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Safety Performance Evaluation of Solid Rocket Motor Grain

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Abstract

Based on the comprehensive safety factor evaluation method and the final load safety factor evaluation method, the safety performance of solid rocket motor grain is evaluated. The numerical calculation of solid rocket motor grain under the conditions of solidification and cooling, vertical storage, ignition and pressure building and sequential loading is carried out, the mechanical response and safety factor of each stage are obtained, and the advantages and disadvantages of the two safety factor evaluation methods are analyzed. The results show that according to the comprehensive safety factor evaluation method, the safety factor of the grain is 0.93, and the motor grain has the risk of failure; According to the final load safety factor evaluation method, the safety factor of grain is 1.42, and the motor grain works normally.

Keywords

Solid Rocket Motor; Safety Performance Evaluation; Safety Factor Evaluation Method; Structural Integrity.

1. Introduction

Solid rocket motor is the core part of solid rocket. The success of rocket launch often depends on whether the solid rocket motor can ignite normally [1,2]. Before ignition, the solid rocket motor will generally bear a variety of loads. The motor grain will produce mechanical response to the load. Excessive mechanical response will deform, fail or even destroy the motor grain [3,4], which directly leads to the failure of normal ignition of solid rocket motor. Therefore, it is very important to accurately evaluate the safety performance of solid rocket motor grain under various loads.

2. Safety Performance Evaluation Method

Internationally, the safety factor is generally used to evaluate whether the solid propellant grain can work normally [4-6], and the safety factor f is defined as:

$$f = \frac{C}{S} \tag{1}$$

In Formula 1, C is the ultimate performance parameter of the material obtained through the test, and the parameters of solid propellant grain generally choose the allowable stress, allowable strain, maximum ductility, etc; S is the mechanical response under the corresponding load, which can generally be obtained by numerical calculation. According to the definition of safety factor, it is generally considered that when the safety factor of solid propellant grain is greater than 1, the grain can work normally. The greater the safety factor is, the more margin is given to the performance

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parameters, and the safer the grain is. However, the safety factor is not the bigger the better. An excessive safety factor will reduce the economic benefits and outweigh the losses.

At present, there are two methods to evaluate the safety performance of solid propellant [7]. One is the comprehensive safety factor evaluation method based on cumulative damage theory adopted by the United States, Britain and other countries. The cumulative damage theory holds that the damage caused by different loads can be accumulated. According to Miner's linear cumulative damage theory [8], the damage is accumulated in a linear way. Comprehensive safety factor assessment is the generalization of miner's law, which uses the reciprocal of safety factor to represent the size of damage, and uses miner's law to add the damage linearly. Therefore, the comprehensive safety factor evaluation method can be expressed as:

$$\frac{1}{f_{total}} = \sum_{i=1}^{n} \frac{1}{f_i} \tag{2}$$

$f$total in formula 2 is the comprehensive safety factor of solid propellant grain, and fi is the safety factor of grain under the i-th load. According to the comprehensive safety factor evaluation method, there is no interaction between different loads, and the loading sequence does not affect the final result.

Another method is the final load safety factor evaluation method adopted by France and other countries:

$$f_{final} = \frac{C}{S_{final}} \tag{3}$$

In Formula 3, C is the ultimate performance parameter of propellant grain under the final load, and Sfinal is the mechanical response of propellant grain under the superposition of all loads. According to the final load safety factor evaluation method, the interaction between all loads is considered, which is reflected in that Sfinal is the final equivalent mechanical response under the superposition of all loads, and different loading sequences will affect the size of Sfinal.

When using the above two methods to evaluate the safety performance of solid rocket motor grain, it is first necessary to obtain the limit performance parameter C of solid propellant. Ultimate strain εm is an important performance parameter of solid propellant. The greater the limit strain is, the better the ductility of propellant is and the grain is less prone to failure. In this paper, the limit strain of propellant under different loads is used εm is used as the ultimate performance parameter for safety performance evaluation.

3. Numerical Calculation of Typical Load of Solid Rocket Motor Grain

The solid rocket motor will experience the following typical loads in the whole life cycle: the temperature load in the solidification and cooling process, the self weight load in the vertical storage process and the pressure load in the ignition and pressure building process.

