Design of Laminated Pressure Vessel

Lakshmi Nair[1], Yezhil Arasu[2], Indu V S[3]

[1]PG Scholar, Department of Civil Engineering, Sree Buddha College of Engineering, Pattoor, Nooranad, Alappuzha, Kerala, India.

[2]Scientist, HDRD, SMG Division, Vikram Sarabhai Space Center, Trivandrum, Kerala

[3]Assistant Professor, Department of Civil Engineering, Sree Buddha College of Engineering, Pattoor, Nooranad, Alappuzha, Kerala, India

Abstract: ***Pressure vessels are closed container contains gasses or liquid under internal pressure. Isotropic materials like metals are used for realizing hardware, the material is not fully utilized in longitudinal/ meridional direction resulting in over weight components. Instead of Isotropic metals, fiber reinforced epoxy composites are used for Pressure Vessels because they offer higher specific strength and moduli and tailoribility characteristics will result in reduction of weight of the structure. The determination of a proper winding angle and thickness is very important to decrease manufacturing difficulties and to increase structural efficiency. In this study, material characterization of FRP of carbon T300/Epoxy for various configurations as per ASTM standards is determined. The design of Laminated Pressure Vessel is described in detail. Netting analysis is used for the calculation of hoop and helical thickness of the Pressure Vessel. A balanced symmetric ply sequence for carbon T300/epoxy is considered for entire Pressure Vessel. Progressive failure analysis of composite Pressure Vessel with geodesic end dome is carried out. The results can be utilized to understand structural characteristics of filament wound Pressure vessels.***

Keywords: FRP, Isotensoid, Geodesic path, Filament winding, Balanced Symmetry

1. Introduction

A composite is a structural material which consists of combining two or more constituents. The constituents are combined at a macroscopic level and are not soluble to each other. Fiber reinforced polymer consists of fiber of high strength and modulus embedded in or bonded to matrix with distinct interface between them. Fibers are principal load carrying members and the surrounding matrix keeps them in desired location and orientation, acts as a load transfer medium between them and protects them from environmental damage due to elevated temperatures and humidity.

Due to their continually improving specific strength and stiffness fibrous composites offer distinct advantages over more traditional materials in the design of Pressure Vessel bodies. The favoured method of manufacture is filament winding in which helical layer wound at alternately +/- the helical wind angle are followed by hoop windings to provide sufficient overall strength and stiffness.

The strength and Stiffness of fibrous composites are highly directional dependent, with the resin or matrix material offering little strength and acts so as to hold the fibers together, give compressive support and protection and provide a shear path for load transfer. The most commonly used family of structural materials are carbon fiber reinforced plastics (CFRP) in which carbon fibers are set in an epoxy matrix. In these structures usual techniques is to build up a laminate from several multi-oriented piles which has the effect of reducing the base materials excellent uni-directional properties. It is the properties of fully assembled laminate which need to be considered and compared with alternative selections.

In the filament winding process either resin soaked or pre-impregnated fibers are placed over a rotating mandrel until the required thickness of composite is achieved. For cylindrical sections both the helix angle and thickness are constant. At the dome ends the fiber placement is programmed so as to follow the geodesic or non-slip path, that being the shortest distance between two points on a generally curved surface.

In this paper, by writing MATLAB programmes, analysed structural behaviour of composite materials and design of Composite pressure vessel are done.

2. Significance of Work

2.1 Scope of the Work

From the referred literature reviews, it is understood that high specific strength and stiffness of fibrous composites are offering distinct advantages over more traditional isotropic materials. In the design Pressure vessels, isotropic materials like metals is not fully utilized in longitudinal/ meridional direction resulting in over weight of Pressure vessels. To overcome this over weight of Pressure Vessels, alternatively FRP of carbon T300/Epoxy for various configurations as per ASTM standards can be adopted.

2.2 Objective of the Work

The objective is to finalize the Composite configuration of Pressure Vessel. By this proper composite configuration, weight reduction of composite Pressure vessel can be achieved with same structural efficiency as that of commonly using materials like steel, aluminum, even titanium.

