Material Modelling and Failure Study of Different Fiber Reinforced Composites for Pressure Vessel

Modelado de Materiales y Estudio de Fallas de Diferentes Compuestos Reforzados con Fibra para Recipientes a Presión

Modelagem de Materiais e Estudo de Falha de Diferentes Compósitos Reforçados com Fibras para Vasos de Pressão

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Summary. - Pressure vessels are essential industrial tools regarding storage of high-pressure fluids. Utilization of pressure vessels in ordinary industrial environment impose serious dangers to human life in case of failure. Manufacturing material and working pressure as per material's strength are necessary arguments for a pressure vessel designer. In this study, five composite materials are selected to investigate the behavior of pressure vessels under high pressure. FEA technique is used to check stresses and deformations in different composite layers. Pressure applied to all materials models in this study is around 20 MPa. Tsai Wu and Maximum stress theories are used to study failure in first two composite layers of different composite materials. Glass Epoxy composites perform well in terms of static loading failure. They demonstrate reasonable strength without experiencing failure in the second layer. T300/976 composites are also suitable for the intended loading conditions of the model because did not exhibit second layer failure, making them a viable option. Therefore, it is recommended to use Glass/Epoxy and T300/976 composites in extreme pressure conditions such as those found in CNG cylinders. Three of the composite materials tested did not satisfy the failure theories. Hence, it is not safe to use them in extreme loading conditions. Although these materials did not show any failure in the first layer, deformations in the second layer made them susceptible to failure.

Keywords: Pressure Vessels; Reinforced Composites; Fiber Composites; Modelling.

Resumen. - *Los recipientes a presión son herramientas industriales esenciales para el almacenamiento de fluidos a alta presión. La utilización de recipientes a presión en el entorno industrial ordinario impone serios peligros para la vida humana en caso de falla. El material de fabricación y la presión de trabajo según la resistencia del material son argumentos necesarios*

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para un diseñador de recipientes a presión. En este estudio, se seleccionan cinco materiales compuestos para investigar el comportamiento de los recipientes a presión bajo alta presión. La técnica FEA se utiliza para comprobar tensiones y deformaciones en diferentes capas compuestas. La presión aplicada a todos los modelos de materiales en este estudio es de alrededor de 20 MPa. Las teorías de Tsai Wu y la tensión máxima se utilizan para estudiar la falla en las dos primeras capas compuestas de diferentes materiales compuestos. Los compuestos de epoxi de vidrio funcionan bien en términos de falla de carga estática. Demuestran una fuerza razonable sin experimentar fallas en la segunda capa. Los compuestos T300/976 también son adecuados para las condiciones de carga previstas del modelo porque no presentaron fallas en la segunda capa, lo que los convierte en una opción viable. Por lo tanto, se recomienda utilizar compuestos de vidrio/epoxi y T300/976 en condiciones de presión extrema, como las que se encuentran en los cilindros de GNC. Tres de los materiales compuestos probados no cumplieron con las teorías de falla. Por lo tanto, no es seguro usarlos en condiciones de carga extremas. Si bien estos materiales no presentaron falla alguna en la primera capa, las deformaciones en la segunda capa los hicieron susceptibles a la falla.

Palabras clave: *Recipientes a presión; Compuestos Reforzados; Compuestos de Fibra; Modelado*

