Structural Integrity Analysis of Propellant in Solid Rocket Motor

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ABSTRACT

Abstract – Design and analysis of propellant grain plays an important role to determine the stress, strain, temperature and the pressure generated the motor can withstand. This paper deals with the design and analysis of case bonded motor using ANSYS R15.0. The dimensions of the model have been arrived by numerical calculations as per the HEMRL Standards. Structural analysis of casing, insulation and propellant is done with different materials. The numerical values are calculated by using plane strain theory. The method adopted can be applied to any complex design or model of composite rocket motor in a much easier way to design th-e grain configuration of rocket motor. As the propellant burns it causes variation in pressure with respect to time and this change in pressure will change the mass flow rate. Due to the viscoelastic character of the propellant it causes damping to the system. A suitable material for insulation is taken into consideration to withstand internal pressure generated in solid rocket motor. The margin of safety of propellant is calculated on the basis of percentage elongation. The solid rocket motor is analysed for pressure load induced stresses to show that the developed stresses and strains are within the controlled values. The numerical and analytical results are compared to verify the designed propellant in solid rocket motor.

Keywords*: Stress, Strain, Ansys, Solid rocket motor, Propellant, Structural analysis, Margin of safety etc.*

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1. INTRODUCTION

Solid rocket with a rocket engine that uses solid propellant as a fuel is known as solid propellant rocket motor. In earlier days the fuel used in solid propellant rockets was gun powder that was used during wartime in 13th century. Until 20th century the propellant used in rocket motor was gun powder, later the liquid propellant rockets were introduced. The liquid propellant are more efficient. Due to the reliability and less maintenance solid rocket motors are used in wide applications. Solid fuel rockets can be stored for long periods, ready to launch at short notice. They are widely used in military applications.

The initial geometry of a solid propellant grain entirely dictates the subsequent burning surface area evolution and hence the mass flow rate and thrust profile. In this sense the thrust-time profile of a conventional solid rocket motor is pre-determined. The absolute magnitude of the thrust profile is determined by the surface area in conjunction with propellant burn rate pressure dependency, propellant density and thermochemical properties and the nozzle geometry. A thrust-time requirement is usually prescribed by the missile designer. The grain designer must then try to meet this requirement as closely as possible and this gives rise to a wide range of geometrical configurations. There are however further design constraints. Grain geometry affects stress levels within the propellant and hence structural integrity.

ISSN: 2321-8169
896 – 902

The objective is to design a 3 dimensional (3D) model from the dimensions and structure of the solid rocket motor. Then analysis is done on the whole composite structure. The main objective of the analysis is to determine the stresses and strains developed in the propellant due to the burning of the propellant. The load generated by pressurisation due

