Design and Analysis of Composite Top Frame of Hydraulic Valve Test Bench

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Abstract - *The purpose of this study is to investigate bending stress and deformation of the composite top frame of hydraulic valve tests bench. In this study, Epoxy/ E-Glass composite frame were first manufactured by Hand layup method. Then compare the numerically and analytically stress and deformation results of composite and conventional steel top frame of hydraulic valve test bench.*

1. INTRODUCTION

The advanced composite materials such as Graphite, carbon, Kevlar and glass with suitable resins are widely used because of their high specific strength (strength/density) and high specific modulus (modulus/density). Advanced composite materials seem ideally suited for long industrial applications. Their higher strength properties can be tailored to increase the bending stress (strength) they can carry as well as decrease thickness at they operate. Frames are used in valve test benches, presses, and other applications. The industry is exploiting composite material technology for machine components in order to obtain the reduction of the weight without decrease in quality and reliability. It is known that weight of frame or a test bench is one of the most important objectives in design, as reduction of weight will affect cost of the test bench. As we know due to the hydraulic particles some of the parts of test stand may get corroded very easily, this can be overcome by composite frame.

1.1 Aim and Scope of the work

This work deals with the replacement of a conventional top frame of test bench with E-glass fibre/epoxy composite top frame of valve test bench. This project is about the fabricating the composite frame, analyzing it numerically and FEM method. The scope of research was on analyzing composite frame with conventional steel frame. In our design we were using AutoCAD to draw out the detailed drawing of frame. The deformation, von misses' stress will be analyzed using numerical calculations and the Finite Element Analysis (ANSYS) Software. From our analysis, we will find uniqueness of composite materials and their responses to various loading conditions.

1.2 Methodology

The numerical and finite element method is used to conduct the analysis for this project. The software used is ANSYS; ANSYS is a comprehensive general-purpose finite element computer program that contains over 100,000 lines of codes. ANSYS is capable of performing static, dynamic, heat transfer, fluid flow, and electromagnetism analyses. ANSYS has been leading FEA program for well over 20 years. The composite material with internal is modeled in SOLID EDGE . The element size used is determined by conducting a mesh density study. The largest element that produces accurate results is used to produce accurate results in a model that runs as quickly as possible. Once an element size is determined, static analysis is performed. The resulting stress obtained from this analysis is validated by comparing it to numerical results.

2. LITERATURE SURVEY

A composite material consists of two or more materials mixed together to give a material with good properties. A typical composite material consists of a material with high mechanical strength and stiffness (reinforcement), for example unidirectional or woven fibres, embedded in a material with lower mechanical strength and stiffness (matrix). To tailor the properties of the composite material, a laminate is formed by stacking on top of each other layers of reinforcement oriented in different directions. The advance in design and application of composites has accelerated in the past decade especially in the aeronautics, defense, and space industries. Commercial applications are also increasing as products needing challenging materials properties are increasing in demand. Some of the properties that can be improved by forming a composite material are strength, fatigue life, stiffness, temperature, dependent behavior, corrosion resistance, thermal insulation, wear resistance, thermal conductivity, attractiveness, weight and acoustical insulation.

2.1 Properties of Composite

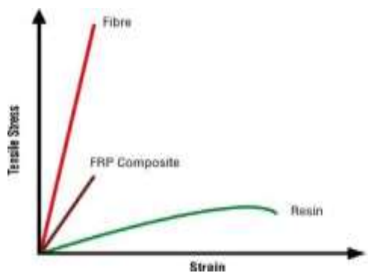

Fig.1 Properties of composite

The properties of the composite are determined by:

i) The properties of the fibre
ii) The properties of the resin
iii) The ratio of fibre to resin in the composite (Fibre Volume Fraction)
iv) The geometry and orientation of the fibres in the composite.

3. TOP FRAME OF HYDRAULIC VALVE TEST BENCH

3.1 Need of Top Frame

Top frame specially used to mount hydraulic cylinder of test bench for testing of various valves. The valves are mounted between top and bottom frames of test bench. Valve's body, shell and seat are tested in hydraulic test bench. If the pressure is applied for the top side, then the top frame will have three through holes, the middle holes for cylinder's ram movement and side tow holes are for guiding tie rod of test bench. By using tie rods the minimum and maximum distance (day-light) can be adjusted. The day-light can be adjusted by the movement of top or bottom frame of test bench and then they are tightened using fastener.

