

# Design and Stress Analysis of Carbon-Epoxy Composite Rocket Motor Casing

Shaik Shaheen <sup>1</sup>, Dr. G. Srinivasa Gupta <sup>2</sup>

P.G. Student, Department of Mechanical Engineering, VNR Vignana Jyothi Institute of Engineering and Technology,  
Bachupally, Telangana, India<sup>1</sup>

Professor, Department of Mechanical Engineering, VNR Vignana Jyothi Institute of Engineering and Technology,  
Bachupally, Telangana, India<sup>2</sup>

**ABSTRACT:** The rocket motor case is an inert or non-energy contributing missile component; the design objective is to make the case as lightweight as possible, within the bounds of technology and cost. The rocket motor casing materials must be lightweight and able to withstand high pressures and elevated temperatures due to the combustion of the fuel. In this paper, it is proposed to characterize parametrically the structural behaviour of rocket motor casing made of carbon-epoxy composite material as well as D6AC steel material. The 3D model is developed using CATIA V5R16 software and stress analysis is carried out using ANSYS 15.0 software. The carbon-epoxy material results are compared with the D6AC steel material results to specify better efficient material.

**KEYWORDS:** Rocket Motor case, Design, Analysis, Carbon-Epoxy, D6AC steel.

## I. INTRODUCTION

The typical solid rocket motor case is basically a double-domed right circular cylinder with opening at both ends and cylindrical extensions called skirts. The motor case shall be of the minimum weight required for structural capability and rigidity while subjected to the critical loads and the effects of the environmental conditions within the overall vehicle design constraints. Analytical verification of the case structural integrity should be established using the recommended practices for structural analysis. To obtain a minimum-weight case, the structure should be designed for the critical service conditions.

The initial selection of case material is generally the choice of the most efficient material that will satisfy the overall critical-loading condition at the critical operating temperature. A composite material is made commonly by combining of two or more distinct materials each of which retains its distinctive properties to create a new material. Generally, a composite material is composed of reinforcement (fibers, particles, flakes, and/or fillers) embedded in a matrix (polymers, metals, or ceramics). The matrix holds the reinforcement to form the desired shape while the reinforcement improves the overall mechanical properties of the matrix. When designed properly, the new combined material exhibits better strength than would each individual material. Composites can contribute 30% less weight of the rocket at launch-time. Glass fiber was used for earlier applications, it is relatively high density but inexpensive. Kevlar, much lower in density and higher in specific strength, is presently in wide use. The graphite/carbon fibers have improved dramatically in recent years and while slightly higher in density than Kevlar, their substantially higher delivered fiber strength in pressure vessels and consequently higher specific strength makes them the frequent materials of choice today. An epoxy resin is typically used as the matrix material as it continues to dominate matrix technology.

NASA SP-8025 [1] has given the details about the case configuration, material selection, case design, case fabrication, testing and inspection for the solid rocket motor metal cases. AGARD-LS-15 [2] has given the design methods in Solid Rocket Motors, in which Dr. P. R. Evans has given about Composite Motor Case Design. MIL-HDBK-17-1F [3] volume-1 composite materials handbook has given polymer matrix composites guidelines.

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In [4], the authors has given the design of carbon-epoxy T-700/ (A16/K5) composite rocket motor casing and compared the results with HE-15 AL alloy metallic casing to quantify the improvement of performance factor. In [5], the paper deals with the design of solid rocket mainly consists of determining the thickness of motor casing which includes the domes at head end, nozzle end and flange for bolted joints, in which the maximum working stress is compared with allowable yield stress of the material.

Paper is organized as follows. Section II is about problem description. The modelling of rocket motor case using CATIA V5R16 software is given in Section III. Section IV presents Carbon-Epoxy (IM10/8552) and D6AC steel material properties. The analysis of rocket motor casing is done by using ANSYS 15.0 software in Section V. The results of the composite and metal materials are compared in the Section VI. Finally, Section VII presents conclusion.

## II. PROBLEM DESCRIPTION

The solid rocket motor casing component is essentially a minimum-weight pressure vessel, so the material should be as lightweight as possible with high strength. In this paper the fiber reinforced composite carbon IM10/ epoxy 8552 is considered. Analysis is done for the maximum and minimum values of deformation, stress and strain in stress analysis the results are compared with the results of metal D6AC steel material.