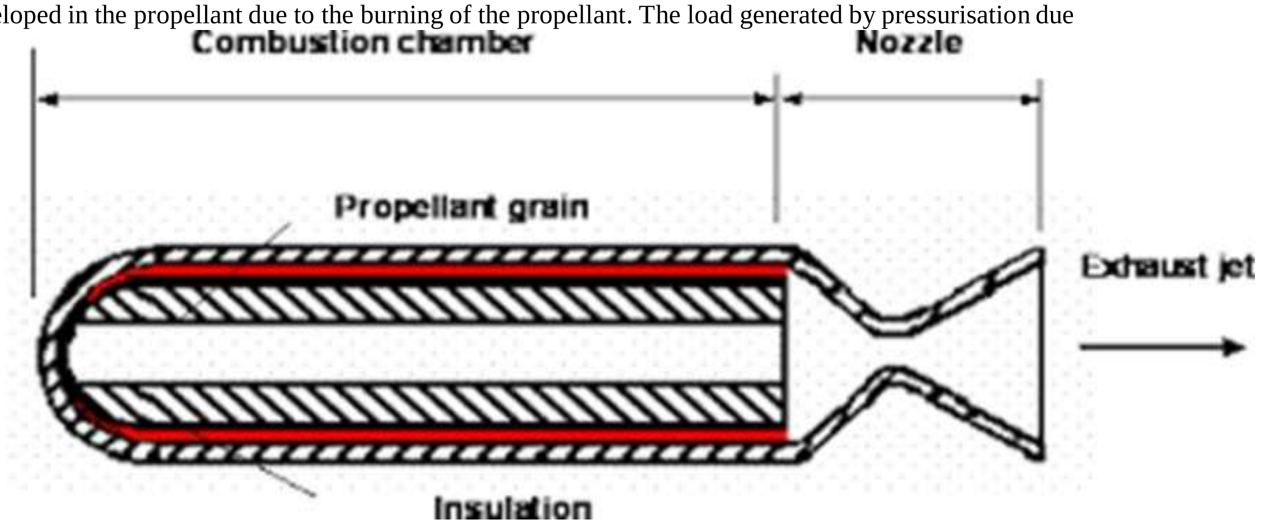


Fig.1 Components of Propellant Grain

to ignition of a solid propellant grain is considered as static load. This static load is the initial maximum pressure obtained either by internal ballistics prediction or from data collected from a static firing. For case bonded systems the propellant grain may be highly constrained and therefore a potentially significant stress can develop at the grain interfaces. The stresses and strains developed are calculated by using Ansys first and then they are verified with analytical calculations. The cumulative strain due to both thermal load and pressure load is used to calculate the margin of safety of the propellant. Factor of safety is calculated from the margin of safety, which explains if the designed propellant can bear the loads applied to it. The strain analysis of two and three composite cylinder of different material with different grain geometries is done below and compared for pressure load and thermal load accordingly the margin of safety is calculated and is checked for most feasible geometry.

2. EXPERIMENTAL DETAILS

2.1 *Analytical Method*

Consider a long thick hollow composite case bonded cylinder as shown in fig. 1. The composite cylinder is made of a homogeneous isotropic material and as it is a long enough in axial direction that the plane strain condition satisfies. This model is subjected to internal pressure.

A. Generalized Assumptions

In this analysis, the following assumptions are taken into consideration:

The materials of each layer are assumed to be homogeneous. The
composite cylinder is made up of multilayer case bonded.
The longitudinal strain developed due to the stress is uniform and constant, i.e. [illegible] = 0

B. Boundary Conditions

Boundary conditions are as:

The solid rocket motor is subjected to internal pressure

[illegible] = −[illegible] When r= a = inner radius

[illegible] = 0 When r= b = outer radius

$\epsilon_z = 0$ For axial strain

In this analysis, following stress and strain equations are used for structural analysis

Radial Stress $$\sigma_r = \frac{P_a a^2 - P_b b^2}{b^2 - a^a} - \frac{P_a - P_b}{b^2 - a^2} \cdot \frac{a^2 b^2}{r^2} \qquad \ldots\ldots\ldots [4]$$

Axial Stress $$\sigma_z = (2\nu) \cdot \left(\frac{P_b a^2 - P_a b^2}{b^2 - a^2} \right) \qquad \ldots\ldots\ldots [4]$$

Hoop Stress $$\sigma_\theta = \frac{P_a a^2 - P_b b^2}{b^2 - a^2} + \frac{P_a - P_b}{b^2 - a^2} \cdot \frac{a^2 b^2}{r^2} \qquad \ldots\ldots\ldots [4]$$

Radial Strain $$\epsilon_r = \frac{1+\nu}{E}[(1-\nu)\sigma_r - \nu\sigma_\theta] \qquad \ldots\ldots\ldots [4]$$

Hoop Strain $$\epsilon_\theta = \frac{1+\nu}{E}[(1-\nu)\sigma_\theta - \nu\sigma_r] \qquad \ldots\ldots\ldots [4]$$

