A Review on Glass Fiber Reinforced Plastic Pressure Vessel Design and Analysis

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Abstract - Pressure vessel of composite materials are known as new generation vessels and have been comprehensively used in many industries. The superior characteristics of a composite pressure vessel such as corrosion resistance, high stiffness, light weight and long life make it a perfect substitute for metallic vessels. Hence, Filament wound composite pressure vessels have become exceptionally popular in various industries and applications that include chemical, sewage, aerospace, oil and gas industries and many more.

This project focuses on study of possible replacement of steel tank used to store compressed air with composite pressure vessel. Comparative analysis carried out between steel tank and glass fiber reinforced plastic (GFRP) tank considering aspects such as cost of manufacturing, weight of tank, thickness of shell and head, manufacturing process and environmental effect of product. From weight calculation, it is observed that GFRP tank is four times lighter than steel tank. GFRP tank requires 2.5 times higher thickness than steel for same internal pressure. It is also observed that manufacturing cost of GFRP tank is lower than steel tank. In addition, it is observed that manufacturing of GFRP tank is possible with less resources (man, machine, land) as compared to steel tank. Furthermore, Life cycle assessment (LCA) for both material shows that GFRP is produce less harmful effect on environment than steel.

Keywords: Composite pressure vessels, Filament winding, GFRP, Finite element analysis, Air storage tank

1. INTRODUCTION

Glass Fiber Reinforce Polymer is polymer matrix composites (PMCs). Glass fiber is embedded in polymer (e.g. epoxy, polyester, and urethane). Fiber provides dimension stability, strength and heat resistance whereas polymers determine electrical, thermal, and chemical properties e.g. corrosion resistance. Strength of GFRP depends on amount and arrangement of fiber. There is mainly threetypes of fiber arrangement possible are presented in Figure 1.1 and stated below,

1. Continuous/unidirectional fiber
2. Woven fiber
3. Chopped fiber

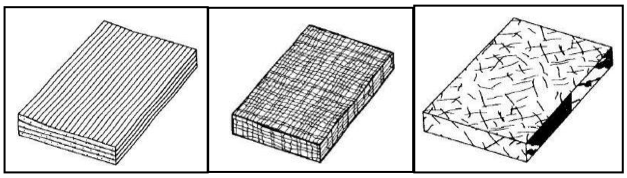

Figure 1.1 Unidirectional fiber, woven fiber and chopped Fiber

1.2 MANUFACTURING METHODS

There are many fabrication methods for PMCs products e.g. hand layup, spray up, compression molding, filament winding, resin transfer molding. Different form of fiber used for different fabrication method. To manufacture tank or vessel, hand lay-up, Spray up and filament winding fabrication methods are used. Hence only these fabrication methods are briefly discussed here.

1) Hand layup method

It is open mold fabrication method. It is widely used and basic process. In this method chopped strand mat or woven fiber mat is used. As seen in Figure 1.8. Mold with desired shape is first coated with mold release agent to prevent bonding of resin matrix to mold. For smooth surface finish, gel coat is applied to mold and after that thermosetting resin and fiber. Roller used for consolidation followed by curing at required temperature.

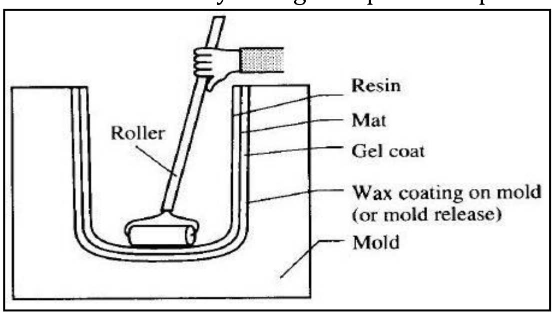

Figure 1.2.1 Hand layup fabrication process

2) Spray up method

It is also open mold method and same as hand lay-up. Difference is chopped fibers and resin are sprayed up with flow of air on the mold as shown in Figure 1.9. Rest process is same as hand lay-up. Better production rate can be achieved in this process compared to hand layup. Laminate that created by spray gun gives same properties is as hand layup using chopped mate but distribution of chopped fiber and resin is uniform in case of spray up method. Due to which this method gives uniform properties throughout laminate and reduces chance of leakage.

