Structural Analysis of Solid Rocket Propellant Motor - A Numerical Study using FEM

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Abstract— Rocket motors are comprehensively employed to produce thrust or impulsive force to impart a preferred velocity to flight vehicle to transmit its delivery to the proposed destination. The working principle of Rocket motor is mainly Newton's 2nd and 3rd laws. Rocket motors are non-air inhalation propulsion class i.e., won't necessitate oxygen from the atmosphere for combustion of the fuel which is stored in the rocket motor. During the period when it is in service conditions of the motor hardware various objective must be taken care of such as Fracture analysis on the material along with Structural analysis and thermal design has to be carried out for a given input parameters for determination of stress levels and temperatures on the hardware. This paper provides the numerical means of aforesaid objectives and results obtained were compared with.

Keywords: Propellant Motor, Structural Analysis, Maraging Steel

I. INTRODUCTION

An Engine that makes use of propellant mass to figure out its high speed propulsive jet is a solid rocket jet engine. Rocket engines are action reaction engine and obtain thrust in conformity with Newton's third law. These systems is used excessively in spacecraft as there is no need of external material to form their jet and are also fine its application in propulsion as well as earthly uses, such as Missile. Most rocket engines falls under the category of internal combustion engine and some are even non combusting in form. Propulsion system of rocket is one the main subsystem of missiles as thrust generated by the rocket motor engine accelerates the missile and gives the supersonic velocity in the missile which is of utmost requirement to take the missile to the necessary altitude and range.

A. Propulsion

Propulsion is a compel or force that originates movement. The force can be caused here is based on Newton's second law i.e. it may be either a differential pressure, or a differential momentum. Rocket engine generates propulsive drive when the fuel burn in the combustion chamber and turns out in the form of gases of high temperature and pressure which gets expanded in the nozzle. This system produces a variation in pressure unnaturally by blowing up and burning a fuel inside a closed chamber called combustion chamber and evacuated the pressure duly. The stored energy of the gas is transformed into kinetic energy of the exhaust gases and propel is produce by the gas pressure on the bare surfaces to the gas.

B. Rocket Propulsion System

Rocket propulsion system is a non-air inhalation system, in which the propulsive exertion i.e. force and thrust is attained by variation of the momentum of the system itself. They do not depend on the atmospheric air, either as oxidizer. Rocket motor propulsion can be classified based on the type of propellant of rocket propulsion units used in a given vehicle and type of construction, the number by the method of producing thrust. According to the type of energy source there are types, they are:

- Chemical rocket propulsion
- Electrical rocket propulsion
- Nuclear and solar rocket propulsion

C. Classification of Rocket Motors

Rocket motors are widely used to impart a desired velocity to a flight vehicle which requires high thrust in order to transport its payload. A rocket motor is atypical energy transfer system. The process of combustion makes it possible to utilize and convert the chemical energy inside the fuel to the thermal energy. High pressure and high temperature combustion product gases are expanded through a converging-diverging nozzle. By this process stored energy of the gas is converted into kinetic energy of the exhaust flow and the thrust is produced by the gas pressure on the surfaces exposed to the gas. Rocket motors are classified in many ways. The most common way is the classification according to the physical state of the propellant. These are as follows:

- Solid propellant rocket motor
- Liquid propellant rocket motor
- Gaseous propellant rocket motor
- Hybrid propellant rocket motor

D. Solid Propellant Rocket Motors (SRM)

As its name suggests, the propellant of the motor is in the solid state. The unique feature of this system is premixing of the oxidizer and fuel and containing and storing it directly in the combustion chamber only. This type of motors are finding its utility in almost all the in all environmental conditions as it includes both fuel and oxidizer. In relationship to other types, solid propellant rocket motors have simple constructional design, are easy to relate and approximately maintenance free in nature. The schematic diagram is shown below.