3.1 Model Establishment

Through ABAQUS finite element simulation software, the three-dimensional model of a solid rocket motor grain is established and the network is divided, as shown in Figure 1, the 1 / 8 finite element model of grain. As shown in Figure 1, the research object of this paper is the front and rear wing pillar solid rocket motor grain. The key parts are the front head, wing slot, middle shaft and tail, and a more detailed grid is divided to increase the calculation accuracy.

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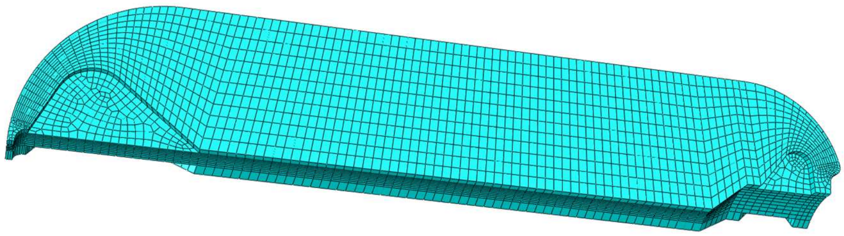

Figure 1. Three dimensional mesh model of solid rocket motor grain

The material parameters of each component are shown in Table 1.

Table 1. Model material parameters

Material	Modulus of elasticity /MPa	Density /(g/mm^3)	Poisson's ratio	Coefficient of linear expansion /K^{-1}
House	206000	7.8	0.3	1.0×10^{-5}
Liner	6.2	1.5	0.495	9.8×10^{-5}
Propellant	E(t)	1.7	0.495	9.25×10^{-5}

The elastic modulus E (t) of the propellant grain is in the form of Prony series [9].

$$\begin{aligned}E(t) &= 0.45475 + 17.2663e^{-t/0.001} + 8.85776e^{-t/0.01} + 4.96828e^{-t/0.1} + 1.66224e^{-t} \\ &+ 0.84601e^{-t/10} + 0.46488e^{-t/100} + 0.41497e^{-t/1000} + 0.14981e^{-t/10000}\end{aligned} \tag{4}$$

3.2 Solidification Cooling

The working condition of solidification cooling stage is: the zero stress temperature of the grain is 58℃, and the room temperature reaches 20℃ after 48 hours of solidification cooling. The calculation results are shown in Figure 2. It can be seen from Figure 2 that the key parts in the curing and cooling process are the central axis, rear wing groove and tail of the grain, and the strain is large. Among them, the maximum strain is at the tail of the grain, and the maximum strain is 0.044.

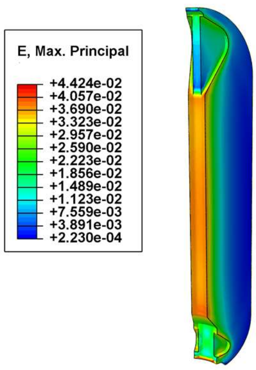

Figure 2. The strain nephogram of solidification cooling

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3.3 Vertical Storage

The working condition of the vertical storage stage is: the grain bears its own gravity and the direction is vertical downward along the central axis of the grain. According to engineering experience, the vertical storage time is 10 years, during which the strain of the grain will gradually increase due to creep effect. The calculation results are shown in Figure 3. It can be seen from Figure 3 that the key parts in the vertical storage process are the rear wing groove and tail of the grain, with large strain. Among them, the maximum strain is in the rear wing groove of the grain, and the maximum strain is 0.104.

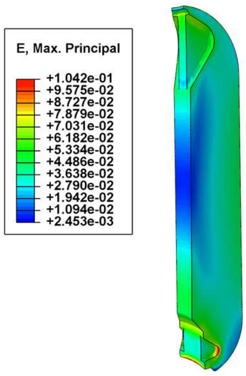

Figure 3. The strain nephogram of Vertical storage

3.4 Ignition and Pressure Building

In the stage of ignition and pressure building, the internal pressure of the grain surges, and the pressure reaches the equilibrium value in a very short time. Therefore, the static analysis method cannot be used to calculate. Refer to references [10, 11]. The change of the internal pressure of the grain with time in the process of ignition and pressure building is shown in Figure 4.