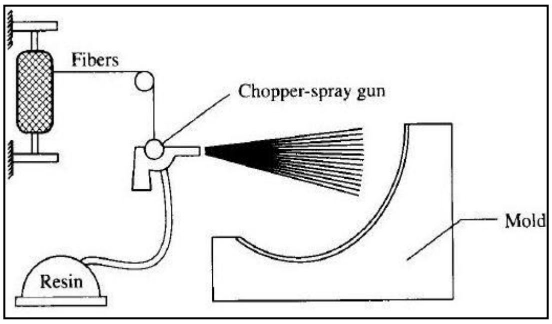

Figure 1.2.2 Spray gun fabrication process

3) Filament winding method

In this method, Fibers are impregnated with a resin by drawing them through an in-line resin bath are wound over a mandrel as seen in Figure 1.2.3. Based on the desired properties of the product, winding patterns such as helical, polar and hoop can be achieved on shell. After that product is cured with or without heat and pressure.

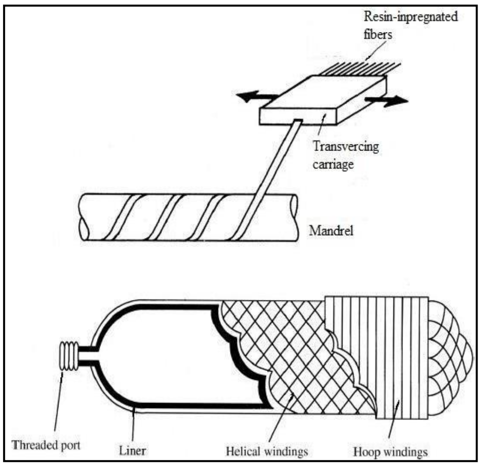

Figure 1.2.3 Filament winding process

2. LITERATURE REVIEW

Many design codes are available for designing of GFRP vessel or tank. Adriano [1] in his research paper compared different design codes (AD-Merkblatt, BS 4994, EN 13121 and ASME RTP-1) and comes up with pros and cons of these design codes.

BS 4994 [2] is first design code for FRP vessel or tank and includes simple design procedure of parts, procedure of determining safety factor and mechanical strength.

Among all fiber used in PMCs glass fiber have properties like high strength, stiffness, resistance to chemical harm, and also cheap in cost compared to other fiber e.g. carbon, aramid. TP Sathishkumar, S Sathiskumar and J Naveen [3] reported mechanical, thermal, water absorption and vibrational properties of different fiber in their research paper. S glass type fiber have high tensile strength compared to all other. They have also concluded that ultimate tensile strength increases with increase in fiber glass weight fraction.

Hamdullah, Culvaci kadirs erbay [4] studied effect of glass fiber content on mechanical properties of composite. Density of composites increased with increase in fiber content up to 55% volume ratio of fiber.

S Sulaiman, S Borazjani and S H Tang [5] have done FEA of filament wound composites pressure vessel under internal pressure. They have done simulation of aluminum pressure vessel over wrapping by carbon/epoxy fiber reinforced polymer (CRPF). Study include FEA of vessel for laminate oriented with different angle and conclude that 55º is optimum ending angle.

A study on "Comparative Life Cycle Analysis of Material in Water Piping System" [6] stated comparative LCA for four different materials FRP, PVC, ductile iron and concrete. They performed analysis of environmental impact of different life cycle stages like installation, production, transportation and use on ozone layer depletion, eco toxicity and energy consumption of all material.

