International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Design & Analysis of Solid Rocket Motor Casing for Aerospace Applications

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Accepted 31 May 2015, Available online 06 June 2015, **Vol.5, No.3 (June 2015)**

Abstract

In rocketry the designing of casing & hardware plays a vital role which is the replication of pressure vessel design. The temperatures induced inside the casing are of the order of 1000°C to 3000°C. The final temperature experienced by the casing at it's external surface (after insulation) is 100°C .To withstand these high temperatures some ablative liners are provided inside the casing. In this paper, structural analysis for the ablative layers materials Maraging Steel, A-286 Iron based alloy, D6AC Steel, Haynes 255 was done. Further, thermal analysis has been carried out with ANSYS for the material which had been selected after structural analysis. Modeling was done by AUTOCAD. The design of rocket Motor Casing is done using ASME section VIII methods for the given input parameters. The structural & the stresses and FOS are arrived from analysis and compared with design values.

Keywords: *Solid* Rocket motor, Casing, D6AC, Maraging Steel, Haynes 255, ANSYS, Thermo structural Analysis, *Ablative liners*

1. Introduction

In a solid rocket motor (SRM) the propellant consists of one or more pieces mounted directly in the motor case, which serves both as a propellant tank and combustion chamber. The propellant is usually arranged to protect the motor case from heating. Most modern propellant charges are formed by pouring viscous mix into the motor case with suitable mould fixtures. The propellant solidifies and the mould fixtures are removed, leaving the propellant bonded to the motor case with suitably shaped perforation down the middle. During operation the solid burns on the exposed inner surfaces. These burn away at a predictable rate to give the desired thrust.

All rockets used some form of solid or powdered propellant up until the 20th century, when liquid rockets and hybrid rockets offered more efficient and controllable alternatives. Solid rockets are still used today in model rockets and on larger applications for their simplicity and reliability.

Since solid rockets can be stored for long periods and reliably launched on short notice, they have been used frequently in military applications such as missiles. The lower performance of solid propellants in comparison with liquid propellants does not favor their use as primary propulsion in modern medium-to-large launch vehicles which are customarily used to launch larger payloads into orbit. However, solids are often used as additional strap-on boosters to increase payload capacity or as spin-stabilized add-on upper stages when higher-than-normal velocities are required.

1.1 Solid motor components

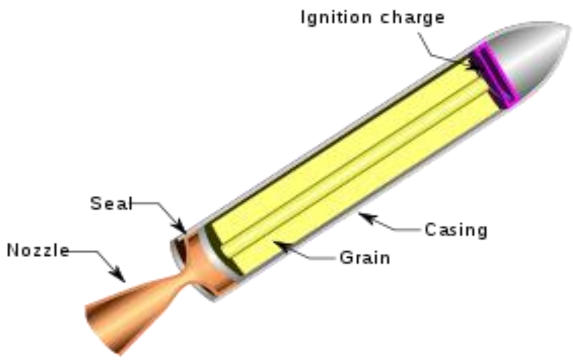

Fig.1: Solid motor components

A simple solid rocket motor consists of a casing, nozzle, grain (propellant charge), and igniter. The grain behaves like a solid mass, burning in a predictable fashion and producing exhaust gases. The nozzle dimensions are calculated to maintain a design chamber pressure, while producing thrust from the exhaust gases.

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Once ignited, a simple solid rocket motor cannot be shut off, because it contains all the ingredients necessary for combustion within the chamber in which they are burned. More advanced solid rocket motors can not only be throttled but also be extinguished and then re-ignited by controlling the nozzle geometry or through the use of vent ports. Also, pulsed rocket motors that burn in segments and that can be ignited upon command are available.

Modern designs may also include a steerable nozzle for guidance, avionics, recovery hardware (parachutes), self-destruct mechanisms, APUs, attitude control motors, controllable divert tactical motors, and thermal management materials.