## III. MODELLING OF ROCKET MOTOR CASE

In CATIA V5R16 software using the geometry the 2D model of the rocket motor case is sketched in sketcher workbench. The 2D model is then imported to part design workbench then it is revolved around  $360^{\circ}$  about V-direction axis to convert into 3D surface model. Finally, the 3D surface model of rocket motor case is generated.

- **2D and 3D model of rocket motor case**

The 2D model of rocket motor case using geometry is sketched in sketcher workbench. In CATIA software select “Mechanical Design” option and in that select “Wireframe and Surface Design” option, the part design workbench will be opened, select a plane and click on “sketch” option to sketch the 2D model using geometry. The sketched 2D model is obtained as shown in Fig.1.

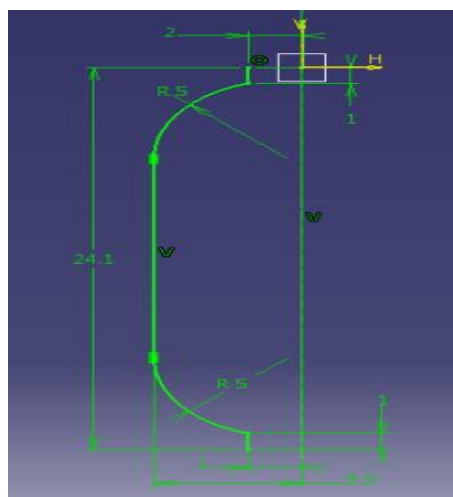


Fig.1: 2D model

The 2D model as shown in Fig.1 is revolved  $360^{\circ}$  about V-direction axis in part design workbench and the 2D model is converted into 3D model as shown in Fig.2.

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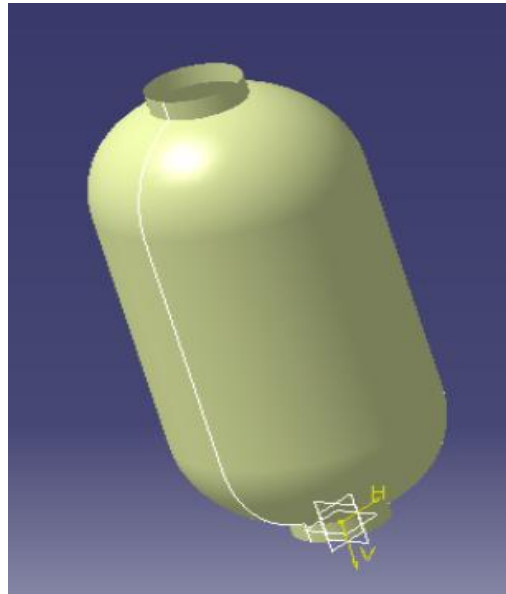


Fig.2: 3D model of 2D model in Fig.1

The rocket motor case consist of cylindrical extensions called skirts which completes the component, so the Fig.2 3D model is attached with cylindrical extensions i.e. skirt sketch as shown in Fig.3.

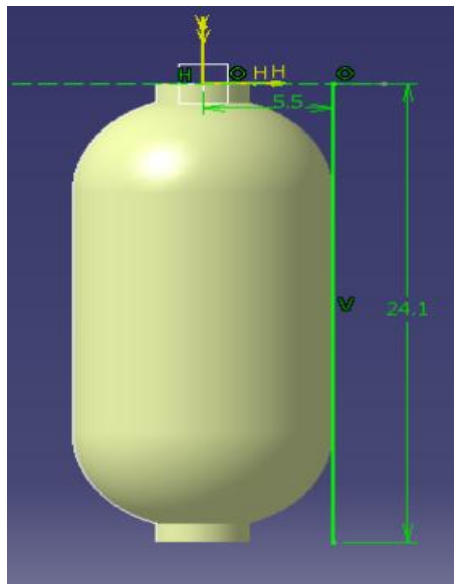


Fig.3: skirt sketch

The 2D model of the skirt is converted into 3D model by revolving it  $360^{\circ}$  about V-direction. Hence the 3D surface model (as shown in Fig.4) of the rocket motor case is obtained.

