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Viscoelastic constitutive modeling of solid propellant with damage

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An isotropic nonlinear viscoelastic constitutive model for solid propellant is proposed. The damage due to cyclic loading and dewetting is modeled. Dewetting is a particle-binder interfacial debonding which induces softening under severe deformation. The cyclic loading effects include rapid a decrease of stress during the unloading and large amount of hysteresis known as Mullins' effect. These effects are modeled by introducing damage functions in the free energy function. The softening due to dewetting is caused by the formation and growth of voids between the matrix and the particles, and a new damage function is proposed to represent the softening behavior. It is represented as a function of the ratio of the volumetric strains before and after dewetting. The volumetric strain at the onset of dewetting is predicted by using viscoelastic dewetting function, which is derived from the viscoelastic dewetting criterion. Cyclic loading effects are accounted for by employing another damage function which is the function of the octahedral shear strain. In addition to the material nonlinearities caused by the damage, geometrical nonlinearity is also considered. The constitutive model is implemented into the commercial finite element code ABAQUS via the user material subroutine UMAT for stress analysis. Laboratory tests of uniaxial and biaxial specimens for the stress response are performed under several different loading conditions. The material parameters and damage functions are calibrated using uniaxial tests only. The effects of strain rate, temperature and loading conditions on the stress are discussed. The computational results are compared with the experiments.

1. Introduction

Solid propellant is used as a fuel for generating thrust in a rocket. It is designed in various shapes depending on the performance requirement and is filled in a metal or composite material combustion chamber. Solid propellant is a particulate composite material of microscopic solid particles and polymeric binder. The solid particles are composed of oxidizer, fuel and small amount additives which are to improve bonding and combustion performance. The binder is a polymer base material such as HTPB (Hydroxyl-terminated polybutadiene) which behaves like a viscoelastic solid under loading. Therefore, the solid propellant can be modeled as a highly filled viscoelastic composite.

The performance of a solid rocket is influenced by the mechanical behavior of the solid propellant. Therefore, an accurate stress analysis of the solid propellant is essential for the loading and other environmental conditions. The internal damage in a solid propellant under complicated loading conditions makes the overall constitutive response quite complex. The typical damage phenomena are cyclic loading effects and interfacial debonding of the particles (Özüpek and Becker, 1997). The interfacial debonding, also called dewetting, is caused by the increase in the local stress between the particles after enough damage has been accumulated in the microstructure. As a result, microvoids are created in the solid propellant, and the softening phenomenon is observed. The main factors which affect the dewetting are stress level, temperature and strain rate. Besides the dewetting, the solid propellant exhibits peculiar behaviors under a repeated loading. The features include a rapid decrease of stress during unloading and an irreversible strain softening called Mullins effect (Ogden and Roxburgh, 1988), which depends on the maximum loading of the previous step. A hysteresis due to viscoelasticity makes the cyclic loading effects more complicated and the nonlinearities become more evident. Therefore, the constitutive model becomes more complicated, and it needs to be carefully modeled to incorporate the above-mentioned features.

The constitutive model of solid propellant considering the damage has been studied by many researchers. Schapery (1984) has investigated composite viscoelastic materials with damage. He developed the J integral theory in viscoelastic material using correspondence principles. Later, he predicted the damage of particle filled rubber using internal state variables with potential (Schapery, 1991). Park et al. (1996) addressed the rate dependent damage growth for viscoelastic material based on Schapery's work. Park and Schapery (1997) used two internal state variables for damage evolution law, and the model was verified experimentally. Ha and Schapery (1998) extended the

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model to three-dimensional case. Hinterhoelzl and Schapery (2004) modified the model to include the effects of anisotropy which were caused by the damage.

Swanson and Christensen (1983) proposed a softening function as a correction to the hereditary integral to take into account strain-softening behaviors. However, the softening function requires many kinds of experiments. Simo (1987) developed a three dimensional nonlinear viscoelastic constitutive model based on a free energy composed of uncoupled deviatoric and volumetric parts. The free energy of standard linear solid was extended to three dimensional finite strain viscoelastic model, and material nonlinearity was employed incorporating softening behavior under deformation. Özüpek and Becker (1992) proposed a modified Simo's model, including the Swanson's softening function. The predicted response of the model was compared with test results of PEN/NG (polyethyleneglycol/nitrolglycerin) propellant, and it was confirmed against uniaxial tests. From experimental observations, Özüpek and Becker (1997) proposed a phenomenological constitutive model. The model represents stress and dilatation responses in terms of hydrostatic pressure, strain rate and cyclic loadings. Canga et al. (2001) modified the model to allow an efficient numerical implementation in a finite element code. Jung and Youn (1999) proposed a constitutive model based on the Simo model introducing the viscoelastic dewetting criterion. Jung et al. (2000) extended the work to improve the cyclic loading damage functions. Xu et al. (2008) introduced a microscopic constitutive law using homogenization theory for composite materials with a micromechanical approach. Jalocha et al., 2015a, 2015b studied on the behavior of solid propellant under orthogonal prestrain. Johlitz et al. (2014) illustrated the modeling procedure of thermo-oxidative ageing of elastomer based on a finite strain theory.

