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SHORT COMMUNICATION

Prediction of Maximum Strain in Finocyl Port Case-bonded Solid Propellants under Pressure Loading

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ABSTRACT

Finite element analysis of case-bonded solid propellants in finocyl port configuration has been carried out using finite element method. The parametric studies have also been conducted for loading conditions, material properties, and geometrical configurations. The results are presented in the form of a universal power law, which can be utilised for primary assessment of peak strain in any finocyl port propellant configuration without using finite element software. This eliminates dependence on finite element software for structural integrity analysis of solid propellants in finocyl port configuration under port pressurisation. The results obtained by finite element analysis and power law are in close agreement.

Keywords: Case-bonded solid propellants, solid propellants, finite element analysis, finocyl port propellant configuration, propulsion unit, propellant port, port pressurisation

1. INTRODUCTION

The grain design for a solid propellant rocket motor frequently necessitates compromises among the conflicting requirements of ballistic performance, structural integrity, mission reliability, and geometrical constraints. Study on structural properties of propellants, their response to loads, and resistance to failure, are the major considerations for the successful development of propulsion units, especially in case-bonded solid propellant configurations[1].

Except for end-burning mode, these propellant configurations invariably contain a central recess, called port. Ports are configured to fulfil the ballistic requirements of desired pressure-time and thrust-time curves on initiation of a propellant. With the advent of modern missiles and rockets, where all efforts are made to achieve increase in range or payload, the attention is focused on effective utilisation of combustion chamber volume of propulsion units. Finocyl-shaped port in case-bonded configuration is a universal choice due to higher volumetric loading, better neutrality, and reduced sliver fraction[2]. However on initiation, propellant port is pressurised and stress concentration zones are created in the propellant. The propellant shows stress-relaxation behaviour and any stress generated is reduced to zero in the course of time. However, strains remain unaffected due to this nature of propellant. So, maximum strain obtained by uniaxial tensile testing of standard propellant sample is compared with maximum strain generated in the propellant configuration under operational condition and maximum principal strain criteria is applied for prediction of failure margin in the propellant grains[3].

This paper deals with the calculation of elastic strain generated due to pressure loading in finocyl-

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shaped port of propellant grain using finite element analysis (FEM–NSYS 5.4). It also includes parametric study to get a power law for predicting elastic strain for any other finocyl shape without using any finite element software.

2. FORMULATION OF THE PROBLEM

All the designed propellant grain configurations, for case-bonded application have to necessarily undergo structural integrity analysis. Only after clearance from structural integrity of propellants under various loading conditions and certification for availability of adequate margin of safety, grain designs are approved for implementation. Due to complexity in configuration, close-form solutions are not available in the literature for different configurations. However, some thumb rules are available for trends in enhancement and reduction in severity of failure of a given propellant grain configuration. Current practice is to use finite element analysis to assess margin of safety for a given propellant configuration. For predicting margin of safety through structural integrity analysis, the following input parameters are needed:

- *Loading conditions*: The propellant grains are subjected to various loading conditions like thermal loading during curing, environmental cycling and storage; jolt, vibration, bump, etc during transportation, handling and operation; and pressurisation loading during initiation. However, this paper deals with pressurisation only. The propellant grains are subjected to port pressurisation during initiation and confirming adequacy of propellant configuration for withstanding generated strain is a prime requirement for the propellant design.

- *Grain geometry*: Finocyl-shaped grain (Fig. 1) has several geometrical governing parameters like number of fins, fin width, lobe diameter, and grain diameter, and all these parameters are considered for the analysis. To take the advantages of symmetry, analysis is conducted for half-fin portion only and peak strain values are recorded for comparison.

- *Material properties*: Although solid propellant behaves as visco-elastic material, elastic analysis is generally preferred to get preliminary estimate of the strain values. Here, propellants are taken as linear elastic materials, so that material constitutive relations and material stiffness can be expressed and used effectively for analysis. This study also helps in applying superposition of changes in geometry, material properties, and loading conditions for modelling[4].