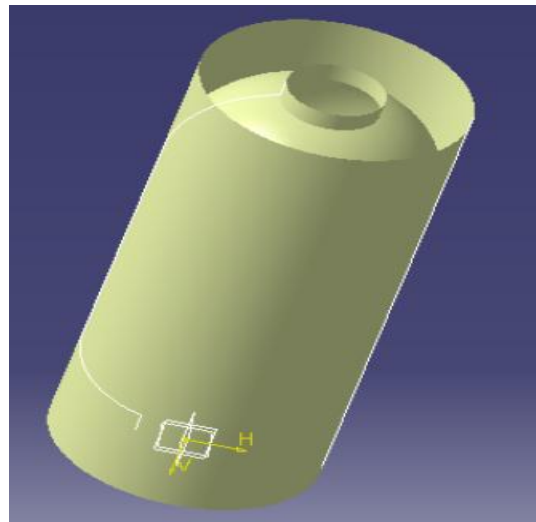


Fig.4: 3D surface model of rocket motor case

The 3D CATIA part model is converted into IGES Format and saved it for analysis the model in ANSYS 15.0 software. During analysis the model is added with materials Carbon-Epoxy IM10/8552 and D6AC Steel.

#### IV. MATERIAL PROPERTIES

- **Properties of Carbon fiber IM10**

Carbon Fiber IM10 is the highest commercially available Tensile strength carbon fiber meeting the demands for next generation aerospace programs and applications.

| Carbon Fiber type | Young's Modulus ( $E_f$ ) (GPa) | Tensile Strength (MPa) | Poisson's ratio( $\nu_f$ ) | Weight/Length (g/m) | Density( $\rho_f$ ) (g/cm <sup>3</sup> ) | Thermal conductivity coefficient( $k_f$ ) (W/K-m) | Thermal expansion coefficient( $\alpha_f$ ) (1/ <sup>0</sup> C) |
|-------------------|---------------------------------|------------------------|----------------------------|---------------------|--|---|---|
| IM10              | 310                             | 6964                   | 0.27                       | 0.324               | 1.79                                     | 6.14  | $-0.7 \times 10^{-6}$   |

Table.1: Properties of Carbon fiber

- **Properties of epoxy matrix 8552**

Epoxy matrix 8552 is a high performance tough epoxy matrix for use in primary aerospace structures. It exhibits good impact resistance and damage tolerance for wide range of applications. It is an amine cured, toughened epoxy resin system supplied with unidirectional or woven carbon or glass fibers.

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| Epoxy Matrix type | Young's Modulus (E <sub>m</sub> ) (GPa) | Tensile Strength (MPa) | Shear strength (MPa) | Poisson's ratio(v <sub>m</sub> ) | Density(ρ <sub>f</sub> ) (g/cm <sup>3</sup> ) | Thermal conductivity coefficient(k <sub>m</sub> ) (W/K-m) | Thermal expansion coefficient(α <sub>m</sub> ) (1/°C) | Moisture expansion coefficient(β <sub>m</sub> ) |
|-------------------|---|------------------------|----------------------|----------------------------------|---|---|---|---|
| 8552              | 3.45                                    | 90                     | 60                   | 0.35                             | 1.3   | 0.18  | 64.3×10 <sup>-6</sup>                                 | 0.38  |

Table.2: Properties of Epoxy matrix

• **Properties of Carbon-Epoxy (IM10/8552) composite**

**1. Lamina Density, ρ<sub>c</sub> :-**

$$\rho_c = \rho_f V_f + \rho_m V_m$$

$$\rho_c = [(1.79)(0.6) + (1.3)(0.4)] \text{ g/cm}^3$$

$$= 1.594 \text{ g/cm}^3$$

**2. Longitudinal Young's Modulus, E<sub>1</sub> :-**

According to RULE OF MIXTURE:  $E_1 = E_f V_f + E_m V_m$

$$= 310 (0.6) + 3.45 (0.4)$$

$$E_1 = 187.4 \text{ GPa}$$

Where V<sub>f</sub> = Volume fraction of Fiber = 0.6  
V<sub>m</sub> = Volume fraction of matrix = 1- V<sub>f</sub> = 1-0.6 = 0.4