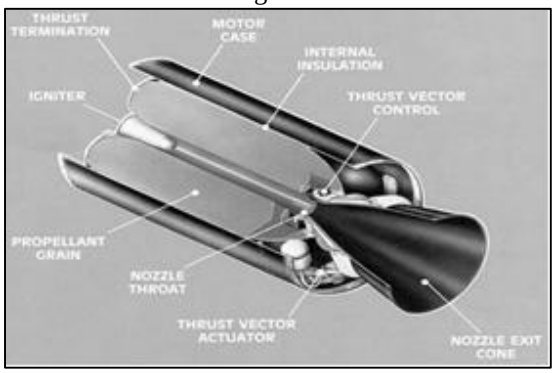


Fig. 1: Main Parts of a Solid Propellant Rocket Motor

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II. MATERIALS AND DESIGN INPUT

When it is discussion about processing requirement of strength and toughness without losing malleability "Maraging steels" a combination of "martensitic" and "aging", comes into front although Maraging steels cannot hold a superior cutting edge here Aging refers to the comprehensive heat-treatment process. Maraging steels are a unique course group of low-carbon ultra-high-strength steels which develops their strength from precipitation of inter-metallic compounds instead of carbon. The most important alloying element is 20- 25% nickel and in order to produce inter metallic precipitates it is added with minor alloying elements, which consists of cobalt, molybdenum, and titanium. Original development was agreed out on 20 and 25% Ni steels to which little additions of Al, Ti, and Nb were made.

The common, non-stainless grades contain 18–19% nickel, 9–12% cobalt, 4-5% molybdenum, and 0.2–1.5% titanium. To provide corrosion resistance addition of chromium is performed that indirectly helps to increase hardenability as they have need of less nickel: high-chromium, high-nickel steels are generally austenitic and not capable to transform to martensite under heat treatment, on the other hand lower-nickel steels can transform to martensite.

III. METHODOLOGY

The methodology adopted *for present work is depicted in* the flow chart below

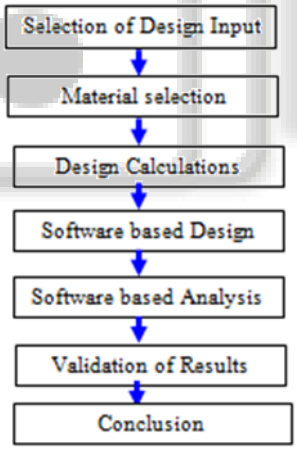


Fig. 2: Flow chart of methodology adopted

A. Selection of Design input

Maximum Expected Operating Pressure (MEOP) and motor maximum diameter considered is taken into consideration as design input. Standard values are referred from pressure vessel code. in brief, the following inputs have been taken for motors hardware design. Design inputs selected are:

- Material
- Motor outer diameter (D)
- MEOP (P)
- UTS
- Yield strength
- Factor of safety (F.S.)
- Weld efficiency (E)
- Biaxial gain
- Mismatch factor

B. Material Selection

Maraging steel -350 grades (MDN-350) is chosen to minimize the hardware weight due to its high specific strength. Chemical composition, Mechanical properties and factor of safety are taken into consideration.

C. Design Calculations

Following calculation are made

- Thickness of motor casing
- Head end and nozzle end dome
- Max. stress on each bolt due to pressure load and preload
- Structural analysis of solid rocket motor hardware

D. Software Based Design

Design and drafting software autocad and creo is selected for solid modeling.

E. Software based Analysis

For analysis purpose FEM based software ANSYS is used

IV. CALCULATIONS

A. Motor Design Calculations

Maximum Expected Operating Pressure (MEOP) obtained from ballistics performance prediction band is 150 ksc. The following inputs have been taken for motors hardware design.

