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Design & Fe Analysis of Composite Pressure Vessel

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Abstract- This paper gives the information about the pressure vessel. Pressure vessel is a closed container designed to hold gases or liquids at a pressure substantially different from the atmospheric pressure. By comparing metallic and FRP (fiber reinforced plastic) pressure vessel. The metallic pressure vessels are having more strength but due to their high weight to strength ratio and corrosive properties they are least preferred in aerospace as well as oil and gas industries. These industries are in need of pressure vessels which will have low weight to strength ratio without affecting the strength .On the other hand FRP (Fiber reinforced plastic) composite materials with their higher specific strength characteristics will result in reduction of weight of the structure. E-Glass Filament-wound composite pressure vessels are an important type of high-pressure container that is widely used in the commercial and aerospace industries. On the other hand FRP composite materials with their higher specific strength characteristics will result in reduction of weight of the structure.

In this paper Finite element analysis of steel pressure vessel and FRP composite pressure vessel is carried out. On the basis of analysis it is found that steel pressure vessel has less strength than FRP pressure vessel and it is also concluded that the pressure inside the vessel can be reduced up to 75 % by replacing steel with FRP material. FRP material is available in various winding angle. Analysis is also carried out to find optimum fiber angle of FRP material used for pressure vessel.

Keywords: FRP, Pressure vessel, composite material, E-glass, Epoxy Resine

1. INTRODUCTION

A pressure vessel is defined as a container with a pressure differential between inside and outside. Damage of a pressure vessel has a potential to cause extensive physical injury and property damage so leak-proof design and manufacturing is important . Shape of pressure vessel may be spherical, cylindrical or cone shape. Spherical pressure vessel has more strength than other shape but its manufacturing is very complicated .

Material used for pressure vessel must be sufficiently ductile and tough. Its elongation is not less than 14% and its impact toughness is not less than 27J. Metallic pressure vessels are having more strength but due to their high weight to strength ratio and corrosive properties they are least preferred in aerospace as well as oil and gas industries. These industries are in need of pressure vessels which will have low weight to strength ratio without affecting the strength. Fiber reinforcement plastic composite material is best suitable alternative for metallic pressure vessel due to its low weight to strength ratio and non-corrosive property.

2. COMPOSITE MATERAL

A composite is basically a combination of two or more structural materials. It is classified into two types- Carbon Fiber Reinforcement Plastic (CFRP) and Glass Fiber Reinforcement Plastic (GFRP). CFRP is a composite of carbon and polymer. It is of very high strength, low weight but highly expensive. While GFRP is a polymer (the resin) and a ceramic (the glass fibers). It is of good strength, low weight compare to CFRP but less costly than CFRP.

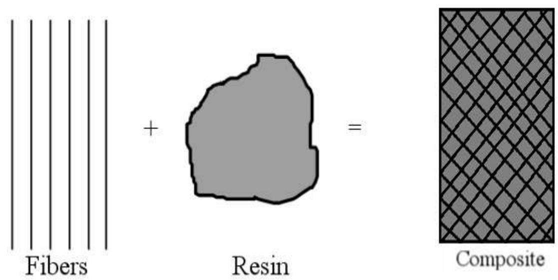


Figure 2.1: Formation of a composite material using fibers and resin.

3. FILAMENT WINDING MATERIAL

3.1 Fiber:The mechanical properties of fibers improve the overall mechanical properties of the fiber/resin composite. The contribution of the fibers depends on four main factors as the fundamental mechanical properties of the fiber, the surface contact of fiber and resin (interface), the quantity of fibers in the composite, and the fiber angle of the fibers in the composite.

Fibers can be divided into groups according to their chemical composition. Well known are A-glass, C-glass, S-glass and E-glass fibers. E-Glass is a low alkali glass with a typical nominal composition of SiO2 54wt%, Al2O3 14wt%, CaO+MgO 22wt%, B2O3 10wt% and Na2O+K2O less than 2wt%. Some other materials may also be present at impurity E-Glass or electrical grade glass was originally developed for standoff insulators for electrical wiring. It was later found to have excellent fiber forming capabilities and is now used almost exclusively as the reinforcing phase in the material commonly known as glass fiber. These fiber mostly used in aerospace design.

