

# STRUCTURAL ANALYSIS OF VISCOELASTIC SOLID PROPELLANT GRAIN

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**Abstract**—A solid propellant rocket is a simple form of chemical propulsion. The fuel and oxidizers are both incorporated in a single solid called propellant grain located inside the combustion chamber. Solid rocket motor structural design is currently based on concept of mechanically weak solid propellant grain casted into a stronger metallic case wrapped with insulation and casing. Solid rocket motor is subjected to various loading during transportation, storage and firing. The finite element method has the capability to deal with the complex structure, material behavior and geometrical properties. Standard displacement finite element formulations for structural analysis are ill conditioned when Poisson's ratio nearly equals to 0.5. Hence for viscoelastic analysis, a special formulation is required as the propellant is nearly incompressible.

Here, an Elastic, viscoelastic and dynamic analysis of a typical cylindrical port grain have been carried for storage and pressure loads. Measurable deformations are observed under loading condition in both elastic and viscoelastic analysis and found close relation among each other. Dynamic analysis of a typical cylindrical port grain shows lesser deformation/strain and considered as insignificant for design purpose.

**Index Terms**—viscoelastic, elasticpropellant, internal pressure, storage, dynamic- viscoelastic.

## 1 INTRODUCTION

In general, propellant is a chemical substance used in the production of energy that is subsequently used generate propulsion of a vehicle, projectile etc and should have the required burning rate at the motor design pressure offering optimum combination of thermodynamics and mechanical properties.<sup>[1]</sup> Solid propellants are used in forms called grains. A grain is any individual particle of propellant regardless of the size or shape and is viscoelastic in nature. The fuel and the oxidizer are both incorporated in a single solid called the propellant grain and is placed inside a container called the combustion chamber bounded by insulation and casing, all together called, a Solid Rocket motor (SRM). Rocket motor metallic casing provides containment for the propellant grain, a pressure vessel during motor burn and a structural member to carry launch vehicle loads. Propellant should have the required burning rate at the motor design pressure and must have a specific impulse and density for rocket applications.

The structural analysis consists of a determination of the stresses, strains and deformations the grain may be subjected to under prescribed loading conditions during its life cycle. Different loading includes ignition pressurisation, thermally induced loads, acceleration, vibration, slump, aerodynamic heating etc. Among them, storage and pressure are most critical loading conditions. Slumping will occurs if propellant rocket motor grain is kept vertically for long term storage. After ignition, high temperature gaseous products of combustion

are accelerated with solid rocket motor to the sonic velocity at the nozzle throat. Load arises due to ignition pressure distributes within the combustion chamber. Variation in coefficient of thermal expansion between propellant and case and material variations strongly influence the stress/strain states of the grain under specific loads. Present study aims at the structural integrity assessment of perforated cylindrical solid propellant rocket motor grain under ignition pressure and gravity loading.

## 2 VISCOELASTICITY

Solid propellant grain is viscoelastic in nature and this time dependent behaviour has significant effect on structural integrity analysis. Viscoelasticity is concerned with materials, which exhibit both viscous and elastic characteristics while undergoing deformation. They exhibit a strain rate effects in response to the applied stresses and is based on the phenomenon of creep and stress relaxation. A constant strain on a viscoelastic material reduces the stress developed in the material over time and this response is termed as stress relaxation. The stress continues to decrease until the material reaches in equilibrium. Likewise, a constant stress on viscoelastic materials increases strain rate along time and regains its initial configuration after the removal of force. This phenomenon is known as creep.

The material functions are obtained from experimental observation, which is necessary to represent them by mathematical functions in order to perform analysis on viscoelastic materials and to interconvert these viscoelastic functions. Among all analytical representations available, the Prony's Series is one of the most used due to the remarkable computational efficiency associated with its exponential basis function. The analytical description of relaxation modulus  $E(t)$ <sup>[2]</sup> and creep compliance  $D(t)$ <sup>[3]</sup> by Prony's series is expressed in Eq.1& 2 respectively.