1) Material = Maraging steel (250 grade)
2) Motor outer dia (D) = 200 mm
3) MEOP (P) = 150 ksc
4) UTS = 175kgf/mm2
5) Yield strength = 168kgf/mm2
6) Factor of safety (F.S) = 1.5 on UTS
7) Weld efficiency (E) = 90%
8) Biaxial gain = 1.1
9) Mismatch factor = 1.15

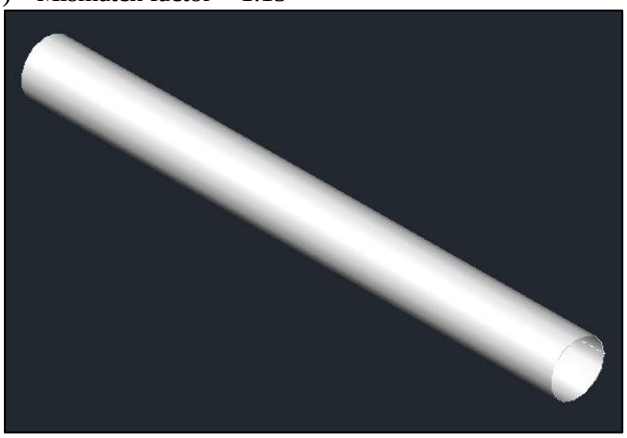


Fig. 3: Cylindrical shell 3d figure

The shell thickness is calculated by using conventional formula from ASME Pressure vessel code. It is given by

$$t = \frac{P * D * Mismatch\ Factor}{biaxial\ \ gain * 2 * (SE - 0.6P)}$$

Calculated thickness (t) : 1.50 mm

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B. DOME

This is fabricated from the forged rod 200 mm diameter. The shape of the dome considered is Tori-spherical type because of easy fabrication. After iterations, the following parameters are chosen.

Crown Radius (L) = 150 mm
Knuckle radius (r) = 15% of 1 = 22.5
L/r = 6.6 mm
M = 0.25*(3+ √(L/r)

$$t = \frac{P*L*M}{2.0*(SE-0.1P)}$$

Thickness (t) = 1.347 mm obtained.

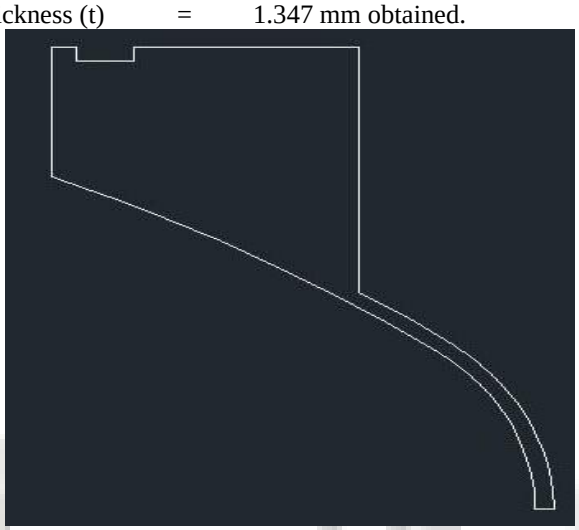


Fig. 4: View of Dome in 2d

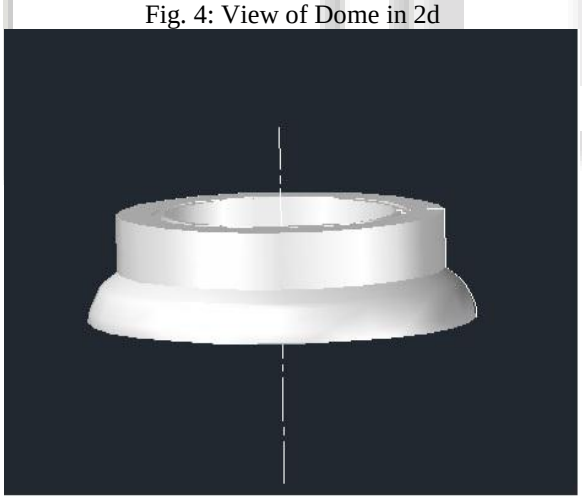


Fig. 5: View of Dome in 2d

C. Max. Stress on Each Stud Due to Pressure Load and Preload

Stress due to pre load on each stud = 0.4
$\sigma_{yield\ bolt}$ = 32.4 kg/mm^2
Stress due to pressure load on each stud = 10.06 kg/mm^2 (22 no. of studs only considered and proof test condition i.e 1.25* MEOP)

$$= 0.4*1.25*\left[\frac{\pi*MEOP*124.5^2}{4*No.ofstuds*stressarea\ of\ bolt*}\right]$$