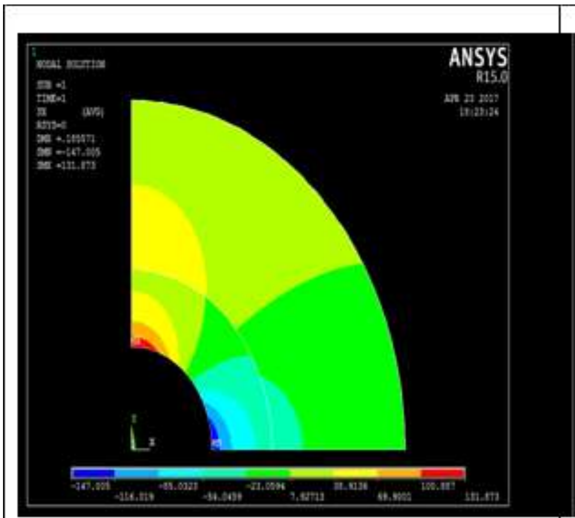
2.2 *Analysis and Comparison*

For validation purpose, we considered an example of composite cylinder of two layers one of copper and another one of steel. A 3-dimensional model was modelled on Ansys Workbench. Due to the axisymmetry of the solid rocket motor and boundary conditions, a quarter of geometric model was modelled on Ansys APDL. It was constructed using solid quad 8 node 183. The material properties are linear isotropic. The symmetrical boundary conditions were applied at the top and bottom of the cylinder, the number of nodes and elements are 27701 and 9100. Both layers are case bonded. The inside layer is made up of copper and outside layer is made up of steel. The inner radius of copper layered cylinder is 100mm and outer radius is 200mm. The inner radius of steel layered cylinder is 200mm and outer radius is 400mm. The internal pressure is 147 MPa, the outer pressure is 0 MPa. For thermal analysis the reference temperature is taken as 331 K and uniform temperature is 293 K. For 3-D model, tetrahedral mapped meshing is used. For 2-D model, quad mapped meshing is used. Finally the internal pressure was applied in radially outward direction at copper layer. Then the radial and hoop, stress and strains were determined.

Table 1: Material and Geometric Properties of Each Layer

	Layer-1(Copper)	Layer-2(Steel)
Young's Modulus	98e6 KPa	196e6 KPa
Poisson's Ratio	0.34	0.3

For Structural Load



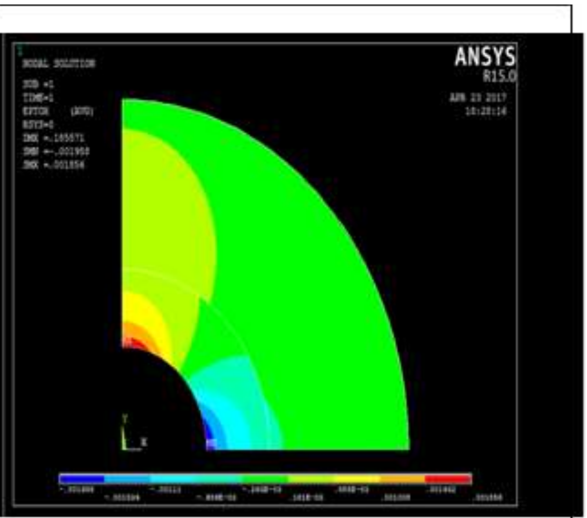


Fig.2 Radial and Hoop Stress

Fig.3 Radial and Hoop Strain

Table 2: Results Comparison

	Analytical	2-D	3-D	Accuracy 2-D w.r.t. 3-D
Hoop Stress	133 MPa	131.873 MPa	138.49 MPa	95.22
Radial Stress	-147 MPa	-147.005 MPa	-145.181 MPa	101.25
Hoop Strain	0.001883 mm	0.001856 mm	0.0019192 mm	101.45
Radial Strain	-0.00196 mm	-0.001958 mm	-0.001968 mm	100.10

As seen in above table, we can conclude that the accuracy is good between all the three comparisons. As the formulae and method is validating for this analysis, we will be using the same method for doing the analysis of various propellants in 2-D only, as it is less time consuming.

Table 3: Material Properties for Each Geometry

	Propellant	Insulation	Motor Casing
Young's Modulus	3.5 MPa	3.5 MPA	207000 MPa
Poisson's ratio	0.4995	0.4995	0.3
Density	1.76 g/cc	1.05 g/cc	7850 Kg/m^3

The strain analysis is done on following different propellant grain geometries, A.