Glass fibers are generally produced by melt spinning techniques. These involve melting the glass composition into a platinum vessel which has small holes for the molten glass to flow. Continuous fibers can be drawn out through the holes and wound onto spindles

3.2 Epoxy resin: This resin first prepared by American scientist Dr. S.O. Greenlee and Switzerland scientist Dr. Pierre Castanin 1936. It is basically the glue that keeps the composite together. A resin must have good mechanical properties, good adhesive properties, good toughness properties and good environmental properties. Epoxy has a wide range of applications, including metal coatings, used in electronics / electrical components, high tension electrical insulators, fiber-reinforced plastic materials, and structural adhesives.

4. MANUFACTURING PROCESS OF COMPOSITE PRESSURE VESSEL

FRP laminates consist of outer corrosion barrier it is generally a thin coating of wax or paint. Structure of FRP is in laminates or plies form. It consists of epoxy resin and E-glass fiber plies with some angle ranging from 450 to 880 and thickness of plies is depending on application. This structure is coated with inner corrosion barrier of thin coating of aluminum material or any suitable anticorrosive material.

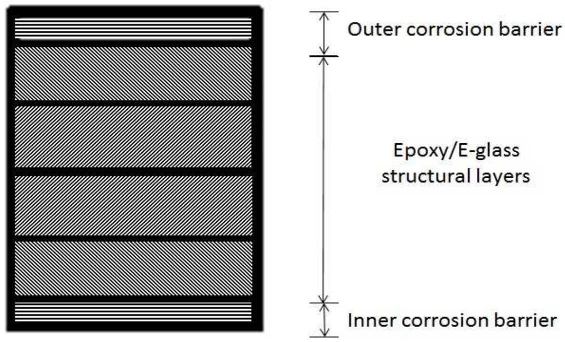


Figure 4.1: Basic FRP Laminates Cross section

4.1 Filament winding-process technology: The process of filament winding is primarily used for hollow, generally circular or oval sectioned products. Fibers can either be use dry or be pulled through a resin bath before being wound around the mandrel. The winding angle is controlled by the rotational speed of the mandrel and the movement of the fiber feeding mechanism. Fig. 4.2 shows filament winding process. Filament winding usually refers to the traditional filament winding process .

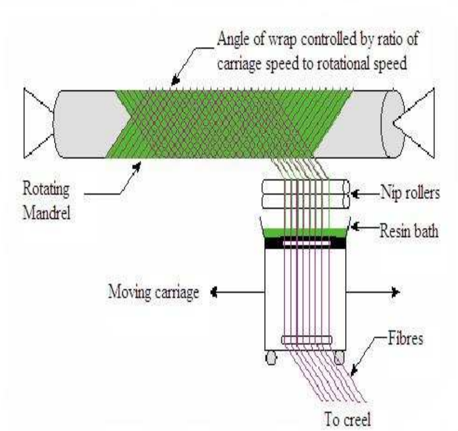


Figure 4.2:Schematic representation of the filament winding process

After winding, the filament wound mandrel is subjected to curing and post curing operations during which the mandrel is continuously rotated to maintain homogeneity of resin content around the circumference. After curing, product is removed from the mandrel, either by hydraulic or mechanical ejector.

4.1.1 Cutting of FRP:

laminated composites is required in both uncured and cured states

Uncured materials (prepress, preforms, SMCs, and other starting forms) must be cut to size for lay-up, molding, etc.

Typical cutting tools: scissors, power shears and steel-rule blanking dies

Other methods are also used, such as laser beam cutting and water jet cutting

Cured FRPs are hard, tough, abrasive, and difficult-to-cut

Cutting of FRPs is required to trim excess material, cut holes and outlines.

For glass FRPs, cemented carbide cutting tools and high speed steel saw blades can be used.

Water jet cutting is also used, to reduce dust problems with straight sawing methods.

5. INTRODUCTION TO FEA

Finite Element Analysis (FEA) is a computational technique that uses the finite element method to analyze a material, object or mechanism and find how applied stresses will affect the material or design. Finite element modeling involves the discretization of the structure into finite nodes and elements. Nodes are used to represent geometric locations in the structure. Domains that are defined by nodes which describe as elements

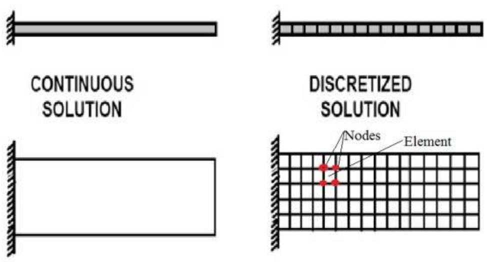


Figure 5.1: Finite element modeling

6. PROBLEM DEFINATION

The metallic pressure vessels are having good strength but due to their high weight to strength ratio and corrosive properties they are least preferred in aerospace as well as oil and gas industries. These industries are in need of pressure vessels which will have low weight to strength ratio without affecting the strength

In this paper a pressure vessel with both ends open is used and it is same as cylinder.