In this paper, a three dimensional nonlinear viscoelastic constitutive model with damage is proposed. The model represents not only the finite strain viscoelasticity but also damage phenomena using proper damage functions. A new type of softening function is suggested. It is a function of the ratio of the volumetric strains before and after dewetting. The viscoelastic dewetting function is derived from the viscoelastic dewetting criterion (Jung and Youn, 1999) and the dewetting function is used to obtain the volumetric strain at the onset of dewetting. The cyclic loading effects are addressed by a cyclic loading function. The constitutive equation is implemented into the ABAQUS via a user material subroutine UMAT. The numerical implementation procedure is explained in detail. The material parameters and functions are calibrated through the uniaxial test data only. The developed constitutive model is experimentally validated.

In Section 2, the constitutive equation is explained. In Section 3, the numerical implementation procedure and formulations are explained. In Section 4, the calibration and the test procedure are described. In Section 5, numerical examples for validation of the constitutive model are presented. Summary of the research is presented in Section 6.

2. Viscoelastic constitutive equation

In this section a nonlinear viscoelastic constitutive model is developed under finite strain considering the damage evolution. It is assumed that the solid propellant is homogeneous and isotropic. A free energy function is used to obtain pseudo elastic stress, and the pseudo stress is extended to corresponding viscoelastic stress using the correspondence principle (Schapery, 1984). Internal state variables are used to address the effects of damage. Damage functions are introduced to represent the damage.

2.1. Free energy

A free energy function with damage is represented as W_d^R. It is a function of a state variable which represents the damage. The free energy includes deviatoric and volumetric parts.

$$W_d^R = \Phi\left(\bar{C}, s\right) + \phi(J_{el}, s) \tag{1}$$

Neo-Hookean hyperelastic energy model is used as a free energy function. In Eq. (2), the material parameters of Neo-Hookean model C_1 and K are functions of the state variables. The void volume fraction c is used for the state variable of the bulk modulus to represent the softening due to the formation of internal microvoids.

$$W_d^R = C_1(s)\left(\bar{I}_1 - 3\right) + \frac{1}{2}K(c)(J_{el} - 1)^2 \tag{2}$$

where $\bar{I}_1$ is the first invariant of the isochoric part of the left Cauchy–Green deformation tensor and J_{el} is the elastic volumetric strain. The total volumetric strain J is decomposed into the elastic volumetric strain J_{el}, the volumetric strain due to void formation J_{void} and the thermal expansion J_{th}. Therefore, the total volumetric strain J is

$$J = J_{el} J_{void} J_{th} \tag{3}$$

The volumetric strain of void J_{void} can be written as

$$J_{void} = 1 + c \tag{4}$$

where c is the void volume fraction. The thermal expansion J_{th} can be written as

$$J_{th} = (1 + \varepsilon_{th})^3 \tag{5}$$

2.2. Correspondence principle

The correspondence principle is useful tool for the analysis of viscoelastic boundary value problems. Because the Laplace transformation of viscoelastic solution can be directly obtained from the existing elastic solution (Christensen, 1982), Schapery (1984) extended this theorem to nonlinear viscoelastic boundary value problems through the use of pseudo variables. The viscoelastic solution is obtained from the pseudo variables. In this research, it is assumed that the pseudo displacement $\mathbf{u}^R$ is equal to the physical displacement $\mathbf{u}$, and the second Piola–Kirchhoff stress is adopted as the pseudo stress.

$$\mathbf{u} = \mathbf{u}^R \tag{6}$$

where the superscript R denotes the variables of the reference nonlinear elastic problem. Thus, the physical viscoelastic strain tensor is equal to that of the reference elastic problem since the same displacements. Therefore the pseudo stress of the reference elastic problem can be represented by

$$\mathbf{S}^R = \frac{\partial W_d^R}{\partial \mathbf{E}} \tag{7}$$

Using the free energy W_d^R in Eq. (2), the pseudo second Piola–Kirchhoff stress of the reference elastic problem is derived from Eq. (7) in terms of the Green strain tensor $\mathbf{E}$. Also, the physical stress is obtained by using the hereditary integral

$$\mathbf{S}(t) = \int_0^t g(t-\tau)\frac{\partial \mathbf{S}^R}{\partial \tau} d\tau \tag{8}$$

where g is the normalized extensional relaxation modulus, and $\mathbf{S}$ is the physical stress in the viscoelastic body. It is assumed that the full viscoelastic response can be captured by a single extensional relaxation modulus $g(t)$.

2.3. Damage model

A mathematical damage model related to void volume fraction is described. The formation and growth of void, due to dewetting, are incorporated through the dilatation model which is based on the analysis of void-containing elastic material. The growth rate of the void volume fraction depends on the pseudo hydrostatic stress σ_h^R and the distortional deformation rate $\dot{\delta}$. The growth rate of void