CYLINDER GRAIN GEOMETRY

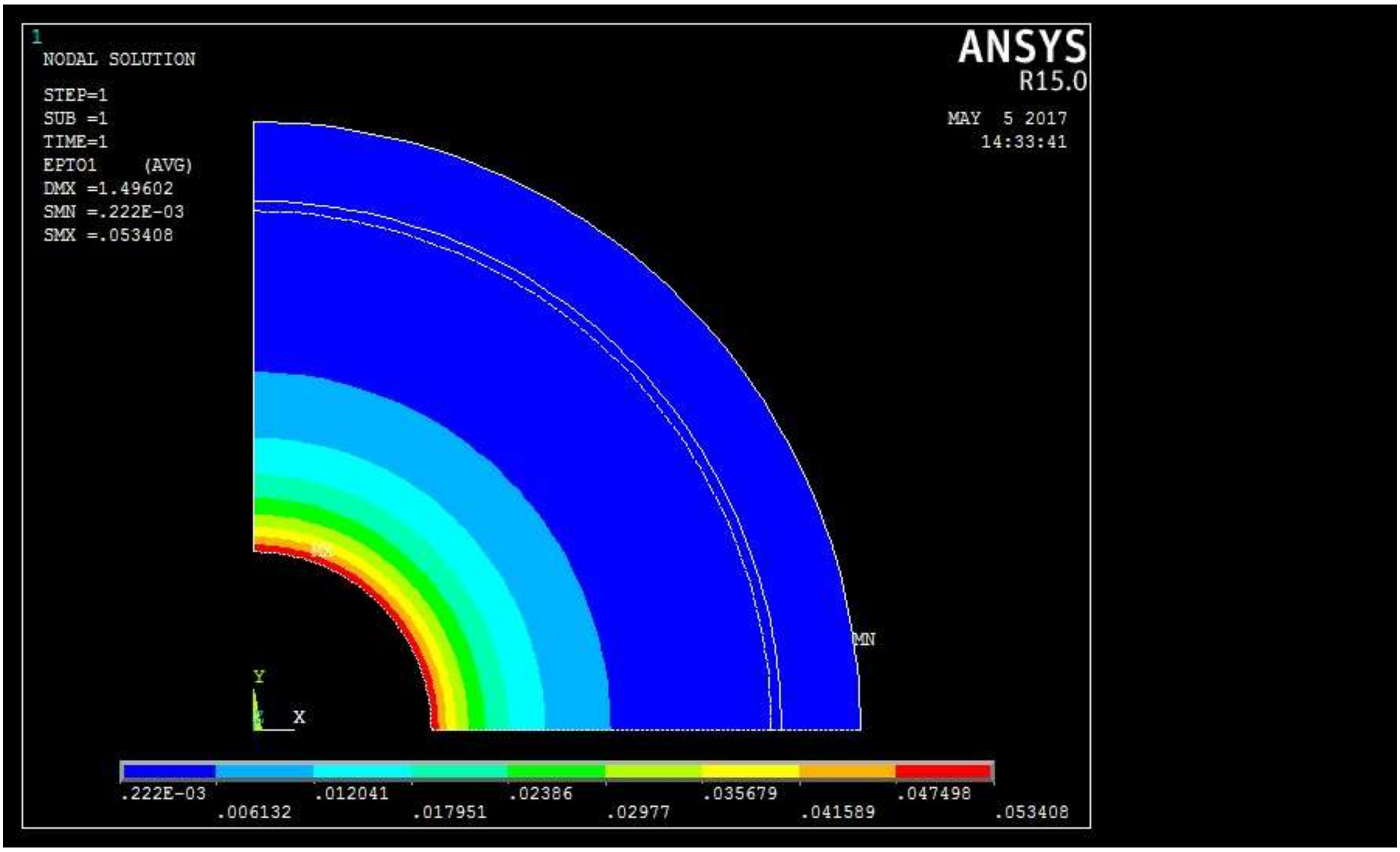


Fig.4. 1st Principal Strain for Cylinder Shaped Grain Geometry

From the 2-D analysis of cylinder grain shaped geometry in fig.4 for pressure= 10 MPa, Strain= 0.053408 mm