**3. Transverse Young's Modulus, E<sub>2</sub> :-**

According to INVERSE RULE OF MIXTURE:  $\frac{1}{E_2} = \frac{V_m}{E_m} + \frac{V_f}{E_f}$

$$= \frac{0.4}{3.45} + \frac{0.6}{310}$$

$$E_2 = 8.483 \text{ GPa}$$

**4. In-plane Poisson's Ratio, ν<sub>12</sub> :-**

According to RULE OF MIXTURE:  $\nu_{12} = \nu_f V_f + \nu_m V_m$

$$= 0.27(0.6) + 0.35(0.4)$$

$$= 0.302$$

**5. Intralaminar Poisson's Ratio, ν<sub>23</sub> :-**

According to Periodic Microstructure:  $\nu_{23} = 0.4953$

**6. In-plane Shear modulus, G<sub>12</sub> :-**

According to Cylindrical Assemblage:  $G_{12} = G_m \left[ \frac{(1+V_f) + (1-V_f)G_m/G_f}{(1-V_f) + (1+V_f)G_m/G_f} \right] = 4.919 \text{ GPa}$

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Where  $G_m$  = shear modulus of matrix = 1.278 GPa

$G_f$  = shear modulus of fiber = 122 GPa

### 7. Intralaminar Shear modulus, $G_{23}$ :-

$$\text{According to stress Partitioning: } G_{23} = G_m \left[ \frac{(V_f) + \eta_4(1 - V_f)}{\eta_4(1 - V_f) + V_f(G_m/G_f)} \right]$$

$$= 4.2647 \text{ GPa}$$

Where  $\eta_4 = \frac{3 - 4V_m + G_m/G_f}{4(1 - V_m)} = 0.6194$

### 8. Longitudinal Coefficient of Thermal Expansion, $\alpha_1$ :-

$$\alpha_1 = \frac{\alpha_f V_f E_f + \alpha_m V_m E_m}{E_1} = -0.2213 \times 10^{-6} \left( \frac{1}{^\circ\text{C}} \right)$$

### 9. Transverse Coefficient of Thermal Expansion, $\alpha_2$ :-

$$\alpha_2 = \alpha_f \sqrt{V_f} + (1 - \sqrt{V_f}) \left( 1 + V_f v_m \frac{E_f}{E_1} \right) \alpha_m = 18.99 \times 10^{-6} \left( \frac{1}{^\circ\text{C}} \right)$$

### 10. Longitudinal Coefficient of Moisture Expansion, $\beta_1$ :-

$$\beta_1 = \beta_m (1 - V_f) \frac{E_m}{E_1} = 0.0028$$

### 11. Transverse Coefficient of Moisture Expansion, $\beta_2$ :-

$$\beta_2 = \beta_m (1 - \sqrt{V_f}) \left[ 1 + \frac{\sqrt{V_f} (1 - \sqrt{V_f}) E_m}{\sqrt{V_f} E_2 + (1 - \sqrt{V_f}) E_m} \right] = 0.095$$

- **Properties of D6AC Steel material**

Alloy D6AC has ultra high strength and is designed for use in high strength structural applications. It is also known for its high yield strength to tensile strength ratio, combined with good ductility.

| Material   | Young's Modulus (E) (GPa) | Tensile Strength (MPa) | Poisson's ratio( $\nu$ ) | Density( $\rho$ ) (g/cm <sup>3</sup> ) | Thermal conductivity(k) (W/K-m) | Thermal expansion coefficient( $\alpha$ ) (1/ <sup>0</sup> C) |
|------------|---------------------------|------------------------|--------------------------|--|---------------------------------|---|
| D6AC Steel | 200                       | 1516.85                | 0.32                     | 0.283                                  | 30                              | -0.7×10 <sup>-6</sup>   |

Table.3: Properties of D6AC Steel material

## V. ANALYSIS OF ROCKET MOTOR CASE

The Rocket Motor Case finite element analysis is performed by using ANSYS 15.0. This paper consists of Static structural analysis.