Total stress on each stud = 36.0+11.3 = 47.3 kg/mm^2
Factor of safety available on each stud: 1.90 on yield strength

D. Flat Plate Closure with Bolted Joint (head end cover)

Head end cover for pulse -2 can also be calculated by using flat plate closure with bolted joint formula which is given by

$$t = d\sqrt{\frac{CP}{SE}+\frac{1.9\,whg}{SEd^3}}$$

Where
d = Diameter up to the centre of O ring = 80 mm
C = 0.3
P = 1.5lgf/ mm^2
E = 1%
W = $\pi/4\ d^2p$ = 27.9 kgf
h_g = 10.5 mm

$$t = 80\sqrt{\frac{0.3*1.5*2.0}{175*1.0}+\frac{1.9*7540*6.0*2.0}{175\,x1.0\,x(80)^3}}$$

t = 11.09 mm

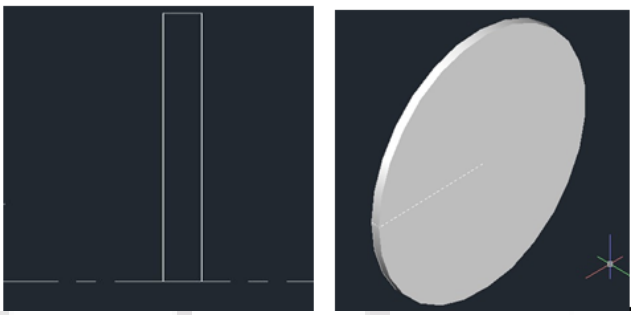


Fig. 6: View of head and cover

E. Nozzle Divergent Thickness

$$t = \frac{P*d}{2\cos\alpha\cos\alpha(\ /F.S)*\eta_{weld}-0.6P)}$$

α= half of the included angle of the cone = 14 °
Thickness obtained is 0.7 mm
The thickness obtained is very small; however from the manufacturing point of view a minimum thickness of 1.0 mm is selected.

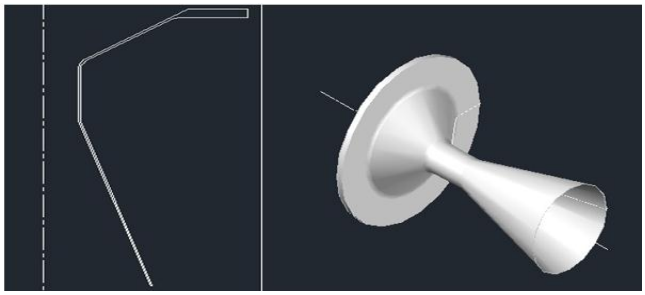


Fig. 7: Convergent, throat and divergent in 2d & 3d

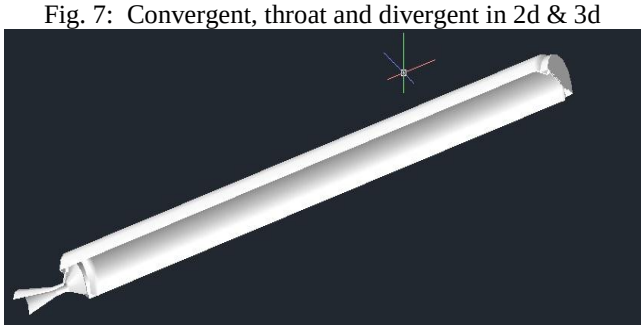


Fig. 8: pressure vessel design

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F. Stress Analysis of Motor Casing

Axi symmetric Finite Element model of motor casing is prepared by using 8-nodded axi symmetric element, (plane 183). Stress analysis of model is carried out for internal pressure of 150KSc by fixing upper bulkhead portion. FE model with boundary condition is shown in figure. Stresses at different location are given in table and locations are shown in figure. Stress pattern is shown in figure.