Resumo. *- Vasos de pressão são ferramentas industriais essenciais para o armazenamento de fluidos sob alta pressão. A utilização de vasos de pressão em ambiente industrial comum impõe sérios perigos à vida humana em caso de falha. O material de fabricação e a pressão de trabalho de acordo com a resistência do material são argumentos necessários para um projetista de vasos de pressão. Neste estudo, cinco materiais compósitos são selecionados para investigar o comportamento de vasos de pressão sob alta pressão. A técnica FEA é usada para verificar tensões e deformações em diferentes camadas compostas. A pressão aplicada a todos os modelos de materiais neste estudo é de cerca de 20 MPa. As teorias de Tsai Wu e tensão máxima são usadas para estudar a falha nas duas primeiras camadas compostas de diferentes materiais compostos. Os compósitos de vidro epóxi têm bom desempenho em termos de falha de carga estática. Eles demonstram resistência razoável sem sofrer falha na segunda camada. Os compósitos T300/976 também são adequados para as condições de carregamento pretendidas do modelo, pois não apresentaram falha na segunda camada, tornando-os uma opção viável. Portanto, recomenda-se a utilização dos compósitos Vidro/Epóxi e T300/976 em condições extremas de pressão como as encontradas em cilindros de GNV. Três dos materiais compósitos testados não satisfizeram as teorias de falha. Portanto, não é seguro usá-los em condições extremas de carregamento. Embora esses materiais não apresentassem nenhuma falha na primeira camada, as deformações na segunda camada os tornavam suscetíveis à falha.*

Palavras-chave: *Vasos de Pressão; Compósitos Reforçados; Compósitos de Fibra; Modelagem*

1. Introduction. - Failure of pressure vessel is very deleterious because failure results in catastrophic bursting of vessel. Safety of pressure vessel is a chief concern due its utilization in different sectors either commercial or domestic. Mostly fracture occurred due material failure. Determination of performance of material under loading conditions is at primacy while designing load bearing equipment's. It is very understood that no material superseded the accident or failure, but selection of material is essential for durability of component, good materials increase life span of component. Metals are showing excellent mechanical properties, but greater density is a hinderance to use them in certain applications. Combination of distinguished properties are evidenced in composite structures due jumble of two different category materials. Utilization of composite materials are very enormous under extreme loading conditions, extensive pressure bearing bodies like fuel tanks etc. The current world is now shifting to composite due its low density to strength ratio, high abrasion, and corrosion resistance in toxic environments. The aerospace studies revealed the application of composite in fuel tanks of space launch vehicles which highly advantageous due low weight. Transport and other commercial sectors are migrating towards composite based vessels. composite material CNG cylinders are easily available in local market. [1]

Afthab Afrathim et al [2] investigated failure of first ply for thin composite pressure vessel. Basalt fiber composite was used to study the burst pressure of pressure vessel first ply. Ansys software was used for simulations and Tsai Wu criteria was used to predict the failure. It was suggested that basalt fiber in comparison with E-glass/Epoxy shown eminent behave under burst pressure of first ply failure. E.S. Barboza et al [3] studied the failure criteria of vessel liner LLDPE and HDPE material, Finite Element Modelling was adapted to reveal the material behave under loading. Burst pressure could be retained in pressure vessel of thickness 15mm. J.P.Xu et al. and J.C Choi et al. [4,14] performed different approaches to attain best suited results under excessive pressure in tanks. Carbon fibers embedded in Epoxy was tested under burst loading in hydrogen gas cylinders. Results disclosed that Tsai-Wu criteria was predicting most precise failure pressure. Gaurav Singh et al [5] studied impacts of Kevlar with HDPE liner in pressure vessel. Ansys software results shown that 35° layers orientation was appropriate due to minimal deformations.
Shah Alam et al [6] conducted study on low-speed impact in pressure vessel. Study mainly focused on residual burst strength and dynamic response of Type IV overwrapped vessel. Results disclosed that Hashin Fiber tension failure were greater in inner layer but less than 1.

Marino Quaresimin et al [7] discussed low velocity impact on laminates of composite material. Author affirmed about matrix control over commencement of failure and minimal value of load for Delamination. Both parameters were not reliant on lay-up sequence however depended on laminate thickness. Absorption ability was influenced by both stacking sequence and laminate thickness. D.J.Chang & O S Sachin et al. [8,15] investigated failure modes of graphite Epoxy vessel pressurized internally. Cut introduced intentionally to study the effects of leakage, burst and fracture. Results shown that burst pressure and impact load were inversely proportional. S.Takalkar et al [9] studied winding angles and shown that winding angles achieved good results after altering the material regarding deformation of fibers under pressure, generation of stress and stress raiser areas and failure of material. Selected material was carbon T300/epoxy evaluated in workbench and results compared by laminate theory.