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- **Static Structural Analysis of carbon-epoxy (IM10/8552) composite material**

The static structural analysis is done to calculate the material deformation and stress distribution. The 3D solid model is imported in ANSYS 15.0 in IGES format. In Material Model, the material properties of carbon epoxy IM10/8552 are given as calculated in section IV. The stress analysis of model is carried out for internal pressure of 1160.3016 psi (8MPa) and force of 1079083lbf. In Mechanical APDL ANSYS the 3D model is imported, for better results and for clear representation the model is symmetrically sectioned. Then the model is meshed as shown in Fig.5.

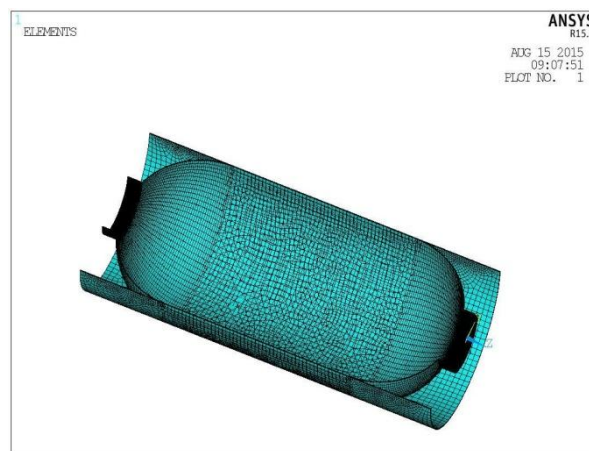


Fig.5: Meshing of rocket motor casing

The element type is given as “shell” and storage of layer data is applied to “all layers” and in “Section” option we can add and give each layer’s thickness and orientation of each layer for the shell 3D model. The total layer thickness is given as 0.06 inches and the fiber thickness is given as 0.015 and the matrix thickness is given as 0.01 which is shown in Fig.6.

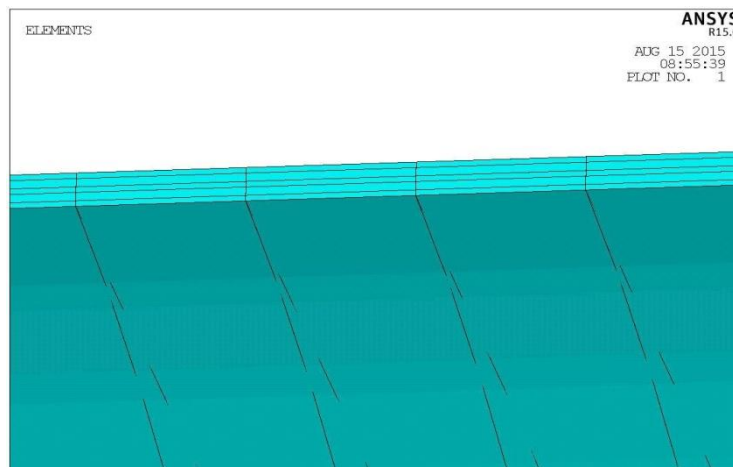


Fig.6: Layers of Carbon-Epoxy Composite

In structural displacement, pressure of 1160.3016 psi and force of 1079083.3187 lbf in X-axis direction are applied on the model as shown in Fig.7.

