Study on structural failure mechanism of explosive separation device based on the damage constitutive model

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Abstract. The explosion separation device is the critical factor to ensure the effective separation of the payload and the launch vehicle. The rationality of the structural strength is usually assessed by the real explosion separation test. The separation of components in the deformation and damage is difficult to be obtained. The traditional method, based on the elasto-plastic constitutive, is also unable to simulate the damage of each component in the separation. The traditional strength check can be calculated by the elasto-plastic constitutive relation for large deformation, while the damage simulation can only be obtained by the progressive damage fracture. The metal material dynamic damage constitutive is applied based on the ABAQUES to simulate the damage and failure of the explosion separation. Then the finite element model of the explosion separation device can be established based on the elasto-plastic damage constitutive model, and the process of the ground test of the explosive separation device can be reproduced by the simulation of the corresponding FEM model. And then the weakness of the explosive separation device is finally determined by the calculation results. The experimental results are consistent with the simulation, which confirms the accuracy of the proposed method. The solution idea provides a reference basis for the product design and dynamic damage simulation.

1. Introduction
The explosion separation device is the critical factor to ensure the effective separation of the payload and the launch vehicle. The rationality of the structural strength is usually assessed by the real explosion separation test. The separation of components in deformation and damage can't be monitored, and the traditional general finite element analysis method, based on the elasto-plastic constitutive is also unable to simulate the explosion interconnected damage in the process of separation. At present, the research on explosive separation devices in engineering mainly focuses on the effect of pyrotechnics on explosive bolts. Four typical reagents were selected in Longfei D’s research[1] to analyze the process of explosive bolts, and the separation of explosive bolts calculated by the self-contained plastic constitutive relation of ANSYS software is basically consistent with the engineering practice. The fracture characteristics of explosive bolts based on the ANSYS elasto-plastic follow-up model were studied in Hao Y’s paper[2], and the optimal fracture structure of explosive bolts was obtained. The explicit dynamics method was used in Xixiong W’s research[3] to predict the impact response of the explosive separation bolts, and the sensitive parameters are identified. Balden The hydrodynamic equations were used in V H’s paper[4] to study the deformation and post-failure response of plates under blast loading. The explosive separation bolts were used in Hongda Z’s research[5] to analyze the impact of the unlocking process, which revealed that the explosion shock and the strain energy shock are the sources of the entire separation shock. The potential damaging
effects of high-order impacts were investigated in Jung-Ryul L’s paper[6] generated by explosive separation devices on equipment. The numerical analysis method is used in Juho L’s research[7] to analyze the phenomenon of separation reliability reduction caused by gap distance. The response and deformation of low carbon steel under impact loading were studied in Bonorchis D’s paper[8] based on a set of independent local explosion load tests. The above researches are mainly studied based on the large deformation and elasto-plastic constitutive of mature finite element software without the damage constitutive, and the damage process of other protective structures caused by the explosive bolts in the separation process was not concerned.

In this paper, the structure deformation of the explosive separation device in the separation test is obtained by the finite element dynamic simulation. Firstly, the material damage constitutive relation is introduced into the material mechanics model based on the ABAQUES. Then the finite element model of the explosive separation device is established. And then the damage process of each components in the separation process is precisely analyzed. The process of the ground test of the explosive separation device can be reproduced, and the weakness of the explosive separation device is finally determined. The prediction results are consistent with the experiment, which proves the effectiveness of the proposed method. The solution idea provides a reference basis for the product design and dynamic damage simulation.

