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Peak Strain in Regressing Finocyl Port Propellant Grains under Pressure Loading

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ABSTRACT

Finite element analysis (FEM) has been conducted for case-bonded finocyl port propellant cross section under pressure loading conditions during burning. Peak strain is found to decrease in course of burning, hence, analysis of any intermediate configuration in course of burning is not required for assessing margin of safety in finocyl port propellant grains. The Power Law proposed[1] has also been used to predict peak strain. Variation in strains obtained by FEM and using the Power Law is found to be matching closely with findings reported in CPIA (Chemical Propulsion Information Agency) publications. Extension in domain of power law to regressing pressurised finocyl port propellant grain eliminates dependence on time-consuming computer- intensive FEM computations without compromising the accuracy of results.

Keywords: Finocyl port propellant grain, rocket propellant, port pressurisation, peak strain, pressure loading, finile element analysis, case-bonded propellants, propellant burning

1. INTRODUCTION

In rocket and missiles applications, propulsive power is released in chemical form by burning solid propellant grains. The mission requirement dictates specifications of thrust-time profiles, which in turn affect propellant port configuration. However, processing ease, ballistic requirements, and structural integrity aspects are to be matched properly for success of a project. Earlier, structural assessment of propellant grains were carried out by actually firing rocket propellant grains in the final proof stages[1]. Initial attempts were made to transform complex port geometries into circular geometries by conformal mapping to arrive at close-form solutions[2]. But the validity of such methods for more number of discontinuities or star points could not be established. Britton[3] has given a very good account of structural integrity analysis procedures. However, with the development of computational power, structural safety margins have been made compulsory in the initial phases of development itself. Every outline of propellant port designed must be assessed before actual production or development. With the advent of case-bonded technology for solid propellants, the propellant grains are more stressed now. Propellants are subjected to pressure loads, thermal loads, acceleration, vibration and handling loads, etc. In the present study, only pressure loads have been considered. Propellant grain configurations are selected as per mission requirements and several shapes like solid sustainer, tube, star, slotted tube, wagon wheel, finocyl[4], etc. Finocyl shaped propellant grains (Fig.1) have been used for large web thickness, large burning area,

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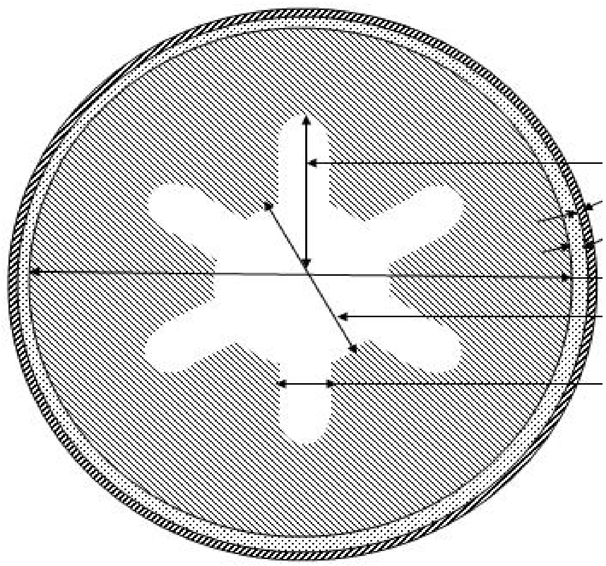

Figure 1. Geometrical parameters of finocyl port case bonded propellant.

good neutrality, and least sliver fraction. It is suitable for case-bonded propellant configurations with high length-to-diameter ratios[5]. Due to propellant stress relaxation during loading, any stress induced in the propellant grain vanishes with time. So, maximum strain values generated in the propellant grains under given loading conditions are evaluated and compared with uniaxial tensile test results to obtain margin of safety. Instantaneous modulus of propellant grain is taken as input for analysis.