Caprino et al. & C Red [10,16] studied the effect of threshold energy with respect to delamination. Author discussed energy storage at first failure and represented elastic model most accurate. V.V Vasiliev et al [11,17] performed fiber reinforcing in one direction to attain minimal weight of vessel. Comparison of two techniques of winding was performed, author shown that geodesic winding was intricate than circumferential winding. M.Z.Kabir [12] investigated the effect of stress distribution over head of pressure vessel. optimization between different shapes were performed for uniform stress distribution. Different shapes of mandrel were suggested to perform optimization of shapes of dome profile. Different researchers [13-19] used Vinylester as a matrix with carbon fibers utilized for pressure vessel. Different winding angle was studied to investigate the suitable properties, loading conditions were severe like pressure applied to bursting limits for checking the performance behavior of new material. Study evidenced carbon/vinylester composite showing good results regarding to ultimate pressure in comparison with simple epoxy as matrix.

The evaluation of cylinders with various composite materials and the prevention of failure in different layers are of paramount importance due to their direct impact on society. To ensure public safety, extensive research has been conducted on different composite materials under extreme loading conditions, specifically focusing on burst pressures in compressed natural gas (CNG) cylinders. By assessing various failure criteria, this research aimed to investigate the layer failure of different composite materials subjected to the same static loading conditions.

A theoretical approach was adopted to establish limits for the safe working of different composite materials used in CNG cylinders, ultimately prioritizing public safety. This research primarily relied on stress analysis techniques and failure theories specific to composite materials. By employing these analytical tools, researchers sought to identify the most suitable material with the desired properties necessary for the construction of CNG cylinders.

2. Failure Theories. – The condition of failure criteria [14] described failure in each layer of composite laminate, governing equations are,

$$F_i \sigma_i + F_{ii} \sigma_i \sigma_j \geq 1$$

$$F_2 = F_3 = F_4 = F_5 = F_6 = 0 \; F_{22} = F_{33} \;\; F_{55} = F_{66} \;\; F_{12} = F_{13}$$

Tsai Wu failure criteria can be written as

$$F_1 \sigma_1 + F_2(\sigma_2 + \sigma_3) + F_{11} {\sigma_1}^2 + F_{22}({\sigma_2}^2 + {\sigma_3}^2) + 2F_{12}(\sigma_1 \sigma_2 + \sigma_1 \sigma_3) + 2F_{23} \sigma_2 \sigma_3 +$$
$$+ F_{44} {\sigma_{23}}^2 + F_{55}({\sigma_{12}}^2 + {\sigma_{13}}^2) \geq 1$$

Where σ_i is stress and F_{ii} are the strength coefficients and E, G and v are the elastic constants.

$$F_{11} = \frac{1}{X_t X_c}$$

$$F_{22} = \frac{1}{Y_t Y_c}$$

$$F_{44} = \frac{1}{{S_{23}}^2}$$

$$F_{55} = \frac{1}{{S_{12}}^2}$$

$$F_1 = \frac{1}{X_t} - \frac{1}{X_c}$$

$$F_2 = \frac{1}{Y_t} - \frac{1}{Y_c}$$

$$F_{12} = -\frac{1}{2}\sqrt{F_{11}F_{22}}$$

Maximum Stress failure criteria represented below [15],

$$\frac{\sigma_1}{X_t} \geq 1 \ , \ \frac{\sigma_2}{Y_t} \geq 1$$

For Compression

$$\frac{\sigma_1}{X_c} \geq 1 \ , \ \frac{\sigma_2}{Y_c} \geq 1$$

For Shear

$$\frac{|\tau_{12}|}{S} \geq 1$$

X_t , X_c, explained tensile and compressive strength in the longitudinal. Y_t, Y_c is called tensile and compressive strength in the transverse direction. S_{12} , S_{23} shear strength of fiber in longitudinal and transverse direction.

