Design and Analysis of Composite Pressure Vessel

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Abstract: ***Cylindrical pressure vessels are widely used for commercial, under water vehicles and in aerospace applications. At present the outer shells of the pressure vessels are made up of conventional metals like steels and aluminium alloys. The payload performance/ speed/ operating range depends upon the weight. The lower the weight the better the performance, one way of reducing the weight is by reducing the weight of the shell structure. The use of composite materials improves the performance of the vessel and offers a significant amount of material savings. Moreover, the stacking sequence is very crucial to the strength of the composite material. This Project involves various objective functions such as stiffness, buckling load and Weight at each level of optimization. Usually composite pressure vessels are designed for minimum mass under strength constraints. A graphical analysis is presented to find optimum fiber orientation for given layer thicknesses. In the present work, an analytical model is developed for the Prediction of the minimum buckling load with / without stiffener composite shell of continuous angle ply laminas (±45°, ±55°, ±65°, ±75°, ±85°) for investigation. Comparisons are made for two different approaches i.e. the finite element model and the theoretical model. A 3-D finite element analysis is built using ANSYS-14.5 version software into consideration, for static and buckling analysis on the pressure vessel.***

Keywords: Composite material, Shells, Fiber orientation, Layer thickness, Stiffeners, Critical Pressure and Buckling.

1. Introduction

Pressure vessels are important because many liquids and gases must be stored under high pressure. Special emphasis is placed upon the strength of the vessel to prevent explosions as a result of rupture. The assemblies, containing thin shells, find wide use in the modern engineering, especially in ships, aircraft and spacecraft industry.

In the present work, an analytical model is developed for prediction of optimum fiber orientations for given layer thicknesses, and mainly minimum buckling load for with or without stiffener composite shell under multi-layered continuous angle-ply loading condition is investigated.

For the sake of analysis, Solid element (Solid 46) is used and analysis was carried out with the aid of the commercial package, ANSYS-14.5. Due to the expensive nature of composite cylinder test specimens, experimentation could not be performed.

The shell whose wall thickness is small compared to the radius of curvature and the corresponding radius of twist is known as thin shell. Plate and shell structures are used in a lightweight load bearing structural parts for various modern aerospace, offshore, nuclear, automotive, and civil engineering structures. These shells are subjected to compressive loads.

Composites are considered to be combinations of materials differing in composition or form on a macro scale. The constituents retain their identities in the composite i.e. they do not dissolve or otherwise merge completely into each other although they act in the idea of a composite material is not a new or recent one concert. In nature, one can find out many composite materials, for example wood is a fibrous natural composite (cellulose fibrous in lignin matrix).

One of the most common methods to manufacture matrix composites is called the hot pressing method. Glass fibers in continuous tow are passed through slurry consisting of powdered matrix material, Solvent such as alcohol, and an organic binder as shown in fig 1.2. The tow is then wound on a drum and dried to form Prepreg tapes. The Prepreg tapes can now be stacked to make a required laminate; heating at about 932°F (500°C) burns out the binder. Hot pressing at high temperatures of about 1832°F (1000°C) and pressures of 7 to 14 Mpa is done.

Design analysis of any composite structural element would require a complete knowledge of properties of individual layers. Each layer is a continuous angle-ply composite laminate consists of parallel fibers embedded in a matrix. Several unidirectional layers can be stacked in a specified sequence of orientation to fabricate a laminate that will meet design strength and stiffness requirements.

The volume fractions are exclusively used in the theoretical analysis of composite materials. Most manmade composite materials made from two materials, these are a reinforced material called fiber and a base material called matrix. For example in concrete columns the concrete is base material which is called matrix and the iron rods come under fibers for reinforcement.

There exist three types of composites.

1) **Fibrous Composites:** It consists of fibers of one material in a matrix material of another material.
2) **Particulate Composites:** These are composed of particles of one material in a matrix of another material.
3) **Laminate Composites:** These are made of layers in which fibers and matrix are made of different materials, including the composites.

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The purpose of matrix is to transfer loads and protect them against environmental attack and damage due to handling. Based upon the properties required, the matrix and fiber materials are selected.

