Crack Propagation Analysis of Damaged Solid Propellant under Impact Overload

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Abstract: The ammunition safety problem is particularly prominent when the storage and transportation launch box is airdropped and landed. A safety evaluation method of rocket air drop based on propellant damage evaluation is proposed. Based on the theory of fracture mechanics and the evaluation method of structural integrity of rocket engine, established a local finite element model of rocket engine with initial damage, the crack propagation analysis is carried out by using the propagation finite element method (XFEM). The results show that when the landing impact overload is 30g (25ms) that the airdrop equipment should be able to withstand, the modified double base propellant has produced the phenomenon of crack instability propagation. When the initial crack direction and load direction are 120 °, the propagation is the most serious and there are safety problems; when the solid propellant is airdropped, it is necessary to increase the buffer to reduce the overload.

1. Introduction
Airborne combat plays an important role in modern war because of its unexpected and rapid mobile Strike ability [1]. Rocket has the characteristics of large killing area, strong mobility and low cost, which is very in line with the needs of modern war. Therefore, it has also become the preferred suppression weapon for airborne troops in various countries, and has been taken as the key research object for the development of heavy air drop weapons and equipment [2]. At present, the safety assessment of airdrop launch box is mostly considered from the whole (allowable stress of box material, rocket overload, etc.), and does not involve the yield and damage of the grain itself. The safety assessment has certain limitations, especially the initial cracks and holes will inevitably occur in the casting process of propellant grain. It may lead to unstable fracture and fatal damage [3], so it is particularly necessary to study the safety of damaged propellant.

Based on the previous airdrop research and combined with the research on the mechanical properties of solid propellant in recent years, this paper puts forward the problem of whether the solid propellant with initial damage is safe during airdrop. Aiming at this problem, based on the structural integrity evaluation method of rocket motor and the extended finite element method (XFEM) to study the crack propagation problem, the detailed modeling of the rocket engine of a rocket is carried out to analyze the crack propagation of the grain under the condition of initial crack.
2. Safety assessment of solid propellant

2.1 Failure criterion of solid propellant containing damage

Damaged propellant refers to the propellant that inevitably produces initial micro cracks and holes in the curing process of composite propellant. Its failure follows the fracture mechanics criterion and cannot be judged by the strength theory of stress or strain. The commonly used failure criteria in fracture mechanics are: energy release rate criterion (g criterion), J integral criterion (J criterion), Stress intensity factor criterion (K criterion) [3], in which K is a parameter only locally related to the crack tip, and its determination is relatively easier than g and J therefore, the failure criterion adopted in this subject is established based on K criterion.

2.2 Crack tip approach and stress intensity factor K

In fracture mechanics, the stress component and displacement component near the crack tip can be expressed as [4]:

$$\sigma_{ij} = \frac{K}{2\pi r} f(\theta)$$  \hspace{1cm} (1)

$$u_i = K \frac{r}{2\pi} g(\theta)$$  \hspace{1cm} (2)

where: $f(\theta)$, $g(\theta)$ and $h(\theta)$ is crack tip Angular function, $r$ is distance from crack tip, $K$ is crack tip stress intensity factor

Stress intensity factor $K$ is a function of crack size, external load and component geometry. It represents the strength of load and deformation at the crack tip. It is a measure of crack propagation trend and crack propagation driving force, and the fracture criterion is obtained [5]: $K > K_{IC}$, crack instability propagation; $K < K_{IC}$, the crack will not expand; $K = K_{IC}$, critical condition of crack instability propagation.

2.3 Experimental acquisition of fracture toughness of modified double base propellant

In the classical fracture theory, for mode I open crack [6], formula 4 can be used to calculate the fracture toughness under different tensile conditions:

$$K_{IC} = \sigma \times \sqrt{\pi a} \times \frac{2b}{na} \tan \frac{na}{2b} G_I$$  \hspace{1cm} (3)

$$G_I = 0.752 + 2.02(a/b)^{0.37(1-sin(\frac{na}{2b})^{3}}$$  \hspace{1cm} (4)

where: $\sigma$ is average stress, $a$ is initial crack length, $b$ is specimen width, $G_I$ is crack shape factor.

Through the tensile load displacement curve of the specimen with initial crack, the average stress is 8.5MPa. By bringing the average stress and crack size parameters into the above formula, the fracture toughness $K_{IC}$ of the modified double base propellant under quasi-static load can be calculated as 28.41 MPa.√mm. This value is the damage evolution parameter in the propellant material parameters in the simulation process.