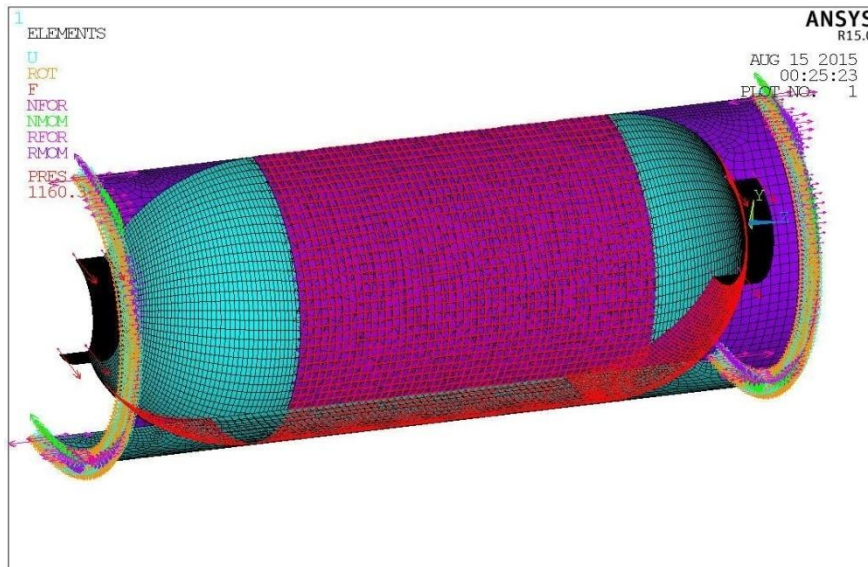


Fig.7: loads and fixed supports applied

After apply the loads, the solution is to be solved using “Solve” by clicking on “current LS” option in “Solution”. In “General Postprocessor” click on “Plot Results” in which select “Contour Plot” option in which we find “Nodal Solution” option which gives various results of analysed given model.

The total deformation obtained is shown in Fig.8. The deformation maximum value obtained is 2.75161 and the deformation minimum value obtained is -0.713754. The deformation value (DMX) of the model is obtained as 4.08539.

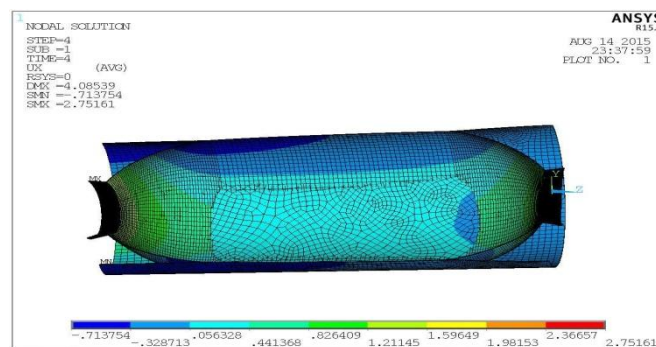


Fig.8: total deformation of carbon-epoxy

The Von-mises stress obtained is shown in Fig.9. The Von-mises stress maximum value obtained is 0.642E+10 and the minimum value obtained is 228101.



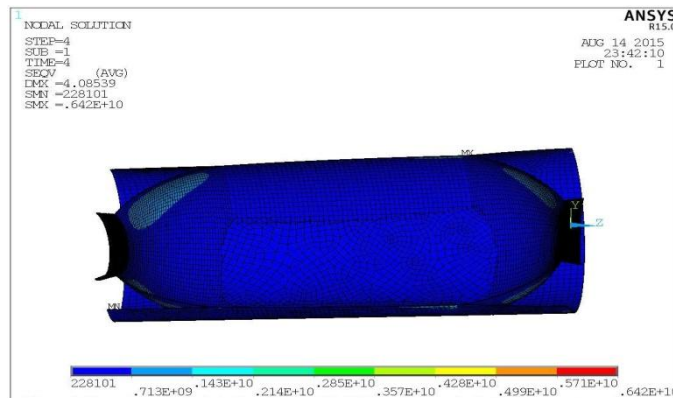


Fig.9: Von-mises Stress of Carbon-Epoxy composite

The Von-mises strain obtained is shown in Fig.10. The Von-mises strain maximum value obtained is 0.12386 and the minimum value obtained is 0.342E-05.

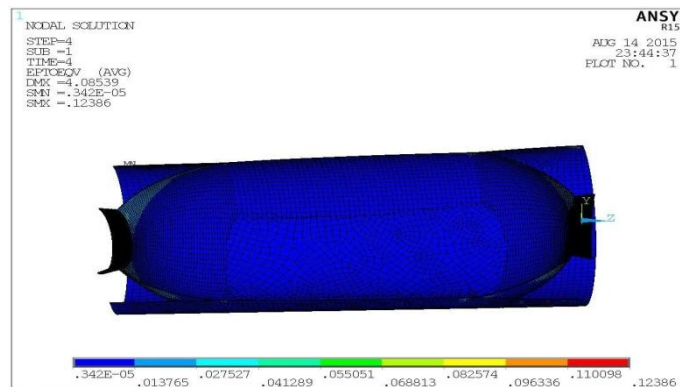


Fig.10: Von-mises strain of Carbon-Epoxy composite

Hence, the structural stress analysis of Carbon-Epoxy IM10/8552 composite material for Rocket Motor Casing is completed and the respective values are obtained as shown in Table.4.