3. COMPOSITE MATERIAL

There are basically four types of structural material: Metals, Polymers, Ceramics and Composites. All four types of material have been used in different application according to their characteristics/features. Continuous research in the field of material science and metallurgy found alternative usage of these materials. Relative importance of these four categories of material in historical context has been presented by Ashby [7] as shown in Figure 3.1.

It shows importance of polymers composites and ceramics is increasing and role of metal is continuously decreasing since 1960s. In the case composites, it is happening because composites gives desirable properties which could not be achieved by either of constituent material by itself [8].

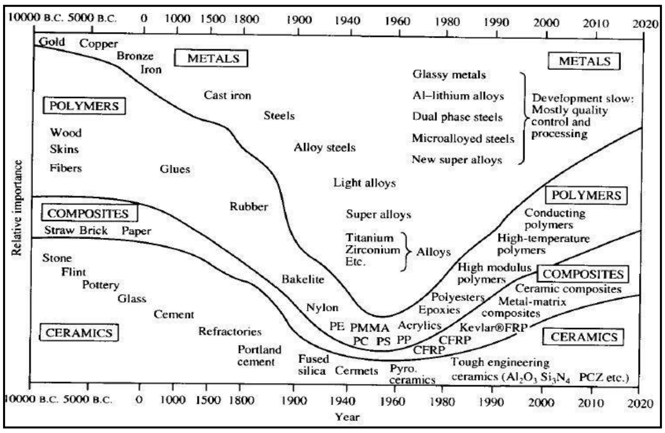

Figure 3.1 Importance of different material in context as a function of time[7].

"Composite is a structural material that is consists of two or more combined constituents that are combined at a microscopic level and are not soluble in each other" [8]. Its properties is superior to either of constituents. One constituents is in form of fiber or particulate, is called the reinforcing phase and other one is called matrix phase in which former one embedded. Wood is one of naturally found composites. Steel reinforced concrete is also an example of composites.

4. DESIGN OF TANK

Glass fiber reinforced polymer is designed as per british standard code BS 4994. Since, Composite material are anisotropic and inhomogeneous in nature, its design procedure is different than ferrous alloy or other materials

4.1 Design of Ferrous Alloy Tank

Pi = $internal\ pressure\ in\ N/mm^2$
= 0.98 × 1.05 = 1.03 N/mm^2
Di = $internal\ diameter\ in\ mm$ = 450 mm
CA = $corrosion\ allowances\ in\ mm$ = 1.5 mm

1. Thickness of Shell

$$t = \frac{Pi \times Di}{2 \times f \times J - Pi} + CA$$

t = 4.59 mm ≅ **5 *mm***

2. Design of domed head

$$t = \frac{Pi \times Di}{2 \times f \times J - 0.2 \times Pi} + CA$$

t = 4.57 mm ≅ **5 mm**

Height of ellipsoidal head hi=112.5 mm

Length of straight flange Sf= 20mm

3. Design of openings

$$K = \frac{Pi \times Do}{1.82 \times f \times (t - CA)}$$

K = 0.53 < 1 hence compensation is not required.

4.2 Design of GFRP Tank

1. Design factor

Method of manufacturing	$K1$ = 1.5
Chemical environment	$K2$ = 1.2
Temperature	$K3$ = 1.0
Expected operating cycle	$K4$ = 1.45 (2×10^4 cycles)
Curing procedure	$K5$ = 1.5

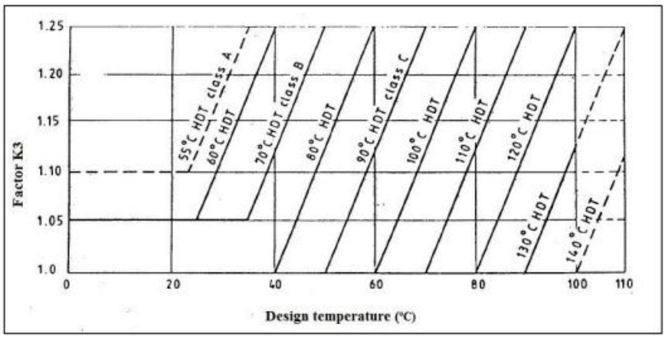

Figure 4.1 Factor relating temperature[3]