3.2. Function of Top Frame

1. To mount the hydraulic cylinder to apply pressure on valves.
2. For guiding tie rod.
3. If hydraulic cylinder is mounted on bottom frame then pressure pad is mounted on top frame.

3.3. Composite Top Frame

The main purpose of composite top frame is to increase the bending tress of frame and other stresses, due to which at less thickness or depth of frame can take same load as of other materials made frame. As it is a hydraulic test bench there will be use of liquid items in test bench due to which material may rusted very early and life of frame may decrease, to overcome this we use composite as material for the top frame of hydraulic test bench.

3.4 Material Selection for Top Frame

3.4.1 Resin

SPECIFICATIONS:

Type – Epoxy lapox T – 22 (atul ceba)

Density – 1050 kg/m3

Tensile strength - 42 M pa

Young's Modulus – 26 G pa

Cost - Rs 550/Kg.

Limiting service temperature – 25-85 degree Celsius

3.4.2 Hardner

SPECIFICATIONS:

Type – K - 46 (Atul Ceba)

Density – 850 Kg/m3

Cost – Rs 610/Kg

Mixture ratio – 2:1

3.4.3 E-GLASS FIBRE

SPECIFICATIONS:

Type – chopped standard mat

Density – 0.00255 Kg/cm3

Tensile Strength – 3.45 G pa

Young's Modulus – 72.5 G pa

3.4 Fabrication of composite top frame

3.4.1 Hand Lay-Up Method

Different stages of the hand lay – up process are as under:

- Mould preparation
- Raw material preparation
- Laying up & curing
- Mould releasing stage

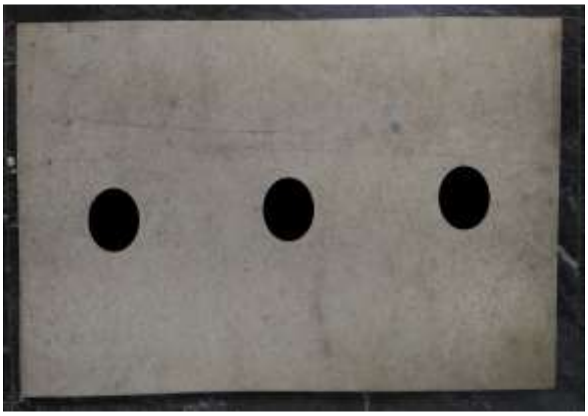

Fig.2 Hand lay-up composite top frame

4. DRAFTING AND MODELING

4.1 2D Drafting of Hydraulic Valve Test Bench and Top Frame of Hydraulic Valve Test Bench

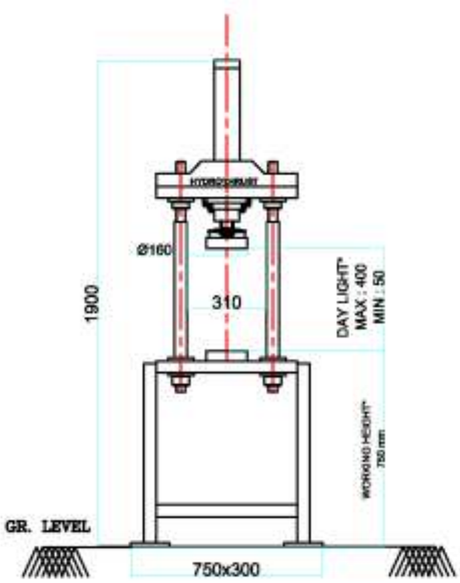

Fig.3 Hydraulic valve test bench

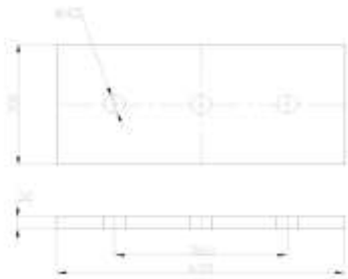

Fig.4 Top Frame

4.2 ANSYS Model Of Top Frame of Hydraulic Valve Test Bench

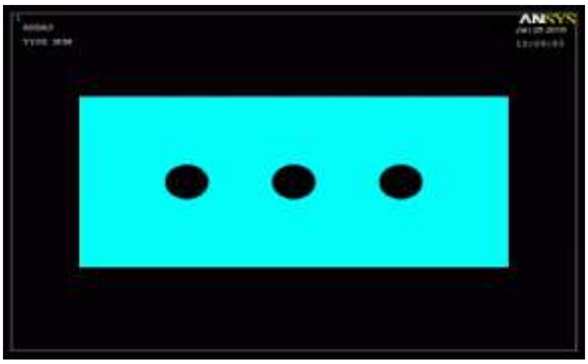

Fig.5 ANSYS model of top frame

5. ANALYTICAL CALCULATION

5.1 Steel Top Frame

Specification:

1) Full length of frame (L_f) = 0.6m
2) Length between centre of tie rod (L) = 0.36m
3) Breadth of frame (B) = 0.3m
4) Diameter holes (D_o) = 0.045m
5) Load on frame (w) = 6.3MT/cm^2
6) Density (ρ) = 7600Kg/m^3
7) Young's modulus (E) = 210 GPa

❖ Mass of the frame (m):

$m = \rho \times A \times D$

$m = \rho \times L_f \times W \times D$

$m = 7600 \times 0.6 \times 0.3 \times 0.03$

$m = 41.04$ kg

❖ Bending moment (M):

$M = wL / 8 \times (1 + 2a)$

$M = [(6.3 \times 36) / 8] \times [(30 - 4.5) / 30]$

$= 24.0975$ T – cm

$M = 23.640 \times 10^6$ N - m

❖ Depth of frame (D):

Bending Moment = Section Modulus [M = Z]
$M = BD^2 / 6$

$24.0975 = [30 \times D^2] / 6$

$D^2 = [24.0975 \times 6] / 30$

D = 2.195cm = 0.02195m

D = 0.03m

❖ Moment of inertia (I):

$I = BD^3 / 12$

$= [0.3 \times 0.03^3] / 12$

$I = 6.75 \times 10^{-7}$ m^4

❖ Section modulus (Z):
$Z = BD^2 / 6$
$= 0.3 \times 0.03^2$
$Z = 4.5 \times 10^{-5}$ m^3

❖ Max bending stress (σ):

$$\frac{\sigma}{Y} = \frac{M}{I} = \frac{E}{R}$$

$$\sigma = \frac{M}{I} \times Y$$

Where: Y = Distance from the neutral axis

Y = D / 2 = 0.03 / 2 = 0.015 m

$\sigma = [(23.640 \times 10^6) / (6.75 \times 10^{-7})] \times 0.015$

$\sigma = 5.2533 \times 10^{11}$ N/m²

❖ Maximum shear stress (τ_{max}):

$$\tau_{max} = \frac{6 \times w \times D^2}{4 \times B \times D^3} = \frac{1.5 \times w}{B \times D}$$

$$= \frac{1.5 \times 6.1803 \times 10^6}{0.3 \times 0.03}$$

$\tau_{max} = 1.0301 \times 10^9$ N/m²

❖ Total deformation (δ):

$\delta = (5wL^4) / (384EI)$

$= (5 \times 6.1803 \times 10^6 \times 0.364^4) / (384 \times 210 \times 10^9 \times 6.75 \times 10^{-7})$

$\delta = 0.00954$ m

5.2 Composite Top Frame

Specification:

Note – All dimensions of frame and load remains same.

1) Fiber volume fraction (V_f) = 0.45
2) Longitudinal elastic modulus (E_1) = 38.6 GPa
3) Transverse elastic modulus (E_2) = 8.27 GPa
4) Major Poisson's ratio (γ_{12}) = 0.26
5) Shear modulus (G_{12}) = 4.14 GPa
6) Density (ρ) = 2500 Kg/m³
7) Young's modulus (E) = 85 GPa

Considerations:

1) Each ply thickness = 0.125 mm
2) It consists of 3 layup and each layup is 15mm thick
3) Total thickness of frame = 30 mm
4) Bottom layup is at 0^0
5) Middle layup is at 30^0
6) Top layup is at -45^0

❖ Mass of top frame (m):

m = ρ x A x D

$m = \rho \times L_f \times W \times D$

m = 2500 x 0.6 x 0.3 x 0.03

m = 13.5 kg

❖ Reduced stiffness matrix [Q]:

$$[Q] = \begin{bmatrix} Q_{11} & Q_{12} & Q_{16} \\ Q_{12} & Q_{22} & Q_{26} \\ Q_{16} & Q_{26} & Q_{66} \end{bmatrix}$$