3. Methodology. - The methodology employed in this study encompassed two distinct research approaches. The first approach involved conducting von Mises stress analysis using finite element analysis (FEA) on various composite materials. To accomplish this, ANSYS Parametric Design Language (APDL) was utilized with the implementation of shell elements. The primary objective of this analysis was to determine the distribution and magnitude of von Mises stresses within the different layers of the composite materials. The second research approach focused on assessing the failure response of the composite materials under uniform static loading conditions. To achieve this, well-established criteria such as the Tsai-Wu criterion and the Maximum stress criterion were utilized. The intention was to evaluate the potential failure modes and overall structural integrity of the composite materials.

To fulfill these objectives, a diverse range of materials underwent FEA analysis. By employing this computational technique, the researchers were able to thoroughly investigate and analyze the Von Mises stresses within each layer of the composite materials. This comprehensive analysis yielded valuable insights into the distribution and concentration of stress, thereby facilitating a deeper understanding of the structural behavior and potential failure mechanisms of the composite materials under investigation.

a. E glass/Epoxy composite
b. Glass/Epoxy composite
c. Carbon/Epoxy
d. Kevlar/Epoxy
e. T300/976 composite

Mechanical Properties are listed in Table 1 of selected composite materials, E and G are in GPa and units of the density are kg/m3. X, Y and Z are longitudinal and transverse directions, and υ represents Poisson's ratio.

Mechanical Properties of Different Composite Materials (E and G units are in GPa)					
Properties	E Glass/Epoxy	Glass/Epoxy	Carbon/Epoxy	Kevlar/Epoxy	T300/976
E_X	33.189	20.6	169	28.5	133
E_Y	7.132	17.2	9	27	9.24
E_Z	7.132	17.2	9	27	9.24
υ_{xy}	0.26	0.112	0.31	0.05	0.318
υ_{yz}	0.26	0.117	0.31	0.489	0.318
υ_{xz}	0.26	0.114	0.31	0.5	0.318
G_{xy}	6.313	17.3	6.5	1.96	6.27
G_{yz}	6.313	7.699	6.5	12.89	6.27
G_{xz}	6.313	7.699	6.5	1.96	6.27
ρ	1630	1900	1745	1400	1630

Table I. Mechanical Properties of Composite Materials.

Parameter	Dimensions (mm)
Overall length	800
Cylinder length	590
Opening diameter	40
Inner shell radius	90
Outside radius	108
Thickness	18
Dome Inner radius	90
Dome outer radius	108

Table II. Geometry details of pressure vessel.

4. Boundary Conditions. - Pressure vessel including all material models constrained at the nozzle ends. Boundary conditions were same for all vessels, pressure vessel was restrained axially at both ends hence no displacement condition was allocated. Meshing in APDL was adopted for composite shell as shown in Figure I. Element type SHELL281 was selected having 8 nodes and having mid nodes as well. It is appropriate for thin to thick structures. Geometry details are given in Table II.

The shell structure was covered with composite layers, consisting of 144 symmetrical cross ply laminates with orientations ranging from 0° to 90°. The overall thickness of the structure was 18 mm. Figure I clearly shows the stacking of six layers, with the first layer at 0° and the second and third layers at 90°, confirming the symmetrical cross ply arrangement of all 144 layers.