$K1 \times K2 \times K3 \times K4 \times K5$ = 3.915
Design factor $K = 3 \times K1 \times K2 \times K3 \times K4 \times K5$
$\boldsymbol{K}$ = **11. 745**

2. Design strain
For 450 g/m^2 chopped strand mat,

$$\text{Strain } \epsilon = \frac{250}{K \times 16000} \times 100$$

$$\epsilon = 0.1216\ \%$$

3. Allowable unit loading
For 450 g/m^2 CSM; allowable unit load,

$U_S = \epsilon d \times XCSM$ = 0.001216 × 14000 = 17.02 N/m^2

$$U_L = \frac{UTUS}{K}$$

U_L = 17.02 N/m^2

For, Unit modulus at ±80º winding angle,
Circumferential unit modulus, $X_\emptyset$ = 28,000 N/mm
Longitudinal unit modulus, X_X = 4,400 N/mm

Allowable unit loading,

Circumferential unit load, U_C = 34.048 N/mm
Longitudinal unit load, U_L = 0.00 N/mm

4. Calculation of unit loading due to internal pressure and weight of tank

- Circumferential Unit Loading,

$$Q_\emptyset = \frac{P_i \times D_i}{2} = 220\ N/mm$$

- Longitudinal Unit Loading,

$$Q_X = \frac{P_i \times D_i}{4} + \frac{4M}{\pi \times D_i^2} = 110\ N/mm$$

Bending moment created due to weight is negligible.

5. Proposed laminate structure for shell

5.1 Proposed laminate construction for shell as below,

I. Corrosion barrier: 1 layer of surface veil 30 g/m^2
2 layer of CSM 450 g/m
II. 1 layers of 450 g/m^2 CSM
III. 8 layers of 600 g/m^2 WR
IV. 3.2 kg/m^2 of unidirectional filament winding at ±80^0 to the vessel axis

5.2 Allowable laminate loading,

$U_{LAM\emptyset} = U_{\emptyset 1} \times m_{\emptyset 1} \times n_1 + \cdots \ldots \ldots + U_{\emptyset n} \times m_{\emptyset n} \times n_n$
= 225.29 N/mm

$U_{LAMX} = U_{X1} \times m_{X1} \times n_1 + \cdots \ldots \ldots + U_{Xn} \times m_{Xn} \times n_n$
= 116.33 N/mm

Allowable unit loading in both directions is greater than induced unit loading, hence proposed laminate construction is acceptable.

5.3 Thickness of shell laminate,

CSM Glass/Resin ratio = 35 % / 65%;
t = 2.08 mm/kg/m^2 of reinforcement

WR Glass/Resin ratio = 50 % / 50%;
t = 1.3 mm/kg/m^2 of reinforcement
CFY Glass/Resin ratio = 65 % / 35%;
t = 0.88 mm/kg/m^2 of reinforcement

Total Thickness = (3 × 0.45 × 2.08) +(8 × 0.6 × 1.3) + (3.2 × 0.88) = 11.864mm

5.4 Thickness of hemispherical head

For hemispherical head K_S = 0.6
Total Thickness = (9 × 0.45 × 2.08) + (6 × 0.6 × 1.3)
Total thickness of head = $\mathbf{11.36\ mm}$