Characteristics of Composites

Fiber reinforced composite materials offer a combination of strength and elasticity that are better than conventional metallic materials. Composites are superior because of their low specific gravities, high strength-weight ratios and high modulus-weight ratios. Structural materials such as steel and aluminium alloys are considered isotropic since they exhibit nearly equal properties irrespective of the direction of measurement. In case of composites, properties depend strongly on the direction of measurement. Many fiber reinforced composites have high internal damping which leads to better vibration energy absorption within the material and results in reduced transmission of noise and vibrations to neighbouring structures. There are several distinct characteristics that make composites different from many conventional materials.

Applications of Composite Materials

The aircraft industry uses composites to meet performance requirements beyond the capabilities of metals. The Boeing 757, for example, uses approximately 760ft³ of composites in the body and wing components, with an additional 361 ft³ used in rubber, elevator, edge panels and tip fairings. The B-2 bomber contains carbon and glass fibers, epoxy resin matrices, and high temperature polyimide as well as other material in more than 10,000 composite components. Composites are also used in race cars, tennis rackets, golf clubs, and other sports and leisure products. Few more applications are given as below.

- Aircraft and military applications
- Space applications
- Automotive applications
- Sporting goods applications
- Marine applications Medical applications
- Pressure Vessels

Lamina and Laminate Analysis

A lamina (considered a unidirectional composite) is characterized by having all fibers (either a single ply or multiple plies) oriented in the same direction. This model allows one to treat lamina as an orthotropic material. A lamina is a collection of laminates arranged in a specified manner as shown in fig.1.3. Adjacent lamina may be of the same or different materials and their orientations with respect to a reference axis may be arbitrary.

Mathematical Modelling

The mathematical modelling of composite shells involves the theory of lamina and laminate analysis. Laminate is a collection of lamina arranged in specified manner. In order to analyze the response of a laminated composite, it is necessary to predict the behavior of individual lamina Composite laminates containing fiber reinforced thermosetting polymers do not exhibit gross yielding, yet they are also not classic brittle materials. Under a static tensile load, many laminates show non-linear characteristics attributes to sequential ply failures. The current design practice in aerospace industry, marine industries use the first ply failure approach. The crack appearing in the failed ply may make the neighboring plies susceptible to mechanical and environmental damage. The design criteria for fiber reinforced composite shell uses the same design criteria as those for metals. They are as follows:

1) Must sustain the ultimate design load in static testing.
2) Fatigue life must be equal or exceed the projected vehicle life.
3) Deformations resulting from the applications of repeated loads and limits design load must not interfere with mechanical operation of the system.

General Design Guide Lines

The principal steps in designing a composite laminates are

1) Selection of fiber, resign and fiber volume fraction.
2) Selection of optimum fiber orientation in each ply and the lamina stacking sequence.
3) Selection of number of plies needed in each orientation which also determines the final thickness of the component.

If the angle of ply laminates are used, the layers with +θ and – θ orientations should be altered instead of in clustered configuration. Thus for example an fourteen layer laminate with 7 of +θ orientations and 7 of -θ orientations should be designed as [+θ/ – θ / +θ / – θ]s instead of [+θ/ + θ / – θ / – θ]s or [+θ/ + θ / – θ / – θ]s.

Pressure Vessel with Torispherical Head

The torispherical head geometry is composed of two circular arcs, crown of radius Rd at the top and knuckle of radius Rk. This is fitted on the cylinder of radius Rc. With reference to Fig. 1.7, Od is the center of curvature of the crown and Ok is the center of curvature of the knuckle.

