will be used in the analysis due to its simplicity and the ease in obtaining the possible failure mode. However, this failure criteria lacks the interaction between the shear and bending deformations.

7. Angle of Twist:

The angle of twist, ρ, will be calculated depending on the shear strain (shown in figure 2) using the following formula:

$$\rho = \frac{\gamma_{xy} * L}{r} \quad (17)$$

Where γ_{xy} is the shear component of the strain. L is the length of the tube.

In addition, the direction of the twist angle will depend on the sign of the resulted shear strain (γ_{xy}). In order to rotate the cylinder in the required direction as shown in figure 2, the sign of the resultant shear strain (γ_{xy}) should be (-). In other words,according to equation (17), the sign of the twist angle depends on the sign of the shear strain (γ_{xy}) and in order to get a (-) shear strain, the shear stress (τ)should be (-) because ($\tau = G\gamma$).

International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2015): 78.96 | Impact Factor (2015): 6.391

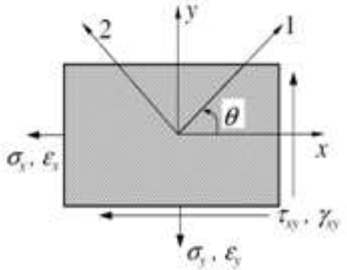


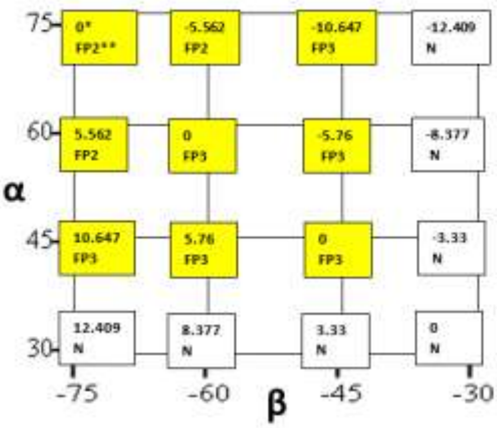
Figure 3: Schematic drawing of the stresses acting on a small element of a composite structure showing the direction of the twist angle (θ ≡ ρ).

In the following results, all combinations of the angles (α and β) will be tested and the results will be discussed.

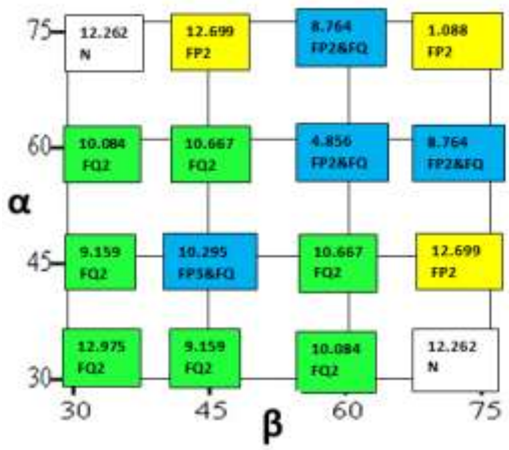
8. Results and Calculations

A MATHCAD code was developed in order to perform the calculations for the twist angle (ρ) as well as the maximum stress failure criteria at every change in the orientation angle of the plies (within the limit specified in the design specification for α&β). All the allowable combinations of the angles (α andβ) were tested against failure and presented in figures (4a to 4d).All the failure results are based on Maximum Stress Failure criteria.In addition, the twist angle for each orientation angle combination has been calculated based on the shear component of the resulted stresses in the lamina.