1.2 Working Principle

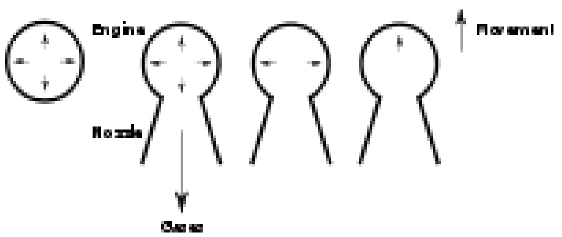

Fig. 2: Working principle

Rocket engines produce thrust by the expulsion of a high-speed fluid exhaust. This fluid is nearly always a gas which is created by high pressure (10-200 bar) combustion of solid or liquid propellants, consisting of fuel and oxidizer components, within a combustion chamber.

The fluid exhaust is then passed through a supersonic propelling nozzle which uses heat energy of the gas to accelerate the exhaust to very high speed, and the reaction to this pushes the engine in the opposite direction.

In rocket engines, high temperatures and pressures are highly desirable for good performance as this permits a longer nozzle to be fitted to the engine, which gives higher exhaust speeds, as well as giving better thermodynamic efficiency

2. Literature Review

ASME Pressure vessel code section VIII division 2 gives the equations for the calculation of shell and dome thickness. Alexander flake developed equation for the calculation of minimum required area of the bolt and the thickness of flange. This approach is called as Schneider approach.

NASA SP-8025 has given the details about the material properties for the various solid rocket motors. Based upon these material properties the material is selected for the solid rocket motor to withstand the pressures that are going to act on the motor casing.

NASA has given the details of the solid rocket motor preliminary design review and structural analysis of the solid rocket motor factory joint including metallic and non-metallic components. A structural analysis is performed to verify the structural integrity of the solid rocket motor at certain working temperature.

NASA has given the solid propellant performance prediction and analysis. Based upon this the performance of the solid propellant rocket motor the design is done by considering the loads that are going to act on the solid rocket motor casing. The effectiveness of this process is predicted and assessed by evaluating the reaction thrust developed through the pressure-imparted momentum of the expanded exhaust gases Mathematical modeling used to simulate solid rocket combustion-chamber internal flow fields is reasonably good for steady-state and transient flow prediction.

Siva Sankara Raju R In their Design and Analysis of Rocket Motor Casing by Using Fem Technique. focused on 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. Modeling of solid rocket motor components and its assembly is done in CATIAV5R19. Stress distributions are due to the effect of working stress developed in the components. The maximum working stress is compared with allowable yield stress of the material. Final conclusion brings out a well designed solid rocket motor for the effective storage of propellant for obtaining the required impulse. 2D Axi-Symmetric structural analysis for solid propellant rocket motor Casing is performed to determine the stress level of all components using ANSYS 12.0.

Mohamad Izwan Ghazali In their Design Fabricate and Testing Small Rocket Motor discussed the study on Solid Rocket Motor (SRM) based solid propellant. This project focus on and discusses the study of optimum design based SRM characteristics including the methods of the optimum design selection and fabrication, analysis using COSMOS and static thrust testing. Before that, the researcher has focus on the fundamental of solid rocket motor for designing and fabricating. There are two main factors need to be considered in the design selection and fabrication which are performance or processability and mechanical strength. The theoretical performance of the propellant was obtained by using CHEM program.

Sidhant Singh In their Solid Rocket Motor for Experimental Sounding Rockets had proposed an Experimental Sounding rockets are major contributors for research in the field of aerospace engineering. However, experimental sounding rockets are rarely used by institutes in India for student research projects. A major factor that forestalls the use of sounding rockets in student research projects is the unavailability of rocket motors which involves complex machining and explosive propellants; this problem was encountered by us while developing sounding rocket for research and learning purpose. The paper is focused on design and construction of a solid rocket motor that can be utilized as the main propulsion unit in experimental sounding rockets by researchers. Initially, basic designs were evaluated and the different concepts of propellant configuration were observed. The availability, ease of manufacturing and casting of propellants was a major factor in determining the suitable propellant.

Roy Hartfield In their A Review of Analytical Methods for Solid Rocket Motor Grain Analysis presents the Analytical methods for solid rocket motor grain design are proving to be tremendously beneficial to some recent efforts to optimize solid-rocket propelled missiles. The analytical approach has fallen out of favor in recent decades; however, for some classes of grains, the analytical methods are much more efficient than grid-based techniques. This paper provides a review of analytical methods for calculating burn area and port area for a variety of cylindrically perforated solid rocket motor grains. The equations for the star, long spoke wagon wheel, and dendrite grains are summarized and the development of the burn-back equations for the short spoke wagon wheel and the truncated star configurations are included. This set of geometries and combinations of these geometries represent a very wide range of possibilities for two-dimensional grain design.