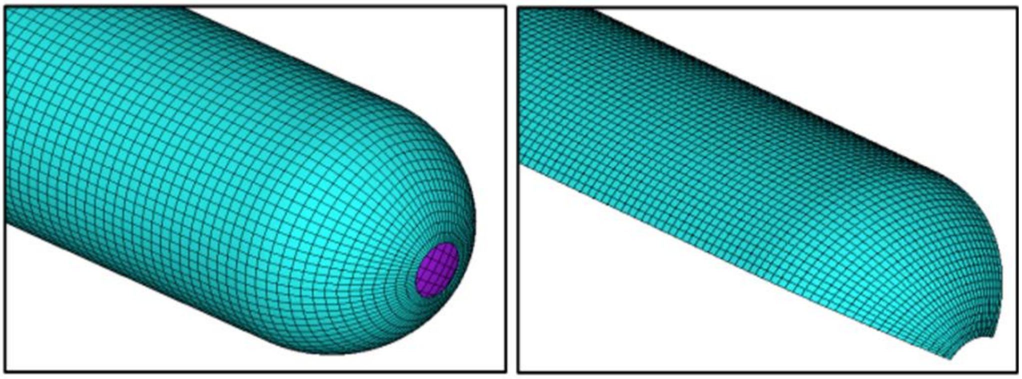

Figure I. Meshing of Full and 90° rotated Pressure vessel.

5. Results and Discussions. –

5.1 E Glass/Epoxy Von Mises stresses. - E glass/epoxy was used as 144 layer stacked in different orientations between 0 to 90º. First layer was oriented longitudinally, and second layer was in transverse orientation.

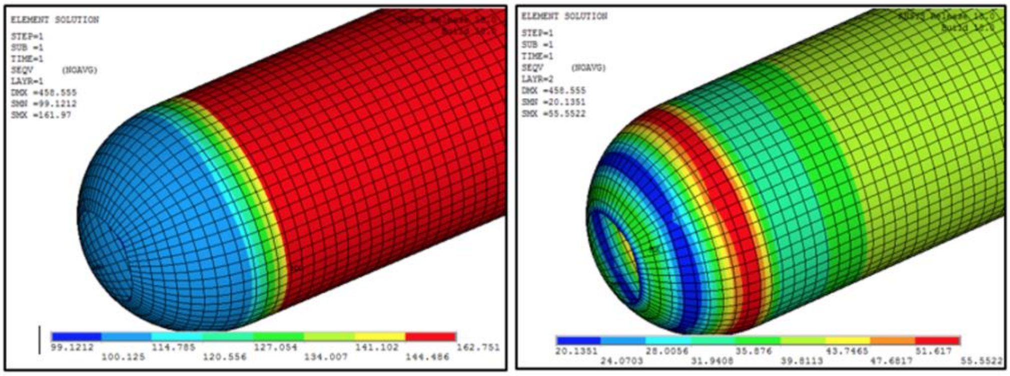

Figure II. Von Mises stresses in E glass/Epoxy (a) Layer 1. (b) Layer 2.

Composite must have high strength and low ductility as compared to the matrix used for the composite. Mechanical properties of E glass/epoxy tabulated in Table1. Von Mises stress distributions were plotted for the geometry with the E Glass/Epoxy composite system as shown in Figure II. Maximum stresses were in the cylindrical region for layer 1 in range of 144 to 162 MPa, and in dome region maximum stressed were in range of 100 to 127 MPa. Stresses in cylindrical region were in range of 34 to 44 MPa for layer 2 and in dome region stresses were in range of 20 to 51 MPa. Maximum stresses occurred at the junction region of the cylindrical and the spherical dome region. Stresses in junction were maximum having value of 55.55 MPa for layer 2.

5.2 Glass/Epoxy Von Mises stresses. - Mechanical properties of Glass/Epoxy composite material is listed in Table 1. Von Mises stress distributions are plotted for the geometry with the Glass/Epoxy composite system as shown in Figure 3. Maximum stresses in cylindrical region for layer 1 were in range of 95 to 102 MPa, in the dome region Maximum stressed were in range of 43 to 68 MPa.