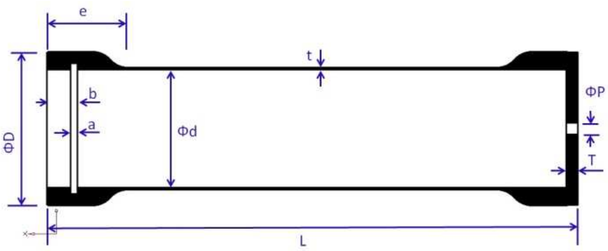


Figure 6.1:Pressure vessel model

7. ANALYSIS OF STEEL PRESSURE VESSEL

7.1 FE Mesh

The process of obtaining an appropriate mesh (or grid) is termed mesh generation (Grid generation), and has long been considered a bottleneck in the analysis process due to the lack of a fully automatic mesh generation procedure. In this work we used hexahedron elements (SOLID45) for FE Modeling.

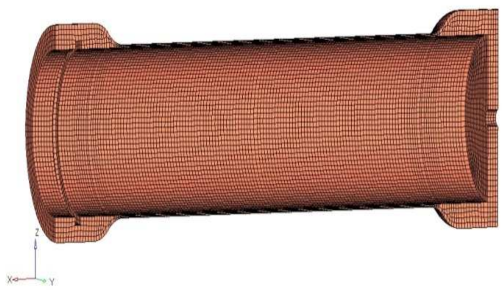


Figure 7.1:FE Model of pressure vessel.

7.2 Material Properties

Steel material used for the analysis is of grade' ASME SA537Class 2' [4].

Table 7.1 Material properties of the steel model

S.No.	Material Property	Value
1	Density (ρ)kg/ m^3	7850
2	Young's modulus (E)Mpa	2.1 E5

3	Poisson's ratio (μ)	0.3
4	Stress induced (σ)Mpa	218.75

7.3 Boundary condition and Loading

Model is fixed at both the ends. Symmetric Boundary conditions are applied as half model symmetry is considered for analysis to reduce model size. Inside pressure 60 baris applied on pressure vessel.

7.4 Analysis and result

Now a day various software available in market for FE Analysis. In this work ANSYS software is used for the analysis and post processing.

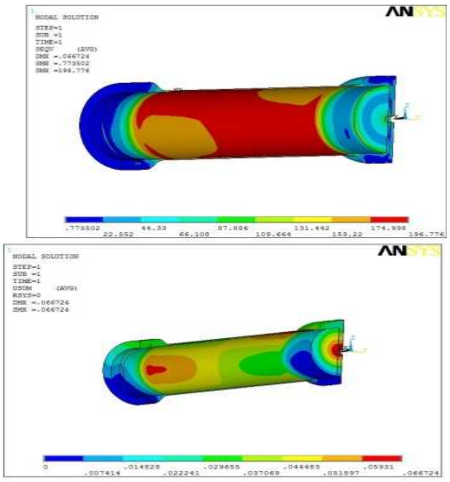


Figure 7.2:Stress and deflection plot for steel pressure vessel.

In this analysis it is found that the maximum stress and deflection for steel pressure vessel is 196.77 Mpa and 0.06 mm respectively, maximum stress in model is less than allowable stress for steel material.

8. ANALYSIS OF FRP PRESSURE VESSEL

8.1 Calculation Of Dome Shape Pressure Vessel

FRP pressure vessel shall be designed in accordance with BS4994. In this dissertation FRP pressure vessel designed for internal pressure 6 Mpa and internal diameter is 100mm.