Mahesh B. Gosavi In their A Review on Failure Modes of Composite Pressure Vessel had proposed Modern composites, using continuous fibers in a resin matrix, are important candidate materials in the engineering of energy-efficient structures. In many applications, fiber / matrix materials are lighter, stronger and more cost effective when compared with traditional materials like metals. Filament-wound tubular structures, more specifically pressure vessels, offer significant weight saving over conventional all metallic ones for containment of high pressure gases and liquids. The main advantage of COPV's over similar sized monolithic metallic pressure vessels is a much better strength-to-density ratio due to significant mass reductions. Currently, a large amount of research works has been concentrated on the stress and failure analysis of the cylindrical part of the composite-metallic vessels. The study of the stress and strain distribution in the structure is of prime interest for designing the vessel. The complicated failure mechanisms and degradation mechanisms are distinct characteristic of composites although they exhibit high stiffness- and strength-density ratios. In this paper various failure modes of composite pressure vessels are studied such as failure due to hygrothermal stresses, influence of flaws, effect of thermal loads etc.

3. Experiment Details

The basic considerations for the design of rocket motor hardware are

Internal Pressure= 130Kg-f/cm^2

Internal diameter of Shell= 190mm

Cylindrical shell length = 2000mm

Opening Diameter at Flat plate= 100mm

Opening diameter at Nozzle= 140mm

Crown radius= 150mm

Knuckle radius= 22.5mm

Throat Diameter= 40mm

Throat length= 40mm

Area Ratio at exit of nozzle = 10

Factor of Safety (FOS)= 1.5

3.1 Problem Statement

Generally solid rocket motors are designed to withstand the pressure exerted inside the casing and provide structural stability. The main design consideration is that, the effect of propellant burning in the casing will result in uniform pressure throughout the casing. In general solid rocket motors are designed to withstand a temperature of 100^{o}C. But in real life the temperatures induced in the casing are of the order of 1000^{o}C to 3000^{o}C. To withstand these high temperatures some ablative liners are provided inside the casing. In this paper the structural analysis is carried out and the results are compared with thermo structural analysis.

3.2 Material Properties

Table 1: Material properties

Material	Maraging Steel	A-286 Iron based alloy	D6AC Steel	Haynes 255
Density (lb/in^3)	0.29	7.9	7.7	8.9
Yield tensile strength (Mpa)	1750	552	465	465
Young's modulus (Gpa)	210	162	208	208
Poisson's ratio	0.3	0.3	0.3	0.3

3.3 Calculations

As per ASME pressure vessel codes VIII section 2nd division. As per UG: 27 section of pressure vessel code, the internal pressure value being P < 0.385 SE, the formulae to be used for shell thickness calculation are

$$\mathbf{T_s} = \frac{P\times R}{(2\times S\times E+0.4\times P)}$$

Thickness of Torispherical Head

$$\mathbf{T_t} = \frac{P\times L\times M}{(2\times S\times E-0.2\times P)}$$

Thickness of Flat Plate

$$T_f = d \times \sqrt{\frac{c \times P}{S \times E} + \frac{1.9 \times h_g \times W}{S \times E \times d^3}}$$

Thickness of Flange

$$T_{fl} = 1.1 \times R_m \times \left[\frac{3 \times P \times l}{\sigma_f \times (1 - N \times d) \times (R_m + l)}\right]^{1/2}$$

Thickness of Nozzle

$$T_i = \frac{P \times d}{2 \times \cos\alpha \times (S \times E - 0.6 \times P)}$$