Flange joint is modeled by arresting relative nodal displacement in appropriate direction. This will not give accurate result for bolt stresses, but aim is to find out the stresses in casing only and this model will fulfill this requirements

Location	Von misses	F.S on UTS
		Von misses
A	44.77	1.95
B	94.23	0.93
C	132.77	0.66
D	80.32	1.1
E	77.73	1.13
F	77.73	1.13
G	164.87	0.53
H	121.3	0.72
I	78.12	1.12

Table 1: Stresses at different locations

G. Weld Mismatch Stresses

Weld mismatch stresses in weld are calculated using formulae given below.

$\sigma 1 = (\sigma 1_{mem} (1+3d/t))/BG$

$\sigma 2 = (\sigma 2_{mem} (1+3 \times f \times \nu \times d/t))/BG$

Where as

$\sigma 1$ = Mismatch stress perpendicular to the weld

$\sigma 2$ = Mismatch stress parallel to weld

$\sigma 1_{mem}$ = Membrane stress perpendicular to weld

$\sigma 2_{mem}$ = Membrane stress parallel to weld

BG = Biaxial Gain

D = Mismatch

t = Thickness of shell

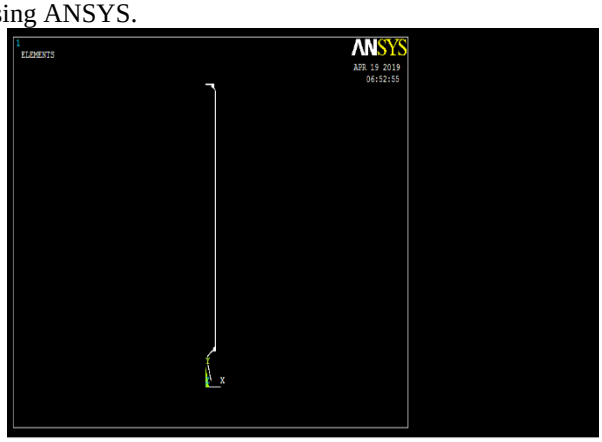
ν = Poisons ratio

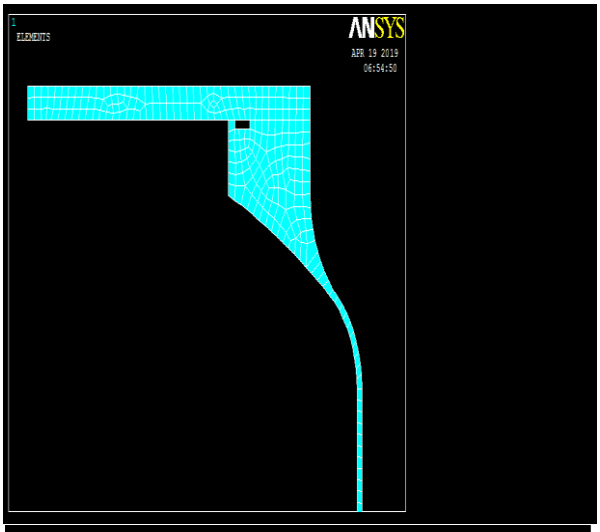
f = ratio of $\sigma 1_{mem}$ and $\sigma 2_{mem}$.

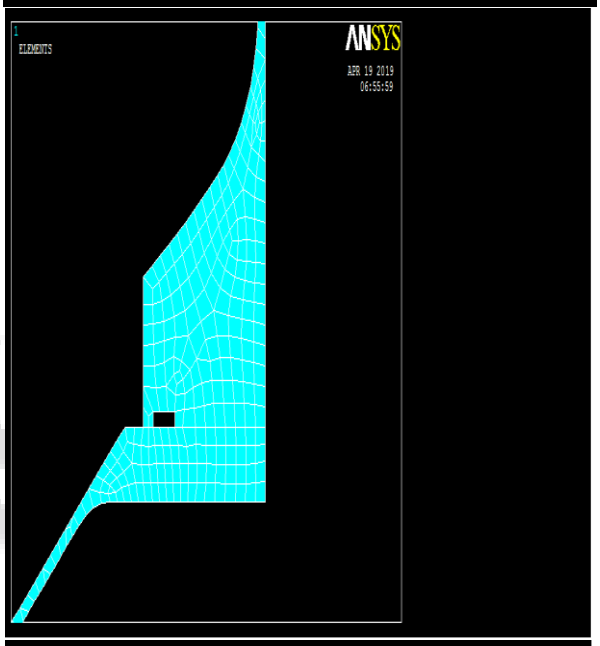
Allowable mismatch For 'C' seam weld 10 % (d/t=0.1)