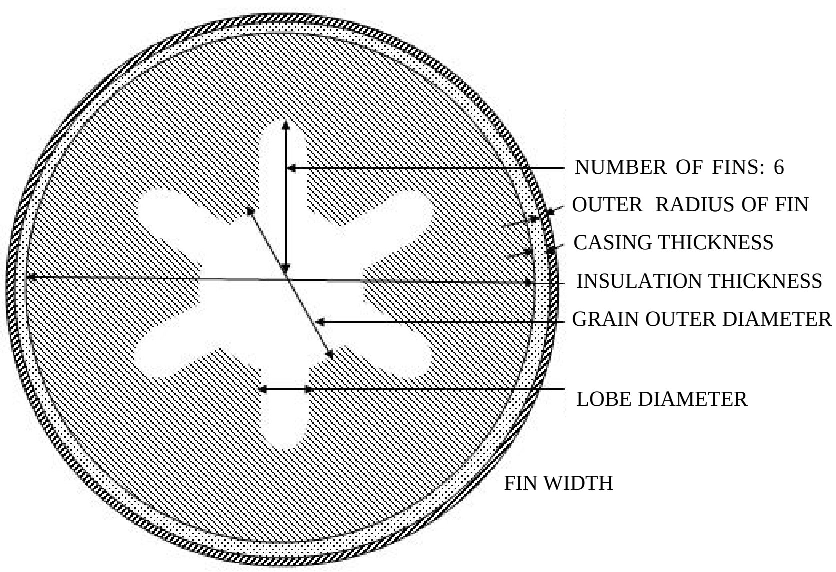

Figure 1. Geometrical parameters of finocyl-shaped port case-bonded propellant grain

3. ASSUMPTIONS FOR FINITE ELEMENT ANALYSIS

The following assumptions have been made for this analysis:

- Both propellant and insulation have similar mechanical properties, which is true in most of the case-bonded configurations.
- Poisson's ratio for propellant/insulation is 0.499, and these behave almost in an incompressible manner.
- Poisson's ratio for metallic casing is 0.300.
- Elastic analysis is conducted assuming a constant modulus for the propellants.
- All the generated strain values are within the elastic limit.
- All the interfaces behave as continuum and there is no void, crack, or discontinuity before or after the analysis.
- Since propellant grains are long, plane strain condition is assumed to exist during loading.
- Longitudinal loading conditions are not considered for the analysis and ends are assumed free.

At first, a reference configuration with the following control parameters is selected and given in Table 1.

Parametric studies have been conducted for this configuration to arrive at controlling correlations for strain. Port pressure of 90 kg/cm^2 is considered and finite element analysis of half-fin is conducted using 8-noded isoparametric element (PLANE82). Peak value of the elastic hoop strain is obtained as 11.876 per cent (Fig. 2). The location of this maximum stress is at the tip of the fin shape.

4. MODELLING

The maximum hoop strain obtained depends on material properties, loading conditions, and propellant port geometry. Pressure as such has a proportional representation on maximum hoop strain value, and higher the pressure, higher is the maximum hoop strain. Although higher modulus of propellant is desirable for lower-generated hoop strain, quantification of effects can be obtained only by conducting finite element analysis for each situation. Effect of all these parameters on maximum hoop strain obtained by finite element analysis during pressure loading on a finocyl port case-bonded propellant grain can be expressed in the form of a power law correlation as given below:

Table 1. Control parameters and their values for reference configuration

Control parameter	Value
Casing characteristics	
Thickness	0.5
Poisson's ratio	0.3
Young's modulus	1900000
Propellant insulation characteristics	
Insulation thickness	0.5
Poisson's ratio	0.499
Young's modulus	50
Propellant configuration	
Number of fins	18
Casing outer diameter	73
Outer radius of fin	18
Lobe diameter	29.600
Fin width	1.600

Maximum hoop strain

$$(\varepsilon_\theta) = K.(P).(E_{prop})^a.(FW)^b.(N)^c.(GOD)^d.(FOD)^e.(MT)^f.(CM)^g$$

where

K	Constant to be determined by computation
P	Pressure loading to which propellant port is subjected
E_{prop}	Young's modulus of the propellant
FW	Width of the fin or diameter of fin tip
N	Number of fins at a cross section
GOD	Grain outer diameter or casing inner diameter

