International Journal of Pressure Vessels and Piping 111-112 (2013) 131–145

Contents lists available at SciVerse ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

# Development of efficient finite elements for structural integrity analysis of solid rocket motor propellant grains

R. Marimuthu [a], B. Nageswara Rao [b,*]

[a] Structural Analysis and Testing Group, Vikram Sharabhai Space Centre, Trivandrum 695022, India

[b] Faculty of Mechanical Engineering, School of Civil and Mechanical Sciences, KL University, Green Fields, Vaddeswaram 522 502, India

ARTICLE INFO

*Article history:*
Received 27 February 2012
Received in revised form
2 June 2013
Accepted 3 June 2013

*Keywords:*
Rocket motors
Incompressible materials
Visco-elastic
Herrmann formulation
Solid propellant grains

ABSTRACT

Solid propellant rocket motors (SRM) are regularly used in the satellite launch vehicles which consist of mainly three different structural materials viz., solid propellant, liner, and casing materials. It is essential to assess the structural integrity of solid propellant grains under the specified gravity, thermal and pressure loading conditions. For this purpose finite elements developed following the Herrmann formulation are: twenty node brick element (BH20), eight node quadrilateral plane strain element (PH8) and, eight node axi-symmetric solid of revolution element (AH8). The time-dependent nature of the solid propellant grains is taken into account utilizing the direct inverse method of Schepary to specify the effective Young's modulus and Poisson's ratio. The developed elements are tested considering various problems prior to implementation in the in-house software package (viz., Finite Element Analysis of STructures, FEAST). Several SRM configurations are analyzed to assess the structural integrity under different loading conditions. Finite element analysis results are found to be in good agreement with those obtained earlier from MARC software.



## 1. Introduction

A solid propellant rocket is the simplest form of chemical propulsion. The fuel and oxidizer are both incorporated in a single solid, called the propellant grain, located inside a container called the combustion chamber. A solid propellant grain is a composition of matter, stable at room temperature, which, once ignited, evolves gas continuously at elevated temperatures without dependence on the atmosphere. Any piece of solid propellant, regardless of its size, configuration or method of manufacture, is referred to as a grain when used in a rocket chamber. A grain must hold its shape over an extended temperature range, and must withstand the stresses and strains imposed on it during handling, ignition, and firing in a rocket. The principal parts of a solid rocket motor are the grain, the casing, the insulation, the nozzle and the igniter as shown in Fig. 1. In order to achieve shorter burning times and higher thrust-to-weight ratios with conventional propellants, various complex grain configurations are used. The types of possible grain configurations are endless, being limited only by the ingenuity of the designer and by the requirements on the scale and shape of the pressure–time curve and the ratio of length-to-diameter of the rocket, in relation to the burning rate of propellants. A few common grain cross-sections are shown in Fig. 2. Solid propellant rocket motors are regularly used in the satellite launch vehicles.

Solid rocket motor (SRM) structural design is currently based on concept of a mechanically weak solid propellant grain cast into a stronger metallic or composite case. The outer case provides the essential structural resistance against service and operational loads, and the low strength of inner propellant grains is used for transmission of loads from grain surface to outer case. In general, solid rocket motors are subjected to diverse loading during transportation, storage and firing. Specification of limiting conditions is one of the challenging tasks for a designer to prevent from the failures (viz., excessive deformation of the propellant, over pressurization due to propellant cracking, casing burn-through due to premature exposure of the insulation because of the grain structural failure or the propellant-insulation-motor casing bond failure) of solid propellant rocket motors. Successful grain design, therefore, depends upon a comprehensive assessment of the grain's structural integrity. This involves a mathematical analysis of the stress–strain state which exists in the rocket motor, evaluation of material properties and selection of a suitable failure criterion [1].

Solid propellant grain segments are cast and cured separately at elevated temperature for the required number of days and then

* Corresponding author. Tel.: +91 8645 246948; fax: +91 8645 247249.
*E-mail address:* bnrao52@rediffmail.com (B. Nageswara Rao).

