Design and Analysis of Filament Wound Composite Pressure Vessel with Integrated-end Domes

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ABSTRACT

Filament-wound composite pressure vessels are an important type of high-pressure container that is widely used in the commercial and aerospace industries. The pressure vessels with integrated end domes develop hoop stresses that are twice longitudinal stresses and when isotropic materials like metals are used for realizing the hardware, the material is not fully utilized in the longitudinal/meridonial direction resulting in over weight components. On the other hand FRP composite materials with their 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 experimentally determined using filament winding and matched die mould technique. The mechanical and physical properties thus obtained are used in the design of the composite shell. The design of the composite shell is described in detail. Netting analysis is used for the calculation of hoop and helical thickness of the shell. A balanced symmetric ply sequence for carbon T300/epoxy is considered for the entire pressure vessel. Progressive failure analysis of composite pressure vessel with geodesic end domes is carried out. A software code SHELL Solver is developed using Classical Lamination-theory to determine matrix crack failure, burst pressure values at various positions of the shell. The results can be utilized to understand structural characteristics of filament wound pressure vessels with integrated end domes.

Keywords: CLT, matrix crack failure, progressive failure, filament winding, geodesic path.

NOMENCLATURE

V_f	Volume fraction
CLT	Classical lamination theory
Sr	Strength ratio
$\sigma_{f\varphi}$	the fiber strength in hoop direction
SR	Stress ratio
σ_{fHl}	the fiber strength in helical
μ	Friction factor on the mandrel surface
ϕ	helical winding angle,
β	Slope of the meridonial contour
FRP	Fiber reinforced polymer

1. INTRODUCTION

Fiber reinforced polymers consist of fibers of high strength and modulus embedded in or bonded to matrix with distinct interfaces between them. Fibers are principal load carrying members and the surrounding matrix keeps them in the desired location and orientation, acts as a load transfer medium between them and protects them from environmental damage due to elevated temperatures and humidity. The composite pressure vessel consists of a durable plastic liner fully wrapped with epoxy-impregnated carbon fiber as shown in Fig. 1. The liner is formed from high-density polyethylene (HDPE) and has two aluminum end bosses, which provide the structural interface to the shell. The function of the liner is to provide a high-pressure gas barrier. The liner is not considered a structural element of the design and, by virtue of its low modulus, is able to transfer all loads to the structural shell.

The composite pressure vessel has a base radius and a polar opening radius. Such a dome is formed by winding resin coated high strength filaments onto an axisymmetric permanent lining or removable mandrel, then heat treating the resulting structure to produce a hard and resistance matrix. The filament patterns produced by the manufacturing methods consist of an even number of superimposed layers that spiral alternately, so that clockwise-wound layer exists for each. The double symmetry of the resulting pattern is adopted herein, and the dome is generally treated as a thin-walled shell of revolution. The shell is subjected to uniform internal pressure and the conditions of thin walled structure and balanced symmetry winding pattern are adopted.
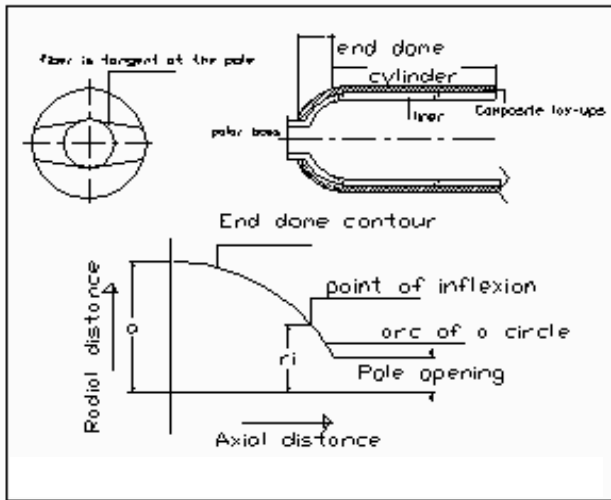
Figure 1. Composite presure vessel with integrated and domes.

2.   THEORETICAL BACKGROUND

Filament-wound composite pressure vessels, which utilize a fabrication technique of filament winding, (Fig. 2) to form high strength and light weight reinforced plastic parts, are of a major type of high-pressure vessel and are widely used in the commercial and aerospace industries such as fuel tanks, portable oxygen storage, rocket motor cases and so on. This kind of vessel consists of a cylindrical drum and dome parts, just like typical pressure vessels. The trajectory of the fiber path and the corresponding fiber angles cannot be chosen arbitrarily because of the stability requirement. The fiber path instability induced by fiber slippage on a mandrel surface is too complicated to be predicted because it is affected by many parameters, such as temperature, mandrel shape, fiber–resin combination, surface treatment and so on. In the present study, hoop and helical thickness values are calculated using netting analyses and fiber angle distribution for both cylinder and end domes is calculated using Claurit's principle for the geodesic domes. Geodesic lines connect two points along the shortest distance over the surface. In this case no friction force is required to keep the fiber from slipping,
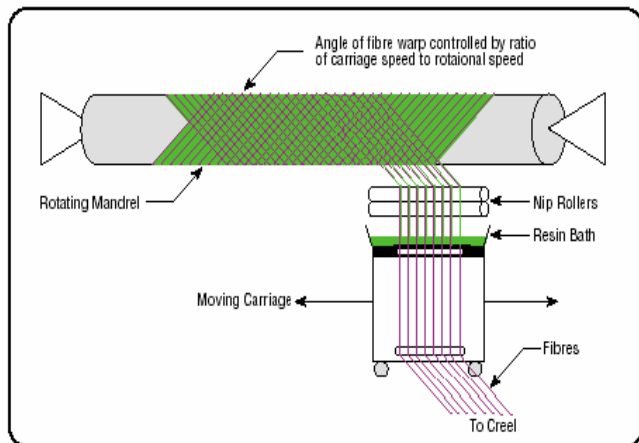