Influence of structural parameters like modulus, Poisson's ratio, etc on generated strain can be obtained, by theory, in strength of material for simple configurations, but getting strain for complex configuration is not possible analytically. In addition, configuration defining parameters like diameter, thickness cannot be correlated to peak strain by any close-form solutions. Effect of configurations has not been adequately reported in open literature. In one of the CPIA (Chemical Propulsion Information Agency) publications[6], structural analysis of solid propellants in star-shaped port configuration has been given in detail. It also gives parametric curves for strain/stress variations in star-shaped configuration. Finocyl-shaped grain is also treated as an extension of star-shaped grain. Rather than stressing more on parallel fin configuration, it stresses more on variation of fin parallelism and fin-tip flattening.

Internal port configurations of propellant grains changes in course of burning. This study analyses various intermediate configurations, obtained from an initial finocyl port in course of burning. Finite element method has been used to assess peak strain, Shekhar model[7] of peak strain under pressure loading on finocyl propellant grains has also been implemented simultaneously for each of the intermediate configurations.

2. FORMULATION OF THE PROBLEM

A typical 6-fin finocyl port configuration is considered for analysis. The input properties and configuration parameters are depicted in Table 1. For analysis of port pressurisation, symmetry is exploited to model only half fin of propellant grain. Since propellant grain is long, plane strain condition is assumed to exist. Both radial boundaries of the half fin are assumed to be symmetrical and transition zone between propellant and metal case is assumed to be adhering at full surface. 8 noded isoparameteric 2-D structural elements were considered for the finite element analysis. For the initial configuration, FEM results of equivalent strains are presented in Fig. 2. The peak value of strain lies at the tip of the fin and the value is 19.15 per cent. Similar analysis was conducted for each intermediate web burnt in steps of 0.5 cm and 1.0 cm. The analysis

Table 1. Input parameters for analysis.

Parameter	Value
Metal casing properties	
Thickness, cm	0.3
Elastic modulus, kg/cm^2	2E06
Poisson's ratio	0.3
Propellant properties	
Number of fins	6
Outer radius of fin, cm	40
Grain outer radius, cm	50
Lobe radius, cm	15
Fin width, cm	2.0
Quasi-elastic modulus, kg/cm^2	20
Poisson's ratio	0.499
Operating condition	
Port pressure, kg/cm^2	90

is extended to 8-fin and 18-fin configurations for completeness of the derived results.

Shekhar model[7] has been derived for calculation of peak strain in the finocyl port case-bonded propellant grains under pressure loads at port. It is a handy tool for strain assessment, and thus, relies on a reference configuration. Once strain in a base configuration is assessed, further calculations of peak strains are possible using the developed power law formulation. During burning of finocyl port propellant grains, only two geometrical parameters viz., fin outer radius and fin width were varied. In addition, different numbers of fins were also considered in the analysis for establishing versatility of formulations. The relevant portion of the model was extracted and reproduced here for peak strain.

$$\varepsilon = K(\text{number of fins})^{a} \times (\text{fin outer radius})^{b} \times (\text{fin width})^{c}$$

where K is a constant and a,b,c are universal indexes validated for all finocyl shaped grains.

The finite element analysis results have been compared with the results obtained by the above model.

3. RESULTS AND DISCUSSION

The web burnt for reference configuration has been changed and analysis is conducted at different burnt webs conditions till 9.5 cm of web burnt state. At 10.0 cm, configuration no longer