2.3 Methodology

The methodology of the work consist of
1) Preliminary design of composite laminates by writing a proper coding in MATLAB.

2) The dome profile is generated using MATLAB code considering the winding angles and helical thickness variations.
3) By using Tsai-Hill failure theory, failure criteria of designed composite pressure vessel was checked.

3. Classification of Composite Materials

Composites are classified by the geometry of reinforcement or by the type of matrix. Three common types of composite materials are:

3.1 Fibrous composite materials

It consists of fibers in a matrix. The advantage of this composite is that long fibers in various form are much stronger and stiffer than the same material in their bulk form, because there will be fewer internal defects in fibers.

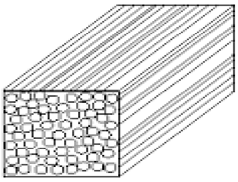

Figure 1: Fibrous composite material

3.2 Laminated composite materials

It consists of layers of atleast two different materials that are bonded together. Lamination is used to combine the best aspects of the constituent materials inorder to have more useful materials.

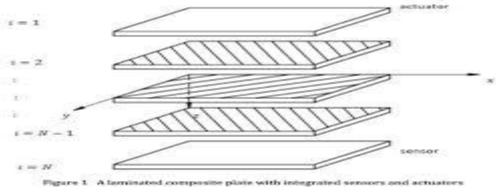

Figure 2: Laminated composite material

3.3 Particulate composite materials

These are consists of particles of one or more materials suspended in a matrix. Particles can be either metallic or non metallic as can the matrix.

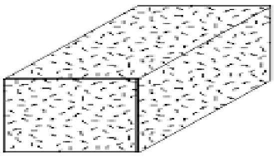

Figure 3: Particulate composite material

4. Classical Laminate Theory

4.1 Assumptions Of Classical Laminate Theory

i. A line originally straight and perpendicular to the middle surface of the laminate is assumed to remain straight and perpendicular to the middle surface when the laminate is extended and bent.

ii. Requiring the normal to the middle surface to remain straight and normal under deformation is equivalent to ignoring shearing strains in plane perpendicular to the middle surface. ($\gamma xz = \gamma yz = 0$)

iii. The normals are presumed to have constant length so that strain perpendicular to the middle surface is ignored. ($\varepsilon z=0$)

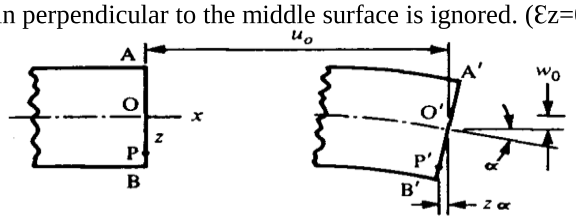

Figure 4: Deformation of a Laminate

4.2 Strain-displacement relation

The strain displacement relations for infinitesimal strains is

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} = \frac{\partial uo}{\partial x} - z\frac{\partial 2w}{\partial x2}$$

$$\varepsilon_{yy} = \frac{\partial v}{\partial y} = \frac{\partial vo}{\partial y} - z\frac{\partial 2w}{\partial y2}$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = \frac{\partial uo}{\partial y} + \frac{\partial vo}{\partial x} - 2z\frac{\partial 2w}{\partial x \partial y}$$

The above equation can be written as

$$\begin{Bmatrix} \varepsilon xx \\ \varepsilon yy \\ \gamma xy \end{Bmatrix} = \begin{Bmatrix} \varepsilon xx(0) \\ \varepsilon yy(0) \\ \gamma xy(0) \end{Bmatrix} + z \begin{Bmatrix} kxx \\ kyy \\ kxy \end{Bmatrix} (1)$$

Where, $\{\varepsilon xx(0), \varepsilon yy(0), \gamma xy(0)\}$ represents mid plane strains and $\{kxx, kyy, kxy\}$ represents mid plane curvature.