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$$E(t) = E_e + \sum_{i=1}^M E_i e^{-\frac{t}{\tau_i}} \quad (1)$$

$$D(t) = D_g + \sum_{j=1}^N D_j (1 - e^{-\frac{t}{\tau_j}}) \quad (2)$$

where,  $E_e$ ,  $\rho_i$ ,  $E_i$ , and  $D_g$ ,  $\tau_j$ ,  $D_j$ , are degrees of freedom of the Prony series. Equations are obtained representing the viscoelastic material by a mechanical model consisting of linear springs and dashpots. The terms  $E_e$  and  $D_g$  are called independent terms. The exponential terms  $\rho_i$  and  $\tau_j$  are known as time constants because they appear in association with the time variable  $t$ . The set of terms  $E_i$  and  $D_j$  are the dependent terms of the Prony series and the number of terms used ( $M$  and  $N$ , respectively) is determined according to the experimental data. Usually, it will be 8 to 16 terms in Prony series in order to have a satisfactory mathematical model to be fitted from experimental data. The Prony series for the shear relaxation is [4]

$$G(t) = G_\infty + \sum_{i=1}^N A_i e^{-\frac{t}{\tau_i}} \quad (3)$$

where,  $G(t)$  is the shear relaxation modulus,  $G_\infty$  is the long term modulus or equilibrium modulus,  $A_i$  is the constants,  $t$  is the time,  $\tau_i$  is the relaxation times.

Under Dynamic loading conditions, the Modulus of Elasticity of viscoelastic material gets changed to Loss Modulus ( $E''$ ) and Storage Modulus ( $E'$ ) as well the Shear Modulus too. Complex variables can be used to express the moduli  $E^*$  and  $G^*$  as follows: [3]

$$E^* = E' + i E'' \quad (4)$$

$$G^* = G' + i G'' \quad (5)$$

Where  $i^2 = -1$  and  $i$  is the imaginary unit.

### 3. MODELLING OF SOLID PROPELLANT GRAIN

Finite element modelling includes defining geometry, material properties, and boundary conditions such that the resulting system is numerically tractable. Plane of symmetry can be assumed if, modelling involving geometry, material properties and boundary conditions that do not vary in the circumferential direction.[5] Hence, an axisymmetric modelling is done for perforated cylindrical solid propellant grain as the material properties and boundary conditions are symmetric along axis, shown in Figure.1.

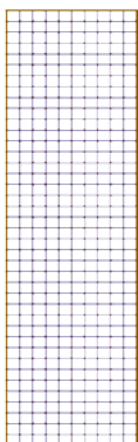


FIG. 1. AXIS-SYMMETRIC 2D MODEL

Modelling is done for 844mm propellant web thickness with inner radius of 500 mm and outer radius of 1401.8 mm. Case thickness of 7.8mm and 5.0mm insulation is provided around propellant grain. The length of the grain is 3000 mm. The general purpose software MARC is utilised for modelling as well for analysis with 8 noded axisymmetric finite element (No.28) Material properties of composite HTPB solid propellant grain is shown in Table:1. Uniaxial tensile test is conducted in laboratory to determine propellant's material properties, and a 16 term Prony series of shear relaxation is used for analysis. In dynamic analysis, propellant material is subjected to frequency test of 50Hz to determine its loss and storage modulus values.

TABLE 2  
MATERIAL PROPERTIES

	Young's Modulus (E) KSC	Poisson's ratio	Density Kg/ cm <sup>3</sup>	Coefficient of thermal Expansion (/°C)
Propellant Grain (HTPB B)	50	0.499	0.00178	0.0001
Rocasin-Insulation	100	0.499	0.002	0.0002
M250 Steel-casing	190,000	0.3	0.0078	0.00001

The master relaxation curve fitted from the experimental results is plotted in Figure.2 and the 16 term Prony's constants obtained are shown in Table:2