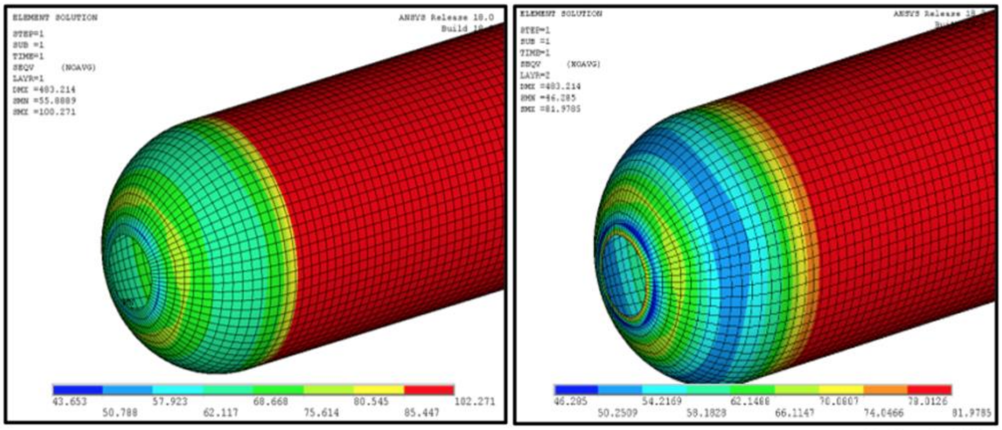

Figure III. Von Mises stresses in Glass/Epoxy (a) Layer 1. (b) Layer 2.

For layer 2 Maximum stress in cylindrical region were in range of 74 to 81 MPa and in dome region stresses were in range of 46 to 62 MPa. Maximum stresses occurred in cylindrical section in both layers.

5.3 Carbon/Epoxy Von Mises stresses. -

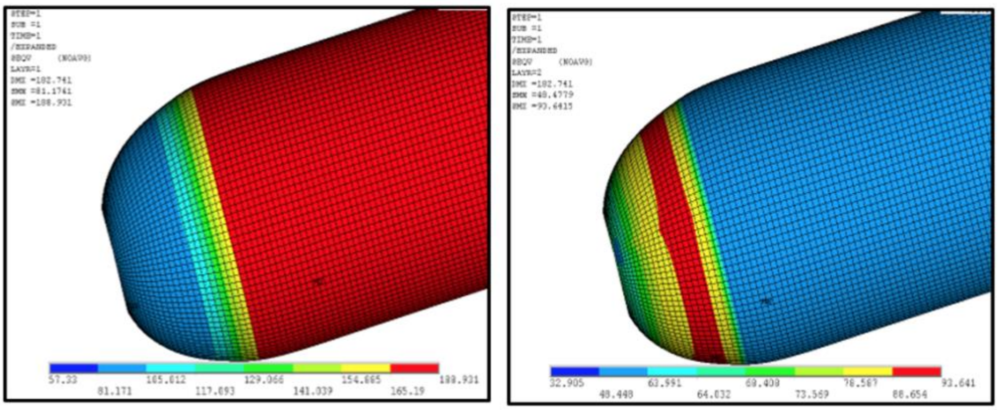

Figure IV. Von Mises stresses in Carbon/Epoxy (a) Layer 1. (b) Layer 2.

Von Mises stresses are shown in Figure IV, Maximum stresses were in cylindrical region for layer 1. Stresses were in range of 165 to 188 MPa. In the dome region stresses were in range of 57 to 81 MPa. Stresses were relatively high in the junction region as compared to the dome having maximum value of 105 MPa. For layer 2 stresses in cylindrical section were in range of 32 to 40

MPa and in dome region stresses were in the range of 73 to 93 MPa. Maximum stresses occurred in the junction region of the cylindrical and the spherical dome region. Stresses in junction were maximum having the value of 94 MPa for layer 2.