In case of cylindrical shell subjected to internal pressure maximum circumferential load (Qϕ) shall be determine by formula.

$$Q\phi = \frac{pD1}{2} \qquad \ldots\ldots\ldots\ldots..8.1$$

Here p= Internal pressure

D1= Internal diameter

This gives

$$Q\phi = \frac{6X100}{2}$$

Qϕ= 300 N/mm

If vessel construction is of CSM backingwith filament winding layer the design unit loading per layer would be determine according clause 9.2 of BS4994.

a) Design factor K

K=3XK1XK2XK3XK4XK5…………..8.2

hereK1: based on method of manufacturing

K2: based on chemical environment

K3: based on operating temperature

K4: based on level of cycling

K5: based on curing procedure

This gives

K=3X1.5X1.2X1.2 X 1.5 X1.5

=10.69

b) Load limited allowable unit loading UL

$$UL = \frac{\text{Ultimatetensile unit strength}}{\text{Design factor K}} \ldots\ldots\ldots\ldots..8.3$$

$$UL = \frac{200}{10.69}$$

UL= 18.36 N/mm per kg/m2glass

c) Determine allowable strain ε on laminate layer

Assuming resin extension to failure is 3%

This value is greater than maximum strain permitted 0.2% therefore take ε= 0.1X3= 0.3%

d) Strain limited allowable unit loading U

U_s =Unit modulus for CSM Xallowable strain…………..8.4

U_s= 14000 X 0.2

U_s=28.02 N/mm per kg/m2glass

e) Design unit loading

Since UL is less than US the value of UL value is taken for design purpose

Design strain on each layer is ε

$L = \frac{18.36 \text{ X } 100}{14000}$ = 0.13%…………8.5

To avoide overloading with CSM layer in the laminate the design strain εdhas to be limited to 0.13% so that design unit loading equivalent to that that strain level will be:

For CSM UZ =UL = 18.36 N/mm per kg/m2glassFor winding UZ = XZXεd= 16000 X 0.13 X10-2

f) Laminate constant can be determine by equation, u1m1n1 + u2m2n2 + ...+ u3m3n3 ≥Qϕ………8.6

if no. of winding layer required = n20.8 X0.8n + 18.36 X 0.45 (n-1) + 18.36 X 1.5= 300n=11.2 ≈ 11

In one layer of winding thickness = 0.5 mm11 X 0.5 = 5.5 mm

2 Layer of CSM = 2 X 0.8 = 1.66Total thickness = 7.2 mm

Flat end of pressure vessel is difficult to manufacture in filament winding process so dome end is preferred in case of filament winding pressure vessel

Unit load Q = 0.66 X p X D1 X Ks……8.7Q = 0.66 X 6 X 100 X 0.8Q = 316.8 N/mm

u1m1n1 + u2m2n2 + ...+ u3m3n3 ≥Qϕ……8.820.8 X0.8n + 18.36 X 0.45 (n-1) + 18.36 X 1.5= 316.8n=11.94 ≈ 12

In one layer of winding thickness = 0.5 mm12 X 0.5 = 6 mm

2 Layer of CSM = 2 X 0.8 = 1.66Total thickness = 7.7 mm ≈ 8 mm

In this dissertation thickness of cylindrical shell used is 7.2 mm and thickness of hemispherical ends is used 8 mm.

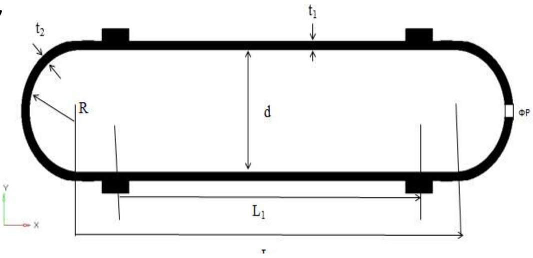


Fig: 8.1. 2-D model of the FRP pressure vessel

8.2 Modeling

Geometric modeling of this pressure vessel is done by CAD software CATIA For modeling fist 2D drafting done in sketcher using geometric command like line, circle, points, trim etc. Then model is converting in 3D model using command Shaft.

The dimensions of the 2-D model are as follows:L1 = 300 mm, L2= 370 mm, R= 50 mm, d = 100 mm, e = 70 mm, t1 = 7.2 mmt2 = 8 mm, ΦP= 10mm, φ= winding angle

The 3-D model of the pressure vessel shown in figure 8.2 is created by using the dimensions of the 2-D model.