4.3 Stresses in a Laminate

The stresses at any location can be calculated from the strains and lamina constitutive relations. The stresses in k^{th} lamina can be given as

$$\sigma_{xy}^{k} = [Q]^{K} * \varepsilon_{xy}^{k}$$

Now, using Equation (1), we can write the stresses as

$$\sigma_{xy}^{k} = [Q]^{K} * \varepsilon_{xy}^{o} + Q\{^{K}\} * z * k_{xy} \quad (2)$$

In these equations, the strains are given at a *z* location where the stresses are required. It should be noted that the strains are continuous and vary linearly through the thickness. If we look at the stress distribution through the thickness it is clear that the stresses are not continuous through the thickness, because the stiffness is different for different laminae in thickness direction. In a lamina the stress varies linearly. The slope of this variation in a lamina depends upon its moduli. However, at the interface of two adjacent laminae there is a discontinuity in the stresses. The same thing is depicted in Figure 5 with four layers.

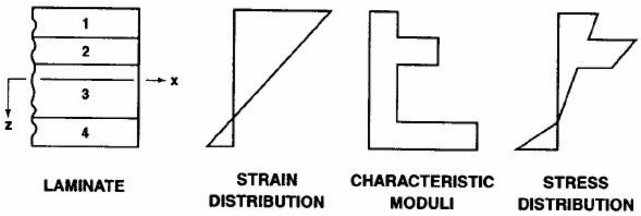

Figure 6: Variation of Strain, Stress and Elastic modulus in a Laminate

4.4 In plane Resultant Forces and Moments

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Resultant forces and moments acting on a laminate is as show in figure 7 and figure 8.

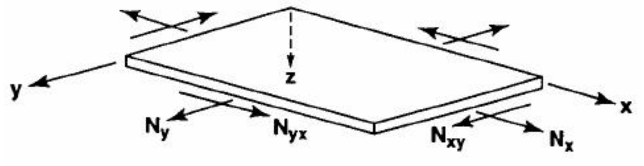

Figure 7: Resultant Forces acting in a Laminate

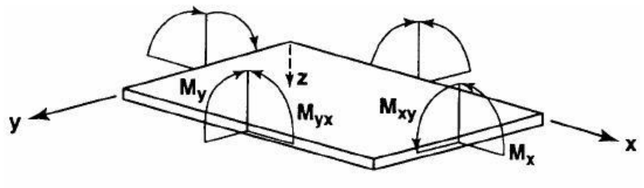

Figure 8: Resultant Forces acting in a Laminate

If we take the case of laminate,

Resultant forces is

$N_{xy} = [A] * \varepsilon^{o}_{xy} + [B] * k_{xy}$

Resultant Moment is

$M_{xy} = [B] * \varepsilon^{o}_{xy} + [D] * k_{xy}$

Where,

$$[A] = \sum_{k=1}^{NLay} [\overline{Q}]^{K} * (z_k - z_{k-1})$$

$$[B] = 1/2 \sum_{k=1}^{NLay} [\overline{Q}]^{K} * (z_k^2 - z_{k-1}^2)$$

$$[D] = 1/3 \sum_{k=1}^{NLay} [\overline{Q}]^{K} * (z_k^3 - z_{k-1}^3)$$

The matrix [A] represents the in-plane stiffness, that is, it relates the in-plane forces with mid-plane strains, the matrix [B] represents the bending stiffness coupling, that is, it relates the in-plane forces with mid-plane curvatures, The matrix [D] represents the bending stiffness, that is, it relates resultant moments with mid-plane curvatures.