Where
P = internal pressure of shell
R = Internal Radius of shell
S = Allowable stress value
E = Joint efficiency = 1
L = Inside spherical or crown radius for torispherical head
W = Total bolt load given for circular heads
hg = Radial distance from the central line
d = internal diameter at closing portion of the shell
Rm= Distance between central axis to oaring axis
l = Distance between oaring axis and bolt axis
α = convergent/divergent angle
M = A parameter given by the following formula

$$M = \frac{1}{4}\left[3 + \sqrt{\frac{L}{R}}\right]$$

Finally the derived thicknesses for each part are as follows

Thickness of Shell	T_s = 1.2mm
Thickness of Torispherical Head	T_t = 1.2mm
Thickness of Flat Plate	T_f = 6.8mm
Thickness of Flange	T_{fl} = 5.4mm
Convergent portion thickness	T_1 = 1.7mm
Throat portion	T_2 = 1.2 mm
Divergent portion	T_3 = 1.2mm

Fig. 3: Final design of rocket motor

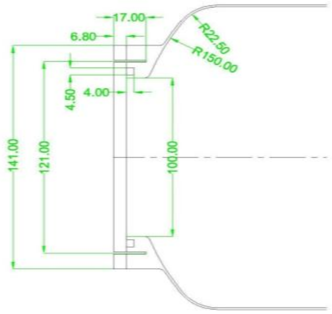

Fig. 4: 2D Drawing of Fore end of rocket Motor

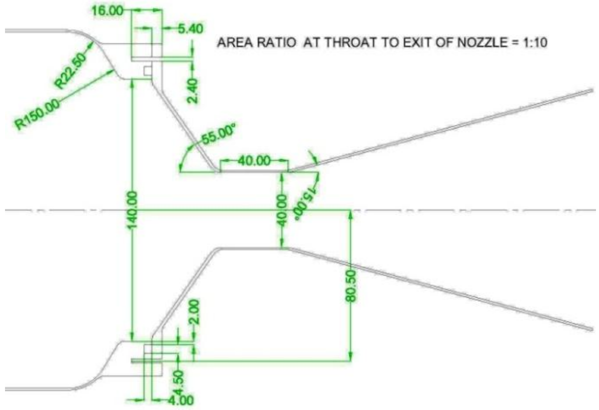

Fig.5: 2D Drawing of Aft end of rocket Motor

Fig.6: Rocket Motor Shell

4. Analysis Results

Stress Analysis of rocket Motor Casing using Maraging steel:

Element type: 8-noded axi-symmetric.

Internal pressure: 130 Kg-f/cm²

Boundary conditions: outer portion of the flat plate portion fixed.

4.1 The Stresses and deformations acting on casing are shown in the following figures –

Design Pressure – 12.75 MPa
Operating Pressure – 7.5 MPa

A. Stresses developed at 12.75MPa pressure

The maximum stress value acting on the shell portion is 504Mpa

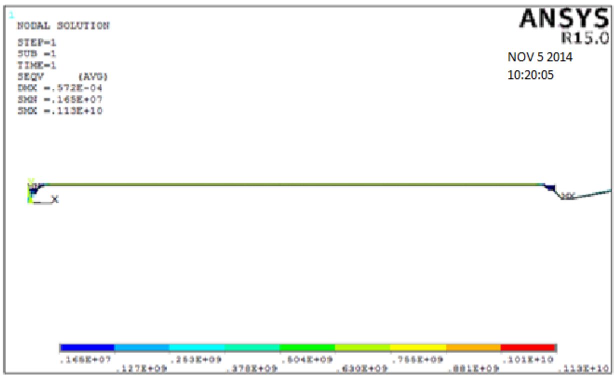

Fig .7: Stresses acting on the shell

i) The maximum stress value acting on the Fore end portion is 253Mpa.