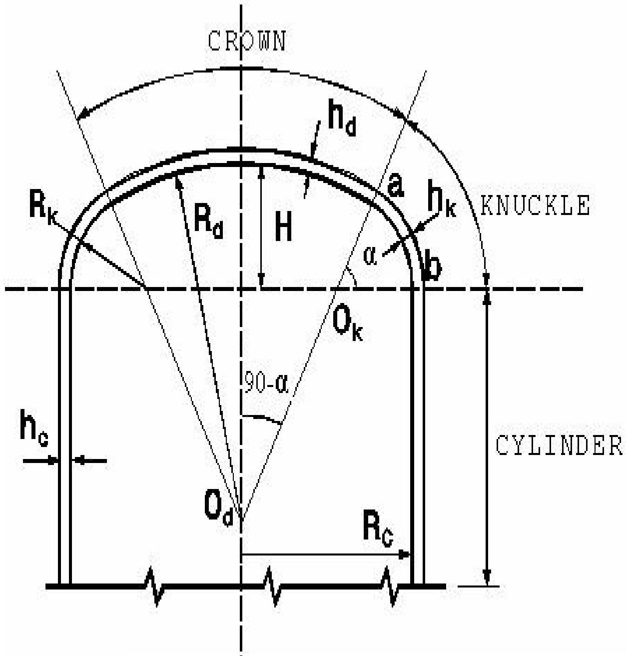

Figure 1.7: Geometry of a typical torispherical pressure vessel

The angle subtended by the knuckle at Ok is computed as:

$$\alpha = \cos^{-1}\left(\frac{R_c - R_k}{R_d - R_k}\right) \qquad (3.1)$$

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This ensures the continuity of slopes at 'a', the junction of crown and knuckle.

CATIA V5 R20:

CATIA-V5 is the industry's de facto standard 3D mechanical design suit. It is the world's leading CAD/CAM/CAE software, gives a broad range of integrated solutions to cover all aspects of product design and manufacturing. Much of its success can be attributed to its technology which spurs its customer's to more quickly and consistently innovate a new robust, parametric, feature based model.

Introduction to Finite Element Method

The finite element method is a numerical procedure for analyzing structures and continua. Usually problem addressed is too complicated to solve satisfactorily by classical analytical methods. The finite element procedure develops many simultaneous algebraic equations, which are generated and solved on a digital computer. The results obtainable are accurate enough for engineering purposes at reasonable cost. In addition it is an efficient design tool by which designers can perform parametric design studies by considering various design cases(different shapes, materials, loads , etc.,), analyze them and choose the optimum design . Hence the method has increasingly gained popularity among both researchers and practitioners.

Basic Steps of Finite Element Analysis

There are three basic steps involved in this procedure
1) Pre Processor (Building the model (or) Modelling)
2) Solution (Applying loads and solving)
3) Post Processor (Reviewing the results)

Solid 46 Element Description

SOLID46 is a layered version of the 8-node structural solid element designed to model layered thick shells or solids. The element allows up to 250 different material layers. If more than 250 layers are required, a user-input constitutive matrix option is available. The element may also be stacked as an alternative approach. The element has three degrees of freedom at each node: translations in the nodal x, y, and z directions as shown in Fig.1.11. One element per layer issue in Solid 46 by dividing a given into N imaginary sub-layers of same orientation and thickness = layer thickness / N. Solid46 is actually useful for modelling sand witched structures with thin layers.

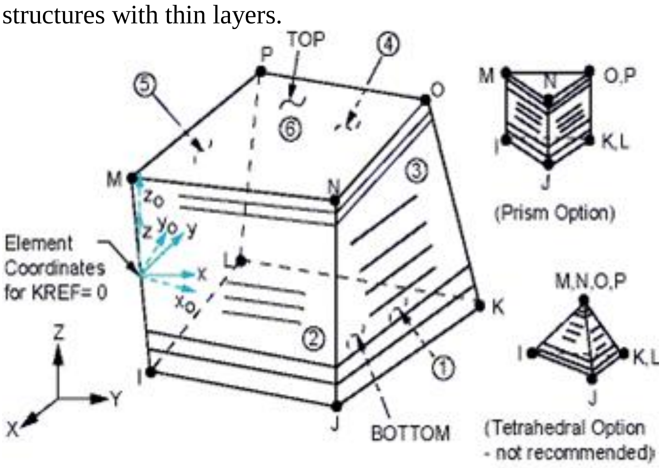

Figure 1.11: Geometry of Solid – 46 Elements

Analysis

The analysis of Steel Cylindrical pressure vessel with the composite cylindrical pressure vessel is done. In addition we would like to change the orientation of composite cylindrical pressure vessel in such a way that the thickness is 1mm with variants of 7 layers, 8 layers, 9 layers and 10 layers of composite allowed with an angle of 45^0,55^0,65^0,75^0 and 85^0. The results for the composite pressure vessel of 1mm with 7 layers and different angles of orientation are as shown below:

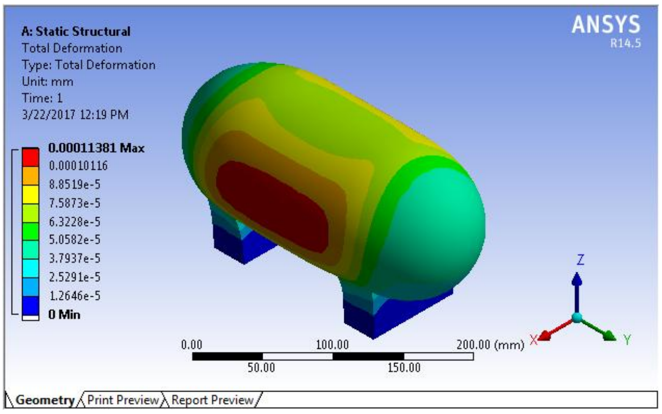

Figure shows the Total deformation of the pressure vessel formed with stain less steel material

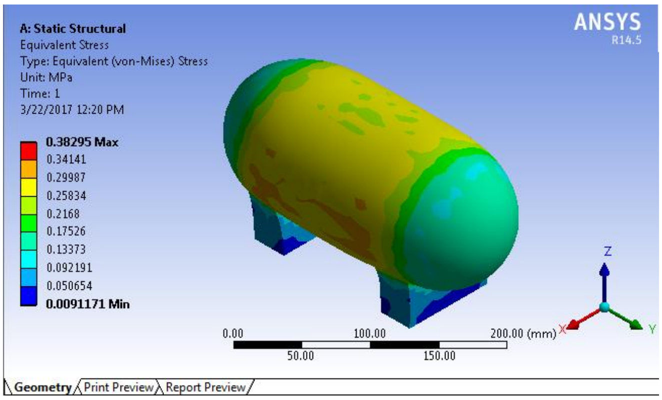

Figure shows the equivalent stress analysis on pressure vessel of stain less steel material

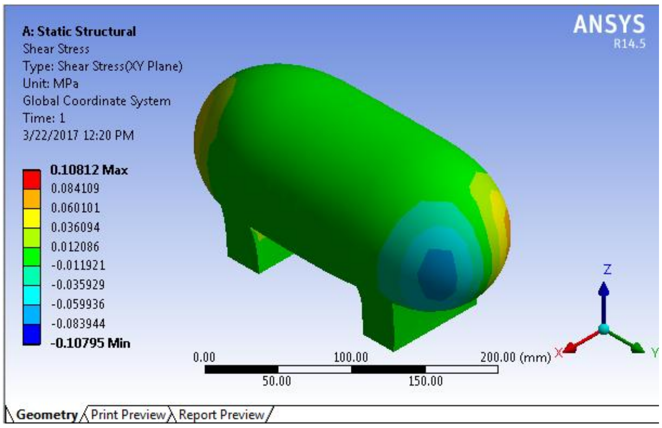

Figure shows the shear stress of pressure vessel of stain less steel material

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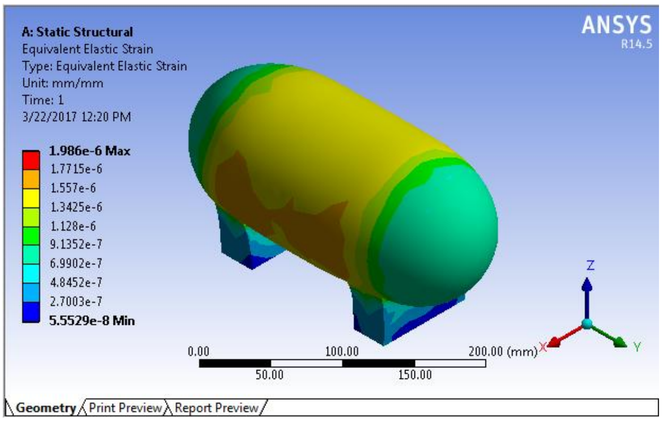