Figure 2. Schematic sketch of filament winding process

since it follows a self-stable trajectory.[1]

3.   DESIGN PROCEDURE

The design of composite structures, unlike that of metals, goes hand in hand with the design of the material system.

Hence, it is required that the selection of the materials and process option for various parts of the casing is done simultaneously. The casing is an axi-symmetric thin shell and during normal operating condition it is predominantly under tensile stress. These stresses vary along the axis of the casing. Filament winding is an obvious choice to develop the casing as it provides an efficient netting system of fibers /roving, in which the benefit of variability of directional strength is utilised.

3.1 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)   Structure obeys Hooke's law.
(v)   The fibers are straight and continuous.

3.2 Casing Design

The composite pressure vessel comprises the cylinder, end domes and the polar bosses fixed at the pole openings. As we progress from the junction towards the composite pole opening on the end dome, at a certain point the meridonial radius of curvature must change sign. This point on the dome is called the inflection point (r_i), and is arrived at by the formula $\phi_I = \tan^{-1}(\sqrt{2})$, $\phi_I = 54.2°$, Geodesic angle of winding at the point of inflection[5] .To avoid reverse curvature the iterative process is discontinued just before the point of inflection and the contour up to the pole opening is obtained by introducing an arc of a circle or frustum of a cone. Care is taken to see that tangency constraint is maintained at all transition points.

3.3 Material Properties

Filament winding is possible either with tapes or with roving with wet resin system. Casing design calls for material with high specific strength and specific stiffness so as to keep the inert mass of the casing to a minimum. Material characterization of composites includes determination of all effective properties over sufficiently large volume to represent the composite which are statistically reproducible. Material characterization of Carbon/Epoxy is done by using filament winding and Matched die mould technique.

Mechanical properties and physical properties like volume fractions and density of various configurations as per the ASTM standards are determined. The properties of CarbonT300/LY556+HT972 are given in Table 1.

3.4 Mandrel

A mandrel is required to wind the filament on its surface and thus develop the thickness of the structure. The different

Table 1. Material characterisation of carbon T300/Epoxy resin.

Property	ASTM test method	Experimental values of Carbon T300/(Epoxy resin(LY556/HT972))
Strength, (Gpa)		
1. Longitudinal ($\theta = 0°$)		
Tensile	D 3039	1.2
Compressive	D 3410	0.6
2. Transverse ($\theta = 90°$)		
Tensile	D 3039	0.017
3. Shear Strength ($\theta = \pm 45°$)	D 3518	0.04
Modulus, (Gpa)		
1. Longitudinal ($\theta = 0°$), E1	D 3039	144
2. Transverse ($\theta = 90°$), E2	D 3039	6.5
3. Shear strength ($\theta = \pm 45°$)	D 3518	5.6
Density, gm/cc	D 3039	1.35
Major Poisson's ratio	D 3039	0.21
NOL Ring test, GPa	D 2291	0.975
Volume fraction	D 3171	0.51

types of mandrels are collapsible mandrels, soluble mandrels and lost mandrels. In the lost mandrel technique, a cast liner is used as a mandrel, which after winding and subsequent curing becomes an integral part of the casing. Generally, it is extensively used for air/gas bottles. Collapsible metallic mandrel is one of the popular mandrel techniques used for winding of casing. However, it does not give any flexibility to the designer for subsequent changes in respect of the geometry of the casing. The soluble mandrel consists of a central drive shaft together with a number of sand discs. This technique allows one to have a lighter mandrel and also the flexibility of design changes in the casing geometry as POP layer can be cast on the sand mandrel.

3.5 Design Loads

Design driver for the proper casing is the internal pressure (Maximum expected operating pressure)[5]

Proof pressure = 1.125 * MEOP

Design pressure = 1.25 * MEOP

3.6 Winding condition

The hoop components of the helical layers are not sufficient to cover the hoop reinforcement requirement. This coupled with the fact that hoop stress is twice of the longitudinal stress for a pressure vessel calls for the application of hoop windings. Another issue to be considered here is that hoop winding is not possible at the domes. Although the higher helical thicknesses near the pole openings take care of the hoop stresses, the helical thicknesses at the dome near the junction are inadequate to provide sufficient cover to the hoop stresses. Accordingly, additional layers (doily) of high strength fabric are laid-up interspersing the helical layers from around the cylinder-to-dome transition to the inflection point at each dome. Thus, helical winding, together with hoop winding, is the processing technique adopted for the realization of the casing. The angle of winding at various points on the end domes (geodesic path) are obtained by using the well known Clairut theorem $r \sin \phi$ = constant, ϕ is the winding angle between a filament and a meridian line in a point on the surface and r is the radius at different stations, where the cylinder radius is the maximum radius and pole radius is the minimum radius.