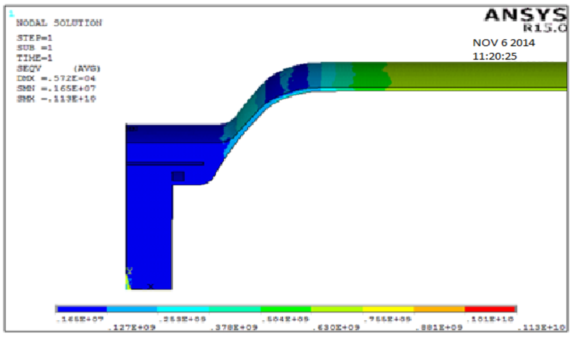

Fig.8: Stresses acting on the Fore end portion

ii) The maximum stress value acting on the Nozzle portion is 1130Mpa

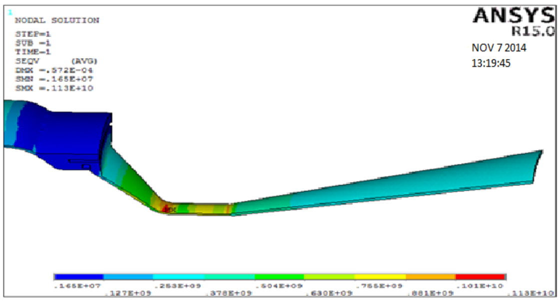

Fig.9: Stresses acting on Nozzle portion

iii) The maximum displacements value acting on the Nozzle portion is 0.05mm

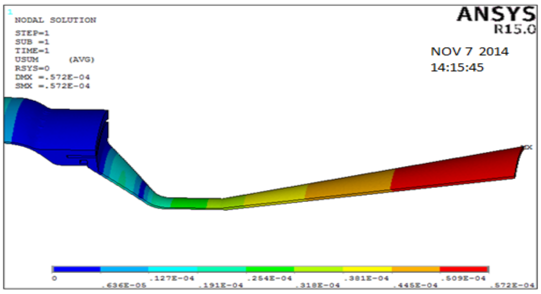

Fig.10: Displacements acting on the Nozzle portion

B. Stresses developed at 7.5MPa pressure

i) The maximum stress value acting on the shell portion is 310MPa

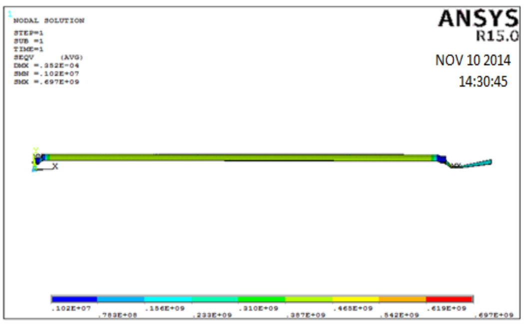

Fig.11: Stresses acting on the shell

ii) The maximum stress value acting on the Fore end portion is 102MPa

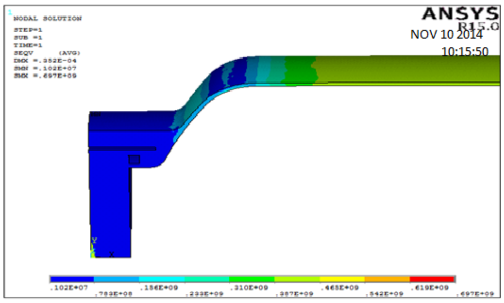

Fig.12: Stresses acting on fore end portion

ii) The maximum stress value acting on the Nozzle portion is 697MPa

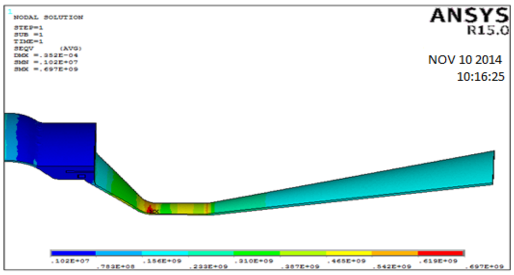

Fig.13: Stresses acting on Nozzle portion

iii) The maximum displacement value acting on the Nozzle portion is 0.03mm

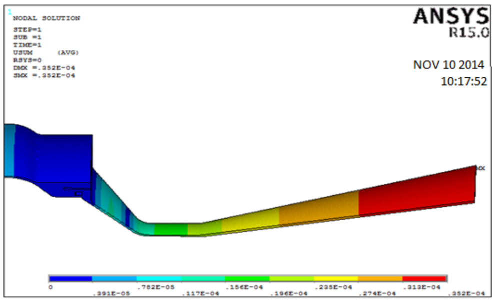

Fig.14: Displacements acting on Nozzle portion

4.2 Stress Analysis of rocket Motor Casing using A-286-Iron based alloy:

A. Stresses developed at 12.75MPa pressure

i) The stresses on Nozzle portion are shown below

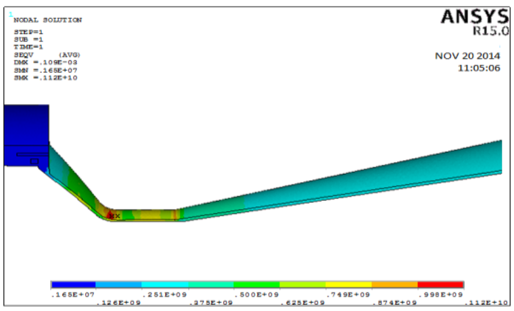

Fig.15: Stresses acting on Nozzle portion.

ii) The maximum stress value acting on the Nozzle portion is 1120MPa.

iii) The maximum displacement value acting on the Nozzle portion is 1mm.