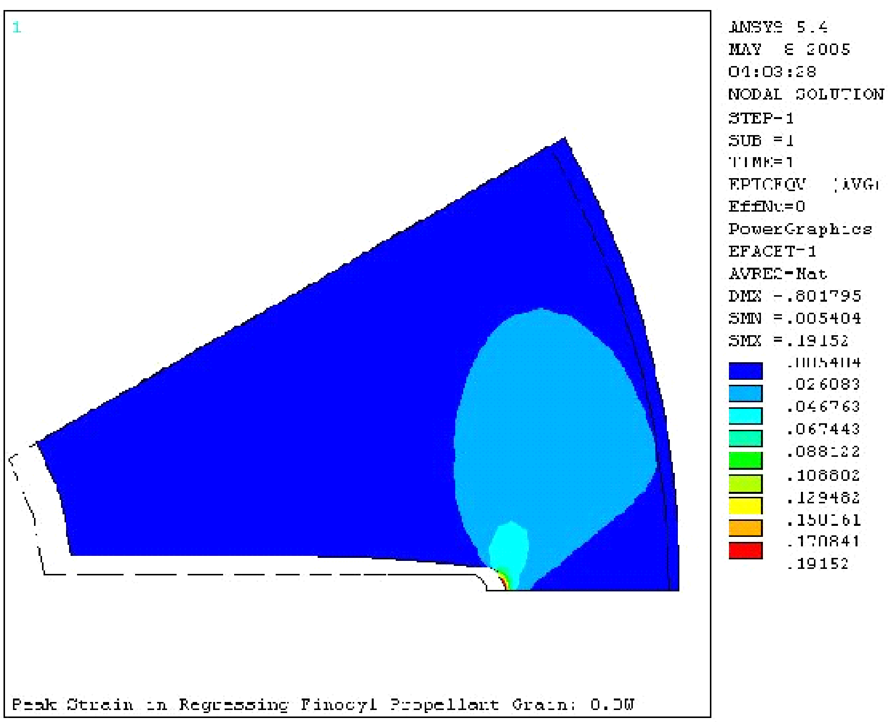

Figure 2. Equivalent strain in initial finocyl port configuration.

remains finocyl in shape; hence, analysis was discontinued thereafter. Equivalent strains for all intermediate configurations of web burnt, using finite element formulation are reproduced in Fig. 3. As propellant burning progresses in the rocket motor, for same level of pressure loading, peak strain generated in subsequent configurations is less than peak strain for the initial configuration. This indicates lower strain for lower web configuration. This may be attributed to the increased contribution of metal casing in bearing the applied port pressure load with reduced web of propellant. Peak strain calculated using finite element analysis method is plotted against web burnt in Fig. 4. Simultaneously, the values of peak strain are calculated using Shekhar's model[7] for each web burnt condition. Peak strain value, as calculated by the model, is superimposed on finite element results in Fig. 4. A close matching has been observed in the strain values.