3.7 Thickness calculation

The cylinder of the filament wound pressure vessel was basically composed of helical and hoop layers whereas the end domes comprise helical and doilies. Doily is a planar reinforcement applied to local areas to provide additional strength, usally in hoop direction. Since it is not possible to wind hoop layers on the end domes directly by filament winding technique, an additional layer either an unidirectional fabric or drum wound hoop layers are developed and placed on the end domes. The preliminary design is performed using netting analysis methods to address the inner pressure loading. Netting analysis assumes that the fibers provide all of the stiffness and strength in the cylinder. This assumption is not only conservative but also an excellent basis for quick calculation of composite thickness. From netting analysis[5].

$$t_{helical} = PR/(2\sigma_{f\phi}) \ (\cos^2 \phi \cos \beta) \tag{1}$$

$$t_{hoop} = PR(1-(\tan^2\phi)/2)/(\sigma_{fH}) (\cos \beta) \tag{2}$$

$$t_{doily} = PR \ (1-(\tan^2\phi)/2)/(\sigma_{fH}) (\cos \beta) \tag{3}$$

$$SR = \text{Stress ratio} = \sigma_{f\phi}/\sigma_{fH} = (t_{hoop})/(t_{helical}) \tag{4}$$

To prevent the failure in the dome or by boss blowout, the pressure vessels were designed with 0.6 to 0.8 stress ratio.

Aditionally, assuming that each filament crosses the equator and all other parallel circles in the dome an equal number of fibers, that is, the filaments do not terminate or double back, one finds that

$$t(2 \pi r) \cos \phi = t_c (2 \pi r_c) \cos \phi_c = \text{constant} \qquad (5)$$

where t, r, ϕ respectively, denote the shell thickness, radius and winding angle of a parallel circle plane of Z=constant.[8]

3.8 Ply sequence

The plies are so arranged as to maintain symmetry of the plies with respect to the midplane. A balanced symmetry is the best option for the axi symmetric structures because the loading in a particular plane does not cause deformations in other planes. The filament thickness of 0.3mm is assumed in this study. The number of helical plies and hoop plies are calculated based on Eqns (1) and (2).

Assume the number of helical layers and the thickness of the hoop fiber to be constant. The helical layers are continuous from one pole opening to the other pole opening, and as such the number of helical layers is constant at each station. Based on the hoop thickness at each station, the numbers of hoop layer are found. Thus the number of hoop layers varies from station to station.

Doilies as hoop layers are placed on the end domes from the cylinder-end dome junction to the pole openings. These doilies can also withstand the bending loads at the junctions. The best practice is to lay the hoop layers as the outer layers in order to give consolidation effect on the helical layers. If possible it is better to put helical and hoop as alternate layers. The structure can be designed such that the failure takes place in the cylinder zone and in the hoop failure mode. The ply sequence for a particular structure is shown in Fig 3. In most cases a hoop failure is preferred since these failures are primarily affected by membrane loading which is more predictable with less scatter in strength. Helical failures are strongly affected by the bending loads present from the discontinuities at the tangent line and at the polar boss regions. Hence design stresses for the helical fibers are almost always selected lower than hoop fiber allowable[5].
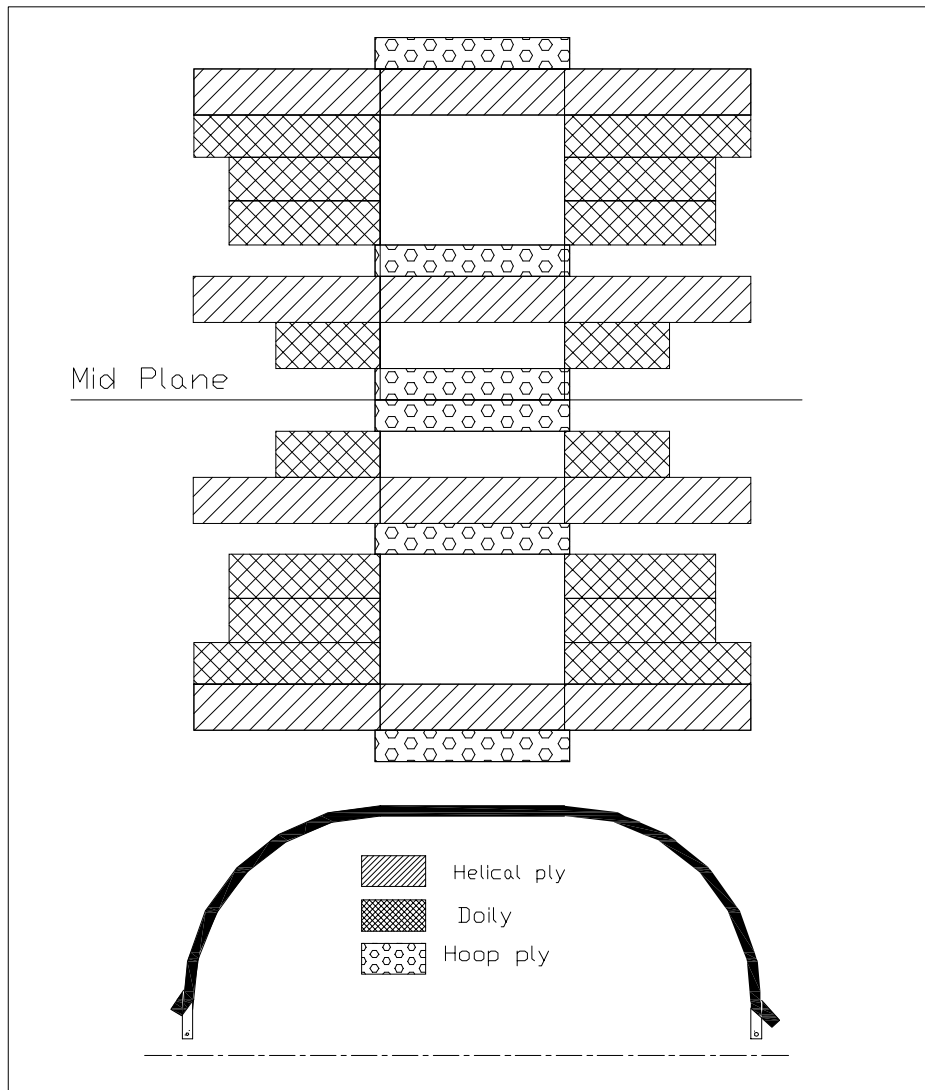