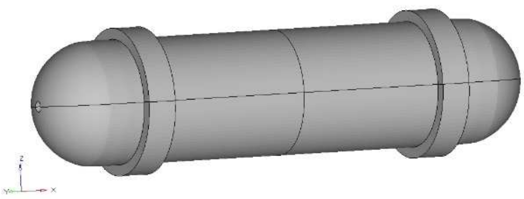


Fig:8.2.CAD model of the cylinder

Fig:8.3:FEA model of FRP pressure vessel

8.3 Material Properties of E glass/ Epoxy resin:

The material properties may be input either in matrix form or layer form; since failure criteria are not available with matrix input, the layer input option is chosen. The material properties of each layer may be orthotropic or isotropic or anisotropic in the plane of the element. For isotropic materials only Young's Modulus (E) and Poisson ratio (ν) need to be defined. The layer configuration is defined layer-by-layer from bottom to top. The bottom layer is designated as layer 1, and additional layers are stacked from bottom to top in the positive normal direction of the element coordinate system.

- Material properties

  (E1, E2, E3, ν 12, ν 23, ν 13, G12, G23, G13) where E1, E2 and E3 represent the Modulus of elasticity in the x, y, and z directions of the element co-ordinate system. ν12, ν23 and ν13 represent the Poisson s ratio in the xy, yz and xz directions, respectively.

  G12, G23 and G13 represent the Shear modulus in the xy, yz and xz direction. For each orthotropic layer, the following properties are specified directions, respectively.

- Layer orientation angle (THETA):This defines the fiber orientation of the layer, in degrees with respect to the element coordinate system.
- Layer thickness (THK) in the positive normal direction.

- Material properties:

The basic fiber (E-glass) and matrix (Epoxy resin) properties, i.e., Modulus of elasticity (E), Shear Modulus (G) and Poissons ratio (ν) that are needed in order to compute the lamina properties are obtained from the manufacturer.
Material properties of Epoxy resin and Eglass fiber supplied by manufacturer are as follow.

Table1:IndividualMaterial properties for fiber and resin

No	properties	Epoxy resin (matrix)	E-glass (fibre)
1	Density (ρ)tonnes/mm3	1.2x10-9	2.6x10-9
2	Longitudinal elastic modulus (E1)Mpa	3400	85000
3	Transverse elastic modulus(E2)Mpa	3100	85000
4	Poisson's ratio (N12)	0.3	0.25
5	Modulus of rigidity(G12) Mpa	1308	35000
6	Modulus of rigidity(G13) Mpa	1308	35000
7	Modulus of rigidity(G23) Mpa	1308	35000
8	Ultimate tensile strength (σTS) Mpa	82.74	2447

Computation of lamina properties:

1 Longitudinal Modulus:

The Longitudinal modulus (E1) can be calculated using the rule of mixtures (ROM) formula. The ROM formula assumes that the strains in the direction of fibers are the same in the matrix and fiber, implying that fiber-matrix bond is perfect.

$$E1 = EfVf + Em\,(1-Vf) \quad \ldots\ldots.1$$

Here Ef, Em is young's modulus of fiber and matrix respectively.

Vf is volume of fiber (0.65)

2.Transverse Modulus

The transverse modulus (E2) that is the modulus in the direction transverse to the fibers can be calculated using inverse ROM formula. The inverse ROM assumes that the transverse stress is same in the fiber and matrix implying that the fiber-matrix bond is perfect.

$$E2 = \frac{E f\ XEm}{E m\ V f + Ef\,(1-V f)} \quad \ldots\ldots2$$

3.Inplane Shear Modulus

The inplane shear modulus (G12) can be calculated using the inverse ROM formula.

$$G12 = \frac{G f\ Gm}{G m\ V f + Gf\,(1-V f)} \ldots\ldots3$$

4. In-plane Poisson's Ratio

The Inplane major Poissons ratio (ν12) is calculated using the ROM formula, which is an accurate prediction and is sufficient for design calculations.

$\nu 12 = \nu f V f + \nu m(1 - V f)$……4

Then the minor Poissons ratio (ν21) can be calculated

$\nu 21 = \frac{\nu 12 \, E2}{E1}$…….5

5. For Continuous Strand Mat

Continuous Strand Mat (CSM) consists of randomly placed continuous winding held together by a binder. The CSM is used to obtain bi-directional properties. The material properties of CSM are determined assuming them as random composites. A layer of composite with randomly oriented fibers can be idealized as a laminate with a large number of thin unidirectional layers, each with a different orientation from 0^0 to 180^0.