B. Stresses developed at 7.5MPa pressure

i) The stresses on Nozzle portion are shown below

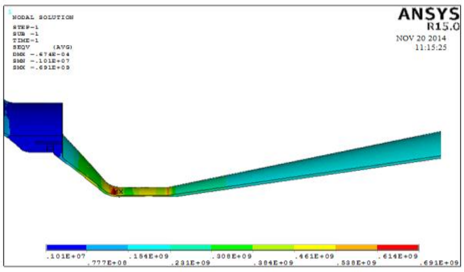

Fig 16: Stresses acting on Nozzle portion

- The maximum stress value acting on the Nozzle portion is 1120MPa.

- The maximum displacement value acting on the Nozzle portion is 1mm

4.3 Stress Analysis of rocket Motor Casing usingD6AC Steel

A. Stresses developed at 12.75MPa pressure

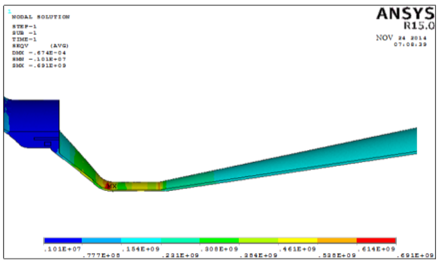

Fig.17: Stresses acting on Nozzle portion

i) The maximum stress value acting on the Nozzle portion is 691MPa.

ii) The maximum displacement value acting on the Nozzle portion is 0.6mm.

B. Stresses developed at 7.5MPa pressure

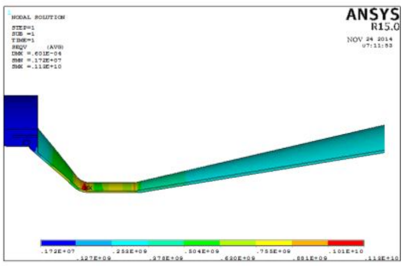

Fig. 18: Stresses acting on Nozzle portion

i) The maximum stress value acting on the Nozzle portion is 1130MPa.

ii) The maximum displacement value acting on the Nozzle portion is 0.6mm.

4.4 Stresses developed at 12.75MPa pressure.

A. Casing using Haynes 255

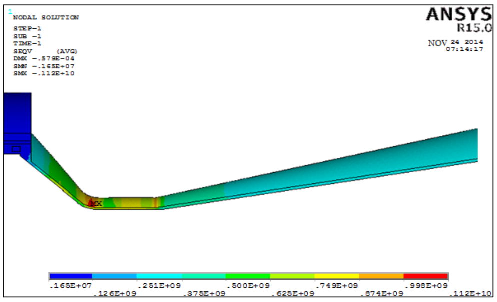

Fig.19: Stresses acting on Nozzle portion

i) The maximum stress value acting on the Nozzle portion is 1120MPa

ii) The maximum displacement value acting on the Nozzle portion is 0.5 mm.

B. Stresses developed at 7.5MPa pressure

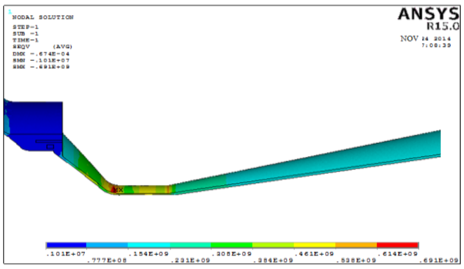

Fig.20: Stresses acting on Nozzle portion

i) The maximum stress value acting on the Nozzle portion is 691MPa.

ii) The maximum displacement value acting on the Nozzle portion is 0.6 mm.

