International Journal of Advance Research in Engineering, Science & Technology(IJAREST),
ISSN(O):2393-9877, ISSN(P): 2394-2444,
Volume 2, Issue 5, May-2015

Virtual Reality Testing of a Laminated Composite Tube

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Abstract

The cylindrical tube having 4 layers of composites with a layup of optimum angles (i.e. α &β) is to be analysed in abaqus as per the design for virtual reality testing. It is designed in such a way that it can the loading condition i.e. 1) an axial compression of 25 KN & also have maximum angle of twist. The theory of laminate is employed in the design of the composite cylindrical tube to analyse the stress & strains of the laminate in material principle direction & in laminate direction (structure direction). The maximum failure criteria are used for safe design of the tube. The selection of winding angles play vital role in the design as it influences the mechanical performance of the component. Numerical and analytical model of the composite tube are prepared. Numerical model of the composite tube are prepared in Abaqus (FE analysis) software and compare with the analytical model. During the design the Mathcad software is used to perform the mathematical calculation. We have used maximum stress failure criterion for the safe design of the tube and Tsai-Wu Criterion is used for more accurate testing.[1]

Keywords *— FE analysis, Abaqus, Laminated composite tube, Tsai-Wu criteria, maximum stress failure criteria, composite design, Numerical model, analytical model*

I. INTRODUCTION

A cylindrical composite tube having 4 layers is made from the UD prepreg sheet material by winding the tapes on to a 50 mm diameter mandrel. The 4 layers of the composites having layup angles α/β/α/β are to be designed to meet the design requirements. The range of the winding angles is to be fallen between ±45° & ± 75° to the axis of the tube considering the practicality i.e.$-75^0 \leq \alpha \leq -45^0$ or $+45^0 \leq \alpha \leq +75^0$ and $-75^0 \leq \beta \leq -45^0$ or $+45^0 \leq \beta \leq +75^0$. The tape widths are dictated by the winding angle α & β so the tape wounded on the mandrel should not leave any gape & should not be overlapped. The thickness of each prepreg is 0.25mm & length of the mandrel is 300mm. The composite tube is to be designed in such a way that it can withstand the internal pressure of 3 MPa & axial compression of 25 KN considering the maximum twist of angle requirement before any mechanism of the failure. The theory of laminate is employed in the design of the composite cylindrical tube to analyse the stress & strains of the laminate in material principle direction & in laminate direction (structure direction). The maximum failure criteria are used for safe design of the tube. The selection of winding angles play vital role in the design as it influences the mechanical performance of the component. Maximum stress failure criterion was used for the safe design of the tube and Tsai-Wu Criterion is used for more accurate testing. Using ABAQUS finite element analysis input templates, the value of winding angles α = -75° and β = -45° is inserted as obtained from the design. The results were obtained from the analysis and assessment of the design is done.[1],[2]

The following design parameters are used.

1.1 Dimensions

L=Length of the tube =	300 mm
D=Diameter of the mandrel=	50 mm
t=Thickness of the prepreg=	0.25 mm
Range of winding angles(α)=	$-75^0 \leq \alpha \leq -45^0$ or $+45^0 \leq \alpha \leq +75^0$
Range of winding angles(β)=	$-75^0 \leq \beta \leq -45^0$ or $+45^0 \leq \beta \leq +75^0$

1.2 Material Properties

(Carbon-epoxy prepreg to be used is from SP (SE 84LV/HSC/300g/400mm/37%/1 blue)

E_1= Longitudinal Young's Modulus=	236 GPa
E_2= Transverse Young's Modulus=	5 GPa
G_{12}= Longitudinal Shear modulus=	2.6 GPa
υ_{12}= Longitudinal Poison ratio=	0.25
σ^*_{1t}=Longitudinal tensile strength=	3800 MPa
σ^*_{2t}=Transverse tensile strength=	41 MPa
σ^*_{1c}=Longitudinal compressive strength=	689 MPa
σ^*_{2c}= Transverse compressive strength=	117 MPa
τ^*_{12}= Longitudinal shear strength=	69 Pa

1.3 Loading Condition:

1) q= Internal Pressure=	3 MPa
2) P= Axial compressive load=	25 KN

Note: In Abaqus analysis, the internal pressure is not considered for result comparison. Only axial compression is considered & the Abaqus result is compared with the result obtained theoretically.