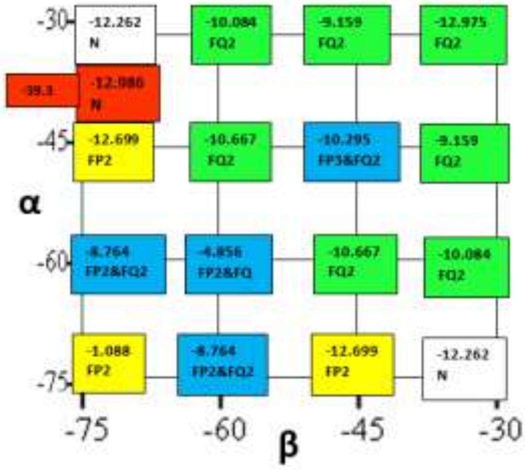
It can be noted from figure 4 that the tube will survive the applied loads (axial compression and internal pressure) without failure when either one of the orientation angles (α or β) is (+30^o) and the other angle is negative or when one of the orientation angles is (-30^o) and the other angle is positive. Furthermore, it is interesting to note that the tube will survive the applied loads with any combination of 30^o and 75^o (regardless of the sign). This will leave us with 18 combinations of orientation angles (white boxes in figure 4) and only 8 of them with a negative twist angle (which is the aim of the design procedure).



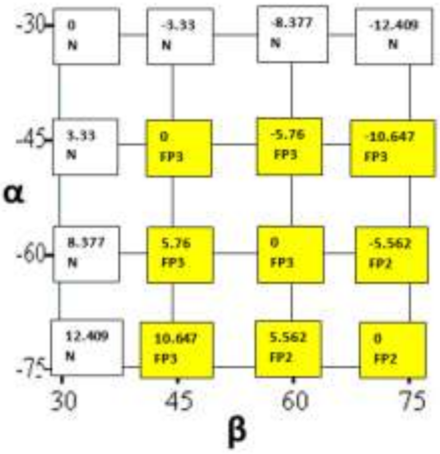
(a)



(b)



(c)



(d)

Figure 4: Results of all possible combinations of orientation angles (α andβ) showing the twist angle and the failure modes. (a) 30≤α≤75 vs. -30≤β≤-75. (b) 30≤α≤75 vs. 30≤β≤75. (c) -30≤α≤-75 vs. -30≤β≤-75. (d) -30≤α≤-75 vs. 30≤β≤75.

*The first raw of each small box refers to the value of the twist angle.

** The second raw of each small box refers to whether there is a failure or not. N: No failure; FP2: failure due to transverse stress under axial compression load; FP3: failure due to shear stress under axial compression load; FQ2: failure due to transverse stress under internal pressure load.

It is clear to see from figure 4 that the tube will never fail under internal pressure loading condition when the orientation angles have different signs. However, various failure scenarios occur when the orientation angles of the tube have the same sign. Thus, manufacturing composite tubes with laminas arranged in the same direction will produce more failure modes than having a different sign orientation angles.

Finally, it has been calculated (using the above mentioned procedure) that the only set of orientation angles for the plies that will survive the loading condition and produce a negative maximum twist angle is -75^o and -39.3^o which can produce a maximum twist angle of (-12.986^o) without failure.This combination of angles applies for both angles interchangeably.

The previous results are based on equation (16) and are listed in table (1). The results of table (1) indicate that there is an interaction between in-plane and shear stresses which results into a values of maximum stress failure parameters approaching 1.

Table 1: Maximum stress failure criterion results

Load	Lamina Angle	Maximum Stress Failure Criterion Parameters
Axial Compression	α	(0.413, 0.835, 0.596)
Axial Compression	β	(0.042, 0.901, 0.398)
Internal Pressure	α	(0.005933, 0.947, 0.172)
Internal Pressure	β	(0.034, 0.905, 0.22)

It is worth to note from the results (figure 4) that no failure is expected to occur in the laminate, under internal pressure loading condition, due to the shear stress component in the material's principle axis.

9. Design Choice According to Maximum Stress Failure Criteria

After performing the full analysis of the whole given range of the orientation angles, the design choice for the orientation angles is either (-75/-39.3/-75/-39.3) or (-39.3/-75/-39.3/-75). These arrangements of the orientation angles will give a maximum twist angle of (12.986^o) in the direction specified in figure 2 without failure.