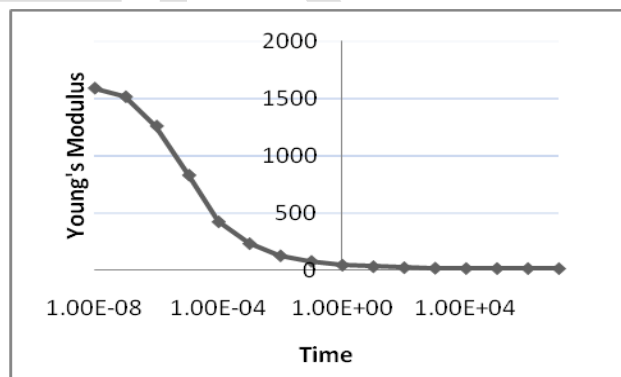


FIG. 2. MASTER STRESS RELAXATION MODULUS CURVE FOR HTPB PROPELLANT

### 4 .RESULTS AND DISCUSSIONS

Elastic, viscoelastic analysis is carried out for storage and internal initial peak pressure load, whereas dynamic analysis is done for internal pressure load..Elastic analysis utilises long term Elastic Modulus for the various materials where the structure behave within its elastic limit, with no loss of strength. In viscoelastic analysis, an instantaneous modulus is used for propellant and in dynamic analysis storage shear and

TABLE 2

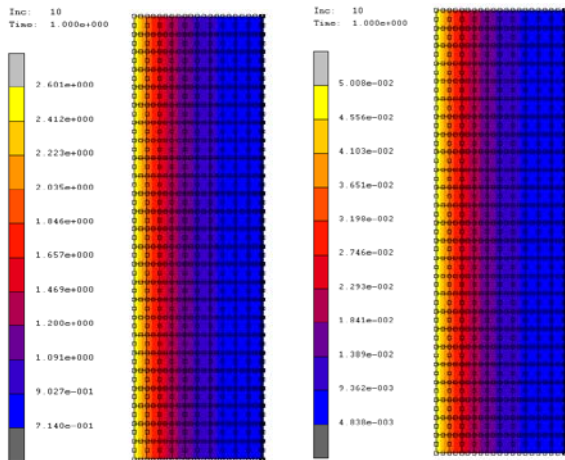
PRONY'S CONSTANTS

	$A_i$	$\tau_i$
1	-0.39	1.00E-08
2	52.9267	1.00E-07
3	129.113	1.00E-06
4	176.743	1.00E-05
5	75.19	1.00E-04
6	46.44	1.00E-03
7	17.4067	1.00E-02
8	15.19	1.00E-01
9	4.6333	1.00E+00
10	3.96667	1.00E+01
11	1.48667	1.00E+02
12	1.38	1.00E+03
13	0.086667	1.00E+04
14	0.03333	1.00E+05
15	0.146667	1.00E+06
16	0.216667	1.00E+07

lossmodulus is used. Stress-strain response of the propellant and other key material properties are determined by conducting laboratory uniaxial test.

4.1 Elastic Analysis Of Solid Propellant Grain

When propellant motor is ignited, it will induce hydrostatic pressure along the inner port. The motor grain is analysed for initial peak pressure load of 50 KSC with its predefined material properties. The Contour bands of displacement and the hoop strain are shown in Figures: 3 (a) & (b) respectively. A maximum displacement of 26.01 mm and corresponding strain of 5.01% is obtained at the inner port of perforated grain.

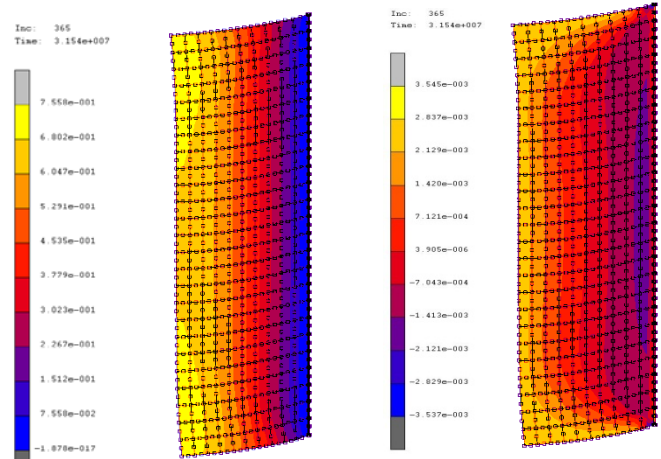


(a) Displacement (b) Strain

FIG. 3. DISPLACEMENT AND STRAIN CONTOURS DUE TO PRESSURE LOADING

After manufacturing, a solid motor grain is stored vertically, till its use. As the storage time increases, propellant slump and

strain also increases. The cylindrical port grain is analysed for long term storage condition with modulus of elasticity of 20 KSC. The contour band of displacement and the hoop strain is presented in Figure 4(a) & (b). A maximum displacement of 7.60 mm and corresponding strain of 0.35% is obtained at the inner portion of perforated grain.