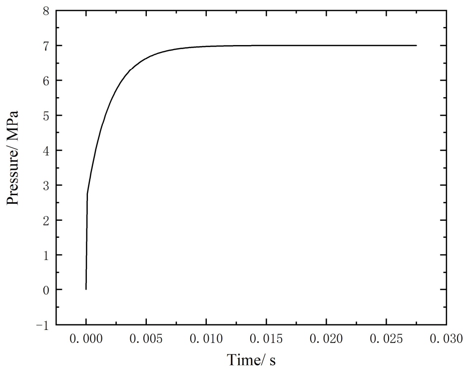

Figure 4. Pressure time diagram of ignition and pressure building stage

Once the motor is ignited, the internal pressure basically reaches the equilibrium pressure within 0.01s. During this time, the grain is most likely to have structural failure. Therefore, the dynamic analysis method should be used to calculate the mechanical response. The calculation results are shown in Figure 5. It can be seen from Figure 5 that the key parts in the ignition and pressure building process are the central axis and tail of the grain, and the strain is large. Among them, the maximum strain is at the central axis of the grain, and the maximum strain is 0.337. The great internal pressure in the

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ignition process leads to very large grain strain. The failure of solid rocket motor is most likely to occur in this stage.

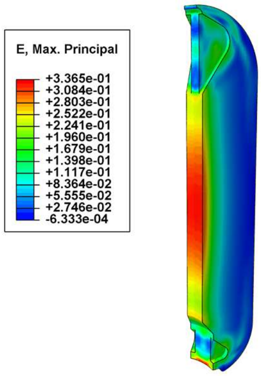

Figure 5. The strain nephogram of ignition and pressure building

3.5 Sequential Loading

Considering the simulation of the actual working process of the strategic missile solid rocket motor, the motor first goes through the solidification and cooling stage after leaving the factory, then vertically stored for 10 years, and finally ignited and launched. It goes through a series of sequential loading. The loading conditions are the same as the three stages mentioned above. The calculation results are shown in Figure 6. It can be seen from Figure 6 that the key part of the sequential loading process is the central axis of the grain, and the maximum strain is 0.373.

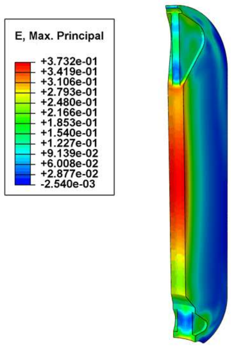

Figure 6. The strain nephogram of sequential loading

4. Safety Performance Evaluation of Solid Rocket Motor Grain

To evaluate the safety performance of solid rocket motor grain, it is necessary to obtain the limit strain of propellant under different loads. For the solidification cooling stage, in engineering, the limit strain value is generally obtained through the stress relaxation failure test of propellant specimens. Through a series of stress relaxation failure tests under different constant strain conditions, the relaxation strain value without fracture failure is selected as the maximum strain of solid propellant under the action of solidification cooling. For the vertical storage stage, the maximum strain of solid propellant at room temperature is obtained by carrying out a series of uniaxial tensile tests on the standard dumbbell shaped specimens of propellant at the stress level. For the ignition and pressure building stage, the uniaxial tensile test under confining pressure is carried out on the standard dumbbell shaped specimen of propellant, and the maximum elongation is taken as the limit strain parameter. According to the test results of reference [12], the limit strain parameters of HTPB propellant at different working stages are obtained, as shown in Table 2.

Table 2. Ultimate strain parameters of HTPB at different working stages

Working stage	Solidification cooling	Vertical storage stage	Ignition and pressure building
Ultimate strain ε_m	0.24	0.40	0.53

Bring the data in Table 2 and the numerical calculation results above into Formula 1 to calculate the safety factor fi of grain in each stage, and the results are shown in Table 3.