II . ANALYTICAL MODEL

Output of Composite Tube design as per theory:

The design of the composite tube is carried out using the maximum stress failure criteria as mentioned below.

Maximum Stress criteria:

The failure function F: F=1

$W1 = \sigma_1 / \sigma^*_{1t} \leq 1$ if $\sigma_1 \geq 0$ or $W1 = \sigma_1 / \sigma^*_{1c} \leq 1$ if $\sigma_1 < 0$

$W2 = \sigma_2 / \sigma^*_{2t} \leq 1$ if $\sigma_2 \geq 0$ or $W2 = \sigma_2 / \sigma^*_{2c} \leq 1$ if $\sigma_2 < 0$

$W12 = \tau_{12} / \tau^*_{12} \leq 1$ F= Max {|W1|}, |W2|, |W12|}

Where,

σ^*_{1t}=Allowable Longitudinal tensile strength

σ^*_{2t}= Allowable Transverse tensile strength

σ^*_{1c}= Allowable Longitudinal compressive strength

σ^*_{2c}= Allowable Transverse compressive strength

τ^*_{12}= Allowable Longitudinal shear strength

If any one of the conditions violate, then design is not safe & choose the optimum the winding angles for safe design.

The output of the composite tube is listed below in tabular form for combination of α= -45 deg & β= -75 deg for maximum twist angle 13.212.

Table-1: Theoretical Results of Maximum Stress Failure Criteria for ply 1&2

Lamina No	Winding angle α	Winding angle β	Angle of twist ρ	Maximum stress failure criteria for load case-1(axial compression)		
				W1	W2	W12
1	-45		13.212	0.424	0.883	0.596
2		-75		0.049	0.948	0.329