Classical Laminate theory is a very powerful and easier theory, In this work Classical Laminate theory is adopted for finding out layer by layer stresses, strains and deformations coming in a laminate under the action of loads. For this, a MATLAB programming is written and from which ABD matrices (stiffness matrices), stresses and strains at each laminae interfaces, effective material properties for different ply sequences can be obtained. For different layup sequences of laminae in laminates, the stiffness matrices will be different, study of those variation of stiffness matrices is an important preliminary design step. Selection of layup sequences is done based on the basis of preliminary design step. A flowchart of the program is as shown in Figure 9

Defining fibre material property
⇩
Input ply sequence, ply thickness, fiber orientation
⇩
Obtain stiffness matrix
⇩
Obtain reduced stiffness matrix
⇩
Obtain transformed reduced stiffness matrix
⇩
Obtain ABD matrix
⇩
Obtain mid plane strain and curvature in laminate
⇩
Obtain each ply strain in x-y coordinate system
⇩
Obtain ply stresses in x-y coordinate system
⇩
Check failure criteria by Tsai-Hill Theory

Fig.9 Flow chart of MATLAB coding for solving Classical Laminate Theory

4.5 Special cases of Laminates

The symmetry or antisymmetry of a laminate, based on angle, material, and thickness of piles, may zero out some elements of the three stiffness matrices A, B, D. Study of those laminate sequence is so important because they may result in reducing or zeroing out the coupling of forces and bending moments, normal and shear forces, or bending and twisting moments.

This will simplifies the mechanical analysis of composites and will also give desired mechanical performance.

$$\begin{pmatrix} A11 & A12 & A16 & B11 & B12 & B16 \\ A21 & A22 & A26 & B21 & B22 & B26 \\ A31 & A32 & A36 & B31 & B32 & B36 \\ B11 & B12 & B16 & D11 & D12 & D16 \\ B21 & B22 & B26 & D21 & D22 & D26 \\ B31 & B32 & B36 & D31 & D32 & D36 \end{pmatrix}$$

4.5.1 Symmetric laminates

A laminate is called symmetric if the material, angle, and thickness of piles are the same above and below the midplane. Here B matrix tends to zero, indicates that the force and moment terms are uncoupled. An example of symmetric laminate is $[0/30/60]_s$. This results can be seen from CLT coding.

$$\begin{pmatrix} 1.2593 & 0.2713 & 0.2970 & 0.0000 & 0.0000 & 0.0000 \\ 0.2713 & 0.5735 & 0.2970 & 0.0000 & 0.0000 & 0.0000 \\ 0.2970 & 0.2970 & 0.3226 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 0.2263 & 0.0168 & 0.0213 \\ 0.0000 & 0.0000 & 0.0000 & 0.0168 & 0.0251 & 0.0104 \\ 0.0000 & 0.0000 & 0.0000 & 0.0213 & 0.0104 & 0.0229 \end{pmatrix} * 10^5$$

4.5.2 Cross-Ply laminates

A laminate is called a cross-ply laminate if only 0^0 and 90^0 piles were used to make a laminate. Here $A_{16}=0$, $A_{26}=0$, $B_{16}=0$, $B_{26}=0$, $D_{16}=0$, $D_{26}=0$, indicates uncoupling between the normal and shear forces and also between the bending and twisting moments. An example of cross ply laminate is [0/90/90/0/90]. This results can be seen from CLT coding

$$\begin{pmatrix} 0.7893 & 0.0290 & 0.0000 & -0.0686 & 0.0000 & 0.0000 \\ 0.0290 & 1.1323 & 0.0000 & 0.0000 & 0.0686 & 0.0000 \\ 0.0000 & 0.0000 & 0.0717 & 0.0000 & 0.0000 & 0.0000 \\ -0.0686 & 0.0000 & 0.0000 & 0.0795 & 0.0024 & 0.0000 \\ 0.0000 & 0.0686 & 0.0000 & 0.0024 & 0.0806 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0060 \end{pmatrix} *10^3$$

4.5.3 Angle ply laminates

A laminate is called a angle ply laminate, if it has piles of same material and thickness and only oriented at +θ and –θ directions. If a laminate has an even number of piles, then A_{16}=0, A_{26}=0. However, if the number of piles is odd and it consists of alternating +θ and –θ piles, then B matrix becomes zero also A_{16}, A_{26}, D_{16}, D_{26} becomes small as the number of layers increases for the same laminate thickness. They are having higher shear stiffness and shear strength properties than cross ply laminates. An example of angle ply laminate is [-40/40/-40/40].