Figure shows the Equivalent Elastic strain of pressure vessel of stain less steel material

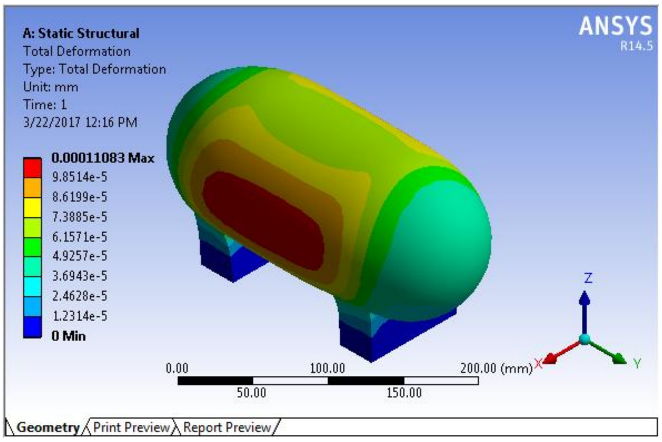

Figure shows the Total deformation of pressure vessel of Non-ferrous material

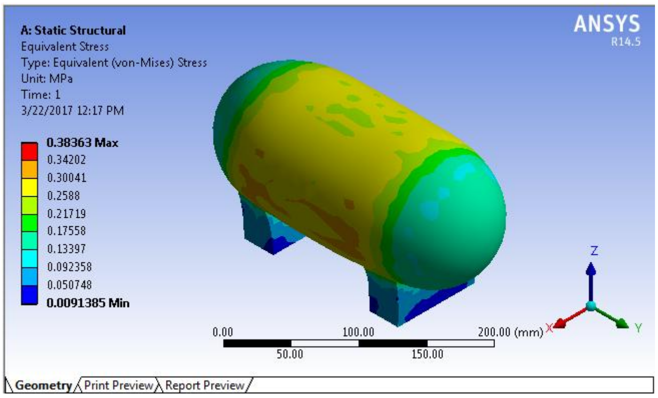

Figure shows the Equivalent stress of pressure vessel of Non-ferrous material

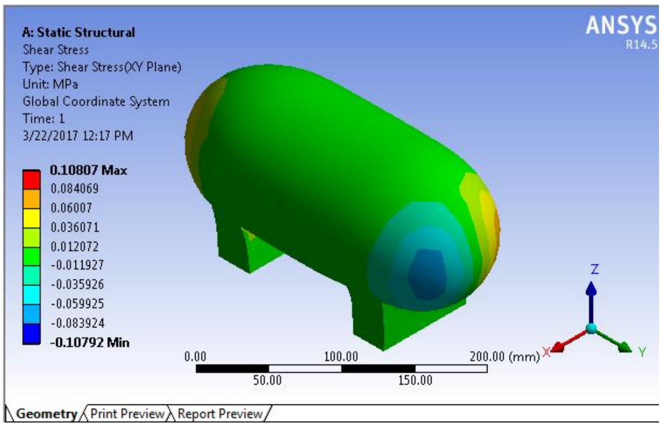

Figure shows the shear stress analysis of pressure vessel of Non-ferrous material

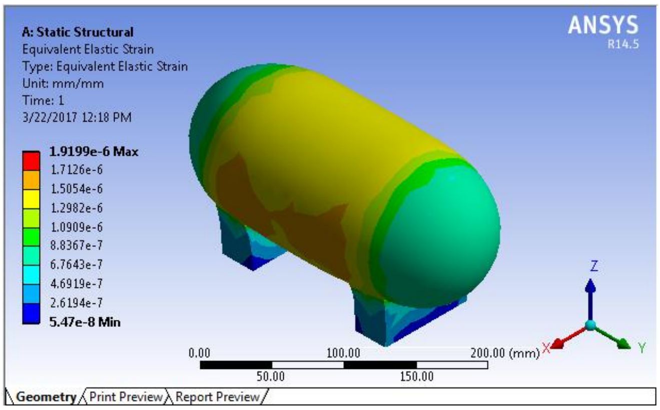

Figure shows the Equivalent Elastic strain of pressure vessel of Non-ferrous material