(a) displacement (b) strain

FIG. 4. DISPLACEMENT AND STRAIN CONTOURS DUE TO GRAVITY LOADING

The elastic analysis results of propellant grain subjected to internal pressure and storage is presented in table: 3 Results are compared with the analytical solutions.

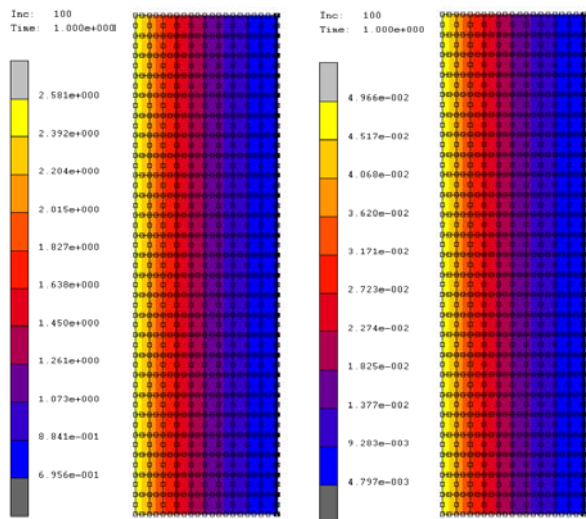
TABLE 3  
ELASTIC ANALYSIS OF PROPELLANT GRAIN

Loads	Displacement(mm)		Hoop strain (%)	
	Analytical	FEA	Analytical	FEA
Pressure (Radial)	25.92	26.01	4.99	5.01
Gravity (Axial)	7.60	7.56	0.35	0.35

4.2 Viscoelastic Analysis Of Solid Propellant Grain

Solid propellants exhibit time dependent behaviour under various loading conditions and hence viscoelastic analysis is carried out. There will be an instantaneous deformation under loading condition as in elastic part and later on viscous behaviour (constant deformation). The load induced by rapid pressurisation due to ignition in rocket motor is provided as a static load and a time depended analysis is carried out on viscoelastic propellant. The maximum displacement and corresponding strain contours obtained is shown in Figures 5(a) & (b).

A maximum of 25.81mm displacement and 4.97% strain had occurred at the inner port of propellant and its intensity decreases as its moves along the radial direction.



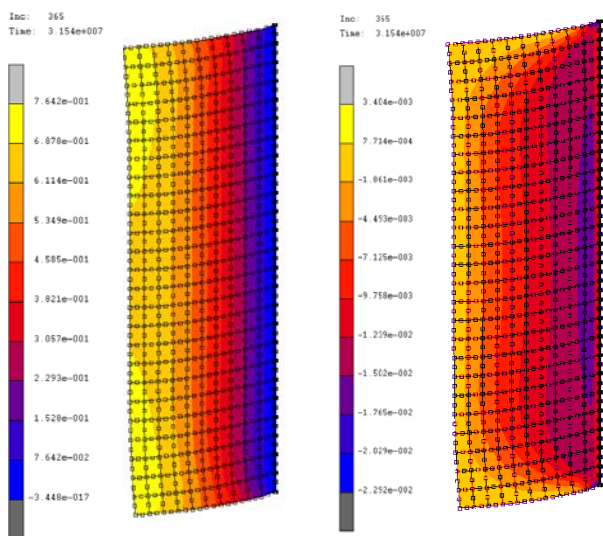
(a) displacement (b) strain

FIG. 5. DISPLACEMENT AND STRAIN CONTOURS DUE TO PRESSURE LOADING

The perforated cylindrical port grain is analysed for long term storage condition with instantaneous modulus of elasticity of 1594.11 KSC. Measurable deformations are expected<sup>[6]</sup> and a maximum displacement of 7.64mm and strain of 0.34% is obtained from the FEA results.