5. Thermo structural analysis constraints

- All DOF = 0 at groove.
- Internal pressure applied=12.75MPa.
- Temperature applied = 100^0c.

(a) The maximum stress value acting on the shell portion is 755Mpa.

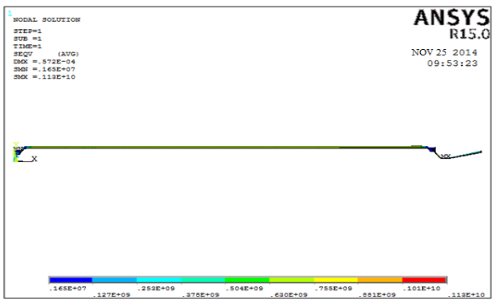

Fig.21: Stresses acting on the shell portion.

(b) The maximum stress value acting on the Nozzle portion is 1130Mpa.

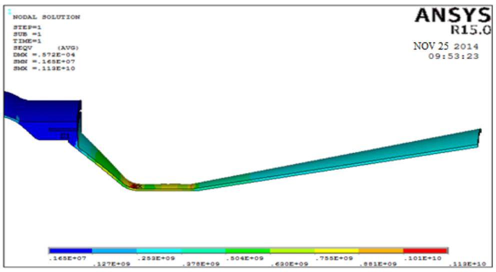

Fig.22: Stresses acting on the Nozzle portion

c) The maximum displacement value acting on the shell portion is .028mm.

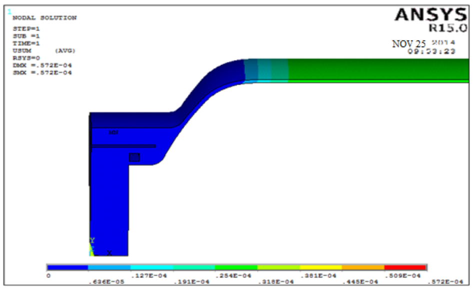

Fig .23: Displacements at Fore end portion.

(d) The maximum displacement value acting on the shell portion is .05mm.

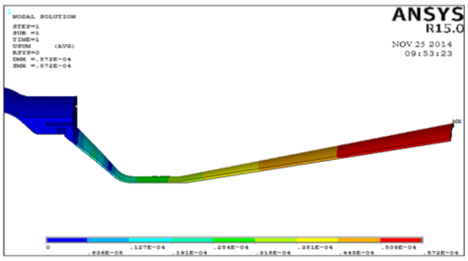

Fig.24: Displacements at Nozzle portion

When 100^{0}c temperature and 7.5MPapressure applied on the body, the stresses and displacements on the body shown below

(a) The maximum stress value acting on the shell portion is 310Mpa.

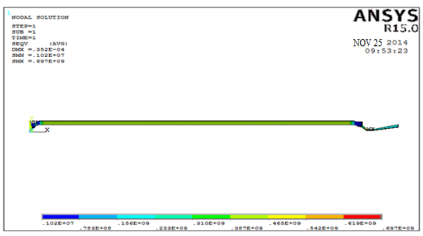

Fig.25: Stresses at Shell portion.

(b) The maximum stress value acting on the Nozzle portion is 697Mpa

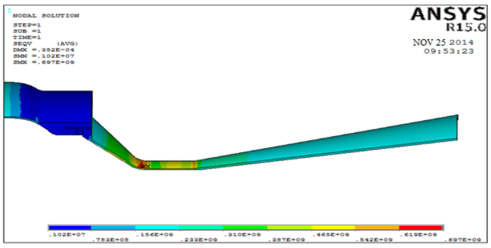

Fig.26: Stresses at Nozzle portion

(c) The maximum displacement value acting o on the Nozzle portion is 0.03mm.