III . NUMERICAL MODEL

3.1 PROCESS OF ABAQUS OUTPUT

Design Requirement

Results for Maximum Stress Failure Criteria (MSTRS) from Abaqus

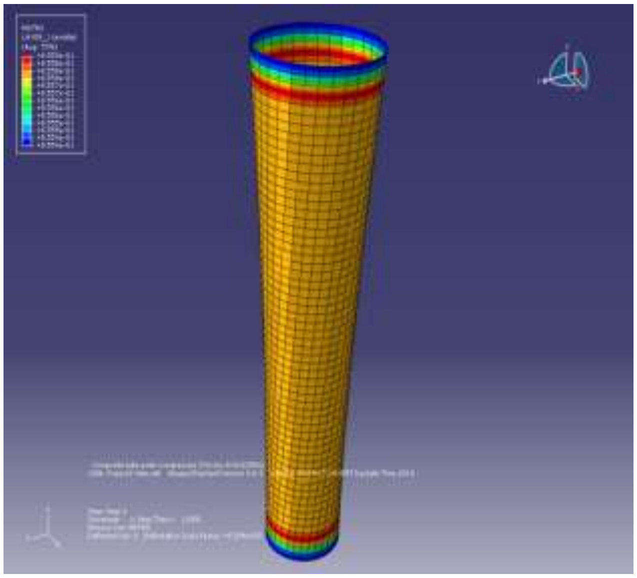

Figure-1: MSTRS-Layer-1

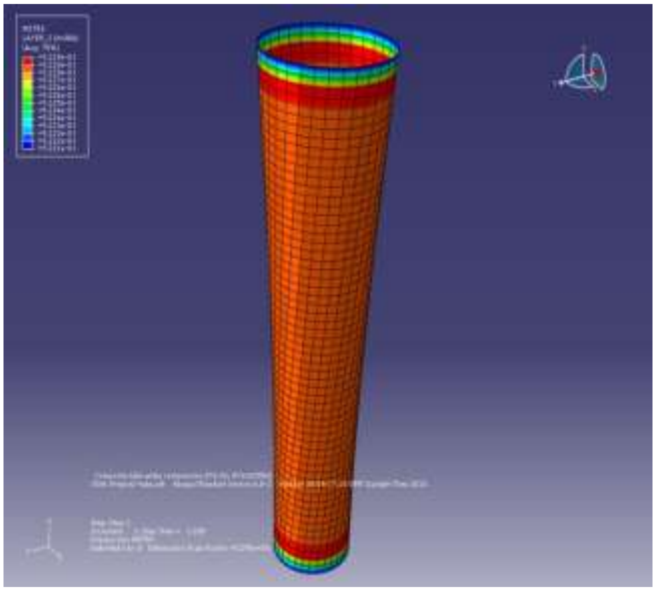

Figure-2: MSTRS-Layer-2

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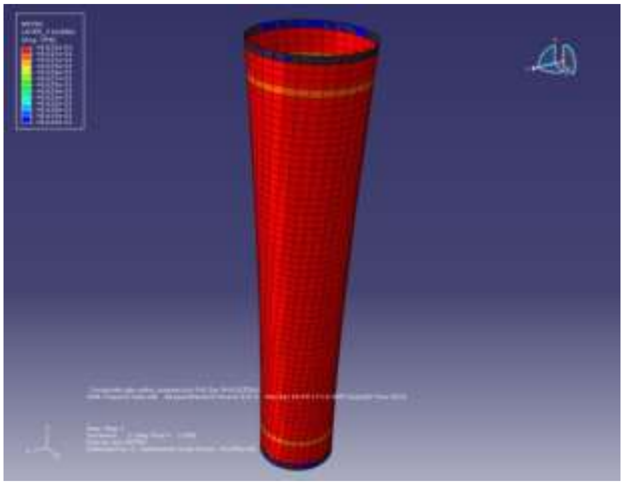

Figure-3: MSTRS-Layer-3

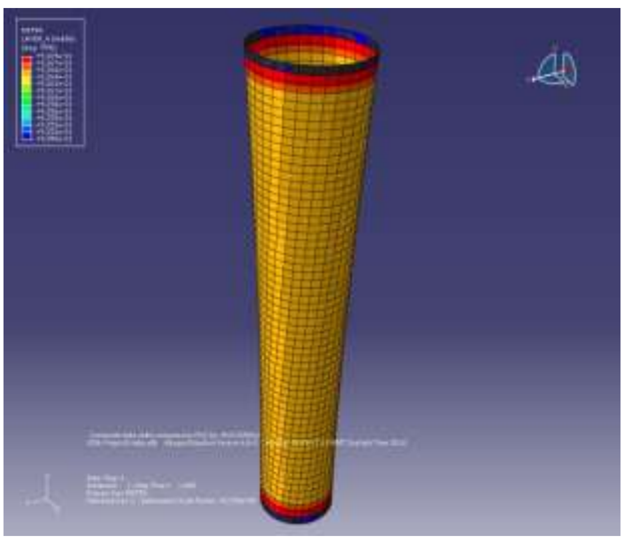

Figure-4: MSTRS-Layer-4

Table-2: Abaqus Results of Maximum Stress Failure Criteria for ply 1, 2, 3 & 4

Lamina No	**Winding angle α**	**Winding angle β**	**Angle of twist ρ**	**Maximum stress failure criteria for load case-1(axial compression)**	
				W_{max}	W_{min}
1	-45		12.7311	0.8559	0.8554
2		-75		0.9229	0.9221
3	-45			0.8633	0.8618
4		-75		0.9269	0.9250