2. Tables

Comparison of Stainless Steel Material to Non-Ferrous material

	Stainless Steel Material	Non- Ferrous Material
Total deformation of the pressure vessel (mm)	0.00011381	0.00011083
Equivalent stress analysis on pressure vessel (MPa)	0.38295	0.38363
Shear stress of pressure vessel (MPa)	0.10812	0.10807
Equivalent Elastic strain of pressure vessel (mm/mm)	$1.986e^{-6}$	$1.9199e^{-6}$

2.1 Sections headings

Section headings come in several varieties:
1) Introduction
2) Literature survey
3) Methodology
4) Model and meshing
5) Result.
6) Conclusion

2.2 References

Sayman [3] studied analysis of multi-layered composite cylinders under hygrothermal loading. Mackerle (2002) gives a bibliographical review of finite element methods applied for the analysis of pressure vessel structures and piping from the theoretical as well as practical points of view. Xia et al. (2001) studied multi-layered filament-wound composite pipes under internal pressure. Xia et al. (2001) presented an exact solution for multi-layered filament-wound composite pipes with resin core under pure bending. Rao and Sinha (2004) studied the effects of temperature and moisture on the free vibration and transient response of multidirectional composites. A three-dimensional finite element analysis is developed for the solution.

Adali et. al. [4] gave another method on the optimization of multi-layered composite pressure vessels using an exact elasticity solution. A three dimensional theory for anisotropic composite cylinders subjected to axis symmetrical loading conditions was derived. The three dimensional interactive Tsai-Wu failure criterion was employed to predict the

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maximum burst pressure. The optimization of pressure vessels show that the stacking sequence can be employed effectively to maximum burst pressure. However Adali's results weren't compared to experimental testing and the stiffness degradation wasn't considered during analysis.

Önder et al. [5] studied the determination of burst failure pressures of composite pressure vessels by using finite element and analytical methods. They also investigated the comparison of filament winding angles of composite pressure vessels at different temperatures. Kam et al. (1997) and Chang (2000) investigated the first-ply failure in composite pressure vessels by using acoustic emission technique. They obtained close results between FEM and experimental methods.

S.Borazjani and S H Tang, [8] Finite element analysis was employed for investigating the structural behavior of pressure vessels. Aluminum alloy was utilized as the inside layer covered with Carbon/Epoxy fiber which was roving at different winding angles. FEA employed failure criteria such as Tsai-Wu, Tsai-Hill and maximum stress to predict the burst pressure, maximum shell displacement and determine the optimum winding angle. Results and discussions were resulted in the following findings: Based on Tsai-Wu and Tsai-Hill failure criteria, 550 winding angle was approved as the optimum winding angle due to its maximum burst pressure and minimum shell displacement. This optimum angle was in good correlation with the experimental results trend and the netting analysis. Determining burst pressure using maximum stress failure theory was lead to less conservative results and higher burst pressure due to estimating the burst pressure based on ultimate strength of Carbon/Epoxy fiber.

Literature reveals that:

- Most of the finite element analyses of composite pressure vessels are based on elastic constitutive relations and traditional thin-walled laminated shell theory.
- A Tsai-Wu failure criterion is regarded to be one of the best theories at predicting failure in composite material.

The present research focuses on:-

- Optimization of composite pressure vessels is done by changing the parameters of the composite materials including filament winding angle, lamination sequence, and material.
- Comparison of filament winding angles of composite pressure vessels
- Comparison of theoretical results with experimental

3. Equations

Elastic Properties of A Lamina

Longitudinal Modulus $E_{22} = \frac{E_f\, E_m}{E_m\, V_f + E_f\, V_m}$ - (3.2)

Transverse Modulus $E_{11} = E_f\, V_f + E_m\, V_m$ - (3.3)

Major Poisson's Ratio $\mu_{12} = \mu_f\, V_f + \mu_m\, V_m$ - (3.4)

Minor Poisson's Ratio $\mu_{21} = \frac{E_{22}}{E_{11}} \mu_{12}$ - (3.5)

Shear Modulus $G_{12} = \frac{G_f\, G_m}{G_f\, V_m + G_m\, V_f}$ - (3.6)

4. Theoretical Calculations

The Weight and volume fractions can be calculated using the following equations

a) Calculation of Volume fraction: The volume of fiber in a cured composite. The fiber volume of a composite material may be determined by chemical matrix digestion, in which the matrix is dissolved and the fibers weighed. Typical values for glass/epoxy and for graphite/epoxy, based upon the fiber type, are 55-67% fiber.