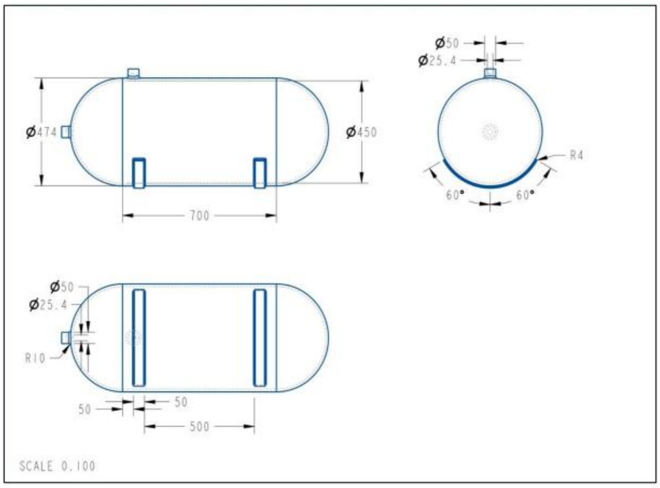

Figure 4.2 2D Design drawing of GFRP tank

5. FINITE ELEMENT ANALYSIS

Finite Element Analysis (FEA) is a numerical technique used to performed stress analysis. We use ANSYS R3 software to analyze tank for both design material structural steel and GFRP. In ANSYS, "Static Structural" analysis system is used for FEA.

1.GFRP Laminate Property Generation

For GFRP, Material properties of laminate changes with different laminate construction. To calculate this laminate properties, Helius composite software is used.

Table 1 Applied laminate in FEA

	Reinforced Material	Angle°
Layer 1	Chopped Strand Mat	0
Layer 2	Woven Roving	0
Layer 3	Filament Winding	80

Figure 5.1 shows laminated construction used in shell and head.

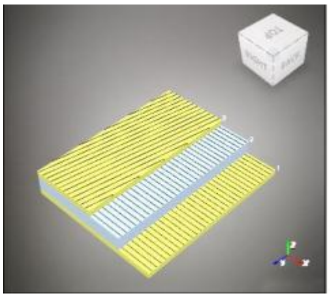

Figure 5.1 Applied laminate in FEA

2. Load applied to Tank

Loading condition in both cases are same and these three conditions are depicted in Figure 5.2 and as stated below,

1. Tanks are fixed at both support.
2. Gravity (9.8 m/s^2) is applied in downward direction
3. Internal pressure of 1.03 N/mm^2 applied on all internal surfaces.

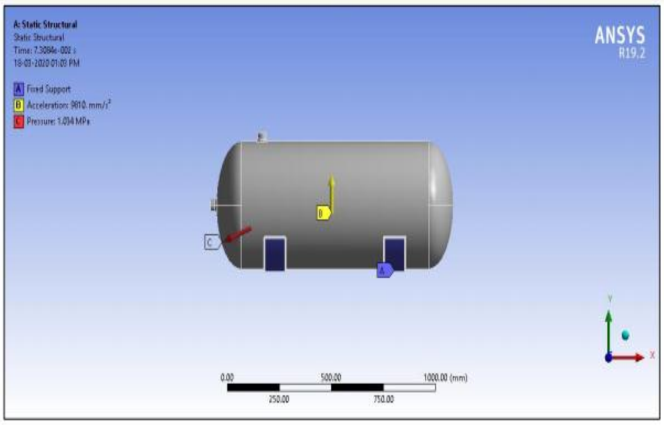

Figure 5.2 Loading enviornmnet

5.1 RESULTS

Case-1 (Steel)

Table 2 Equivalent stress (steel)

	Shell	Head	Overall
Max. Stress (Mpa)	50.64	72.179	103.98
Avg. Stress (Mpa)	-	-	35.76

Table 3 Maximum principal strain (steel)

	Shell	Head	Overall
Max. Strain (%)	0.02	0.031	0.045
Avg. Strain (%)	-	-	0.016

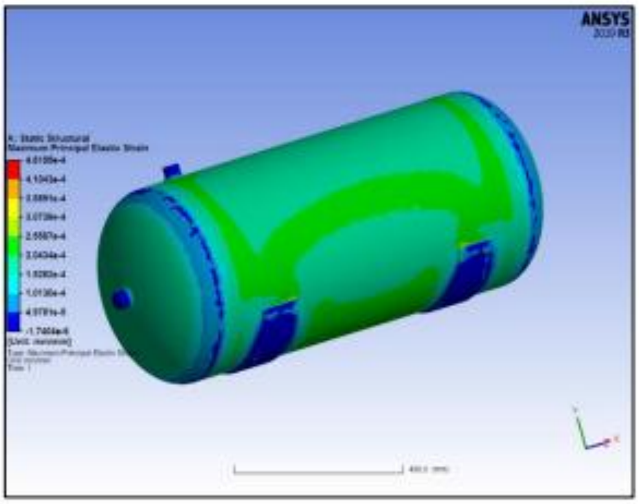

Figure 5.1.1 Equivalent stress and maximum principal strain (steel)