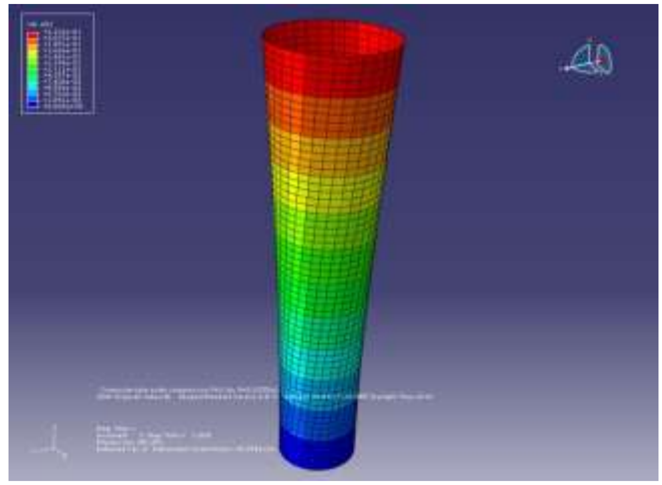

Figure-5: Angle of rotation of composite tube

3.1.1 Observation of Abaqus result & theoretical result for maximum stress criteria:

- The result for ratio of maximum stress criteria obtained from Abaqus as shown in Figure-1 to 4 & angle of rotation shown in Figure-5 is tabulated in the table-2 for better understanding.
- In the view of the table-1 for theoretical value of ratio for maximum stress criteria for composite tube and table-2 for Abaqus value, it is noted that the value of ratio for maximum stress failure criteria obtained from Abaqus result is less as compare with theoretical value. This shows that the stress values for each layer in material direction is estimated higher as per the theory which is less as obtained by numerical simulation i.e. Abaqus.
- The rotation angle (angle of twist) obtained from Abaqus result is **12.7311** deg which is less than the theoretical value i.e. **13.212** deg. By observing the Figure-5, it is noted that the angle of twist is 0 at bottom & gradually increased when passes away from bottom & becomes maximum at top of the tube.
- By observing the Figure-1, 2, 3& 4 and table-2, it is noted that the value obtained by maximum stress failure criteria in Abaqus for layer 1&3(-45 deg) is differed by a small amount which must be identical as per maximum stress failure criteria. The same is applicable for layers 2 & 4(-75 deg). As per maximum stress failure criteria theory, it is assumed that the stress values for layer 1 & 3(-45 deg) & layer 2 & 4(-75 deg) are same & due to this reason the stress calculation is carried out only for one layer of winding angle i.e. one for -45 deg & one for -75 deg. However as per the Abaqus results, it is shown that the stress distribution for layer

1 & 3 is moreover same with minor difference & similarly applicable to layer 2 & 4.

➢ The reason behind the accurate result obtained by Abaqus is that numerical simulation is used in Abaqus which approximates the result at each node of the object which is not possible theoretically as we calculated. This would be the reason for getting lower stress in Abaqus i.e. accurate result.

➢ By observing the above results, it is noted that the maximum stress occurred in layer 2 & 4(-75 deg) due to the winding angle i.e. 0.9269 as per the maximum stress criteria which is less than unity. Hence design is safe. However this design is checked in other criteria (Tsai Wu failure criteria) in order to check the accuracy of the different failure criteria. This is explained in the assessment of the design.