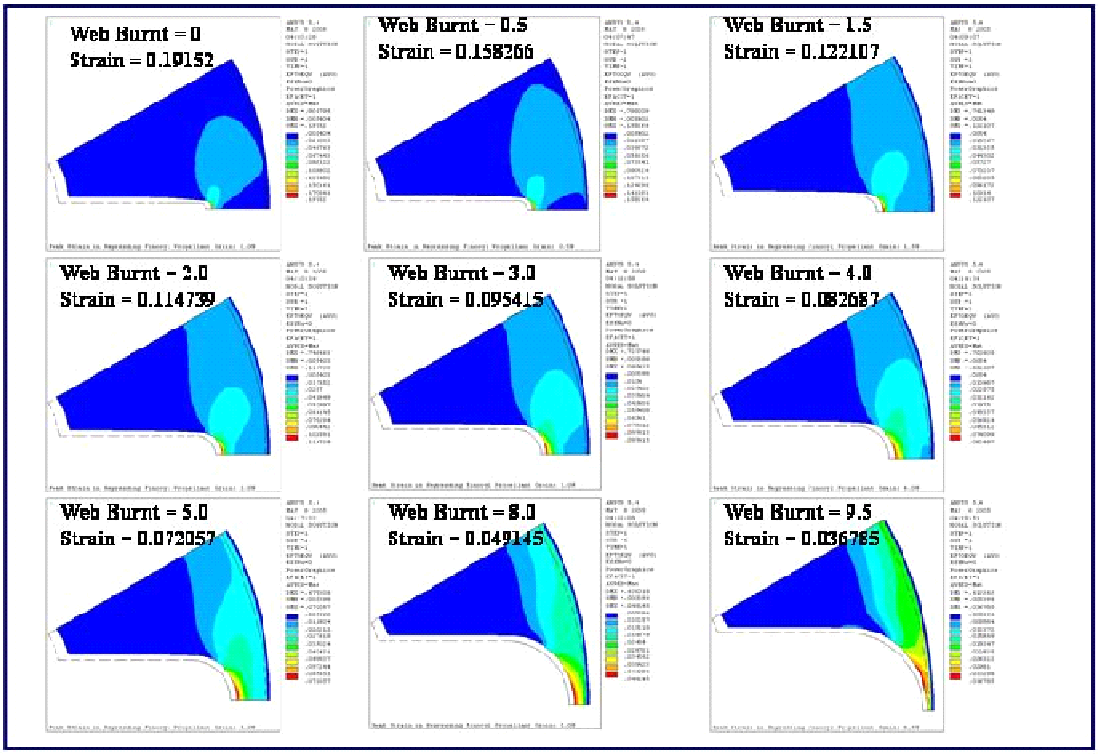

Figure 3. Peak strain variation in 6 fin initial finocyl.

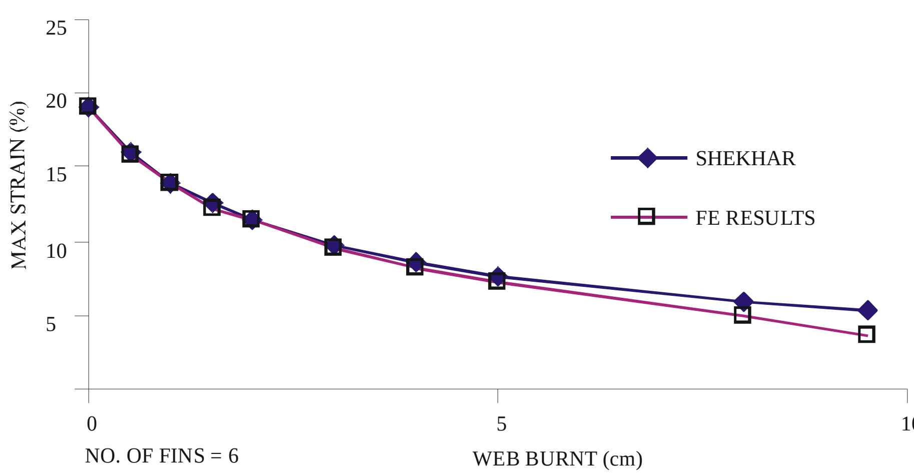

Figure 4. Comparison of FEM and Shekhar's model.

To explore the versatility of Shekhar's model, same geometric dimension was considered with changed number of fins. Analysis was conducted for 8-fin and 18-fin finocyl configuration for assessing peak strain value under pressure loading of the same level. The resulting configurations are shown in Fig. 5. Equivalent peak strain from finite element method for initial configuration of 8-fin finocyl under pressure loading was found to be 17.5 per cent. In course of burning, propellant is consumed and shape of finocyl sector of the configuration changes. Finite element analysis for different web burnt for 8-fin finocyl configuration was carried out. For higher web burnt, value of peak strains was found to be lower than lower web burnt conditions.

For prediction using Shekhar's model, peak strain values for 6-fin finocyl configuration is taken as reference and values of peak strain for 8-fin configuration has been predicted to be 16.68 per cent. Peak strain using FEM and results by Shekhar's model is plotted in Fig. 6 and results are found to be matching closely. For an initial configuration with 18-fins finocyl configuration, peak strain value using FEM is found to be 11.73 per cent. The value of peak strain changes as propellant burning continues and till finocyl shape is retained, peak strain variations using finite element method is obtained. Peak strain value is reduces with web burnt. Same results are calculated from Shekhar's model using 6-fin configuration as reference and it was found that Power Law of Shekhar is giving peak strain matching to peak strains by FEM (Fig. 7).

