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Effects of liner properties on the stress and strain along liner/propellant interface in solid rocket motor

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ABSTRACT

The aim of this study is to perform viscoelastic structural analyses to determine the effects of liner properties on the stress and strain along the liner/propellant interface in a solid propellant rocket motor. A simplified axisymmetric model composed of propellant, liner, insulation, and case was established, and nonlinear viscoelastic analyses were implemented in the finite element package ANSYS. The responses of the model under the cooling load and the ignition pressurization load were calculated. The results show that under the cooling load, the increasing of the thermal expansion coefficient (CTE) and equilibrium modulus of liner leads to the increasing of the stress along the liner/propellant interface. Under the ignition pressurization load, the stresses along the liner/propellant interface increase with the increasing of the initial modulus, and decrease with the increasing of Poisson's ratio of liner. In order to reduce the interface stress and improve the serve life of solid rocket motor, a liner with low modulus and CTE, and high Poisson's ratio should be applied between the insulation and propellant from the viewpoint of interface stress.

1. Introduction

Cased-bonded solid rocket motors are regularly used in defense and space technologies where the long ranges and high payload-carrying capacity are required. The case-bonded motor primarily consists of a motor case, insulation, liner and propellant grain as major subsystems. The thin liner is applied to ensure a good bond between the insulator and the propellant in case-bonded rocket motors, because the compositions of the insulation and propellant are incompatible with each other [1]. Solid rocket motors are subjected to diverse loads during manufacturing, transportation, storage and firing. Under these load conditions, interface debonding between propellant and liner is one of the major failure modes [2,3]. Therefore, it is essential to evaluate the values and distributions of stress and strain along the interfaces for assessing the structural integrity and the ultimate service life of a solid rocket motor.

In the last two decades, finite element analysis becomes the most popular method to perform the integrity assessment of solid rocket motors under diverse load conditions. In order to accurately predict the stress and strain response of the propellant grain, the development of viscoelastic damage constitutive models [4,5] and finite element formulation [6] for propellant materials have been the subjects of a number of investigations. Using the established constitutive models and finite element techniques, the effects of aging [7], stress reliever configuration [8], mechanical parameters [9] of propellant on the structural integrity of solid rocket motors were analyzed, and different load conditions [10–12] were also evaluated by the researchers.

Contrary to the amount of works concerning with the constitutive models and failure of solid propellants, very few works were reported on the effect of liner property on the response in solid rocket motors and their implications for structural integrity. The liner usually is not constructed as a separate layer in the numerical model of solid rocket motor [6]. The reasons are manifold. First, the thickness of liner is typically less than 1 mm. Thus it imposes difficulties to construct and mesh the full geometry model of solid rocket motor with such a thin liner, and also to carry out the numerical calculations. Second, the characterization and quantitative description of the liner material are difficult due to the property gradient produced during the grain and liner processing [13]. Lastly, the binder of liner usually has been based on the same polymer system as the propellant [14], thus it is considered reasonable to assume that the liner has the same mechanical properties as the propellant [7,15].

The liner has to hold the propellant and the insulation without debonding under all the load conditions, thus its composition has to be compatible with both propellant and insulation. The liner

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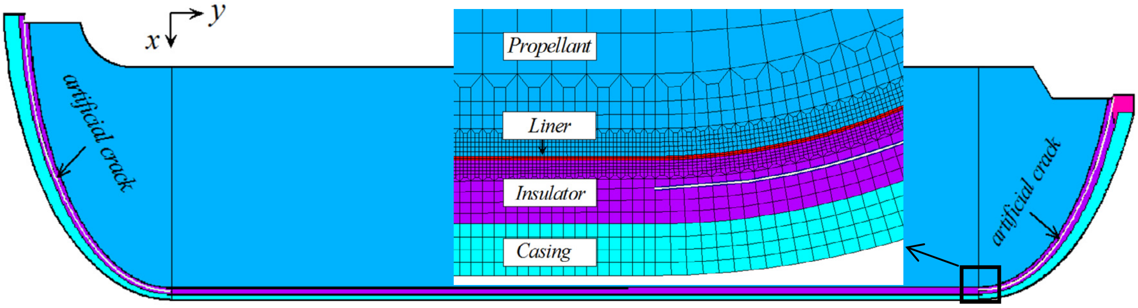

Fig. 1. Geometry model and detailed view of local mesh of solid rocket motor.

acts as a protective shield for the insulation by providing a limited fire protection effect [14]. In order to meet these requirements, the compositions including the filler, crosslinking agents and additives in a liner are different from those used in the propellant [14,16]. As a result, the mechanical properties of liner, such as the modulus, Poisson's ratio and thermal expansion coefficient (CTE) are really different from those of the propellant material. The property differences can cause high stress concentration and stress gradient at the liner/propellant interface, which even result in the interface debonding [13]. Thus, for an accurate integrity assessment of a solid rocket motor, it is necessary to construct the liner as a separate layer in the numerical model to predict the response at the liner/propellant interface.