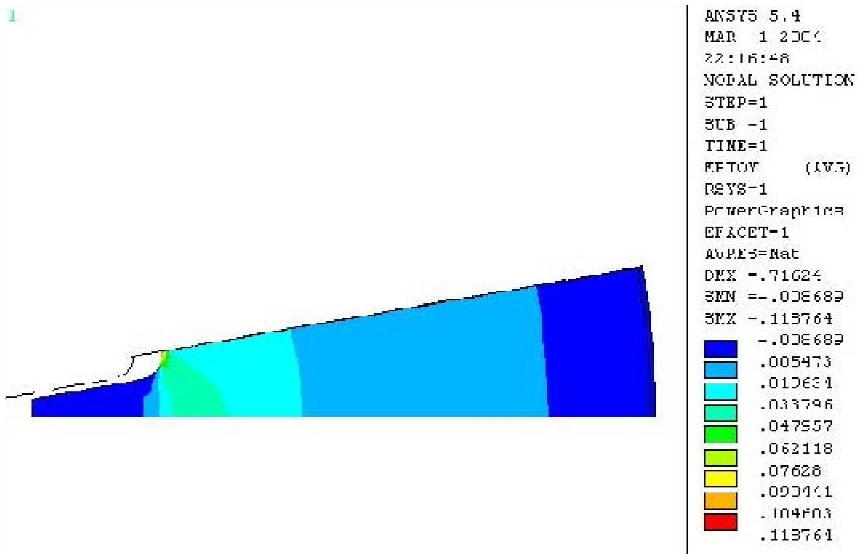

Figure 2. Strain plot for reference configuration under pressure loading

FOD	Outer diameter of fins
MT	Metal thickness
CM	Case modulus

Here, exponents *a*, *b*, *c*, *d*, *e*, *f*, and *g* are constants and are to be obtained by varying one parameter at a time and conducting analysis using FEM.

5. RESULTS & DISCUSSION

At first, only one parameter, say modulus of the propellant formulation is varied from 20-70 kg/cm^2 and value of maximum hoop strain for a half-fin configuration using finite element analysis for each situation is obtained. In each case, maximum hop strain lies at the tip of the fin as depicted in Fig. 2. However, the value of maximum strain reduces as propellant modulus increases. Maximum hoop strain values are plotted against modulus of the propellant (Fig. 3) for the reference configuration, and a power law is fitted to the data. Power law exponent is obtained as –0.68 for parametric studies for propellant modulus.

