Research on Creep Constitutive and Numerical Simulation of Composite Solid Propellant

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Abstract: Through the composite creep solid propellant creep experiment, the composite solid propellant curve is obtained. The power rate constitutive model, linear viscoelastic model and Schapery nonlinear constitutive model are used to describe the creep process. The study shows that Schapery modified nonlinear constitutive model can better describe the creep properties of composite solid propellants. Through the ABAQUS user subroutine, the finite element application of Schapery's creep-type nonlinear constitutive model is studied. The research results in this paper can provide a reference for the analysis of the creep effect of the grain during the vertical storage of the solid rocket motor.

1. Introduction

The creep effect of solid rocket motor grains is an important research content in the analysis of the integrity of the solid rocket motor vertical storage structure. The solid rocket motor propellant, as a viscoelastic material, exhibits time-related effects under the action of force, temperature and other loads. Features, such as delayed deformation, delayed recovery, and viscous flow, are mainly manifested as creep, relaxation, and strain rate correlation. The typical creep process can be divided into three stages: decelerated creep, stable creep and accelerated creep. The strain rate shows that under a constant load, the strain rate first decreases and then increases. The creep process of composite solid propellant has three stages of typical creep process [1]. During the creep process, the creep rate of the decelerated creep stage decreases continuously. As time goes by, the creep rate tends to a stable value and reaches the stable creep stage, after which the creep rate rises sharply and the material is destroyed. Since the solid rocket motor is in storage for most of the entire life cycle, the grain will be deformed under the action of long-term creep, which will change the typical safety factor of the solid rocket motor. Therefore, the creep of solid propellant must be studied. Based on creep experiments, this paper uses different constitutive models to describe the first two stages of the creep process of composite solid propellants, and finally provides research methods for the engineering application of creep models.

2. Description of creep constitutive model

Bill[2] When studying the relationship between the rupture time of the composite solid propellant and the loading stress, it is found that the creep rupture time of the propellant and the stress satisfy the following relationship
\sigma = B \times \lg t_f + \sigma_{t_0} \quad (1)

In the formula: \sigma is the stress of the grain; B is the damage index; t_f is the creep rupture time; \sigma_{t_0} is a constant. Therefore, this relationship can be used to obtain the creep stress of the composite solid propellant breaking per unit time. Wang Xin[1] fitted the material parameters through creep experiments under different stresses, and the fitting results are as follows

\sigma = -0.1124 \times \lg t_f + 1.1817 \quad (2)

Since the solid rocket motor grain bears a small stress during storage, it is 0.013 MPa [3], and the fracture time under the action of a stress of 0.013 MPa is 792 years obtained by formula (2). The third stage of the creep process will not be reached in a long time. Therefore, this section mainly studies the first two stages of the creep process of composite solid propellant.

In order to describe the creep process of composite solid propellant, a universal material testing machine was used to conduct a creep experiment under a load of 0.6 MPa, and the obtained creep curve is shown in Figure 1. It can be seen from the image that the composite solid propellant has a shorter period of time in the first stage of the creep process, and the strain change is greater, after which the creep deformation is more stable.

![Creep curve](image)

**Figure 1. Creep curve**

2.1 Power-law constitutive model description

The time hardening theory was first proposed by Kayahob [4]. The theory believes that the decrease in creep rate during creep shows that the main factor of material hardening is time, that is, when the temperature is constant, there is a relationship between stress, creep rate and time. Certain relationship

\dot{\epsilon}_c = A\sigma^n t^{-m} \quad (3)

Where \dot{\epsilon}_c is the strain rate; \sigma is the equivalent stress; n is the stress index; A and m are the material constant. The parameters obtained by Origin fitting are shown in Table 1, and the comparison chart of time hardening theoretical data and experimental data is shown in Fig. 2.

| \sigma/MPa | n  | m   | A    |
|------------|----|-----|------|
| 0.6        | 2  | -   | 0.832| 17067 |

Table 1 Time hardening theoretical parameters
2.2 Description of linear viscoelastic constitutive model

The linear viscoelastic model mainly uses different combinations of elastic elements and viscous elements. At present, the Burgers model is mostly used to describe the creep behavior of viscoelastic materials. The Burgers model is composed of the Kelvin model and the Maxwell model in series. The model is shown in Figure 3, and the constitutive equation is shown in the formula (4)

\[ \varepsilon = \frac{\sigma}{E_1} + \frac{\sigma}{E_k} \left[ 1 - \exp \left( -\frac{E_k}{\eta_k} t \right) \right] + \frac{\sigma}{\eta_3} t \]

(4)

Where \( E_1 \) and \( E_k \) are General elastic modulus and high elastic modulus; \( \eta_k \) and \( \eta_3 \) are the kinematic viscosity of the chain segment and the bulk viscosity; \( \sigma \) is the applied stress; \( t \) is the creep time.