 ISSN: 2321-8169
896 – 902

Percentage elongation= 40 %

Margin of Safety= $\frac{\%\, Elongation \times 0.85 \times 0.8}{Strain} - 1$ …… [14]

= 4.0928

B. FIN GRAIN GEOMETRY

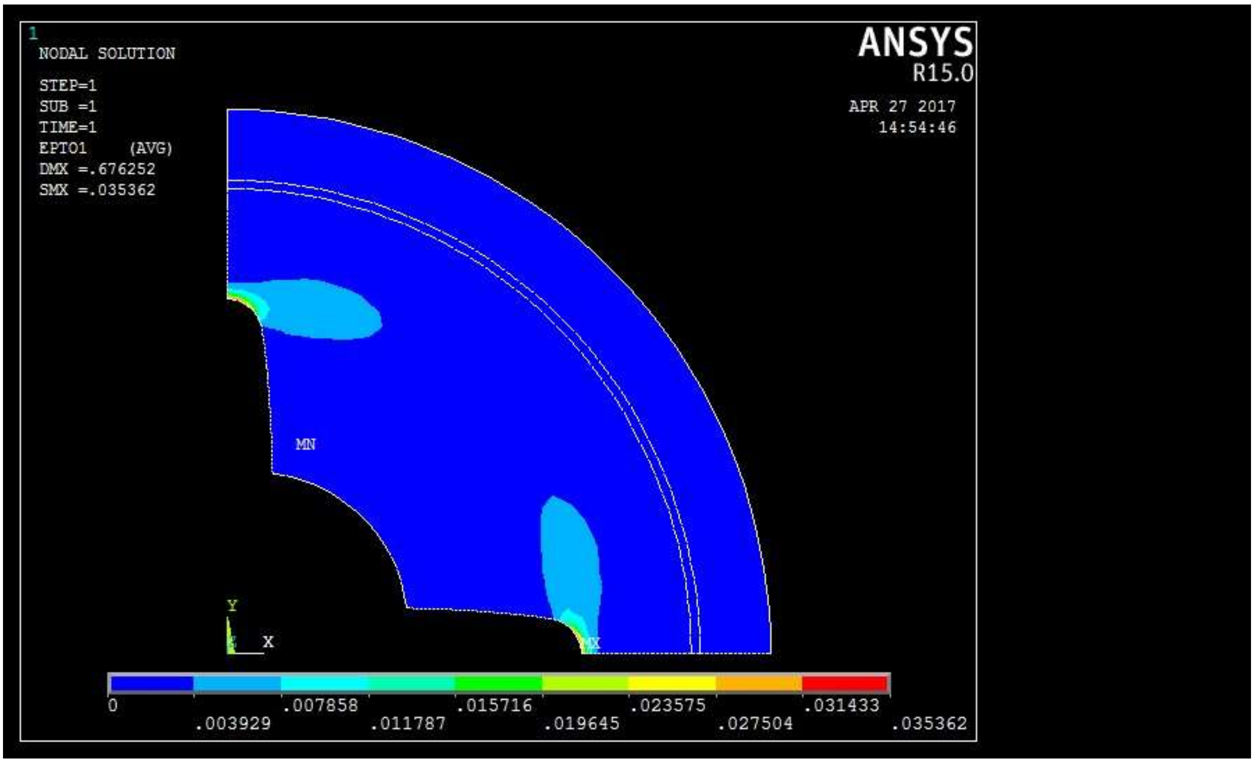


Fig.5. 1st Principal Strain for Fin Shaped Grain Geometry

From the 2-D analysis of fin grain shaped geometry in fig.5 for pressure= 10 MPa, Strain= 0.035362 mm

Percentage elongation= 40 %

Margin of Safety= $\frac{\%\, Elongation \times 0.85 \times 0.8}{Strain} - 1$

= 6.6918

C. STAR GRAIN GEOMETRY

From the 2-D analysis of star grain shaped geometry in fig.6 for pressure= 10 MPa, Strain= 0.027145 mm