| Material                         | Deformation |           | Von-mises stress |         | Von-mises strain |           |
|----------------------------------|-------------|-----------|------------------|---------|------------------|-----------|
|                                  | Maximum     | Minimum   | Maximum          | Minimum | Maximum          | Minimum   |
| Carbon-Epoxy IM10/8552 composite | 2.75161     | -0.713754 | 0.642E+10        | 228101  | 0.12386          | 0.342E-05 |

Table.4: ANSYS Results obtained for Carbon-Epoxy IM10/8552 composite Material

- **Static Structural Analysis of D6AC steel material**

The 3D model is imported in ANSYS 15.0 in IGES format. In Material Model, the material properties of D6AC Steel are given as calculated in section IV Table.3. The stress analysis of model is carried out for internal pressure of 1160.3016 psi (8Mpa) and force of 1079083lbf. In Mechanical APDL ANSYS the 3D model is imported, the model is symmetrically sectioned. Then the model is meshed as shown in above Fig.5.

The element type is given as “shell” and storage of layer data is applied to “all layers” and in “Section” option we can add and give each layer’s thickness and orientation of each layer for the shell 3D model. The total layer thickness is given as 0.06 as the material is metal and not a composite the shell is given one layer thickness which is shown in Fig.11.

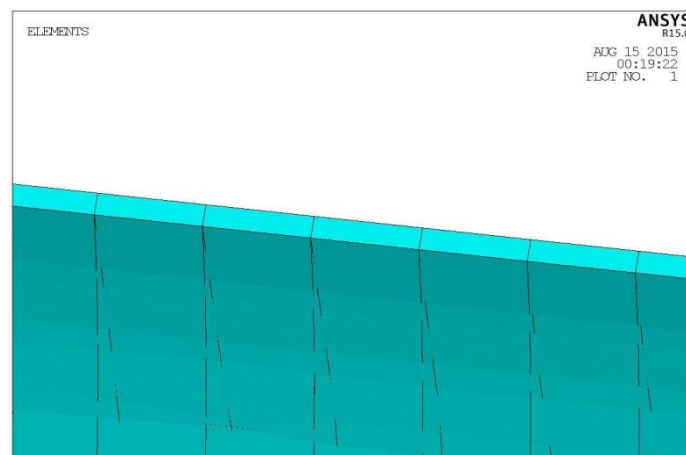


Fig.11: Layer of D6AC Steel Material

After apply the loads as shown in Fig.7, then the solution is to be solved using “Solve” by clicking on “current LS” option in “Solution”. In “General Postprocessor” click on “Plot Results” in which select “Contour Plot” option in which we find “Nodal Solution” option which gives various results of analysed given model.

The total deformation obtained is shown in Fig.12. The deformation maximum value obtained is 0.802038 and the deformation minimum value obtained is -0.237021. The deformation value (DMX) of the model is obtained as 1.17863.

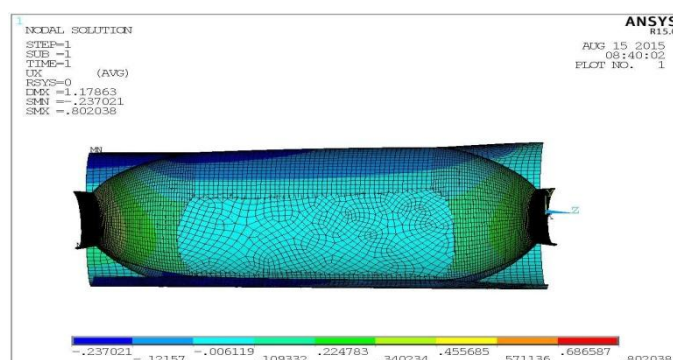


Fig.12: total deformation of D6AC steel

The Von-mises stress obtained is shown in Fig.13. The Von-mises stress maximum value obtained is 0.448E+10 and the minimum value obtained is 189399.