Although the above calculated combination of orientation angles (-39.3,-75) gives the highest twist angle of (-12.986^o), the tube is vulnerable to fail transversally under both loading conditions because the values of the failure criteria are very close to 1 (table 1). Therefore, in the next sections, maximum stress failure criterion will be justified using another criterion (Tsai-Wu) numerically.

10. Finite Element Analysis of the Composite Tube Design

In this part of the research, the composite tube designed in the previous sections was tested by using finite element method based on advanced laminate theory to assess whether the design is successful or not.

Only the axial compression loading is considered in the following analysis. Using a special ABAQUS finite element analysis input template, the required winding angles (chosen according to the maximum stress failure criteria) were inserted to ABAQUS.

Both Maximum stress failure criterion and Tsai-Wu failure criterion were used when failure analysis was performed.

11. Tsai-Wu Failure Criterion

In 1971, Tsai and Wu presented a new failure criterion for analysing the failure of anisotropic materials. This theory took into account the bending stresses in the composites and is based on the following function (using force tensors):

$$F = F_{ij}\sigma_i\sigma_j + F_i\sigma_i i, j = 1,2,3,\ldots,6 \qquad (18)$$

Where σ stands for shear stress and F for force tensors. According to this failure criteria, any composite structure will fail when violating the following condition:

$$F \leq 1$$

After a series of simplifications, equation (18) becomes (for two-dimensional cases):

$$F = F_{11}\sigma_1^2 + 2F_{12}\sigma_1\sigma_2 + F_{22}\sigma_2^2 + F_{66}\tau_{12}^2 + F_1\sigma_1 + F_2\sigma_2 \qquad (19)$$

And the independent variables (F_{11},F_{12},F_{22},F_{66},F_1andF_2) can be found separately using the following formulas:

$$F_{11} = \frac{1}{\sigma_{1t}^{*}\sigma_{1c}^{*}} \quad F_{22} = \frac{1}{\sigma_{2t}^{*}\sigma_{2c}^{*}} \quad F_{66} = \frac{1}{(\tau_{12}^{*})^2}$$

$$F_1 = \frac{1}{\sigma_{1t}^{*}} - \frac{1}{\sigma_{1c}^{*}} \quad F_2 = \frac{1}{\sigma_{2t}^{*}} - \frac{1}{\sigma_{2c}^{*}}$$

$$F_{12} = \frac{1}{2(\sigma_{2t}^{*})^2}\left[1 - \sigma_{2t}^{*}\left(\frac{1}{\sigma_{1t}^{*}} - \frac{1}{\sigma_{1c}^{*}} + \frac{1}{\sigma_{2t}^{*}} - \frac{1}{\sigma_{2c}^{*}}\right) - (\sigma_{2t}^{*})^2\left(\frac{1}{\sigma_{1t}^{*}\sigma_{1c}^{*}} + \frac{1}{\sigma_{2t}^{*}\sigma_{2c}^{*}}\right)\right]$$

After finding the six independent variables using the above formulas, equation (19) can be applied and the results were compared to maximum stress failure criterion.

12. Comparison between Maximum Stress and Tsai-Wu Failure Criteria

As mentioned earlier, a special ABAQUS input file was generated and the selected winding angles (according to the maximum stress failure criterion) were applied. Both maximum stress and Tsai-Wu failure criteria were implemented numerically and were tested under an axial load of (25KN compressive force) and the results were compared.

Table (2) lists the comparison between these two failure criteria under a (25KN) compressive load.The results listed in table (2) showed no failure in all four layers according to the maximum stress failure criterion. However, the tube failed at the secondand the fourth layers (***β*** angle layers) when tested against Tsai-Wu failure criterion. This confirmed initial concerns at the analytical phase of high probability of failure due to stress interaction. Furthermore, the values of the Tsai-Wu failure criteria for the first and the third layers are close to that obtained by applying the maximum stress failure criterion for the same layers (~0.9). This indicates that the Tsai-Wu failure criterion gives more conservative results of the likelihood of material failurecompared with the maximum stress failure criteria.