$$\begin{pmatrix} 5.8187 & 3.2903 & 0.0000 & 0.0000 & 0.0000 & 0.3917 \\ 3.2903 & 3.4367 & 0.0000 & 0.0000 & 0.0000 & 0.2838 \\ 0.0000 & 0.0000 & 3.6322 & 0.3917 & 0.2838 & 0.0000 \\ 0.0000 & 0.0000 & 0.3917 & 0.3103 & 0.1755 & 0.0000 \\ 0.0000 & 0.0000 & 0.2838 & 0.1755 & 0.1833 & 0.0000 \\ 0.3917 & 0.2838 & 0.0000 & 0.0000 & 0.0000 & 0.1937 \end{pmatrix} *10^4$$

4.5.4 Non Symmetric Laminate

Here Laminate usually exhibit coupling between the direct stress and curvature. This type of laminate will bend when in-plane tension is applied. Here the terms A_{16},=A_{26}=0. An example of Non-symmetric laminate is [45/-45/0/90/0].

$$\begin{pmatrix} 9.7457 & 1.8665 & 0.0000 & 0.8160 & -0.4731 & -0.1715 \\ 1.8665 & 6.3164 & 0.0000 & -0.4731 & 0.1301 & -0.1715 \\ 0.0000 & 0.0000 & 2.2938 & -0.1715 & -0.1715 & -0.4731 \\ 0.8160 & -0.4731 & -0.1715 & 0.8492 & 0.1871 & 0.1029 \\ -0.4731 & 0.1301 & -0.1715 & 0.1871 & 0.4262 & 0.1029 \\ -0.1715 & -0.1715 & -0.4731 & 0.1029 & 0.1029 & 0.2227 \end{pmatrix} *10^4$$

4.5.5 Balanced Laminates

A laminate is balanced when it consists of pairs of layers of the same thickness and material where the angles of piles are +θ and –θ. Here the terms A_{16},=A_{26}=0. If the number of piles in a balanced laminate is odd, it can be made symmetric. Here in addition to A_{16}=A_{26}=0, the coupling stiffness matrix B=0. An example of balanced-symmetric laminate is [0/90/45/-45/-45/45/90/0].

$$\begin{pmatrix} 1.2219 & 0.3617 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.3617 & 1.2219 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.4301 & 0.0000 & 0.0000 & 0.000 \\ 0.0000 & 0.0000 & 0.0000 & 0.3934 & 0.0267 & 0.0137 \\ 0.0000 & 0.0000 & 0.0000 & 0.0267 & 0.2288 & 0.0137 \\ 0.0000 & 0.0000 & 0.0000 & 0.0137 & 0.0137 & 0.0413 \end{pmatrix} *10^3$$

In this work, out of five different types of laminate sequences, Balanced-symmetric laminate sequence is adopted for laminated pressure vessels because the loading in a particular plane does not cause deformations in other plane.

5. Design of Composite Pressure Vessel

If a pressure vessel constructed from an orthotropic fibrous composite in which the matrix acts only as binder for the fibers and contributes nothing to the composite strength and stiffness. This simplification is known as netting theory. In composite pressure vessels the fibers should be orient along the principal stress directions i.e. axial and hoop. Hence there are two desired layers and each can be sized independent of the other. Using the filament winding process it is a relatively simple task to lay fibers in the hoop direction whereas it is almost impossible to position fibers axially without slippage occurring. In order to overcome this problem it is usual to wind fibers at a low helix angle θ relative to the cylinder axis. Assuming that the matrix contributes nothing to composite strength, the axial load is balanced only against the component of helical layer stress in the axial direction and required helical thickness is:

$$t_x = pd/4\sigma_a \cos^2\theta \quad (3)$$

To balance the applied hoop load there are contributions from both the axial and hoop layers:

$$\sigma_a t_x \sin^2\theta + \sigma_a t_y = pd/2 \quad (4)$$

Substituting for tx from equation (3) in equation (4), required hoop thickness is:

$$t_y = pd/2\sigma_a (1-\tan^2\theta/2) \quad (5)$$

The total composite thickness is the sum of helical and hoop thickness, which is:

$$Tc = tx + ty = 3pd/4\sigma_a \quad (6)$$

From equation (6), it shows that the total composite thickness for a minimum mass isotensoid vessel independent of the helical layer wind angle.