3.2 Assessment of the design

Results for Tsai Wu Failure criteria from Abaqus

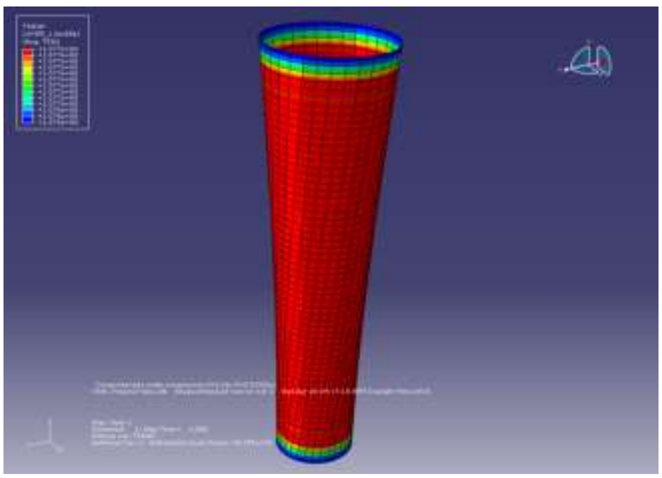

Figure-6: Tsai Wu-Layer-1

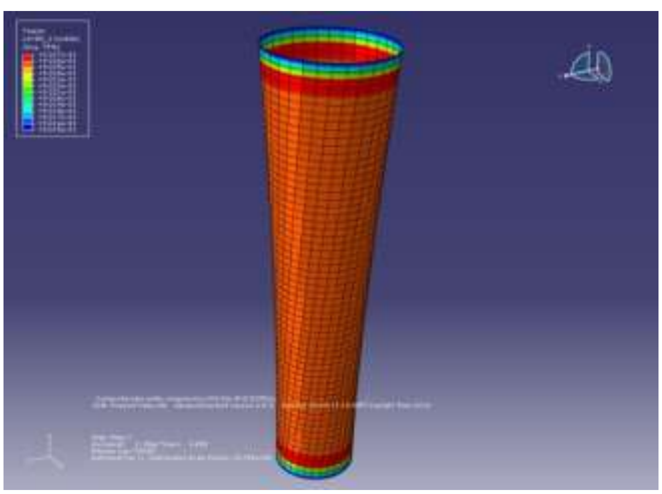

Figure-7: Tsai Wu-Layer-2

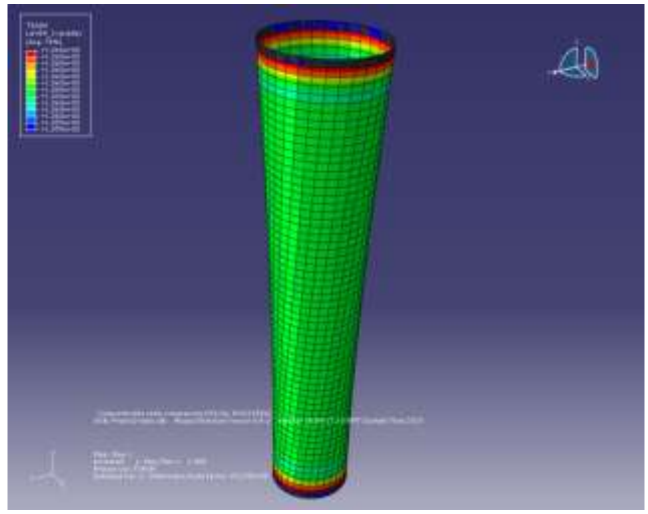

Figure-8: Tsai Wu-Layer-3

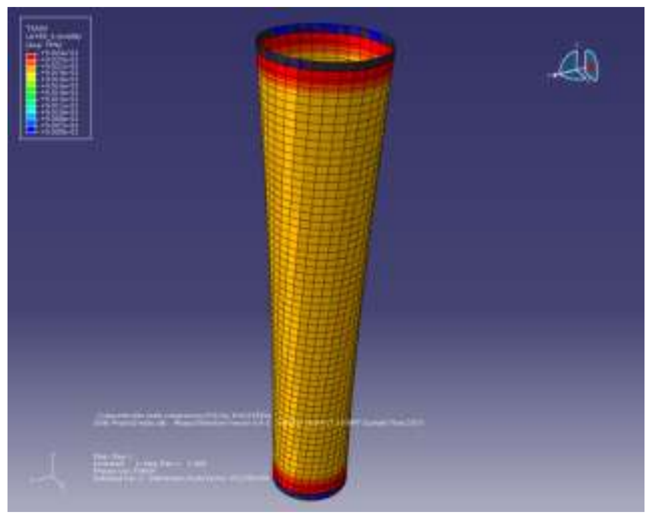

Figure-9: Tsai Wu-Layer-4

Table-3: Abaqus Results of Tsai Wu Failure Criteria for ply 1, 2, 3 & 4

Lamina No	**Winding angle α**	**Winding angle β**	**Angle of twist ρ**	**Maximum stress failure criteria for load case-1(axial compression)**	
				W_{max}	W_{min}
1	-45		12.7311	**1.077**	1.076
2		-75		0.9027	0.9015
3	-45			**1.060**	1.059
4		-75		0.9024	0.9005

3.2.1 Observation on the results of Tsai Wu obtained from Abaqus for composite tube:

- By referring the Figure 6,7,8 & 9 and table-3, it is observed that the composite tube gets failed in layer 1 & 3 i.e. layers of -45 deg for the same compression loading condition of 25 KN but it is safe in layer 2 & 4 i.e. -75 deg. This represents that the maximum stress failure criteria is not so accurate with respect to Tsai Wu failure criteria.
- The design of the composite tube having 4 layers based on the maximum stress failure criteria is not reliable as it may get fail if it is analysed in Tsai Wu failure criteria.
- The drawback of the Tsai Wu failure criteria does not disclose the kind of failure mode which is more important for any composite tube failure analysis.
- The maximum stress criterion is not conservative for stress states that are not dominated by one component of stress and thus does not predict any failure in such cases. Still there are interaction effects which produce failure when two or more stress components are close to their limits. Tsai Wu criterion uses a simple quadratic equation and it accounts for different behaviour in tension and compression. Maximum stress theory gives the information about the mode of failure.
- The mathematical expression of the Tsai-Wu failure criteria is explained below.