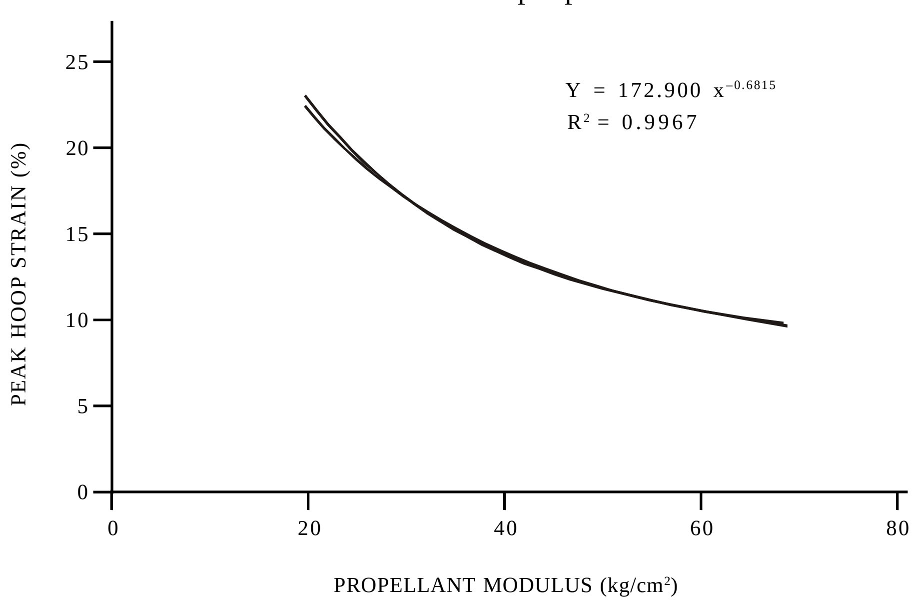

Figure 3. Variation of peak hoop strain with propellant modulus

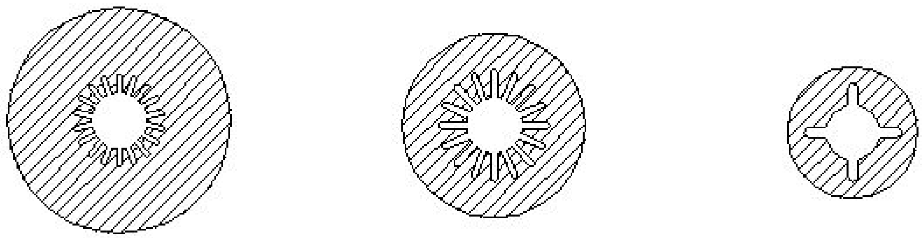

Figure 4. Relative dimensions and configuration of case studies

Similar analysis has been conducted for each of the parameters, and exponents of power laws have been obtained in each case. During parametric study, it was observed that change in lobe diameter or inner diameter of the fin does not affect maximum strain.

The values of these exponents are obtained as

$a = -0.68, \quad b = -0.40, c = -0.48, d = 2.42$
$e = -1.63, \quad f = -0.38, g = -0.45$

This derived power law can be used to get maximum strain in the propellant configuration by simply taking ratio of changed parameters along with relevant exponents. If reference configuration, as depicted in parametric study, is taken as base, maximum strain in a trial configuration is given by the following expression:

$$(\varepsilon_r) = (P_r/P_t).\ \{(E_{prop})_r/(E_{prop})_t\}^a.\ (FW_r/FW_t)^b.\ (N_r/N_t)^c.(\mathrm{GOD}_r/\mathrm{GOD}_t)^d.(\mathrm{FOD}_r/\mathrm{FOD}_t)^e\ (\mathrm{MT}_r/\mathrm{MT}_t)^f.\ (\mathrm{CM}_r/\mathrm{CM}_t)^g.\ (\varepsilon_t)$$

where subscripts r and t depict reference and trial configurations, respectively.

6. CASE STUDIES

As a case study, two trial cases were selected. Reference configuration, as used in parametric study, and configurations for two trial cases are shown in Fig. 4 to depict their relative sizes and difference in configurations. Input conditions have been depicted for all cases in Table 2 and all the other parameters, except those mentioned in the table, are kept constant. Power law was used to get maximum strain for the trial configurations, for which actual finite element analysis was also conducted. For *Case 1*, power law modelling gave maximum strain as 7.665 per cent as against finite element analysis result as 7.874 per cent. Similarly, for *Case 2*, peak strain by power law modelling and finite element analysis were 3.448 per cent and 3.300 per cent. Since for both the cases results are closely matching, power law modelling gives value of maximum hoop strain directly without any finite element software. So,

Table 2. Comparison of modelling and FEM results

Parameter	Reference	Case 1	Case 2
Pressure (kg/cm^2)	90	120	62
Propellant modulus (kg/cm^2)	50	40	40
Fin width (cm)	1.6	2.0	3.4
Number of fins	18	16	4
Grain outer diameter (cm)	72	59.0	42.14
Fin outer diameter (cm)	29.6	36.0	31.4
Peak strain (%) by modelling	11.8764	7.665	3.448
Peak strain (%) calculated by FEM	11.8764	7.874	3.300

it is established that these exponents are universal and can be utilised for predicting peak strain values for port pressurisation of different finocyl-shaped case-bonded solid propellant grains.

Finite element analysis needs specific costly software, computer time for preprocessing and analysis. In addition to skilled manpower to run the software, these can be dispensed with using derived power law. Power law correlation is an easy, quick, and handy way to predict structural strains due to port pressurisation in a finocyl port case-bonded solid propellant grain without any computer and with the same accuracy.

7. CONCLUSION

The parametric studies of finocyl-shaped propellants enabled the quantitative measurement of maximum strains for each change in the operating parameters and configuration. A simple relation is also derived to predict the behaviour of a case-bonded finocyl-shaped solid propellant under pressure loading conditions. A close matching is observed between finite element analysis and the modelled results. Using the power law maximum hoop strain for any configuration can be obtained without using any finite element software.

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