The contour bands of maximum displacement and the hoop strain for gravity is shown in Figure 6.

From Figures 5 & 6, it is observed that displacement and corresponding strain is maximum at the inner port and decreasing along its radial direction. Elastic and viscoelastic results are plotted for pressure as well as gravity loading.



(a) displacement (b) Strain

(a) displacement (b) strain

FIG. 6. DISPLACEMENT & STRAIN CONTOUR DUE TO GRAVITY LOADING

Figures.7 and 8 shows the variation of displacement and corresponding strain along radial direction for pressure loading. Similar decreasing graph along propellant web can be seen for gravity loading also.

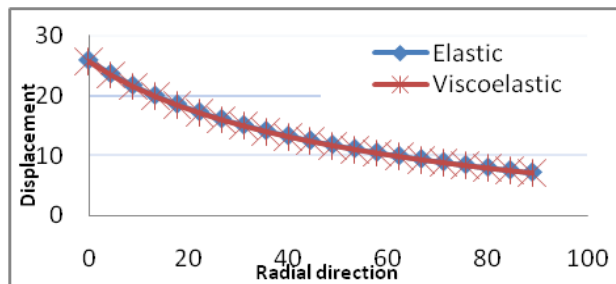


FIG. 7. DISPLACEMENTS ALONG PROPELLANT WEB

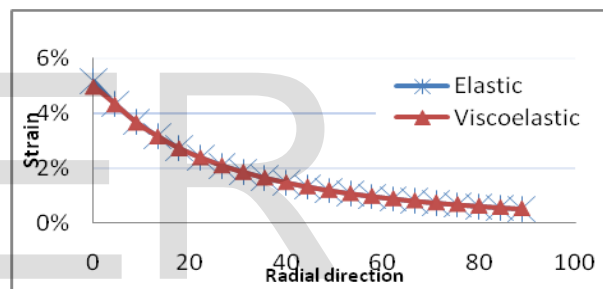


FIG. 8. DISPLACEMENTS ALONG PROPELLANT WEB

The variation of time dependent displacement at a node in the inner part, for internal pressure and gravity is shown in Figures 9 and 10 respectively. Strain will follow the same path of displacement for both pressure as well as gravity loading.

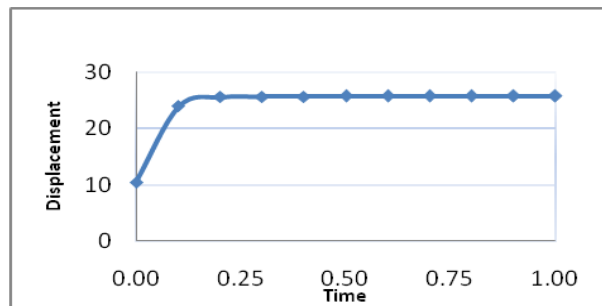


FIG. 9. VARIATION OF DISPLACEMENT WITH TIME (PRESSURE)

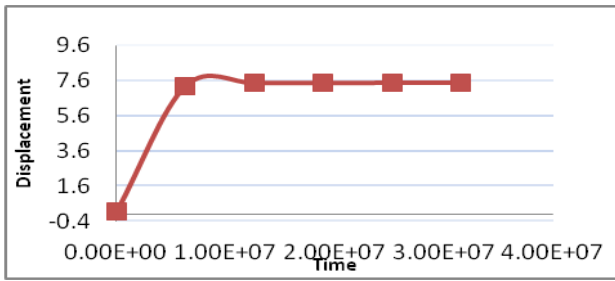


FIG. 10. VARIATION OF DISPLACEMENT WITH TIME (GRAVITY)

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The viscoelastic analysis results of propellant grain subjected to internal pressure and storage is concluded in Table:4

TABLE 4  
VISCOELASTIC ANALYSIS OF PROPELLANT GRAIN

Results	Displacement (mm)		Hoop strain (%)	
	Analytical	FEA	Analytical	FEA
Pressure (Radial)	25.92	25.81	4.99	4.97
Gravity (Axial)	7.60	7.64	0.35	0.34

### 4.3 Dynamic Analysis For Ignition Pressurisation

From the point of view of dynamics, a solid propellant rocket motor is an unique structure in that it is composed of a substantial mass of propellant material bounded by relatively mass less, thin-walled cylinder. Due to the viscoelastic nature of the propellant, it can be expected to provide considerable damping to the system. Few earlier studies show that dynamic effect is important for the structural integrity of solid propellant under diverse loading during shipment, ignition etc<sup>[7]</sup>. So dynamic effect for this particular problem is checked to ensure its safety conditions.