$F= F_{ij}\sigma_i\sigma_j+F_i\sigma_i$

Where i,j= 1,2,..,6

For safe design $F\leq 1$

Here F_{ij} is the interaction coefficient which is not considered in the maximum stress failure criteria & it is responsible accuracy.

The Tsai-Wu theory measures the interaction coefficient between the layers which is an additional advantage compared to Maximum Stress Theory & this is the reason for accurate results we obtained in the Tsia-Wu.

Hence the Tsai-Wu failure criterion is more accurate than the maximum stress failure criteria. [3]

- This shows that the improvement is required in our design for safe design as per Tsai-Wu criteria & this improvement can be done by providing the other ply to strengthen the laminate to reduce the stress in layer 1 & 3.

3.3 Suggested Improvement in the Design:

- In Tsai-Wu criteria lamina 1& 3 are failing. We have designed tube by doing orientation [α/β/ α/ β] of four plies as α= -45& β= -75 it was observed that laminates are symmetry but not balanced so to balance, it is orientated by following value of α= -45& β= 75 & this gives the laminate in symmetry After doing analysis in abaqus it was observed that the failure criteria are satisfied but the maximum angle of twist is affected and reduced drastically. Hence this approach cannot be considered for the same loading condition.
- From the above proposed design we were able to make design safe but the maximum angle of twist criteria is not satisfied so another approach is considered to make safe design & this can be carried out by increasing the number of lamina. The current design shows the 4 lamina used to achieve the objectives & this can be improved by increasing the lamina. We have increased the lamina from 4 to 5 to visualise the effects on the design & found that the stresses are within the permissible range but found the laminate is not balanced & symmetry which is not good practice for sound design of the composite tube. In order to have symmetry design, the 6 laminas can be used which can give the stresses within limit with maximum angle of twist with little change satisfying the design requirements.
- Another approach is to increase the thickness of the lamina 1st and 3rd of 0.35 mm and after the analysis it was observed that Tsai-wu criteria is satisfied and maximum angle of twist is not reduce much.

3.4 More realistic assessment of the load carrying capacity:

The design of the composite tube does not seem more realistic as the design of the tube laminate gets failed in lamina 1 & 3 as per Tsai Wu failure criteria as the value is exceeding 1 i.e. 1.077. The more realistic assessment for load carrying capacity of the composite can be calculated as below.

The realistic load carrying capacity of the composite tube:
For 25 KN the value for Tsai Wu is 1.077, so for 1 KN the value of Tsai Wu is as below.

$1 \text{ KN} = \frac{1.077}{25} = 0.4308.$

So the realistic load carrying capacity of the composite tube is 23.2 KN. which will give the value of Tsai Wu is 0.999456 < 1.

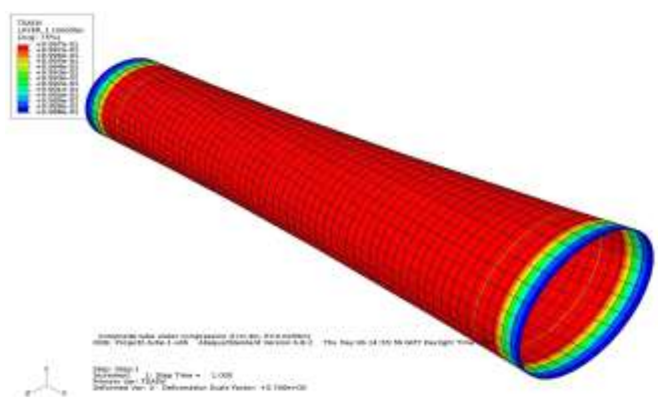

Figure-10: Tsai Wu-Layer-1(realistic load)