Finocyl-shaped port is referred as simple slotted grain configuration in CPIA publication[6] and strain concentration factor is empirically shown to be a function of two angles (Fig. 8). First is filled fin angle (a1) and other is sectorial symmetry angle (a2). The strain concentration factor is given by

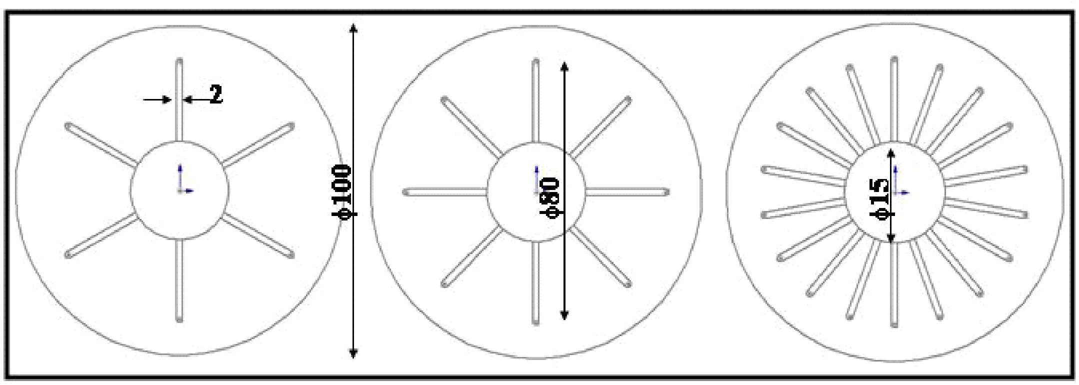

Figure 5. Geometry of configuration for analysis.

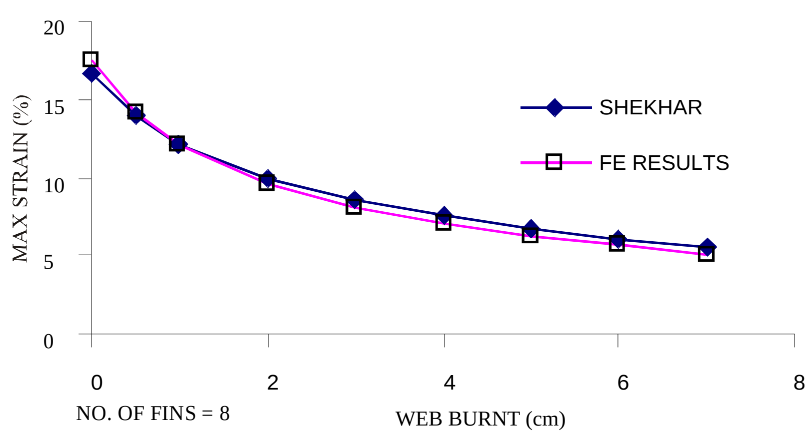

Figure 6. Comparison of FEM and Shekhar's model.

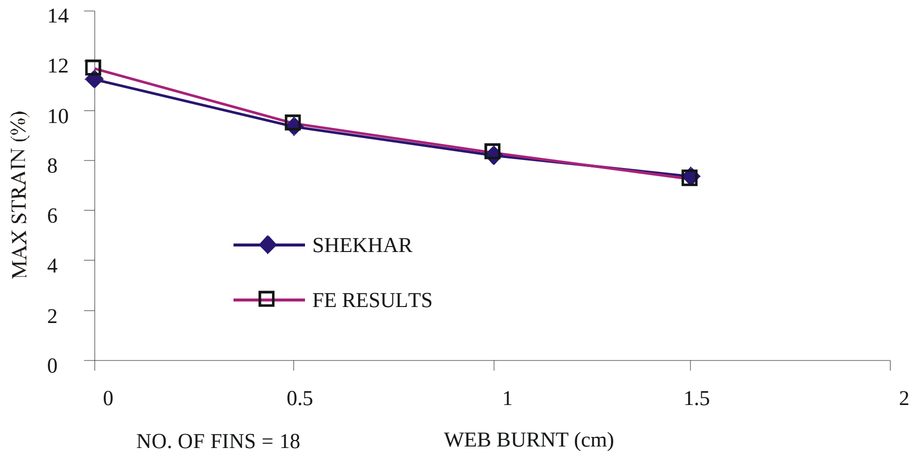

Figure 7. Comparison for 18-fin finocyl.