Percentage elongation= 40 %

Margin of Safety= $\frac{\%\, Elongation \times 0.85 \times 0.8}{Strain} - 1$

= 9.0202

ISSN: 2321-8169
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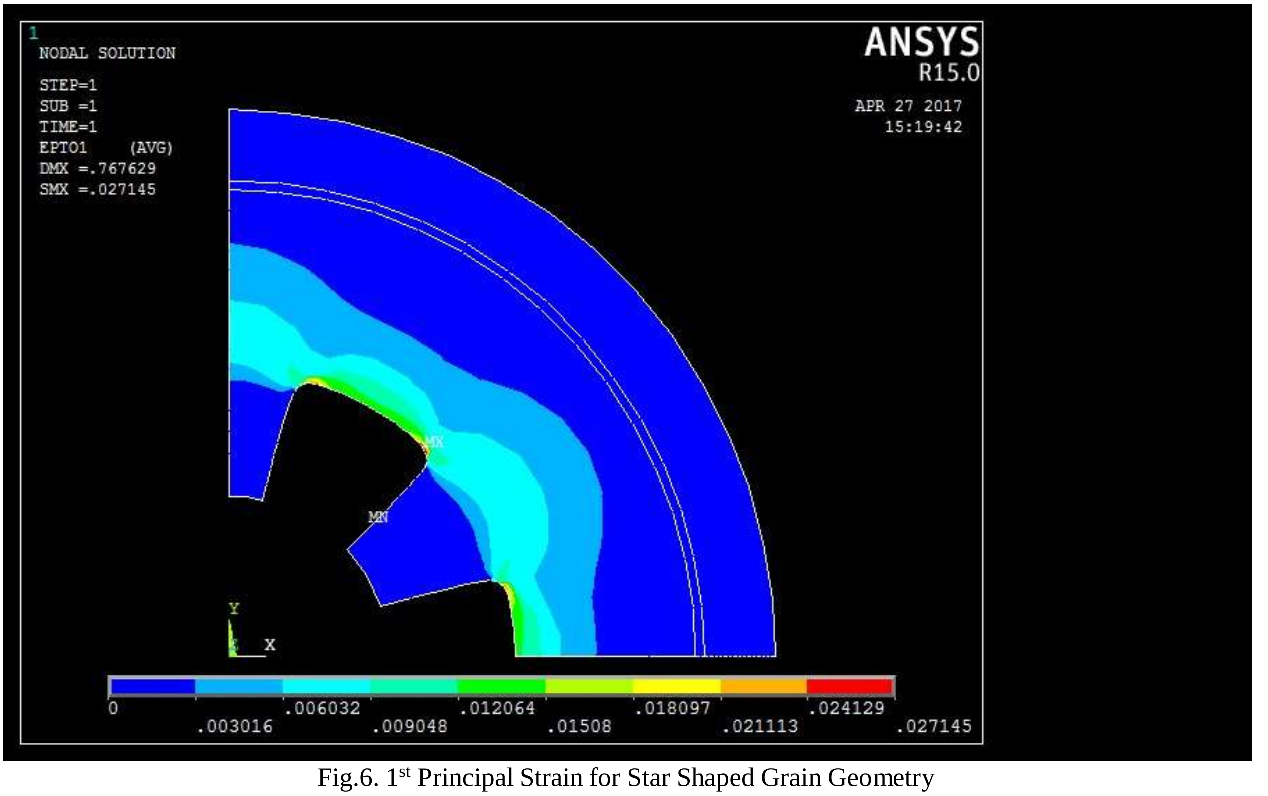

Fig.6. 1st Principal Strain for Star Shaped Grain Geometry

3. CONCLUSION

Sr. No.	Grain Geometry	Margin Of Safety
1	Cylinder	4.0928
2	Fin	6.6918
3	Star	9.0202

From the above result table, margin of safety for cumulative loads is quite high and more than adequate. Hence the margin of safety of cylinder shaped geometry is minimum and maximum for star shaped geometry. It can be concluded that the star shaped geometry is the most feasible geometry.

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