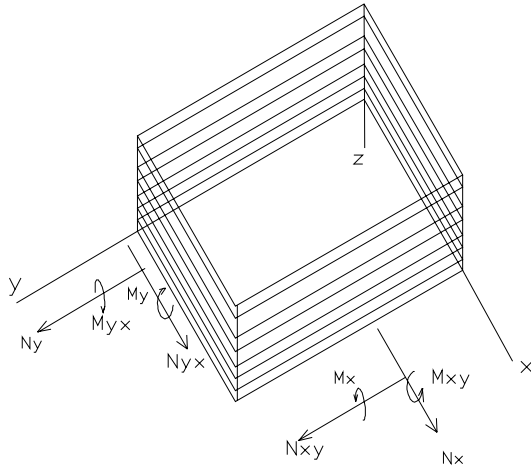**Figure 3. Balanced symmetric ply sequence of shell**

Figure 4. Stress resultants of laminated plate.

4. ANALYSIS OF THE PRESSURE VESSEL

Classical Lamination Theory (CLT) is the simplest method used for the analysis of the structure. The most important limitation of the CLT is that each ply is assumed to be in a state of plane stress and that interlaminar stresses are neglected. The lamina stress–strain Fig 4 relations are given as[3]

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \zeta_{xy} \end{Bmatrix}_k = \begin{Bmatrix} \overline{Q11} & \overline{Q12} & \overline{Q16} \\ \overline{Q12} & \overline{Q22} & \overline{Q26} \\ \overline{Q16} & \overline{Q26} & \overline{Q66} \end{Bmatrix}_k \times \begin{Bmatrix} \varepsilon_x^o & + & Zk_x \\ \varepsilon_y^o & + & Zk_y \\ \gamma_{xy}^o & + & Zk_{xy} \end{Bmatrix}$$

The force per unit length, N_x, is given by

$$N_x = \sum_{K=1}^{N} \left\{ \int_{Zk-1}^{Zk} (\sigma_x)_k \, dZ \right\} \quad (7)$$

The force per unit length, N_y, is given by

$$N_y = \sum_{K=1}^{N} \left\{ \int_{Zk-1}^{Zk} (\sigma_y)_k \, dZ \right\} - (8)$$

The moment per unit length, M_x is given by

$$M_x = \sum_{K=1}^{N} \left\{ \int_{Zk-1}^{Zk} (\sigma_x)_k \, ZdZ \right\} - (9)$$

The laminate extensional stiffness's (A_{ij}), Laminate coupling stiffness's (B_{ij}) and laminate bending stiffness's (D_{ij}) are given as follows using ref. 3

$$A_{ij} = \int_{-t/2}^{t/2} (\overline{Q_{ij}})_k \, dZ$$

$$B_{ij} = \int_{-t/2}^{t/2} (\overline{Q_{ij}})_k \, ZdZ$$

$$C_{ij} = \int_{-t/2}^{t/2} (\overline{Q_{ij}})_k \, Z^2 dZ$$

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{Bmatrix} A & B \\ B & D \end{Bmatrix} \begin{Bmatrix} \varepsilon^o \\ k \end{Bmatrix} \quad (10)$$

where subscripts i, j = 1, 2 or 6

where t = laminate thickness as shown in Fig 5; $(\sigma_x)_k$= stress in the kth lamina

ε^o = midplane strain; k = curvature

For a balanced symmetric laminate, $B_{11} = B_{22} = B_{66} = 0$ and $A_{16} = A_{26} = 0$

The external loads are, $N_{xy} = M_x = M_y = M_{xy} = 0$

For cylinder: $N_x = Pr/2$; $N_y = Pr$

For Hemispherical dome [1]: $N_x = Ny = Pr/(2*\cos \beta)$

4.1 Progressive Failure Analysis

Failure is addressed wrt that of a unidirectional lamina considering it as a part of a composite orthotropic laminate. Strength of a lamina is the basic aspect considered for the strength and failure analysis of a laminate. The strength of the lamina is directional dependent. The lamina failure criterion can either be with independent failure mode where the onset as well as the mode of failure can be predicted or the interaction failure criterion where only the onset of failure is predicted[11].