6. Elastic Modulus

$E_{csm} = \frac{3}{8}E_1 + \frac{5}{8}E_2$ …….6

7 Shear Modulus:

$G_{csm} = \frac{1}{8}E_1 + \frac{1}{8}E_2$ ……7

Where E_1 and E_2 are the longitudinal and transverse moduli of a fictitious unidirectional layer having the same volute fraction as the CSM layer

8. Poisson's Ratio

$\nu_{CSM} = \frac{E\,csm}{2Gcsm} - 1$ ……8

The following tables summarize the lamina

Fiber type	1 (Mpa)	2 Mpa)	12	23	12 Mpa)	23 Mpa)
Fibers /Winding	6440	042	.21	.24	202	202
Mat (CSM)	6817	6817	.2	.2	316	316

properties for the FRP Material

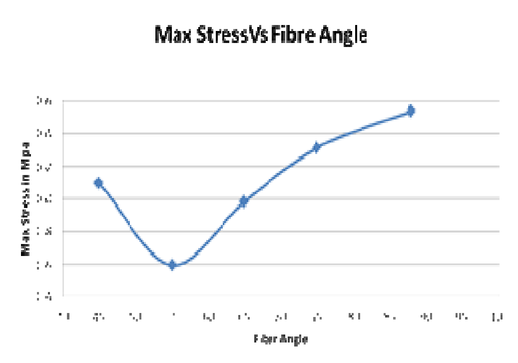
9. FE ANALYSIS FOR FIBER ANGLE OPTIMIZATION

For the optimization composite pressure vessel the internal pressure and thickness of the pressure vessel are kept constant and analysis are made for different fiber angles.

Table 9.1 Different fiber angle orientation and stress value

S. No.	Fiber Angle	Max Stress(Mpa)
1	[+45/-45/-45/+45]	160.97
2	[+55/-55/-55/+55]	155.96
3	[+65/-65/-65/+65]	159.82
4	[+75/-75/-75/+75]	163.12

Above table shows the results for different fiber angle in which iterations are made for angles [45o /-45o]s , [55o /-55o]s , [65o/-65o]s , [75o /-75o]s and [88o /-88o]s which are symmetrical



The above graph shows that the fiber angle 55° is optimizing angle for the composite pressure vessel.

10. WEIGHT CALCULATION

Table 10.1 Weight calculation of pressure vessel

Percentage of weight reduction= ((6.43-1.55)/6.43)*100=75.89%

By using the composite pressure vessel instead of steel pressure vessel weight has reduced to 75.89%

11. STRUCTURAL EFFICIENCY

The structural efficiency of pressure vessels is defined as:

e=PV/W.......Where P=Internal pressure,

V=container volume,

W=weight

Table 11.1 Structural efficiency calculation of pressure vessels

Sr. No	Material	Pressure (Mpa)	Volume in mm3	Weight in Kg	Efficiency
1	Steel	6	$8.2x10^5$	6.43	$7.65x10^5$
2	Composite	6	$8.2x10^5$	1.55	$3.17x10^6$

For the same pressure and volume of the cylinder the percentage of structural efficiency increased in composite pressure vessels is given by

= ((3.17x106-7.65x105)/ 3.17x106)*100 = 75.86%

12. CONCLUSION

In this study the FE analysis of Steel pressure vessel and filament wound FRP pressure vessel is done using ANSYS software. In these study analytical results is compared with Ansys results of steel material.

Following points are concluded.

i) In the stress analysis, it is found that the maximum stress in the FRP pressure vessel is less than allowable stress for FRP Material. Hence design of pressure vessel using FRP is safe.

ii) Graph of Maximum Stress Vs. varying pressure at constant thickness and fiber angle is linear

iii) From Table 10.1 it is found that optimum fiber angle for fiber wounded pressure vessel is 55o

iv) For current design weight of FRP pressure vessel is less than steel pressure vessel. Percentage weight reduction in case of FRP pressure vessel is 75.89%

v)Structural efficiency of FRP pressure vessel more than steel pressure vessel. Increase in structural efficiency in case of FRP pressure vessel is 75.86%

vii)Use of FRP pressure vessel instead of steel pressure vessel can reduce weight of pressure vessel about 75% and corrosion problem of steel pressure vessel also get solved.

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