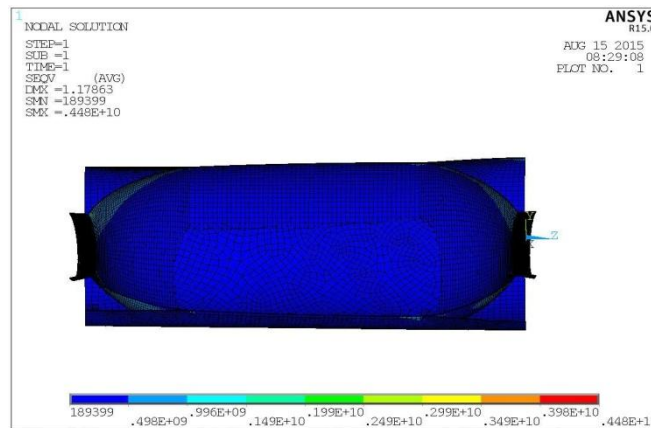


Fig.13: Von-mises Stress of D6AC Steel

The Von-mises strain obtained is shown in Fig.14. The Von-mises strain maximum value obtained is 0.023913 and the minimum value obtained is 0.579E-06.

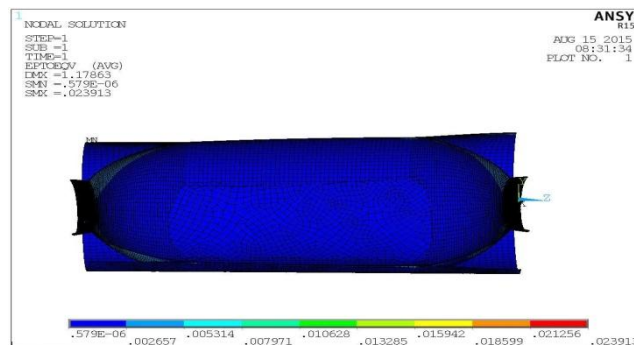


Fig.14: Von-mises strain of D6AC Steel

Hence, the structural stress analysis of D6AC Steel material for Rocket Motor Casing is completed and the respective values are obtained as shown in Table.5.

| Material   | Deformation |           | Von-mises stress |         | Von-mises strain |           |
|------------|-------------|-----------|------------------|---------|------------------|-----------|
|            | Maximum     | Minimum   | Maximum          | Minimum | Maximum          | Minimum   |
| D6AC Steel | 0.802038    | -0.237021 | 0.448E+10        | 189399  | 0.023913         | 0.579E-06 |

Table.5: ANSYS Results obtained for D6AC Steel material

## VI. COMPARISON OF STRESS ANALYSIS RESULTS

The Table.6 shows the maximum and minimum values of total deformation, von-misses stress and von-misses strain of Carbon-Epoxy IM10/8552 and D6AC Steel. The maximum total deformation occurred in carbon-epoxy composite material. The maximum stress and strain is also obtained in Carbon-Epoxy IM10/8552 composite material.

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| MATERIAL                      | TOTAL DEFORMATION |           | VON-MISSES STRESS |         | VON-MISSES STRAIN |           |
|-------------------------------|-------------------|-----------|-------------------|---------|-------------------|-----------|
|                               | Maximum           | Minimum   | Maximum           | Minimum | Maximum           | Minimum   |
| <b>CARBON-EPOXY IM10/8552</b> | 2.75161           | -0.713754 | 0.642E+10         | 228101  | 0.12386           | 0.342E-05 |
| <b>D6AC STEEL</b>             | 0.802038          | -0.237021 | 0.448E+10         | 189399  | 0.023913          | 0.579E-06 |

Table.6: Comparison of results obtained between carbon-epoxy IM10/8552 composite and D6AC steel material

## VII. CONCLUSION

The structural analyses for both materials are completed; from the results obtained the maximum stress value is more in carbon-epoxy composite material than D6AC Steel. The deformation value of carbon-epoxy IM10/8552 material is large compared to D6AC Steel and even the maximum strain is more in carbon-epoxy composite material compare to D6AC Steel. When we compared with corresponding values of stress, strain and deformation, the differences of these values are considerably more for Carbon-Epoxy composite than D6AC Steel, hence it can be concluded that Carbon-epoxy IM10/8552 composite is efficient material than D6AC Steel for Rocket Motor Casing.

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