Here, ignition pressure loading case is considered and investigated for dynamic analysis. The mechanical properties of the propellant are such that it contributes little to the stiffness of the composite structure and contribute little to the dynamic characteristics.

of perforated cylindrical solid propellant grain for maximum frequency of 50Hz and the corresponding displacement and strain obtained are shown in Figure:11 (a) and (b) respectively.

From the dynamic analysis it is seen that maximum displacement is 0.0183mm and maximum strain is 0.0035% which is negligibly small and hence dynamic effect is insignificant for a solid propellant grain.

### 5 . CONCLUSION

An extensive structural analysis of a cylindrical solid propellant grain is carried out for elastic, viscoelastic and transient dynamic, general purpose FEA software packages. An axis-symmetric model was used. Results shows that (i) Elastic and viscoelastic analysis results for internal pressure and storage loads matches well (ii) The maximum displacement, hoop strain is attained at the inner port of grain and decreases along its radial direction (iii) A progressive displacement and strain with time is analysed for viscoelastic analysis and reaches equilibrium later. (iv) Dynamic analysis on propellant grain under ignition pressurization load is insignificant.

### REFERENCES

- [1] "Solid propellant grain structural integrity analysis". NASA SP 8073, (1973).
- [2] Andrzej Hanyga „Małgorzata Seredyńska"Relations Between Relaxation Modulus and Creep Compliance in Anisotropic Linear Viscoelasticity" *Journal of Elasticity*(2007) 88:41-61
- [3]Viscoelasticity In Wikipedia.(2016),<https://en.wikipedia.org/wiki/Viscoelasticity>
- [4] J.L.White," Finite elements in linear viscoelasticity" AFFDL- TR-68-150.
- [5] "Structural Assessment of Solid Propellant Grains",AGARD Advisory report 350 (1997).
- [6] K.Renganathanand HariPrasad.M.P"Nonlinear Viscoelastic Stress Analysis of a Circular Perforated Solid Booster Propellant Grain for vertical storage" HEMCE 2014
- [7] Shiang-WoeiChyuan, "Dynamic analysis of solid propellant grains subjected to Ignition pressurization loading"*Journal of Sound and Vibration* 268 (2003).

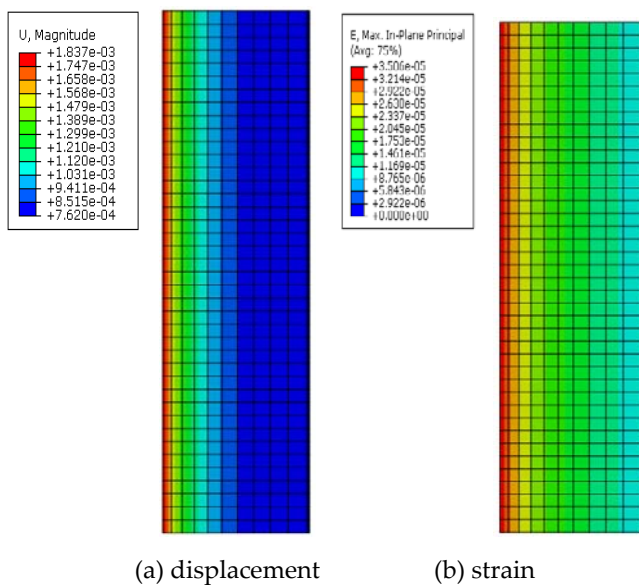


FIG. 11. DISPLACEMENT AND STRAIN CONTOUR DUE TO DYNAMIC LOADING

An acceleration of 181.3 cm/sec<sup>2</sup> is obtained at the inner portion