(2 . a2 – a1) / {2 (a2 – a1)}. This expression is reported to have produced results which are in close agreement with actual port strain measurements of MINUTEMAN-WING II and POLARIS A3 motors. The regressing finocyl during rocket motor operation leads to reduction in angle 'a1'. This leads to reduction in strain concentration factor as propellant burning progresses. Comparison of strain concentration factor by formulation in CPIA publication and by Shekhar's model has been depicted in Fig. 8. A close matching ensures that formulation depicted by Shekhar's model is on par with the reported results. This validates the proposed model for finocyl-shaped port configuration in general and regressing propellant grain during rocket operation in particular.

In each of the three reported cases, the value of peak strain under pressure loading reduces during burning, which can be accepted as normal finocyl port behaviour. This result relieves designers from calculating peak strain for each of intermediate configurations during propellant design. Initial propellant configuration is generally more critical from pressure loading point of view and availability of sufficient margin of safety in the beginning ensures structurally safe propellant grain configuration.

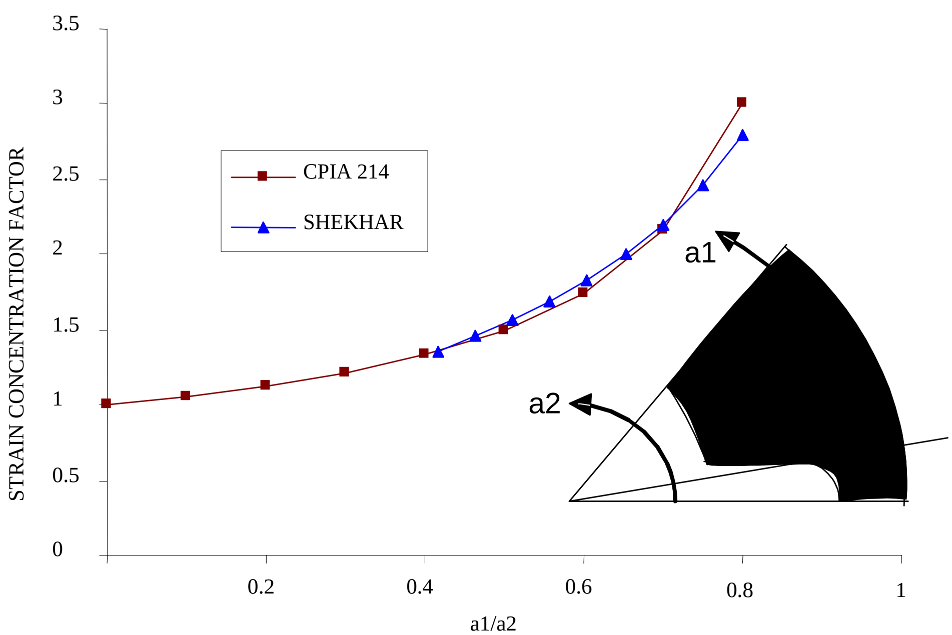

Figure 8. Comparison of strain concentration factors.

4. CONCLUSION

The case-bonded finocyl port propellant grain under pressure loading conditions has been analysed at regressing web stages. It has been found that for the same pressure loading, the initial finocyl configuration has higher strain as compared to any subsequent configurations. In course of burning, propellant web reduces and metallic casing shares higher load at any reduced web condition; thus reducing peak strain at critical propellant port locations. Close matching of FEM results and Power Law by Shekhar indicates that without using computational-intensive FEM, Shekhar's model can be implemented for assessing peak strain values under pressure loading on a fincocyl port propellant grain. In addition, close matching with results published in CPIA establishes the correctness of the formulation. This gives propellant grain designer a useful input for shaping propellant port for various mission requirements.

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Mr Himanshu Shekhar obtained his MTech (Mech Engg) from the Indian Institute of Technology (IIT), Kanpur and has been working in DRDO since 1994. He has worked for creation of infrastructure for processing case-bonded solid propellant motors. He has modelled several processes and their controlling parameters for smooth, effective, and quicker operations. He has done structural integrity analysis of solid rocket propellants. He has participated in several seminars and has more than 12 publications to his credit. He is working as Scientist E at the High Energy Materials Research Laboratory, Pune.