0308-0161/$ – see front matter 
http://dx.doi.org/10.1016/j.ijpvp.2013.06.001

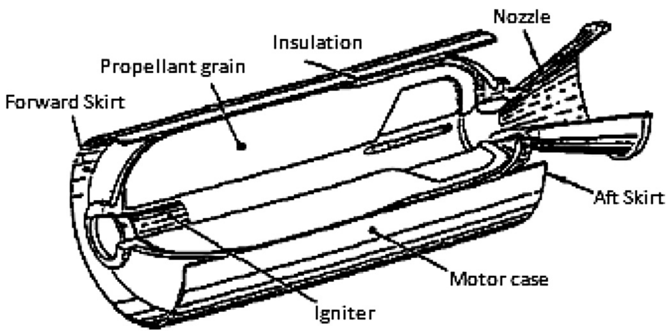


**Fig. 1.** A typical solid rocket motor.

cooled to the room temperature before storage. Thermal stresses and strains are developed due to long time cooling from the stress-free temperature. During the propellant burning, the internal pressure developed inside the motor induces a compressive hydrostatic stress state. While the tensile strains and displacements at the inner surface of the grain, which are maximum during the initial phase of burning, decreases with time, due to the reduction of the grain web-thickness. Thus, for structural integrity analysis, it is necessary to obtain viscoelastic solution corresponding to the initial maximum motor pressure at time just after the ignition transient and slump displacements in the grain under long-term vertical/horizontal storage conditions.

Analytical solutions are obtained for cylindrical grain reinforced by metallic casing under thermal, vertical storage and internal pressure loading conditions [1,2]. Though insulation is also a polymeric material, its Young's modulus is usually lower and its coefficient of thermal expansion is higher than the propellant grains. Therefore, to get an accurate estimation of hoop stresses and strains at the port surface and at both interfaces (i.e., propellant to insulation and insulation to casing), it is necessary to consider the insulation as a separate layer. The major portion of the solid propellant rocket motor can be considered to be a multilayer thick cylinder consisting of three layers of different materials namely, solid propellant grain, insulation and metallic or composite casing. An exact solution is obtained for the generalized plane strain of

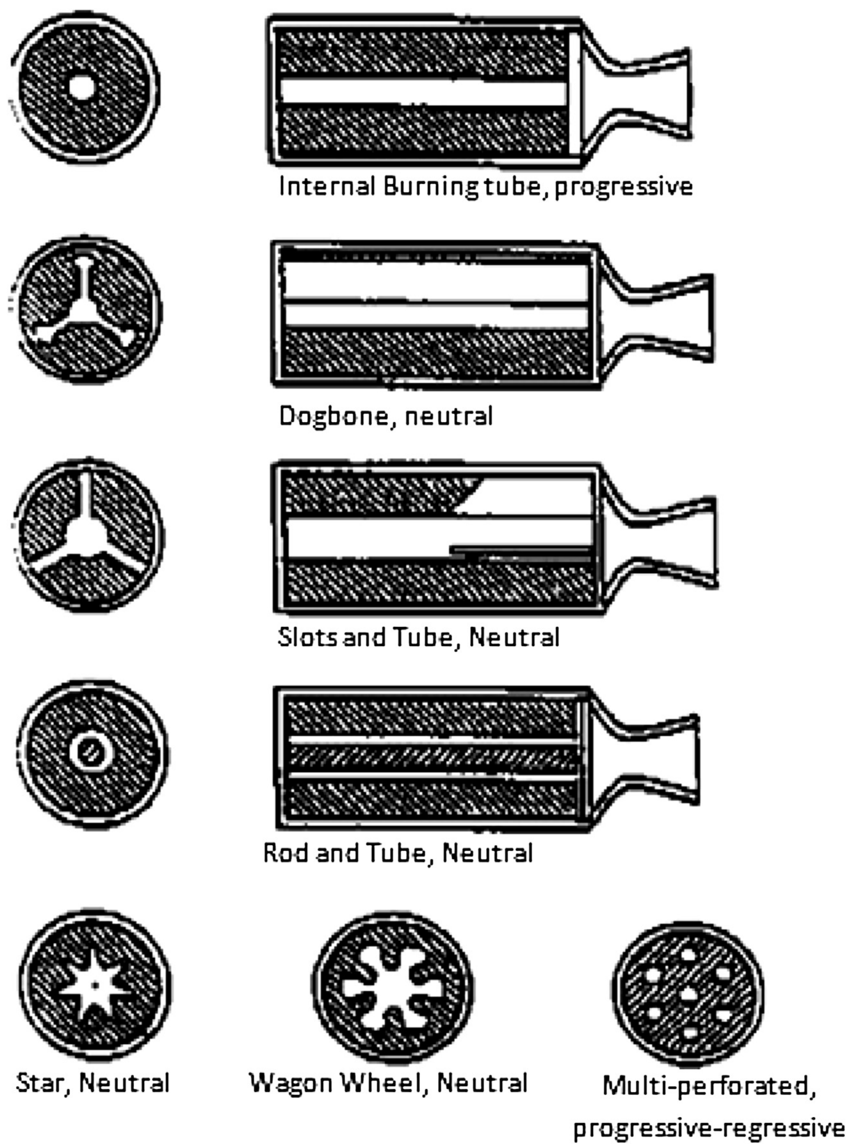


**Fig. 2.** Different typical star configurations.