Failure in a composite is initiated due to the following:
(a) Fiber-dominated failure (breakage, micro-buckling, dewetting)
(b) Bulk matrix dominated failure (cracking, voids)
(c) Interface/flaw-dominated failure (crack propagation, edge delamination).
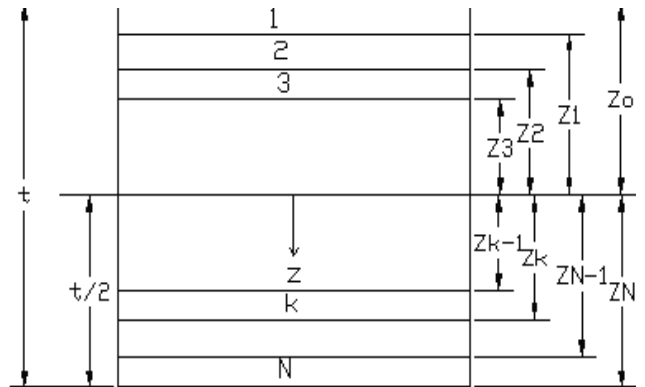

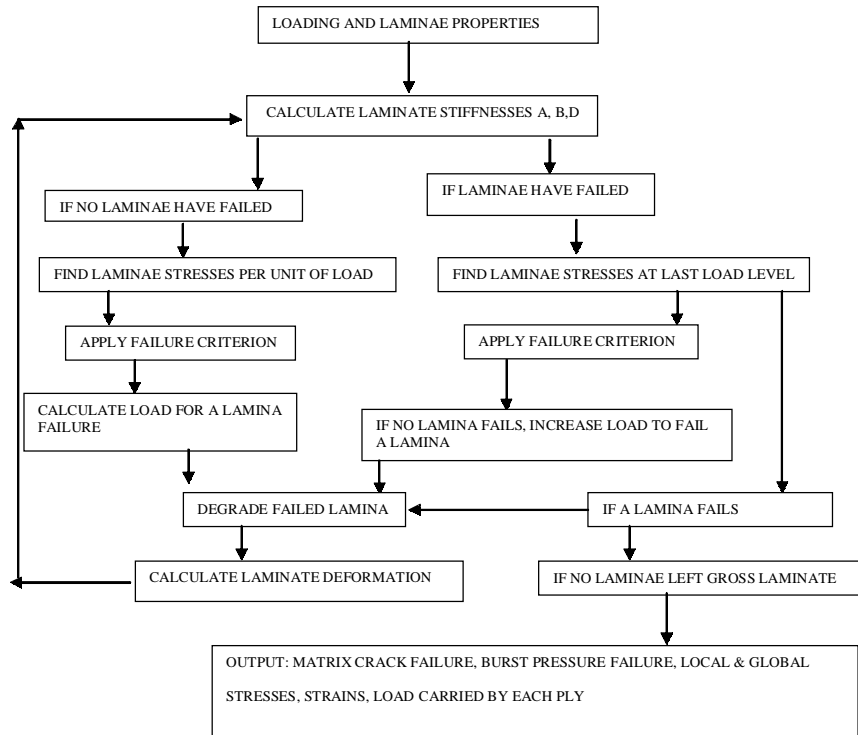**Figure 5. Laminated plate geometry and ply numbering system.**

Figure 6. Analysis of laminate strength and load-deformation behavior.

The failure of a lamina in a laminate, i.e., the first ply failure (FPF) does not necessarily signify failure of the structure, as the failure of fiber reinforced plastic laminate is gradual and progressive. When a particular lamina fails in a laminate, a redistribution of stress takes place in the remaining lamina. The laminate can be considered failed when the maximum load level is reached following a multilayer failure, i.e., the ultimate laminate failure (ULF). It is therefore important to study the behavior of the laminate after failure has occurred in a lamina until the laminate fails totally so that the load carrying capacity of the laminate is determined.

4.2 Solution Procedure

The proposed analysis is performed using the code, SHELLSOLVER developed based on CLT.

The concept of strength ratio is applied to all failure theories.Strength ratio is the ratio of maximum load that can be applied to the load applied.It gives the information about how much load can be increased if the lamina is safe, or how much load should be decreased if the lamina has failed. The overall procedure of laminate-strength analysis, which simultaneously results in the laminate load-deformation behavior, is shown in Fig. 6.