5.4 Kevlar/Epoxy Von Mises stresses. –

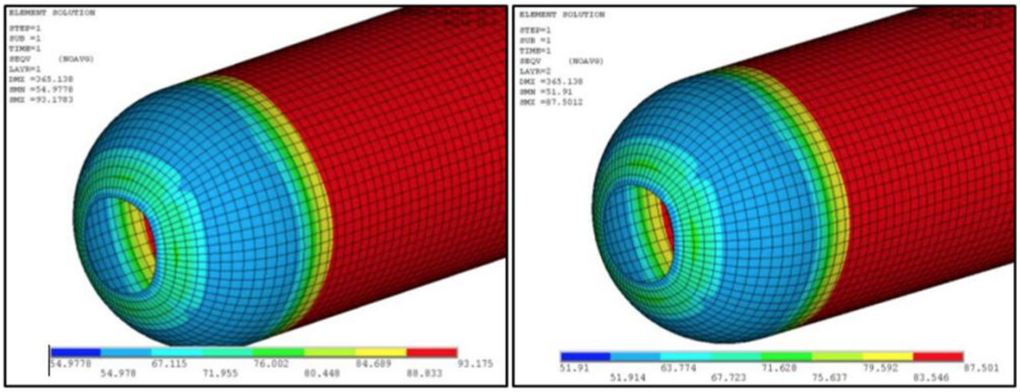

Figure V. Von Mises stresses in Kevlar/Epoxy (a) Layer 1. (b) Layer 2.

The Von Mises stresses are shown in Figure V, for layer 1 Maximum stresses were generated in cylindrical region in range of 89 to 93 MPa and dome region stresses were in range of 54 to 76 MPa. Stresses in cylindrical region were in range of 83 to 87 MPa and in dome region stresses were in range of 51 to 71 MPa. Maximum stresses occurred in cylindrical section in both layers. Mechanical properties of Kevlar/Epoxy are tabulated in Table I.

5.5 T300/976 Von Mises stresses. –

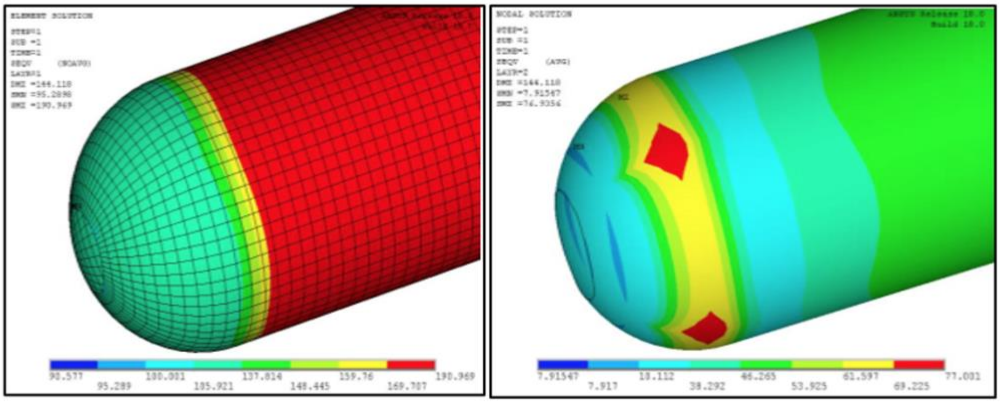

Figure VI. Von Mises stresses in T300/976 (a) Layer 1. (b) Layer 2.

Von Mises stress distributions are plotted for the geometry with T300/976 composite system as shown in Figure VI. Maximum stresses were in cylindrical region of layer 1 in range of 169 to 190 MPa and in dome region stresses were in the range of 100 to 140 MPa. Stresses were relatively high in junction region as compared to dome. High stresses due to the change in fiber directions from the cylindrical region to spherical region of pressure vessel. Range of stresses in cylindrical region were 38 to 53 MPa and in dome region range of stresses were 7 to 79 MPa. Maximum stresses occurred in junction region of cylindrical and spherical dome region. Stresses in junction were maximum around 79 MPa of layer 2.

5.6 Discussion of Failure Theories Results. - The results of different composite systems were evaluated with respect to their ability of sustaining stresses and deformations in normal working conditions. Tsai Wu and maximum stress failure theories applied to the different composite systems. Based on results, some composites listed above were quite satisfactory while others would not be used due to their strength limitations. Strength of some of the composite systems is tabulated in the Table II. Longitudinal, shear and transversal properties of the composite systems are important for evaluation. Glass/Epoxy composite had approximately same strength in both the longitudinal and transverse directions.