$$Q_{11} = \frac{E_1}{1 - \gamma_{11}\gamma_{21}}$$

$$\gamma_{21} = \frac{\gamma_{12}}{E_1} \times E_2$$

= (0.26 x 38.6) / 8.27

$\gamma_{21} = 0.0557$

$$= \frac{0.26}{1 - (0.26 \times 0.0557)}$$

Q_{11} = 39.167 GPa

$$Q_{12} = \frac{\gamma_{12} E_2}{1 - \gamma_{11}\gamma_{21}}$$

$$= \frac{0.26 \times 8.27}{1 - (0.26 \times 0.0557)}$$

Q_{12} = 2.182 GPa

$Q_{21} = Q_{12}$ = 2.182 GPa

$$Q_{22} = \frac{E_2}{1 - \gamma_{11}\gamma_{21}}$$

$$= \frac{8.27}{1 - (0.26 \times 0.0557)}$$

Q_{22} = 8.392 GPa

$Q_{66} = G_{12}$ = 4.14 GPa

$$[Q] = \begin{bmatrix} 39.167 & 2.186 & 0 \\ 2.186 & 8.392 & 0 \\ 0 & 0 & 4.14 \end{bmatrix} GPa$$

❖ Bending stiffness matrix [D]

$[D] = \frac{1}{3}\sum_{k-1}^{3}[Q_{ij}][h_k^3 - h_{(k-1)}^3]$

The plyup angles = [0^0, 30^0 & -45^0]

For plyup angle 0^0:

$[Q]_{0^0}=[Q]$

$$= \begin{bmatrix} 39.167 & 2.186 & 0 \\ 2.186 & 8.392 & 0 \\ 0 & 0 & 4.14 \end{bmatrix} GPa$$

For plyup angle 30^0:

Where, C = cosθ and S = sinθ

$C = 0.866, C^2 = 0.75, C^3 = 0.65$ & $C^4 = 0.562$

$S = 0.5, S^2 = 0.25, S^3 = 0.125$ & $S^4 = 0.625$

$Q_{11} = Q_{11}C^4 + Q_{22}S^4 + 2(Q_{12} + 2Q_{66})S^2C^2$

$= (39.167x0.562) + (8.392x0.625) + 2(2.186+2 x 4.14)0.75x 0.25$

Q_{11} = 31.182 GPa

$Q_{12} = (Q_{11} + Q_{22} - 4Q_{66}) S^2C^2 + Q_{12}(C^4 + S^2)$

= (39.167+8.392-4x4.14)0.25x0.75 + 2.186(0.562x0.25)

Q_{12} = 7.587 GPa

$Q_{16} = (Q_{11} - Q_{12} - 2Q_{66}) C^3S - (Q_{22} - Q_{12} - 2Q_{66})S^3C$

= (39.167-2.186-2x4.14)0.65x0.5 -

(8.392-2.186-2x4.14)0.125x0.866

Q_{16} = 9.552 GPa

$Q_{22} = Q_{11}S^4 + Q_{22}C^4 + 2(Q_{12} + 2Q_{66})S^2C^2$

=(39.167x0.625)+(8.392x0.562)+ 2(2.186+2x4.14)0.75x0.25

Q_{22} = 33.12 GPa

$Q_{26} = (Q_{11} - Q_{12} - 2Q_{66}) CS^3 - (Q_{22} - Q_{12} - 2Q_{66})C^3S$

= (39.167-2.186-2x4.14)0.866x0.125

– (8.392-21862x4.14)0.65x0.5

Q_{26} = 3.781 GPa

$Q_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})S^2C^2 + Q_{66}(S^4 + C^4)$

=(39.167+8.392-2x2.186-24.14)0.75x0.25 + 4.14(0.625x0.562)

Q_{66} = 11.459 GPa

$$[Q]_{30^0} = \begin{bmatrix} 31.821 & 7.587 & 9.552 \\ 7.587 & 33.12 & 3.781 \\ 9.552 & 3.781 & 11.459 \end{bmatrix} GPa$$

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For plyup angle -45^0:

$C = 0.707, C^2 = 0.5, C^3 = 0.353$ & $C^4 = 0.25$

$S = -0.707, S^2 = 0.5, S^3 = -0.353$ & $S^4 = 0.25$

$$[Q]_{-45^0} = \begin{bmatrix} 17.123 & 9.389 & -7.681 \\ 9.389 & 17.123 & -7.681 \\ -7.681 & -7.681 & 10.797 \end{bmatrix} GPa$$

$$[D] = \frac{1}{3}\begin{bmatrix} 39.167 & 2.186 & 0 \\ 2.186 & 8.392 & 0 \\ 0 & 0 & 4.14 \end{bmatrix} 10^9 + \frac{1}{3}\begin{bmatrix} 31.821 & 7.587 & 9.552 \\ 7.587 & 33.12 & 3.781 \\ 9.552 & 3.781 & 11.459 \end{bmatrix} 10^9 + \frac{1}{3}\begin{bmatrix} 17.123 & 9.389 & -7.681 \\ 9.389 & 17.123 & -7.681 \\ -7.681 & -7.681 & 10.797 \end{bmatrix} 10^9$$

$$[D] = \begin{bmatrix} 63.56 & 13.167 & -7.523 \\ 13.167 & 30.393 & -8.003 \\ -7.523 & -8.003 & 17.131 \end{bmatrix} 10^3\ Pa - m^3$$

$$[D]^{-1} = \begin{bmatrix} 1.762x10^{-5} & -6.38x10^{-6} & 4.756x10^{-6} \\ -6.38x10^{-6} & 3.98x10^{-5} & 1.58x10^{-5} \\ 4.756x10^{-6} & 1.58x10^{-5} & 6.785x10^{-5} \end{bmatrix} \frac{1}{Pa - m^3}$$

❖ Total deflection (δ):

$\delta = (5wL^4) / (384E_xI)$

$E_x = 12 / (h^3 \text{ x } D^{-1}_{11})$

$= 12 / (0.03^3 \text{ x } 1.762 \text{ x } 10^{-5})$

$E_x = 2.5224 \text{ x } 10^{10}$ Pa

$I = BD^3 / 12$

$= (0.3 \text{ x} 0.03^3) / 12$

$I = 6.75 \text{ x } 10^{-7} m^4$

$\delta = (5 \text{ x } 6.1803 \text{ x } 10^6 \text{ x } 0.36^4) / (384 \text{ x } 2.5224 \text{ x } 10^{10} \text{ x } 6.75 \text{ x } 10^{-7})$

δ = 0.07939 m

δ = 79.39 mm

❖ Max curvature [X]:
Max curvature is at middle of frame and can given as,

$$\begin{bmatrix} X_x \\ X_y \\ X_{xy} \end{bmatrix} = \begin{bmatrix} D_{11}{}^{-1} \\ D_{12}{}^{-1} \\ D_{16}{}^{-1} \end{bmatrix} \frac{wL^2}{8B}$$

$$= \begin{bmatrix} 1.762^{-5} \\ -6.38x10^{-6} \\ 4.756x10^{-6} \end{bmatrix} \frac{6.1803 \times 10^6 \times 0.36^2}{8 \times 0.3}$$

$$\begin{bmatrix} X_x \\ X_y \\ X_{xy} \end{bmatrix} = \begin{bmatrix} 5.88 \\ -2.129 \\ 1.587 \end{bmatrix} \frac{1}{m}$$

❖ Global strains(ε):
At top of layup -45⁰

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \tau_{xy} \end{bmatrix} = Z \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

$$= 0.015 \begin{bmatrix} 5.88 \\ -2.129 \\ 1.587 \end{bmatrix}$$

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} 0.0882 \\ -0.03194 \\ 0.02381 \end{bmatrix}$$

❖ Global stresses (σ):

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = [Q] \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \tau_{xy} \end{bmatrix}$$

$$= \begin{bmatrix} 39.167 & 2.186 & 0 \\ 2.186 & 8.392 & 0 \\ 0 & 0 & 4.14 \end{bmatrix} \begin{bmatrix} 0.0882 \\ -0.03194 \\ 0.02381 \end{bmatrix}$$

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} 3.3847 \\ -0.0752 \\ 0.0986 \end{bmatrix} 10^9 \text{ Pa}$$

❖ Principal normal stresses ($\sigma_{max,min}$):

$$\sigma_{max,min} = \frac{\sigma_x \pm \sigma_y}{2} \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2}$$

$$= \left(\frac{3.3847 \pm (-0.0752)}{2} \sqrt{\left(\frac{3.3847-(-0.0752)}{2}\right)^2 + 0.0986^2}\right) 10^9$$

$\sigma_{max} = 2.998 \times 10^9$ N/m²

$\sigma_{min} = 2.867 \times 10^9$ N/m²

❖ Maximum shear stress (τ_{max}):

$$\tau_{max} = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2}$$

$$= \sqrt{\left(\frac{3.3847-(-0.0752)}{2}\right)^2 + 0.0986^2} \times 10^9$$

$= 1.7328 \times 10^9$ N/m²

6. RESULT AND DISCUSSION

6.1 Results

In this section, both finite element analysis and analytical results were presented. Analytical calculations and FEM results compare design of composite frame with the existing steel frame. Finite element analysis utilized to study the mechanical behavior of composite frame.