5.1 Assumptions

i. Fiber and matrix strains are equal
ii. Tensile and compressive deformations are equal
iii. Shear stresses developed in the fiber matrix interfaces are low
iv. The fibers are straight and continuous

5.2 Design of cylinder and dome

The design of cylindrical region is very simple and straightforward when compared to the design of the dome region. The reason is that for the cylindrical region any helical winding angle will follow geodesic path. So we are able to wind the cylindrical region at any desired angle. Throughout the cylindrical region we will have a constant winding angle θ_c and the thickness of helical winding and hoop winding remains unchanged.

But when we consider the design of end domes it is seen that the angle of winding keeps on changing from the pole opening to the dome-cylinder transition region inorder to maintain the geodesic path. The other difficulty with the dome region is that we are not able to provide hoop winding as it can cause slippage of the fiber. For maximum structural efficiency it is important that the stresses in the pressure vessel head are constant and equal to the maximum material allowable. The variable stresses in a fiber can cause shearing of the resin and cause failure of the pressure vessel. So it is necessary to design the profile of the dome so that the fibers wound on these dome will have the same stress throughout the fiber. Such a dome is often termed as Isotensoid Geodesic domes.

For orthotropic materials the head end dome needs to be designed carefully, such that all filaments are loaded to identical stress levels i.e. isotensoids. For achieve this aim a first order differential equation, obtained from Clairaut's theorem is used.

$$\frac{dy}{dx} = -\left((1-x_b^2)^{0.5}\, x^3\right) / \left(x^2 - x_b^2 - (1-x_b^2)\, x^6\right)^{0.5}$$

This equation can be solved numerically to produce the x, y coordinates of the isotensoid geodesic pressure vessel dome. It can be seen that the only parameter of equation is x_b, the ratio of the pole radius to equatorial radius from which all the other terms are derived.

- Wind angle at the equator is given by equation
  $\theta_c = \sin^{-1} x_b$
- Helical thickness t_{hel} at the equator is given by
  $t_{helc} = pd/(4\sigma_a \cos^2\theta_c)$
- Wind angle at any point is given by equation
  $\theta = \sin^{-1}(x_b/x)$
- Thickness at any point is given by equation
  $(t_{hel})_{dome} = (t_{hel})_c\,(\tan\theta/\tan\theta_c)$

For finding out the design parameters, a MATLAB programming is written, from which, inner profile is obtained and considering the helical thickness and the winding angle outer profile is also computed. From these two profile shapes, the middle profile is obtained .In addition to the profile shape and helical thickness, hoop thickness in the cylindrical region $(t_{hoop})_c$ is also computed using the MATLAB program. A flowchart of the program is as shown in Figure 10.