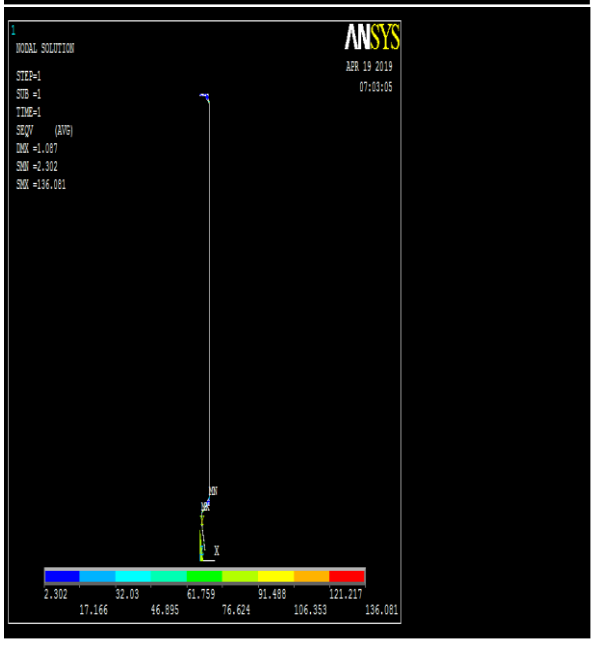
V. RESULTS & CONCLUSION

Following results were obtained with FEM based Analysis using ANSYS.

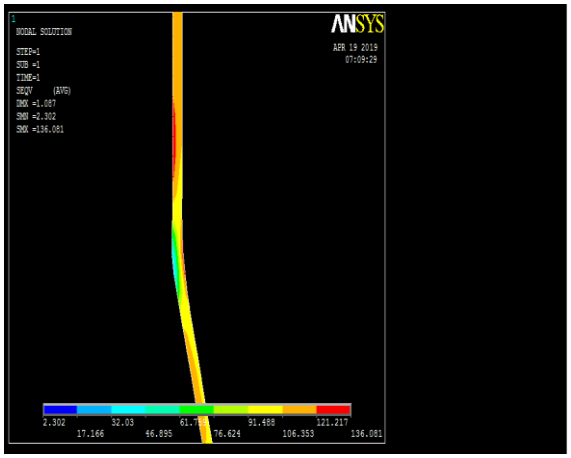








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The results calculated analytically based on ASME standards matched to numerical analysis results with 2.0 % error approximately in either direction.

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Place figures and tables at the top and bottom of columns. Avoid placing them in the middle of columns. Large figures and tables may span across both columns. Figure captions should be below the figures; table heads should appear above the tables. Insert figures and tables after they are cited in the text. Use the abbreviation "Fig. 1", even at the beginning of a sentence.

Table Head	Table Column Head		
	Table column subhead	Subhead	Subhead
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Sample of a Table footnote. (Table footnote)

Table 1: Type Styles

Fig. 1: Example of a figure caption. (figure caption)

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Figure Labels: Use 8 point Times New Roman for Figure labels. Use words rather than symbols or abbreviations when writing Figure axis labels to avoid confusing the reader. As an example, write the quantity "Magnetization", or "Magnetization, M", not just "M". If including units in the label, present them within parentheses. Do not label axes only with units. In the example, write "Magnetization (A/m)" or "Magnetization {A[m(1)]}", not just "A/m". Do not label axes with a ratio of quantities and units. For example, write "Temperature (K)", not "Temperature/K".

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