Case-2 (GERP)

Table 4 Equivalent stress (GFRP)

	Shell	Head	Overall
Max. Stress (Mpa)	27.125	11.2	55.663
Avg. Stress (Mpa)	-	-	13.408

Table 5 Maximum principal strain (GFRP)

	Shell	Head	Overall
Max. Strain (%)	0.25	0.10	0.528
Avg. Strain (%)	-	-	0.145

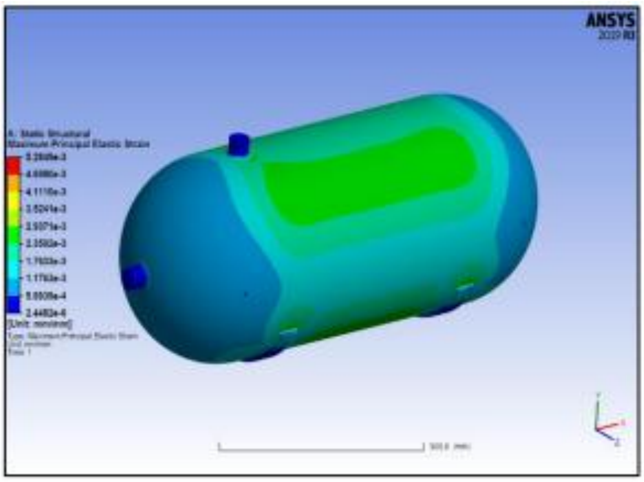

Figure 5.1.2 Equivalent stress and maximum principal strain (GFRP)

Result from helius composite software: Figure 5.1.3 shows stress induced into GFRP tank at different ply location along the thickness of shell. Maximum value found at bottom of filament winding PLY is 69.3 MPa.

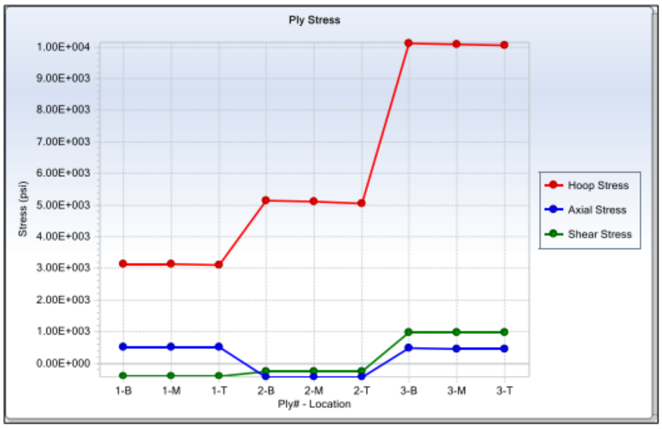

Figure 5.1.3 Stress at different PLY location (B-Bottom, M- Middle, T–Top)

5.2 Outcomes of Finite Element Analysis

Figure 5.2.1 shows comparison between allowable stress and maximum stress value that we get from analytic and FEA method in both cases. It can be seen that maximum stress value of analytic calculation and ANSYS are less than allowable stress. Hence design is safe in both the cases.