Table 3. Safety factor of HTPB under different working stages

Working stage	Solidification cooling	Vertical storage stage	Ignition and pressure building	Sequential loading
Ultimate strain ε_m	0.24	0.40	0.53	0.53
Maximum strain ε	0.044	0.104	0.337	0.373
Safety factor f_i	5.45	3.85	1.57	1.42

Bring the data in Table 3 into formula 2 to calculate the overall safety factor $f$total of the comprehensive safety factor evaluation method:

$$f_{total} = \frac{1}{1/f_1 + 1/f_2 + 1/f_3} = \frac{1}{1/5.45 + 1/3.85 + 1/1.57} = 0.93 \tag{5}$$

The final load safety factor evaluation method is used to evaluate the overall safety performance of solid rocket motor grain. The final load experienced by the grain is the internal pressure load in the ignition pressure building stage, so the limit strain εm is taken as 0.53, and the numerical calculation results of grain strain under sequential loading are brought into formula 3 to obtain the safety factor $f$final of the final load safety factor evaluation method.

$$f_{final} = \frac{\varepsilon_m}{\varepsilon} = \frac{0.53}{0.373} = 1.42 \tag{6}$$

The analysis and calculation results show that the overall safety factor $f$total of the comprehensive safety factor evaluation method is less than that of the final load safety factor evaluation method. According to the definition of safety factor, when the f is greater than 1, it is considered that the safety performance of the grain is good and the motor can work normally, and the larger the f is, the safer the motor is; When the f is less than 1, it is considered that the safety performance of the grain is poor and the motor may fail, and the smaller the f is, the more likely the motor is to fail.

According to the calculation results of the comprehensive safety factor evaluation method, if $f$total is less than 1, it is considered that the motor grain has the risk of failure; However, according to the calculation results of the final load safety factor evaluation method, $f$final is greater than 1, so it is considered that the motor grain will not fail. The reason is that when the comprehensive safety factor

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assessment method calculates the overall safety factor, the research object of the safety factor fi in each stage is the part with the largest strain. The comprehensive safety factor assessment method believes that the part with the largest strain in each stage is the same part. In fact, according to the calculation results, the maximum strain in the solidification cooling stage is at the tail of the grain; The maximum strain position in the vertical storage stage is in the rear wing groove of the grain; At the stage of ignition and pressure building, the maximum strain is located at the central axis of the grain. The parts with the largest strain in each stage are different. Theoretically, the safety factor of all parts and each stage should be calculated to obtain the overall safety factor of each part, and the smallest safety factor is the theoretical overall safety factor. However, according to the needs of the project, in order to avoid tedious calculation and waste a lot of manpower and material resources, the comprehensive safety factor evaluation method used in this paper simplifies the maximum strain part to the same part. It can be seen that the calculation result of the comprehensive safety factor evaluation method is smaller than the theoretical value, and the safety standard of grain is more strict.

The final load safety factor evaluation method only considers the ultimate strain of the final working stage (ignition and pressure building stage) of the grain, and ignores the intermediate stage. In fact, the motor grain may also fail during the intermediate stage. The calculation result of the final load safety factor evaluation method is larger than the theoretical value, and the standard for grain safety is relatively loose. However, the economic benefit of using the final load safety factor evaluation method is higher, so it can be considered that the final load safety factor evaluation method exchanges a certain safety margin for higher economic benefit.

5. Conclusion

Based on the safety factor evaluation method and numerical calculation method, this paper evaluates the safety performance of solid rocket motor, and draws the following conclusions:

(1) The solid rocket motor grain goes through the stages of solidification and cooling, vertical storage and ignition and pressure building. The maximum strains are at the tail of the grain, the rear wing groove of the grain and the central axis of the grain, and the maximum strains are 0.044, 0.104 and 0.337 respectively. In the process of sequential loading, the maximum strain of the grain is at the central axis of the grain, and the maximum strain is 0.373.

(2) According to the comprehensive safety factor evaluation method, the value of $f$total is 0.93, less than 1, and the motor grain has the risk of failure; According to the final load safety factor evaluation method, $f$final is 1.42, greater than 1, and the motor grain works normally.

(3) The comprehensive safety factor evaluation method is lower than the theoretical result and has a large safety margin, which can better ensure the safety of solid rocket motor grain. The final load safety factor evaluation method is higher than the theoretical result, the safety margin is small, and the economic benefit is higher.

Acknowledgments

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