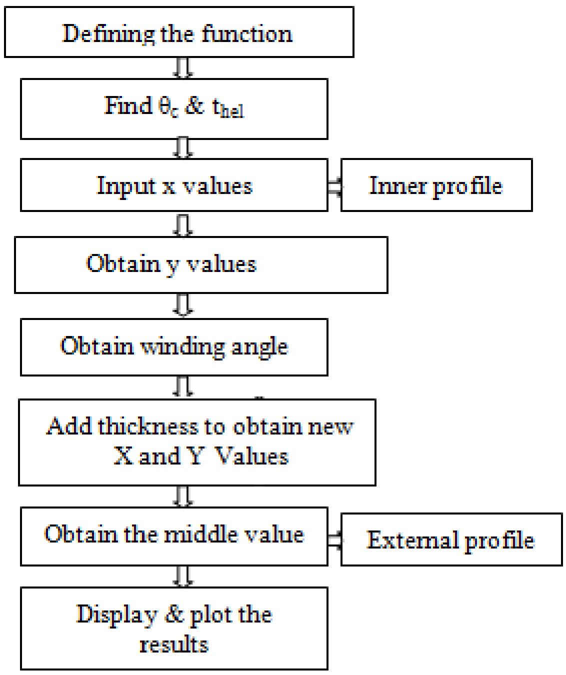

Figure 10: Flow chart of MATLAB coding for finding out designed parameters

5.3 Material Properties

Filament Winding is possible either with tapes or with rovings with wet resin system. Pressure vessel design calls for materials with high specific strength and specific stiffness so as to keep the inert mass of the casing to a minimum**.** The materials that are considered here are transversely isotropic composite material. Among the various fibers available in the market, choice was converged on T300 fibers considering cost, availability and suitability of the application. Fiber thickness used is 0.2mm. Elastic and strength material property of the unidirectional composite is given in table 1 and table 2.

Table1: Elastic Material Properties of T300 Fibers

E_1(Gpa)	136
E_2(Gpa)	9.8
E_3(Gpa)	9.8
ν_{12}	0.28
ν_{13}	0.28
ν_{23}	0.15
G_{12}(Gpa)	4.7
G_{13}(Gpa)	4.7
G_{23}	5.2

Table 2: Strength Properties of T300 Fibers from NOL ring Test

$\bar{\sigma}_1$(Mpa)	1200
$\bar{\sigma}_2$ (Mpa)	70
$\bar{\tau}_{12}$(Mpa)	70

5.4 Design Procedure

5.4.1 Design Requirement

Table 3: Design Requirement of Pressure Vessel

Parameters	Requirements
Maximum Expected Operating Pressure	6 Mpa
Inner diameter of cylinder	1960mm
End boss diameter	170mm
Allowable stress of material used	835 Mpa

5.4.2 Designed Values

For the design requirement, MATLAB coding for design purpose was run and the design values obtained from MATLAB Program is given in table 4

Table 4: Design Requirement of Pressure Vessel

Designed parameters	Obtained values
$(t_{hoop})_c$	6.9327
$(t_{hel})_c$	3.6302
θ_c	9.9947
$(t_{hel})_{dome}$ (Max Value)	66.3944
$(t_{hel})_{dome}$ (Min Value)	3.6306
Number of hoop layer	36
Number of helical layer	20

5.4.3 Isotensoid Geodesic Dome Profile

Based on the program written for the design in MATLAB, the dome profile shape is obtained, which is as shown in figure 11.

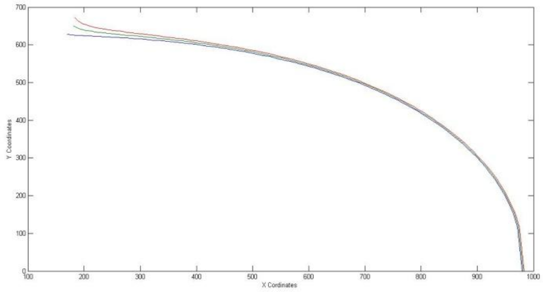

Figure 11: Isotensoid- Geodesic dome profile

From the program it was possible to compute the thickness variation and the variation in the angle of winding from the end boss opening to transition region in the dome and it is plotted in figure 12 and 13 respectively