6.2 ANSYS Results

6.2.1 The Equivalent (von-mises) stress of composite top frame shown in Fig.

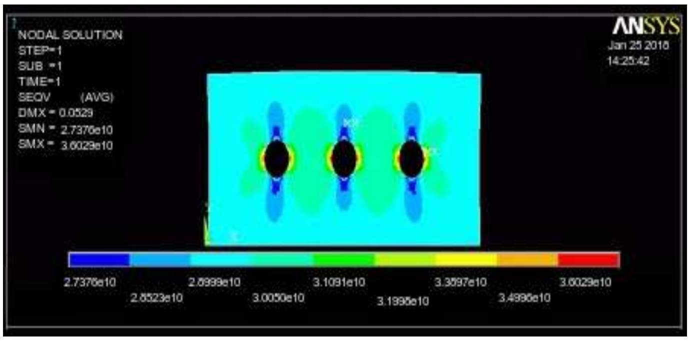

Fig.6 Equivalent stress of composite frame

6.2.3. The Total deformation of composite top frame shown in fig.

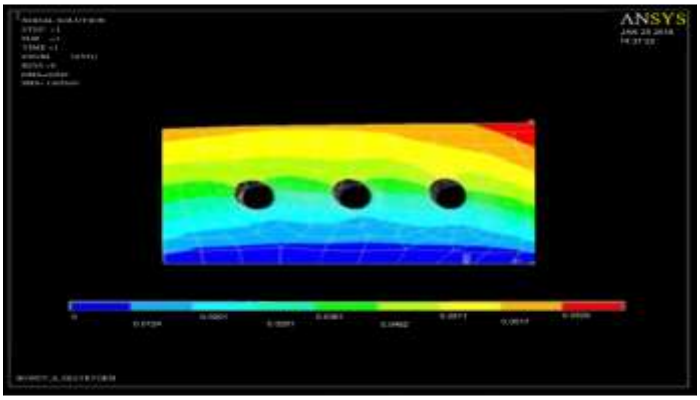

Fig.7 Total deformation of composite frame

6.3 Validation and comparison of Analytical and ANSYS Results

The following table gives the comparison of analytical and ANSYS results.

Results	Steel	E-Glass	
	Analytical	Analytical	Ansys
Mass (Kg)	41.04	13.5	13.5
Max bending stress (N/m²)	$5.2533x10^{11}$	$2.998x10^{9}$	$3.6029x10^{10}$
Deflection (m)	0.00945	0.07939	0.0529
Max shear stress (N/m²)	$1.0301x10^{9}$	$1.7328x10^{9}$	-

Table No.1 Comparison of Analytical and ANSYS

6.4. Discussions:

The conclusions obtained in FEA and Analytical results of Composite shaft are summarized as follow:

1. The Design bending stress obtained for composite frame is less than bending stress obtained for steel frame.

2. Shear strength obtained for composite fame is same as of steel frame.

3. Total deformation of the composite frame 12% more than steel frame.

4. The mass of composite frame is 3times less than steel frame.

7. CONCLUSIONS

1. The usage of composite materials has resulted in considerable amount of weight saving in the range of 81% to 72% when compared to conventional steel frame.

2. If we look at weight saving we can definitely replace composite with conventional steel frame but if we consider the obtained results such as deformation, bending stress of composite frame then it is somewhat difficult to replace steel frame. The bending stress of composite frame is 6.86% less than steel frame.

3. Apart from being lightweight, the use of composites also ensures long life due it anti-corrosion and fatigue life.

4. If we consider cost of glass/epoxy composite, it is slightly higher than steel but lesser than carbon/epoxy.

5. Hydraulic cylinder is mounted on top frame by fasting, in case of composite frame through holes are produced on frame and then mounted with nut and bolt system.

6. The composite frames are best in case ware conditions.

7. The composite are recyclable so they can be reuse.

8. So in comparison of mass, cost, safety and recycling steel frame can be replaced by composite frame.

9. The successful application of the present design can make a huge improvement in industrial application.

8. ACKNOWLEDGEMENT

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