3. Establishment of finite element simulation model

Based on the above results, the fracture toughness of propellant is taken as the failure criterion, and the structural integrity of engine charge is analyzed. By consulting relevant literature and investigating the existing airdrop equipment, it is found that the landing impact overload that the equipment should be able to withstand during airdrop is 30g (25ms). Therefore, the maximum overload that the rocket can withstand during airdrop is set as 30g [7].
3.1 extended finite element method
The extended finite element method (XFEM) introduces the enrichment function based on the traditional finite element method to reflect the discontinuity of the displacement field of special elements. The approximate displacement expression is\cite{8}:

\[ u = \sum_{i=1}^{N} N_i(x) \left[ u_i + H(x) \alpha_i + \sum_{\alpha=1}^{4} F_\alpha(x) h_\alpha \right] \]  

where: \( N_i \) is traditional finite element shape function, \( u_i \) is traditional node degrees of freedom, \( \alpha_i \) is the improved degree of freedom of nodes related to jump function is only effective for element nodes whose shape function is cut by crack, \( F_\alpha(x) \) is asymptotic function of crack tip stress.

3.2 finite element modeling of solid propellant with damage
A rocket engine is composed of shell, front baffle plate, rear solid plate and propellant grain. The charge type is seven star hole slot charge, and the filling mode is free filling, that is, there is a gap between the propellant grain and the engine shell; The engine model thus established is shown in Fig 1, and the propellant material parameters are determined according to Literature 10,

![Figure 1](image.png)

Figure 1 Three dimensional model of solid propellant

The tail of the grain is bound to the solid plate, and the side and front of the grain contact and collide with the shell and the drug retaining plate respectively; The shell is a thin-walled structure, and the shell element is used to divide the grid, and the other parts are solid elements. Firstly, the position where the maximum stress of propellant grain is found through the calculation without prefabricated crack, and then the cracks with different initial angles are prefabricated at this position.

For the three-dimensional solid element, the two-dimensional plane can be used as the initial prefabricated crack. In fracture mechanics, the size of the micro crack is usually less than 2mm. Therefore, the crack with a length of 2mm is preset at the root of the inner hole of the star groove of the grain. The initial crack angle is the angle between the prefabricated crack direction and the load loading direction. The crack is created in the interaction module of ABAQUS.

4. Calculation and result analysis of simulation mode
Figure 2 shows the change of damage dissipation energy under 30g (25ms) overload at different initial crack angles, and figure. 3 shows the change law of the maximum damage dissipation energy under each working condition with the initial crack angle; The time when damage dissipation occurs is the time of crack propagation. It can be seen from the figure that when the included angle between the initial crack direction and the load direction is less than 60°, there is no damage dissipation in the crack; From 60° to 120°, the damage dissipation increases with the increase of the initial angle. When it is greater than 120°, the damage dissipation energy begins to decrease. The most serious case of crack propagation is when the initial crack angle is 120°.
As shown in figure 4, when the initial crack is 120 °, under the impact overload of 30g (25ms), the maximum stress of the modified double base propellant grain containing the initial crack is 12.35mpa, resulting in obvious crack propagation. The crack response of the grain is reduced to 25g (25ms), 20g (25ms) and 15g (25ms). As shown in the figure, the maximum stress is reduced from 10.33mpa to 5.72mpa, and the overload is 20g (25ms) At this time, the stress is 7.37mpa. Although the yield stress has not been reached, the crack propagation phenomenon also occurs, indicating that the initial damage will reduce the grain strength, which also verifies the observation that the stress or strain strength theory can not be used as the failure criterion of damaged propellant proposed in this paper. When the overload is reduced to 15g (25ms), the crack does not expand.
When the initial crack is 120 °, the damage dissipation energy of the model under different overloads is shown in figure 5. With the decrease of overload, the time of crack propagation will be significantly delayed; when the overload is reduced to 20g, there is only slight damage dissipation at the end of the calculation; When the overload is reduced to 19g, the damage dissipation will not occur and the crack will not expand.

5. Conclusion
Based on the extended finite element method (XFEM) of ABAQUS, the crack propagation of a modified double base propellant with damage under airdrop load is analyzed. The following conclusions are drawn:

1. There are obvious differences in strength with different initial crack angles. When the initial crack direction and load direction are 120 °, the damage dissipation energy is the largest and the crack propagation is the most serious.

2. When the landing impact overload that the airdrop equipment should be able to bear is 30g (25ms), the damaged solid propellant will have obvious crack instability and propagation. When the load is reduced to 19g (25ms), the crack will not expand. Therefore, when airdropping the damaged rocket propellant, it is necessary to increase the buffer mode to reduce the rocket overload.

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