This tells us about the suitability of the composite in these conditions. Carbon/Epoxy have high strength in reinforcement direction while the low strengths in transversal directions was unable to withstand the applied working pressures and failure observed in layer 2 of pressure vessel at the junction region. Failure analysis shown in Table III revealed results of detailed analysis of composite materials for high-pressure cylinders under normal working pressures. Tsai Wu, and Maximum Stress failure criterion were evaluated for the first two layers of the total 144 layers because they were under extreme loading in comparison of others.

Failure theories depicted values for each layer, Table III represented comparative study of failure theories data for both layers. It is indicated failure of layers under induced stresses and same working loads with fixed axial displacements. Boundary condition for each of the reduced model changes but overall theme remain same that is the axial displacement is fixed in each model and the symmetries are further applied to each of the model. Results variation is due to the variation of boundary conditions applied. It was conspicuous that only T300/976 and Glass/Epoxy composite systems can withstand the applied internal pressure while all the other systems failed in one or both of layers. Carbon/Epoxy can endure the pressure for the 1st layer but for the 2nd layer it failed according to the applied criterion. Carbon/Epoxy sustained internal pressure without failure for layer 1 but for layer 2 it was crashed. Kevlar/Epoxy was unable to sustain the internal pressure for both of layers and it failed according to the applied failure criterion. EGlass/Epoxy was capable to sustain internal pressure for layer 1 but layer 2nd failed as per defined failure criterion.

Composite	**Longitudinal**	**Transversal**	**Shear**
	Strength (MPa)	**Strength (MPa)**	**Strength (MPa)**
Carbon/Epoxy	2266	70	84.108
Glass /Epoxy	380	334	324
T300 /976	1427	39	90
Kevlar /Epoxy	1170	20.9	73
EGlass/Epoxy	743	23	69

Table III. Strength Properties of Selected Composite Materials.

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Composite	Layer 1			Layer 2			
	Stresses (MPa)	Tsai Wu	Smax	Stresses (MPa)	Tsai Wu	Smax	Status
Carbon/Epoxy	183.4	0.12	0.08	121	2.01	1.73	Layer 2 failure
Glass/Epoxy	102.2	0.30	0.29	81.9	0.46	0.27	No failure
Kevlar 49 /Epoxy	93.1	2.11	2.03	87.5	7.2	4.67	Both layers failure
E Glass/Epoxy	162.7	0.68	0.82	55.5	1.7	1.63	Layer 2 failure
T300 /976	190	0.19	0.21	77	0.29	0.34	No failure

Table IV. Failure Analysis of Different Composite Materials.

6. Conclusions. - The results of the varying composites systems concluded that Glass Epoxy results are favorable in term of failure under static loading, Glass/Epoxy composite showing reasonable strength without failure of 2nd layer. T300/976 is also suitable as per loading conditions for required model because there was no 2nd layer failure in this Composite material. Total 5x Composite material evaluated under equal static pressure of 20 MPa but only two of them classify the theories of failure hence it is recommended to use Glass/Epoxy and T300/976 in extreme pressure conditions of CNG cylinders. 3x composite material failed to classify the failure theories hence it is not safe to utilize them in extreme conditions of loading, however these materials are not showing any failure in 1st layer, but deformations resulted in 2nd layer are susceptible to failure. Therefore, it is evaluated that other systems i-e Carbon/Epoxy, E Glass/Epoxy, Kevlar/Epoxy should not be used for the application as they will fail under the static structural analysis.

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Nota contribución de los autores:

1. Concepción y diseño del estudio
2. Adquisición de datos
3. Análisis de datos
4. Discusión de los resultados
5. Redacción del manuscrito
6. Aprobación de la versión final del manuscrito

AS ha contribuido en: 1, 2, 3, 4, 5 y 6.

JJ ha contribuido en: 1, 2, 3, 4, 5 y 6.

MU ha contribuido en: 1, 2, 3, 4, 5 y 6.

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