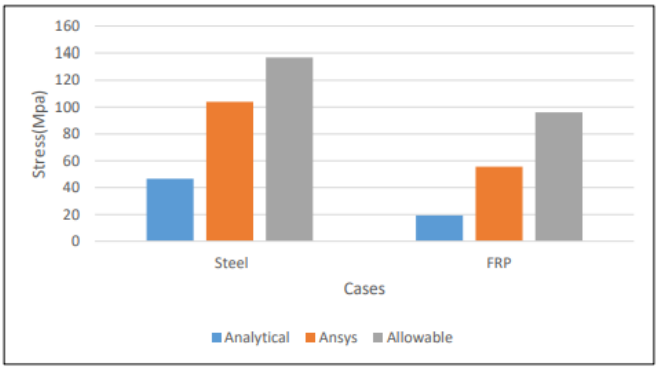

Figure 5.2.1 Comparative maximum stress results

6. RESULTS

6.1 Weight and Thickness

Weight of both tank compared as seen in Figure 6.1. From graph it can be seen that steel tank is four times heavier than that of GFRP tank.

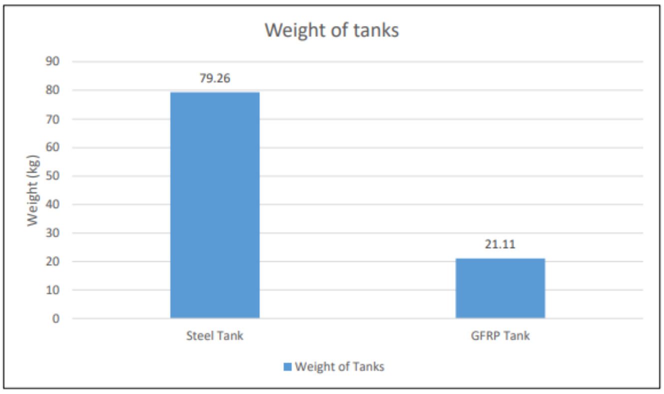

Figure 6.1 Weight of Tanks

Thickness for both material of shell and head is shown in Figure 6.2. Thickness required for GFRP tank is 2.4 times higher than that of steel tank. To sustain same internal pressure, Thickness required for GFRP is higher than that of ferrous material. Reason for that is Pressure vessel is subjected to bi-directional state of stress and only unidirectional of GFRP strength is higher than ferrous alloy. To achieve strength in both directions, GFRP requires higher thickness than ferrous alloy.

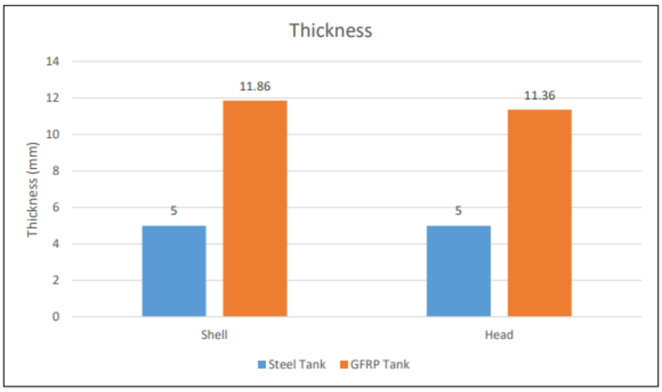

Figure 6.2 Thickness of shell and head

6.2 Cost of Manufacturing

Values are calculated considering material cost, machine cost, labor cost & tool cost. These values shows that cost of manufacturing for GFRP tank is approximately less than that of ferrous alloy tank.

6.3 Environmental Effect of Product

It shows that production stage for both material (FRP, Ductile steel) has highest impact on environment. In addition, steel has more hazardous impact on environment than FRP in all stages from production, transportation, usage.

3. CONCLUSIONS

Following are some points that can be concluded,

[1] GFRP tank weight is significantly lower than that of steel tank, which helps in overall weight reduction of air compressor.
[2] Manufacturing process for GFRP tank is less complex than of steel tank. Former one's production process requires less tool and machinery compared to steel tank.
[3] GFRP tank is cost effective than ferrous alloy tank.
[4] Life cycle assessment shows GFRP tank have less environmental effect as compared to steel tank.

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