Table 2: Comparison between maximum stress and Tsai-Wu failure criteria for every ply

Failure Criteria	*Layer Number*			
	Ply 1	Ply 2	Ply 3	Ply 4
Maximum stress failure criteria	0.9037	0.8334	0.9102	0.853
Tsai-Wu Failure criteria	0.9036	1.091	0.9035	1.064

The basic difference between the two failure criteria is that the Tsai-Wu failure criteria consider the interaction between the stresses acting on the lamina while the maximum stress failure criteria does not take this interaction into account. However, it is not possible to obtain the mode of failure based on the Tsai-Wu failure criterion as compared to the maximum stress criterion because it does not take into account the lack of homogeneity of the material.

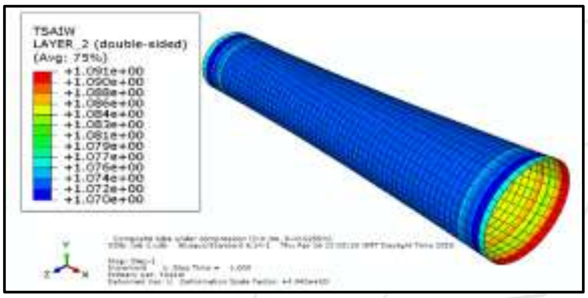


Figure 5: Numerical results of the Tsai-Wu failure criterion for the second layer of the composite material.

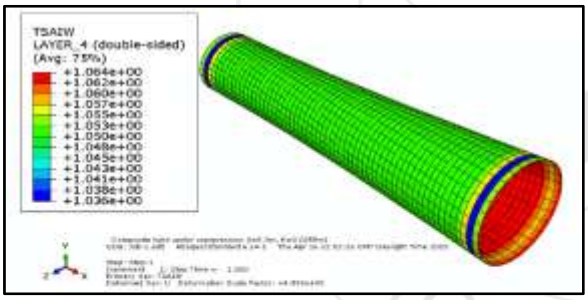


Figure 6: Numerical results of the Tsai-Wu failure criterion for the fourth layer of the composite material.

The results of the maximum stress failure criteria parameter (table 2)are close to each other. This gives an indication of an existence of an interaction between the in-plane and shear loading. This interaction may refer to a source of failure of the tube when applying another criterion to assess the tube failure which takes into account this interaction between the loads.

Figures (5) and (6) show the numerical results of theTsai-Wu failure criterion for the second and fourth layers respectively.

13. Tube Load Carrying Capacity

A Finite Element analysis was carried using ABAQUS to assess the load carrying capacity of a tube design. This analysis was performed to determine the maximum allowable compressive load that can be applied to the tube without failure (under maximum stress and Tsai Wu criteria). This was implemented by applying an initial axial compression load of 25KN with the selected winding angles (α= -75 and β= -39) from the initial theoretical composite tube design. Then performing an analysis using Maximum Stress Failure Criterion (MSTRS) and Tsai-Wu Failure Criterion (TSAIW).

Table 3: Effect of reducing the axial load on the maximum stress failure criterion results

Axial Compression Loading (N)	MSTRS Failure Assessment			
	Ply 1	Ply 2	Ply 3	Ply 4
25000	9.31E-01	8.33E-01	9.10E-01	8.53E-01
24000	8.68E-01	8.00E-01	8.74E-01	8.19E-01
23500	8.49E-01	7.83E-01	8.56E-01	8.02E-01
23400	8.46E-01	7.80E-01	8.52E-01	7.99E-01
23000	8.31E-01	7.67E-01	8.37E-01	7.85E-01
22900	8.28E-01	7.63E-01	8.34E-01	7.82E-01
22890	8.27E-01	7.63E-01	8.33E-01	7.81E-01
22500	8.133E-01	7.501E-01	8.192E-01	7.678E-01
22000	7.952E-01	7.334E-01	8.010E-01	7.508E-01
21500	7.771E-01	7.168E-01	7.828E-01	7.337E-01
21000	7.591E-01	7.001E-01	7.646E-01	7.166E-01
20800	7.52E-01	6.93E-01	7.57E-01	7.10E-01
20700	7.48E-01	6.90E-01	7.54E-01	7.06E-01
20620	7.45E-01	6.87E-01	7.51E-01	7.04E-01
20600	7.45E-01	6.87E+02	7.50E-01	7.03E-01