The interpretation of the results depends on the failure criterion adopted. The following four failure theories are considered representative and are more widely used[3]:
(1) Maximum stress theory.
(2) Maximum strain theory
(3) T Sai-Hill failure theory
(4) T Sai-Wu failure theory[11].
The first two failure theories are more efficient in the

case of isotropic materials and better equipped when failure modes are predictable. T sai-Hill criterion takes strain energy into consideration and is good for orthotropic material systems. However, it assumes individual laminas as isotropic. On the other hand, Tsai-Wu criterion takes strength tensors into consideration and is applicable to a more general case of anisotropy material system. Also T sai-Wu criterion can distinguish between tensile and compressive strengths. The design philosophy (netting theory considered along with stress ratio) of the composite pressure vessel leads to tensile failure of hoop fibers. The procedure for the proposed analysis is performed in the following steps[13]:

Step 1: Initially consider 1MPa pressure and run the program.

Step 2: Check the Strength ratio (SR) for longitudinal, transverse and shear directions for all theories of failure.

Step 3: If SR >1, then the lamina is safe and the applied stress can be increased by a factor of SR. If SR<1, the lamina is unsafe and the applied stress needs to be reduced by a factor of Sr. A Value of Sr=1 implies the failure load.

Step 4: If lamina has failed, degrade the material properties by 90 % in the transverse direction.

The Load carried by each layer for the entire shell, global and local stress-strains for the shell, matrix crack failure and burst pressure values at various positions of the shell can be computed by the above method.

5. RESULT

A composite pressure vessel of length 673.2mm (pole to pole), diameter 350mm and 160mm pole opening diameter

is considered for the study. The MEOP of 9.6MPa (96bar) is used in designing the structure. CarbonT300/ LY556+HT972 is used for the development of the entire structure. The volume fraction of the composite is 0.51.Hoop stress of 1200MPa determined experimentally by NOL ring test is used for the hoop strength. Considering 0.8 stress ratio, helical strength of 960MPa is used for determing the helical thickness. The angle of winding from Clauirt's principle is computed to be 27.2^0 on the cylindrical zone and the angle of the filament at the pole opening is 90^0 as shown in Fig. 8.The thickness of the shell along the meridonial cut for the composite shell is shown in Table 2. A balanced symmetric ply sequence is designed for the shell. The number of helical layers and the thickness of the hoop layer are maintained constant in the design of the shell.Consider

4 helical layers continuously wound from one pole to other pole opening. The number of hoop layers varies along the longitudinal axis as shown in Table 3. A constant hoop thickness of 0.3mm is maintained. The burst pressure values, matrix cracking, load carrying capacity of the plies in both longitudinal (N_x) and circumferential (N_y) directions along the shell are indicated in Fig. 7-11, respectively.

6. DISCUSSIONS

It is very important to characterize the material and determine the mechanical and physical properties of the FRP before one proceeds to design. Composites are combination of different constituent materials; the characterization of composites involves characterization of individual constituent materials, characterizing them in their different forms and

Table 2. Details of thickness of the shell along the meridonial cut of the shell

Axial coordinate (mm)	Winding angle (deg)	Slope of the contour (deg)	Radius (mm)	Helical thickness (mm) Reqd	Helical thickness (mm) Prvd	Hoop thickness (mm) Reqd	Hoop thickness (mm) Prvd	Doily thickness (mm) Reqd	Doily thickness (mm) Prvd	Total thickness provided (mm)
0.0	90	63	80	35.2	25.0	0.0	0.0	0.0	0.6	25.6
10.6	54.7	56	98	5.8	5.2	0.0	0.0	0.0	0.6	5.8
29.5	41.3	46	121.3	3.2	3.1	0.0	0.0	1.5	1.8	4.9
37.9	38.2	42	129.5	2.4	2.2	0.0	0.0	2.3	2.4	4.6
68.8	31.7	30	151.9	1.7	1.7	0.0	0.0	2.3	2.4	4.1
110.2	28.3	16	169	1.4	1.44	0.0	0.0	2.3	2.4	3.8
155.6	27.2	0	175	1.38	1.38	1.52	1.8	0.0	0.0	3.2
326.1	27.2	0	175	1.38	1.38	1.52	1.8	0.0	0.0	3.2
517.6	27.2	0	175	1.38	1.38	1.52	1.8	0.0	0.0	3.2
565.2	28.3	-16	169	1.7	1.7	0.0	0.0	2.3	2.4	4.1
604.5	31.7	-30	151.9	2.4	2.2	0.0	0.0	2.3	2.4	4.6
635.4	38.2	-42	129.5	2.4	2.2	0.0	0.0	2.3	2.4	4.6
643.7	41.3	-46	121.3	3.2	3.1	0.0	0.0	1.5	1.8	4.9
662.6	54.7	-56	98	5.8	5.2	0.0	0.0	0.0	0.6	5.8
673.2	90	-63	80	---	25.0	0.0	0.0	0.0	0.6	25.6

Table 3. Details of number of plies and ply sequence of the shell.