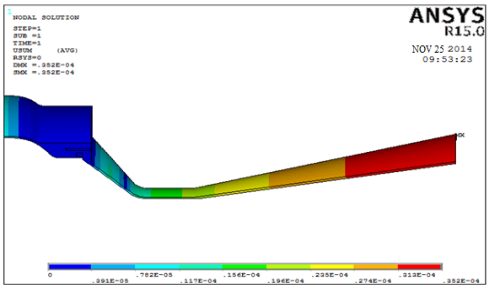

Fig.27: Displacements at Nozzle portion.

Table 2 : Comparision of Stress values of various materials

Material	Applied pressure	Maximum Stress
Maraging steel	7.5MPa 12.75 MPa	670 MPa 1130 MPa
Aluminum	7.5MPa 12.75 MPa	1780 MPa 2861 MPa
A-286-Iron based alloy	7.5MPa 12.75 MPa	691 MPa 1120 MPa
D6AC Steel	7.5MPa 12.75 MPa	699 MPa 1126 MPa
Haynes 255	7.5MPa 12.75 MPa	697 MPa 1120 MPa

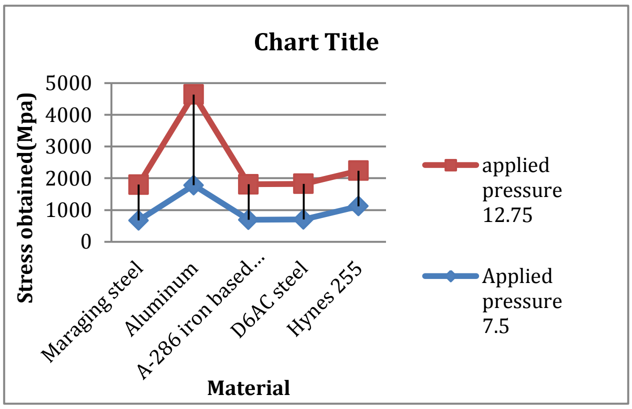

Fig.28 : Comparision of Stress various materials

After observing stress values of various materials Maraging steel is having minimum stress values.

Table 3 : Comparision of displacement values of various materials

Material	Applied pressure	Maximum Deflection
Maraging steel	7.5MPa 12.75 MPa	0.03mm 0.05mm
Aluminum	7.5MPa 12.75 MPa	0.102mm 0.175mm
A-286-Iron based alloy	7.5MPa 12.75 MPa	0.06mm 0.07mm
D6AC Steel	7.5MPa 12.75 MPa	0.061mm 0.067mm
Haynes 255	7.5MPa 12.75 MPa	0.05mm 0.06mm

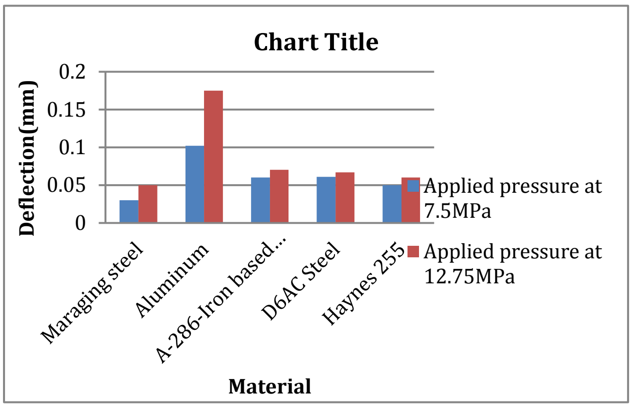

Fig.29: Comparision of displacement values of various materials.

After observing the above results Maraging steel is best suitable for Rocket motor hardware taking displacement into considerations.

Conclusions

The following conclusions are drawn from present work

1. After structural analysis of the Rocket motor casing it is clear that the stress developed at various locations of the casing are within allowable limit and a factor of safety of (FOS) 1.5 is obtained by designing the casing using ASME codes.
2. After observing the stress values of various materials aluminum is having more than 50% high stress values compared to other materials.
3. When displacement taken into consideration margining steel is having 50% low values compared to other materials.
4. So Maraging steel is best suitable for rocket motor casing when displacements taken into consideration because of the displacements developed by the Maraging steel are very low.

Future Scope

1) CFD Analysis for the Solid rocket motor casing also to be performed.
2) Composite Rocket motor casing can be designed and compared with other materials.
3) Design and Analysis of Solid rocket motor insulation can be done.

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