Tables (3) and (4) demonstrate the results obtained from each ply for the assessment of varying axial load. When the composite tube was tested with the initial axial load 25KN,it was found that for MSTRS all plies (layers) passed, although ply 1 and ply 3 demonstrated results above $9.0\text{x}10^{-1}$ which are very close to the failure point. However, when testing the tube for TSAIW under the same loading condition, ply 2 and ply 4 failed as highlighted in table 4. By decreasing the axial load to 23400N, ply 4 passed against both criteria but ply 2 still fails against TSAIW criterion. This required further decrease to the axial load and it was found that all plies passed at an axial load of 22900N.

Table 4: Effect of reducing the axial load on the Tsai-Wu failure criterion results

Axial Compression Loading (N)	TSAIW Failure Assessment			
	Ply 1	Ply 2	Ply 3	Ply 4
25000	9.04E-01	1.091	9.04E-01	1.064
24000	8.67E-01	1.048	8.67E-01	1.022
23500	8.49E-01	1.026	8.49E-01	1.001
23400	8.46E-01	1.02E+00	8.46E-01	9.96E-01
23000	8.31E-01	1.00E+00	8.31E-01	9.79E-01
22900	8.28E-01	1.00E+00	8.28E-01	9.75E-01
22890	8.27E-01	9.99E-01	8.27E-01	9.75E-01
22500	8.132E-01	9.822E-01	8.132E-01	9.580E-01
22000	7.952E-01	9.603E-01	7.951E-01	9.367E-01
21500	7.771E-01	9.385E-01	7.77E-01	9.154E-01
21000	7.590E-01	9.167E-01	7.590E-01	8.941E-01
20800	7.52E-01	9.08E-01	7.52E-01	8.86E-01
20700	7.48E-01	9.04E-01	7.48E-01	8.81E-01
20620	7.45E-01	9.00E-01	7.45E-01	8.78E-01
20600	7.45E-01	8.99E-01	7.45E-01	8.77E-01

14. Design Improvement

After being failed under Tsai-Wu criterion, the composite tube design could be enhanced to enable it to withstand more axial load. This can be achieved through the following recommendations. The first analysis was preformed to test the tube resistance by altering the arrangement of the plies of the composite tube as shown in table (5). A symmetrical arrangement recorded a decrease for both failure criteria whoever, the tube still fails against TSAIW.

Table 5: Results of Design Improvement after changing the layup

Layup under Axial Compression Loading (25KN)	MSTRS Failure Assessment	TSAIW Failure Assessment
[β / α / β / α]	0.9172	1.081
[β / α / α / β]	0.9022	1.084
[α / β / β / α]	0.9037	1.072

The second analysis was performed by increasing the number of plies by adding more layers of composite material. It was demonstrated from table (6) that the tube design passed with considerably low value for MSTRS and TSAIW criteria. This also includes a symmetrical layup which obtained the lowest value.

Table 6: Results of Design Improvement after adding more composite layers

Axial Compression Loading (N)	MSTRS Failure Assessment	TSAIW Failure Assessment
[β / α / β / α / β]	0.7202	0.8502
[α / β / α / β / α]	0.7243	0.8922
[β / α / α / α / β]	0.7302	0.9014
[α / β / β / β / α]	0.7102	0.8421

Further recommendations are suggested such as increasing the thickness of plies applied, changing the material to one that has better mechanical properties or using type of fibre with higher modulus (E).

15. Discussion and Conclusion

A composite tube was designed by varying the orientation angles of its plies. The tube has to withstand two loading conditions (axial compression and internal pressure) independently and without failure. In addition, the tube has to produce the maximum twist angle (in the specified direction) under axial compression loading condition only.