The main objective of this work is to study the effect of liner property on the stress and strain along the liner/propellant interface using a solid rocket motor model composed of a propellant grain, a liner, an insulation, and a composite case. Nonlinear viscoelastic structure analyses based on an axisymmetric model were performed using the finite element package ANSYS, and the loads corresponding to the cooling process and propellant burning were considered. The numerical model used in this study is presented in section 2. The effects of liner property on the interface responses are analyzed in section 3. The design of liner property, the effect of stress singularity at the pre-inserted crack tips and material nonlinearity are discussed in section 4, and conclusions are made in section 5.

2. Numerical model

2.1. Geometry structure and finite element model

The solid rocket motor considered in this work is a circular-port case-bonded configuration with an ellipsoid dome in the front and aft ends as shown in Fig. 1. There is a transition cone between the mid cylinder segment and the rear circular port in the aft end. The case interior is covered with an insulation, and the propellant grain is bonded to the insulation by a thin liner. The artificial-cracks are inserted at the center of the insulation in the front and aft ends to remove the stress concentration during the cooling process. In order to reduce the complexity of the model, the geometry structures of the front and aft ends are simplified and the slots in the propellant grain are not included in the model. The following analysis focuses on the stress and strain along the liner/propellant interface of the mid cylinder segment, where is considered to be prone to debond.

The outer case diameter of the mid cylinder segment is 702 mm, the thickness of the case, insulation and liner are 15 mm, 12.5 mm and 1 mm respectively, the inner radius of the grain is 178 mm, and the length of the mid cylinder segment is 1820 mm. Due to the axisymmetry of the geometry and the applied loads in this work, an axisymmetric model is constructed and the numerical simulations were implemented in the ANSYS software.

The composite case and the aluminum bosses were modeled with reduced integration formulation in this work. For the solid propellant, liner and insulation, the materials are incompressible or nearly incompressible. Standard displacement formulations for the structural analysis are ill-conditioned as Poisson's ratio approaches to 1/2, and unable to capture the actual structural deformation due to volumetric clocking phenomenon [17]. A mixed displacement/pressure element formulation employed by ANSYS was used to overcome the volumetric locking of elements, in which pressure is treated as an independent variable to prevent computational problems with incompressible or nearly incompressible materials. Further details about the mixed displacement/pressure element formulation can be found in reference [18].

Approximately 61686 nodes and 58670 axisymmetric elements (PLANE182) were used for the analyses. The contact elements (TARGE169 and CONTA172) were overlaid on the surfaces of the pre-inserted artificial cracks. The mesh density in some critical areas is much higher than that in other sub-critical parts in order to reduce the number of degrees of freedom. A detailed view of typical local mesh is illustrated in Fig. 1. In order to accurately predict the stress/strain state in the liner and the adjacent propellant and insulation, the liner was divided into two elements along the thickness direction, and the meshes of the adjacent propellant and insulation were refined to match the mesh density and to improve the calculation accuracy in these regions.

2.2. Material models

The major structural components of the solid rocket motor considered in this work are made of a fiberglass reinforced plastic (FRP) composite case, Ethylene propylene diene monomer (EPDM) insulation, Hydroxyl-terminated polybutadiene (HTPB) based propellant grain and liner. Aluminum bosses are located at the rear port of the motor. The FRP case and aluminum bosses are modeled as linear-elastic. Their elasticity modulus E, Poisson's ratio v, thermal expansion coefficient α are from reference [7] and listed in Table 1.

The EPDM insulation has good hyperelastic properties, and it is modeled with a Moony–Rivlin strain energy potential:

$$U = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \left(J^{el} - 1\right)^2 / D_1 \qquad (1)$$

where U is the strain energy potential, I_1, I_2 are the first and second deviatoric strain invariants, respectively. J^{el} is the elastic volume ratio. D_1 is material incompressibility parameter. For the almost incompressible case, the last term in Eq. (1) is negligible. C_{10}, C_{01} are material constants. The values of C_{10} and C_{01} used in this work were determined by fitting the uniaxial tensile experimental data [3] and given by $C_{10} = 0.15248$ (MPa), $C_{01} = 1.22047$ (MPa). The shear modulus can be calculated by $G = 2(C_{10} + C_{01})$ [19]. Poisson's ratio v is assumed to be 0.495, and thermal expansion coefficient (CTE) α is assumed to be $1.8 \times 10^{-4}/°C$ [15].