Axial coordinate (mm)	Radius (mm)	Winding angle(deg)	Thickness provided (mm)	No. of plies provided Helical	No. of plies provided Hoop	No. of plies provided Doily	Ply sequence
0.0	80	90	25.6	4	0	2	$[\pm\alpha/90/\pm\alpha]_S$
10.6	98	54.7	5.8	4	0	2	$[\pm\alpha/90/\pm\alpha]_S$
29.5	121.3	41.3	4.6	4	0	6	$[\pm\alpha/90/90/90/\pm\alpha]_S$
37.9	129.5	38.2	4.6	4	0	8	$[\pm\alpha/90/90/90/\pm\alpha/90]_S$
68.8	151.9	31.7	4.1	4	0	8	$[\pm\alpha/90/90/90/\pm\alpha/90]_S$
110.2	169	28.3	3.8	4	0	8	$[\pm\alpha/90/90/90/\pm\alpha/90]_S$
155.6	175	27.2	3.2	4	6	0	$[90/\pm\alpha/90/\pm\alpha/90]_S$
326.1	175	27.2	3.2	4	6	0	$[90/\pm\alpha/90/\pm\alpha/90]_S$
517.6	175	27.2	3.2	4	6	0	$[90/\pm\alpha/90/\pm\alpha/90]_S$
565.2	169	28.3	4.1	4	0	8	$[\pm\alpha/90/90/90/\pm\alpha/90]_S$
604.5	151.9	31.7	4.6	4	0	8	$[\pm\alpha/90/90/90/\pm\alpha/90]_S$
635.4	129.5	38.2	4.6	4	0	8	$[\pm\alpha/90/90/90/\pm\alpha/90]_S$
643.7	121.3	41.3	4.6	4	0	6	$[\pm\alpha/90/90/90/\pm\alpha]_S$
662.6	98	54.7	5.8	4	0	2	$[\pm\alpha/90/90]_S$
673.2	80	90	25.6	4	0	2	$[\pm\alpha/90/90]_S$
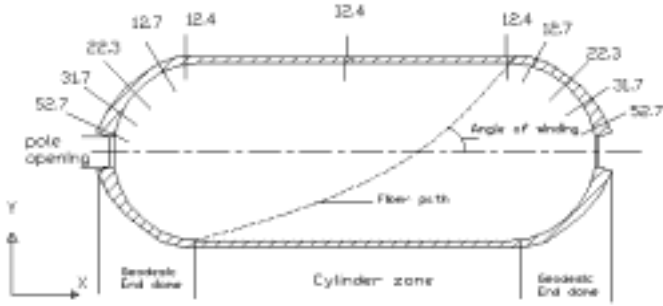
Figure 7. Burst pressure at various stations of the shell, MPa.

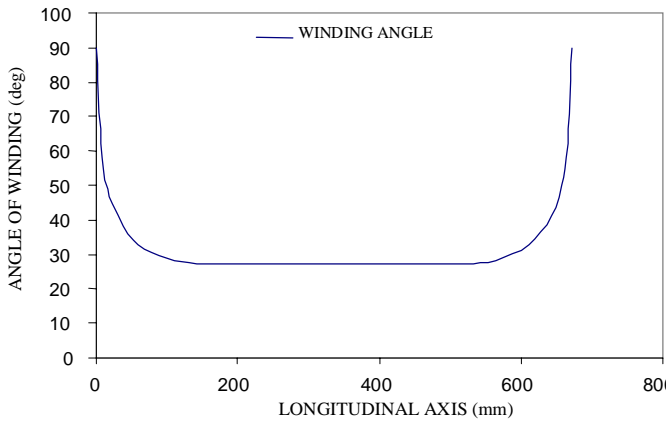**Figure 9. Matrix crack failure along the longitudinal axis.**

Figure 8. Winding angle along the meridian for the Composite shell.

characterization of final composite material of different combinations. Added to these, there are different production process and matrix curing variables which affect individual properties. All these factors reflect the wide scope and complexities involved in characterization of composites. The individual constituent material characterization is a necessary requirement but is not sufficient since the given reinforcement and resin combination can give different composite properties depending upon the composite construction and fabrication variables, like, fiber orientation/
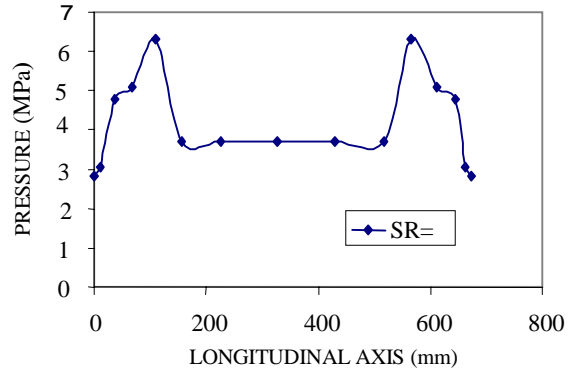
laminate stacking sequence, reinforcement/resin ratio, manufacturing process, etc. Thus composite material characterization is required to be done in addition to individual constituents. This can be done for individual laminate, i.e., uni-directional properties or for oriental plied laminates. The values determined as per ASTM standards are observed to be close to the manufacturers' data.