The only combination which satisfied the design conditions (axial compression and internal pressure loading) and give a maximum twist angle is found to be (-75^o, -39.3^o) with a twist angle of (12.986^o). This result give an indication that the maximum twist angle in one direction can be achieved by arranging the fibers in one direction (with respect to desired twist angle). Thus, if the design procedure is aiming at obtaining the maximum shear component, it should seek the same direction for the orientation angles of the plies.

It has been noted that the composite tube is more vulnerable to fail under axial compression load when the plies have different sign orientation angles (different directions), while the contribution of the internal pressure load starts to affect the tube failure when the tube has the same sign for the orientation angles (same direction). This is because the internal pressure tends to open the cylinder by the hoop and radial stresses, and since the reinforcement in the other direction acts as a band for the original fibers. Therefore, the absence of these reinforcements (in the case of the same direction for the orientation angle) will lead the tube to fail under internal pressure loading.

All combinations of orientation angles have been tested and checked against failure using maximum stress failure criterion. One of the biggest advantage of this criterion is its simplicity and the ease in identifying the possible failure mode. However, maximum stress failure criterion lacks the interaction between shear and bending effects which reduces its accuracy. This reduction in accuracy should be considered when dealing with composite structures. Therefore, the design procedure should not rely solely on the maximum stress failure criterion in the assessment of the likelihood of failure of composite structures.

Tsai-Wu failure criterion was implemented in this research to assess the tube failure. Although the tube showed no failure under maximum stress failure criterion, the tube failed under Tsai-Wu failure criterion. This is because stress interactions taken into account in the case of Tsai-Wu criterion. However, Tsai-Wu criterion lacks the identification of failure mode as well as material inhomogeneity.

Although the selected angles of orientation give the maximum twist angle of 12.986^o, the tube is very close to fail transversely under axial compression load because the value ($\frac{|\sigma_2|}{\sigma_2^*}$) is very close to 1 (about 0.9). This means that more material should be put in this direction to overcome this possible failure scenario as shown in design improvement procedure. However, this change in the number of plies will alter therequired twist angle (12.262^o in this case). Other recommendations were proposed such as changing the material properties.

References

[1] Hoppel, C. P. & De Teresa, S. J., 1999. Effect of an Angle-Ply Orientation on Compression Strength of Composite Laminates. Army Research Laboratory, Volume TR-2003.

[2] Khandan, R. et al., 2010. Optimum Design of Fibre Orientation Angles in Composite Laminate Plates for Minimum Thickness. Proceedings of the ASME 2010 International Mechanical Engineering Congress & Exposition, Volume 40424, pp. 1-8.

[3] Parnas, L. & Katirici, N., 2002. Design of fiber-reinforced composite pressure vessels under various loading conditions.. Composite structures, Volume 58, pp. 83-95.

[4] Reddy, P. K., Nagaraju, C. & Krishna, T. H., 2012. Optimum Design And Analysis Of Filament Wound Composite Tubes In Pure And Combined Loading. International Journal of Engineering Research & Technology (IJERT), 1(8).

[5] Soden, P. D., Kitching, R., Tse, P. C. & Tsavalas, Y., 1993. Influence Of Winding Angle On The Stregth And Deformation Of Filament-Wound Composite Tubes Subjected To Uniaxial And Biaxial Loads. Composites Science and Technology, Volume 46, pp. 363-378.
[6] Teng, T. L., Yu, C. M. & Wu, Y. Y., 2005. OPTIMAL DESIGN OF FILAMENT-WOUND COMPOSITE PRESSURE VESSELS. Mechanics of Composite Materials, 41(4), pp. 333-340.
[7] Tsai, S. W. & Wu, E. M., 1971. A General Theory of Strength for Anisotropic Materials. J. Composite Materials, Volume 5, p. 58.
[8] Xia, M., Takayanagi, H. & Kemmochi, K., 2001. Analysis of multi-layered filament-wound composite pipe under internal pressure. Composite structures, Volume 53, pp. 483-491.