V_f = volume fraction of fibers = $\frac{\frac{W_f}{\rho_f}}{[\frac{W_f}{\rho_f}]+[\frac{W_m}{\rho_m}]}$ (3.7)

W_f = weight of fibers = $\frac{V_f\, \rho_f}{[V_f\, \rho_f] + [V_m\, \rho_m]}$ (3.8)

W_m = weight of matrix

ρ_f = density of fibers

ρ_m = density of matrix

$W_f = \frac{V_f\, \rho_f}{[V_f\, \rho_f] + [V_m\, \rho_m]}$ (3.8)

W_f = 0.65,

W_m = 0.35,

ρ_f = 2500,

ρ_m = 1611

$$V_f = \frac{\frac{W_f}{\rho_f}}{[\frac{W_f}{\rho_f}]+[\frac{W_m}{\rho_m}]} = \frac{\frac{0.65}{2500}}{[\frac{0.65}{2500}]+[\frac{0.35}{1611}]} = 0.55 m^3$$

V_m = 1.0 - 0.55 = 0.45 m^3

b) Calculation of Density: Density defined in a qualitative manner as the measure of the relative "heaviness" of objects with a constant volume. (Density = mass/volume). It is usually expressed in kg/m^3. The Density of the composite for the given volume fraction is

$$\rho_c = \rho_f\, V_f + \rho_m\, V_m \quad (3.9)$$

= 2500 x 0.55 + 1611 x 0.45 = 2100 Kg/m^3

The days are long gone when it was considered that the heavier the product better the quality. The light weight composite component makes more desirable to manufacturers, as well as consumers and workers. Composite materials include outstanding Strength, excellent durability, High heat resistance and significant weight reduction. The present work clearly emphasizes on the usage of composite materials in the production of cylindrical pressure vessels. Weight calculations have been carried out by varying the materials like conventional and composite materials, to find out the material that has minimum weight.

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Carbon fiber Composites are roughly quarter weight of the Standard Pressure Vessels of Steel Alloys.

Length (height "h") of the cylinder = 1030 mm

Diameter of the cylinder (d) = 670 mm
Thickness of the shell (t) = 10 mm
R - r = t
r = R – t
r = 335 – 10
r = 325 mm

Volume = Π r 2 h
= Π X (335^2 -3252) X 1030
= 21356546.86 mm3
= 21.356546 x 10^6 mm6
= 21.356546 x 10^{-3}

Density ρ = mass / Volume
Weight = m.g = ρ. v. g
Density of steel = 7.86 gm / cm3 = 7.86 x 10^3
m = ρ V = 7.86 x 21.356 x 10^{-3} = 167.858 kg

Glass Epoxy
2.1 x 103 x 21.356 x 10-3 = 44.847 kg

Carbon Epoxy
1.55 x 103 x 21.356 x 10-3 = 33.10 kg

Aramid Epoxy
1.32 x 103 x 21.356 x 10-3 = 28.189 kg

5. Conclusions

This project work involves the comparison of conventional steel and Composite material cylindrical pressure vessel under static loading conditions the model is preferred of in Catia V5 R20 and then analysis is perform through ANSYS 14.5 from the result obtained it will be concluded that the development of a composite cylindrical pressure vessel having constant cross sectional area, where the stress level at any station in the Composite pressure vessel is considered drop and rise due to the orientation of composite, has proved to be very effective. Taking weight into consideration, we can conclude that 7 layers give lesser weight. The results are found to be effective for the composite lamina for 45 ^{0} orientations. The Lamina stacking sequence is appropriate which is free from extension – bending, coupling which reduces the effective stiffness of the lamina, since the laminates are symmetric. Appropriate number of plies needed in each orientation and thickness of the shell is safe from static and buckling analysis is concerned.

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