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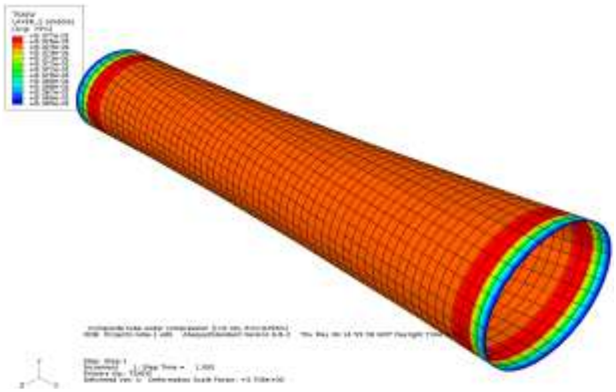

Figure-11: Tsai Wu-Layer-2(realistic load)

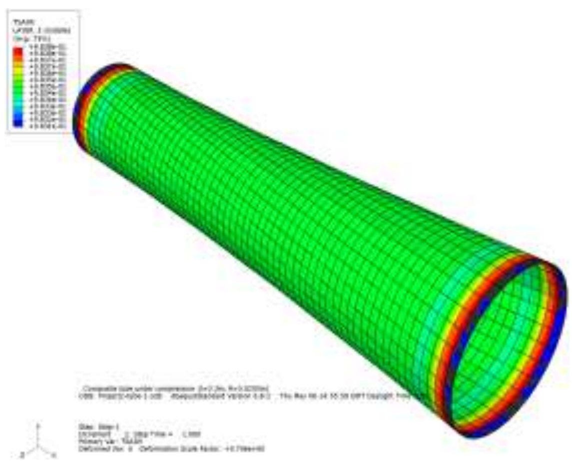

Figure-12: Tsai Wu-Layer-3(realistic load)

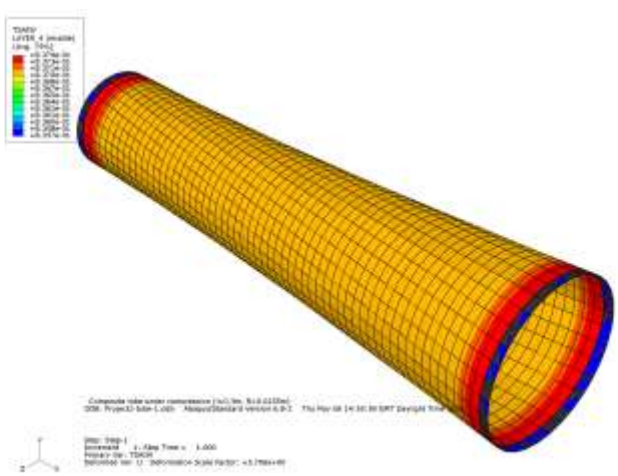

Figure-13: Tsai Wu-Layer-4(realistic load)

- By observing the figure-10, 11, 12 & 13, it is seen that the obtained stress value as per Tsai Wu failure criteria considering the realistic load is less than unity for each layer.
- ***Hence the realistic load carrying capacity of the composite tube is 23.2 KN & this gives safe result for maximum stress failure criteria & Tsai-Wu criteria.***

IV CONCLUSION :

- The maximum stress failure criterion is less accurate than the Tsai-Wu criteria due to the interaction coefficient (F_{ij}).
- The stress distribution on each layer depend the winding angle of each layer.
- The composite design carried out in this paper is symmetry but not balanced. For sound design of the composite tube, it is mandatory to have the balanced & symmetry. But in order to achieve the objective of maximum angle of twist, we have to compromise with our design i.e. design is symmetry but not balanced which is responsible for higher stress.
- The Tsai-Wu criteria shows that the existing design fails as per this criteria & but shows safe as per the maximum stress criteria. This represents that there is a scope to improve the existing design. The existing design can be improved by adding the other layers to minimise the stress & this affects little change in angle of twist which is closer to the value of angle of twist of previous design 7 meeting the design requirements.
- The Abaqus results represent the accurate result due to the numerical simulation which is more realistic than the theoretical results.

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