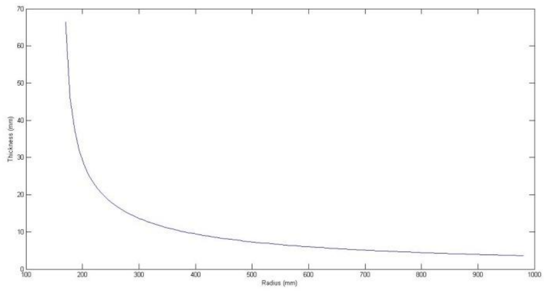

Figure 12: Variation of thickness with radius

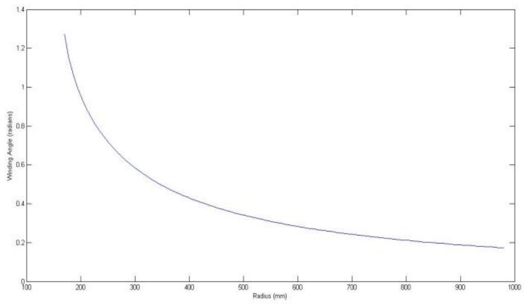

Figure 12: Variation of Winding angle with radius

5.4.4 TSAI-HILL Failure Criteria

Tsai-Hill criterion takes strain energy into consideration and is good for orthotropic material system. Design is verified on the basis of Tsai-Hill failure theory.

$$\left(\frac{\sigma_1}{\hat{\sigma}_1}\right)^2 - \frac{\sigma_1\sigma_2}{\hat{\sigma}_1^2} + \left(\frac{\sigma_2}{\hat{\sigma}_2}\right)^2 + \left(\frac{\tau_{12}}{\hat{\tau}_{12}}\right)^2 = 1$$

Where, $\overline{\sigma_1}$, $\overline{\sigma_2}$ are the ply tensile strength parallel to and along the fiber direction and $\overline{\tau_{12}}$ is the interlaminar ply strength, which can be taken from table 2 and σ_1, σ_2 and τ_{12} are the individual ply stresses, which can be obtained by running MATLAB program for Classical Laminate theory.

For cylindrical portion 36 hoop layer and 20 helical layer is obtained, hoop angle is 90^0 and helical angle is 9.9947^0, which can be arranged in a balanced-symmetric fashion i.e., for each $+\theta$, there will be $-\theta$.

For laminated pressure vessels, the stress resultants caused by internal pressure are

$$N_X = PR \;\&\; N_Y = PR/2$$

Where, Subscripts X and Y denotes hoop and longitudinal directions respectively.

$N_X = PR = 6*980 = 5880$ N/mm

$N_Y = PR/2 = 6*980/2 = 2940$ N/mm

Failure criteria is checked for cylindrical portion directly using MATLAB programming for Classical Laminate Theory.

Number of helical layers in cylinder portion obtained from program is 20 numbers and helical angle is 9.9947^0, so as to get balanced-symmetric fashion, it was arranged as alternatively + and - 9.9947^0, and number of hoop layer is 36, hoop angle is 90^0. So for total 56 layers MATLAB program was run and at some layers failure index obtained was 1.0058 >1. So total number of layers increased to 64 and MATLAB program was run again and found that failure index was 0.7838 <1.

Since failure index in both helical and hoop layer is less than 1, Design of Laminated Pressure vessel is safe.

6. Results and Conclusions

Structural Efficiency of Laminated Pressure Vessel is similar to Metallic Pressure Vessel, with the advantage of reduction in weight. A laminated Pressure Vessel of diameter 1960mm and 170mm pole opening diameter is considered for the study. The MEOP of 6Mpa is used in designing the structure. Carbon T300 is used for the development of the entire structure. Hoop stress of 1200Mpa determined experimentally by NOL ring test is used for the hoop strength and a helical strength of 70Mpa is used. The angle of winding from Clairaut's principle is computed to be 9.994^0 on the cylindrical zone and the angle of filament at the pole opening is 90^0. The designed values are as shown in table 4. A balanced symmetric ply sequence is designed for the shell. For practical case, it is important to have hoop fibers outside the helical fibers to get better consolidation effect on the helical fibers. It is desirable to have alternate hoop and helical layers with hoop layers as the top most and the bottom most layers. Since failure index according to Tsai-Hill theory in each layers is coming less than 1, the design of Laminated Pressure Vessel is safe.

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