7. CONCLUSIONS

In a ply stacking sequence if hoop fibers are placed inside the helical fibers, burst pressure of 13.2 MPa, in the cylindrical zone is computed in the failure analysis. On the other hand when hoop fibers are placed outside the helical layers, burst pressure of 12.4 MPa is computed. Negligible variation is noticed in the above cases; however for all practical cases it is important to have hoop fibers outside the helical fibers to get better consolidation effect on helical fibers. When no hoop layers are inside of the helical, the helical tends to pull away from the laminate in a highly localized mode of failure, called transverse fiber pull out. Hence it is desirable to have alternate hoop and helical layers with hoop layers as the top most and the bottom most layers. Burst pressure value of 12.4MPa is computed in the cylindrical zone. This value increases as one moves towards the pole openings. The end domes take larger
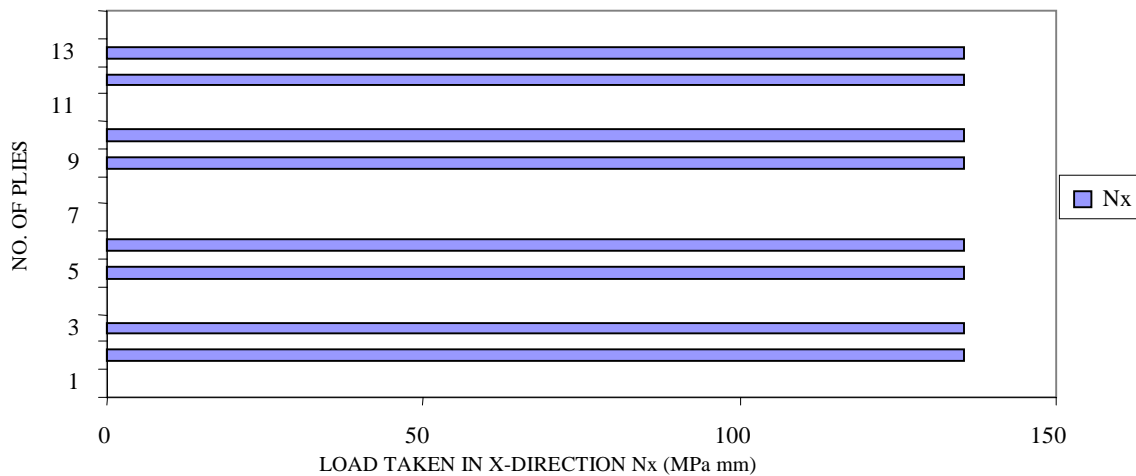

Figure 10. Load carried by each ply on the cylindrical zone.
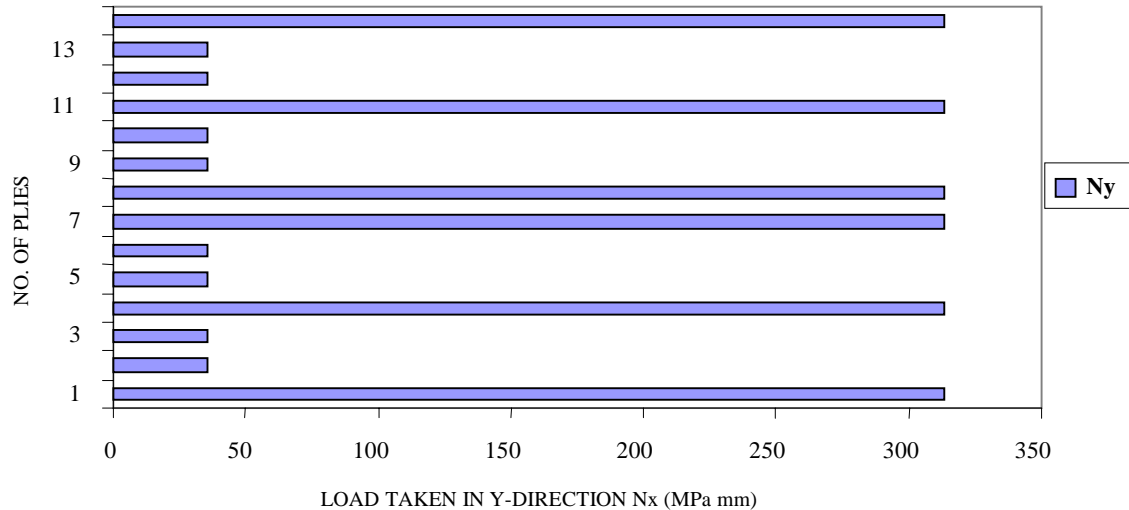
Figure 11. Load carried by each ply on the cylindrical zone.

pressure values. Composites are very weak in transverse direction, matrix crack occurs at lower pressure values. This means that the fibers in the filament wound structure carry most of the applied pressure load and the matrix makes a small contribution to supporting the internal pressure. The first matrix cracking occurs at about 2.8MPa near the poles. Hoop fibers happen to fail first in the transverse direction through out the shell. In case of fiber breakage, failure occurs at the helical layers in the cylindrical zone. Here the fiber breakage is considered as the burst pressure value of the shell. The load taken by each layer on the cylindrical zone is studied as N_x and N_y. In case of X-direction/longitudinal direction, hoop fibers take 0 MPa-mm and the helical fibers hold a load of 135.6 MPa-mm. Whereas in Y-direction/circumferential direction, Hoop fibers carry 313.9 MPa-mm and helical fibers share only 35.82 MPa-mm. It is understood that the hoop fibers contribute maximum load bearing capacity only in Y-direction whereas the helical fibers can contribute in both the directions. Further, depending on the angle of the helical fibers, the load carrying capacity varies in X and Y directions.

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