When the composite solid propellant is in the decelerating creep stage, the instantaneous strain when the experimental data \( t = 0 \) is used, and \( E_1 = 2.727 \) calculated from the formula (4); when the time tends to infinity, the formula is as follows

\[ \varepsilon'_{t \to \infty} = \frac{\sigma}{E_1} + \frac{\sigma}{E_k} + \frac{\sigma}{\eta_3} t \]

(5)

This formula is equivalent to the case where the data curve in Figure 2 is extended to infinite length on the straight line, \( \sigma/E_1 + \sigma/E_k \) is the intercept of the straight line, and \( \sigma/\eta_3 \) is the slope of the straight line. \( E_k = 3.75 \) and \( \eta_3 = 409090 \) are calculated. By formula (4), by origin fitting, \( \eta_k = 24572.46 \) is obtained, and the parameter summary table is shown in Table 2. The comparison image between the fitted data and the experimental data is shown in Figure 4.
2.3 Schapery creep type nonlinear constitutive model

The description of the first two stages of the creep process of viscoelastic materials uses a more nonlinear constitutive model called Schapery creep type nonlinear constitutive [5], as shown in the following formula

\[
\varepsilon(t) = D_0 g_0 \sigma + g_1 \int_0^t \Delta D(\psi - \psi') \frac{\partial (g_2 \sigma)}{\partial \tau} d\tau
\]

(6)

\[
\psi = \int_0^t dt' / a_\sigma[\sigma(t')](a_\sigma > 0)
\]

(7)

\[
\psi' = \psi(\tau) = \int_0^\tau d\tau / a_\sigma[\sigma(t')]
\]

(8)

In the formula, \( D_0 \) and \( \Delta D(\psi) \) are transient creep compliance and increment, \( g_0, g_1, g_2, a_\sigma \) are stress-related parameter functions. Zhang Yongjing et al. [6] applied the Schapery creep-type nonlinear constitutive model of HTPB to the creep study of composite solid propellant, as shown in the formula

\[
\varepsilon(t) = g_0 A_0 \sigma + g_2 A_1 (t/\sigma)^n = \varepsilon_0 + \frac{g_2 A_1 \sigma}{a_\sigma^2} t^n
\]

(9)

When \( \sigma \) is a constant, the above formula can be changed to

\[
\varepsilon(t) = \varepsilon_0 + m \sigma t^n
\]

(10)

Where \( \varepsilon_0 \) is the initial strain caused by elasticity, \( \sigma \) is the equivalent stress, \( t \) is the creep time, and \( m \) and \( n \) are functions related to the stress \( \sigma \). According to the creep experimental data, the parameters obtained by the Origin software fitting are shown in the table, and the fitting results are shown in the figure 5.
Table 3 Schapery creep type nonlinear constitutive model

| $\sigma/\text{MPa}$ | $\varepsilon_0$ | $n$ | $m$ |
|-------------------|----------------|-----|-----|
| 0.6              | 0.0            | 22  | 36579 | 0.1547 |

Figure 5 Experimental data and Schapery creep-type nonlinear constitutive model data diagram

2.4 Conclusion

By using different constitutive models to describe the first two stages of the creep process of the composite solid propellant, it is found that the Schapery constitutive model has the best fitting effect. The Schapery constitutive model can better control the creep of the composite solid propellant. Change behavior to describe.

3 Finite element application of Schapery creep constitutive model

In the $n$th incremental step, the ABAQUS main program provides stress $\sigma$, elastic modulus $E$, and time increment $\Delta t$. Get the material parameters from generalization, calculate the strain increment, and output the updated strain.

ABAQUS main program: update strain

$$\varepsilon(t+\Delta t) = \varepsilon(t) + \Delta \varepsilon$$

Whether the number of iterations exceeds the default value

Whether the time increment greater than the minimum value

Figure 6. The process of using the CREEP subroutine to realize the creep constitutive model of composite solid propellant
In ABAQUS, the internal models of material parameters are mainly time hardening rate constitutive, strain hardening rate constitutive, etc. Strain hardening rate mainly studies the creep condition of changing stress, which is not applicable to the creep study of constant stress state. According to the study of different creep constitutive models in the previous section, the Schapery creep constitutive model can better describe the creep behavior of composite solid propellants compared with the time hardening theoretical model and Burgers model. Therefore, this section mainly discusses the application of Schapery creep constitutive model in finite element software.

For creep analysis, in addition to the conventional creep model, ABAQUS also provides the ABAQUS user subprogram interface. You can use FORTRAN language to import the constitutive model into ABAQUS for calculation through the ABAQUS_CREEP subprogram interface, as shown in the flowchart 6 shown.

In the finite element analysis process, the ABAQUS main program and the Creep subprogram need to realize data interaction and share some variables. The description of related variables is shown in Table 4.

| Variable | Function description |
|----------|----------------------|
| DESWA    | Volume expansion strain increment |
| STATEW   | State variable matrix  |
| PREDEF   | The predefined field matrix, which includes the values of all predefined variables specified by the user at the end of the increment (the initial value at the beginning of the analysis and the current value during the analysis) |
| DPRED    | An array containing the increments of all predefined variables in the time increment |
| TIME     | Incremental time |

The calculation model of the composite solid propellant specimen is the same as the original size model of the experimental specimen. The upper part is fully constrained, and a constant surface force is applied to the lower end face. The boundary conditions are applied as shown in Figure 7. The Schapery creep constitutive model is used as the material's creep parameters for input through the secondary development of FORTRAN. The simulation results of stress and strain under the action of 0.6MPa are shown in Figure 8. It can be seen that the force and deformation of the calculated area are relatively uniform during the creep process of the material, and the stress and strain are 0.6MPa and 0.53 respectively, which are in good agreement with the experimental results. The stress versus time curve at one point in the selected calculation area is shown in Figure 9, and the comparison chart of creep strain and the result is shown in Figure 10.
4 Summary

Compared with the time hardening theory and Burgers model, the Schapery creep constitutive model can better describe the creep behavior of solid propellants. The Schapery creep constitutive model can be programmed through the user subroutine CREEP. The calculation results show that the creep deformation can be well fitted to the experimental data. This program can be used for long-term creep of solid rocket motors during vertical storage. Research on variable effects.

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