2. Dynamic damage constitutions of metallic materials
The stress failure under the external load of elasto-plastic metal materials is as shown in Figure 1, e.s. the elastic deformation \( \sigma < \sigma_e \), the elasto-plastic hardening \( \sigma_e < \sigma < \sigma_y \), and the stiffness degradation \( \sigma > \sigma_y \). Permanent plastic deformation and damage will arise in the elastic-plastic hardening, and large deformation will arise accompanied by the damage degree increasing with the accumulation of permanent deformation. The material unloading stiffness will stay invariable before \( \sigma \) rising to \( \sigma_y \) for the first time, the material yield strength \( \sigma_y \) will be enlarged by the plastic deformation in accordance with the law of hardening, which is called the pre-damage. The material properties will be softened by continued increasing load, while the stress level \( \sigma \) is exceeding the strength limit \( \sigma_y \) for the first time, which eventually leading to fracture, as is called the post-damage. The damage critical level is defined while the stress level is rising to the strength limit \( \sigma_y \) for the first time.

![Figure 1. Constitutions of metallic materials.](image)

According to the elasto-plastic theory, the hardening damage constitutive model of materials in the pre-damage is established, which can be expressed as:

\[
\{d\sigma\} = [D]^p \{d\varepsilon\}
\]

(1)

Where \([D]^p\) is the deformation stiffness of the material in the pre-damage, \(\{d\varepsilon\}\) is the strain increment vector, and \(\{d\sigma\}\) is the stress increment vector.

For metallic materials commonly used in structural design, the material hardening rate can be
described by the yield surface equation as follows:

\[
\sigma_{eq} - \{\sigma_y + R(\dot{\varepsilon}_p)\} = 0
\]  \hfill (2)

Where \(\sigma_{eq}\) is the Von Mises equivalent stress; \(\sigma_y = \sigma_x + R(\dot{\varepsilon}_p)\) is hardening yield strength, \(\sigma_x\) is material static yield strength, \(p\) is material hardening function.

The differences between the material constitutions under dynamic load and static load are mainly reflected in the effect of strain rate on the hardening rate of metal materials. The influences of plastic hardening rate of different materials are different, which is not relative to the geometry characteristics. Comper_Symonds model and Johnson_Cook model [9-11] are two commonly used strain rate models in engineering. The independent influence function of the strain rate was introduced based on the static stiffness ratio as formula (2), and then the proportional relation of the dynamic hardening yield strength \(\sigma'_y\) and static infant flower yield strength \(\sigma_y\) were established.

Comper_Symonds model can be described as

\[
Y = \frac{\sigma'_y}{\sigma_y} = 1 + \left(\frac{\dot{\varepsilon}}{D}\right)^n
\]  \hfill (3)

Johnson_Cook model(simplified) can be described as

\[
Y = \frac{\sigma'_y}{\sigma_y} = 1 + C \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)
\]  \hfill (4)

Where \(D\), \(n\), \(C\) is the strain rate correlation coefficient, \(\dot{\varepsilon}_0\) is the reference strain rate of Johnson_Cook. The static damage constitutive model of metal materials can be transformed into a dynamic solution while the static hardening yield strength \(\sigma_y\) in equation (2) is replaced by the dynamic hardening yield strength \(\sigma'_y\).

3. Research on structural damage mechanism of explosive separation device

![Figure 2. The explosion separation device.](image)

The explosion separation device is mainly composed of explosive bolts and capturing assembly, as shown in Figure 2. The capturing assembly is composed of the buffer parts, the cover plate and the base. The buffer parts are used to slow down the impact of the explosive bolt on the cover plate and the base during the rapid separation. The cover plate and the base must be kept sealed before and after the separation to prevent the separation products from flying out to form residue. A gap of about 5 mm was discovered between the base and the cover plate after the explosion separation test, and the
structural sealing was damaged. The redundancy will be presented in the form of the fragments from the buffer parts hit by the explosive bolts, which poses the hidden danger to the safety of flight test. The explosion separation is unobservable and the damage of each part is difficult to analyze, then the finite element simulation is adopted to analyze the damage and deformation of each part in the separation, which can provide detailed exhibition for the separation and damage process.

The finite element analysis for explosion damage in the separation process is carried out based on the metal material damage constitutive. Firstly, the crash simulation model is established, the separation speed of the explosive bolt is determined, and then the damage process after separation of all components is simulated, the weakness of the components is determined.

The finite element model of explosive separation device is as shown in Figure 3. The elasto-plastic model is used to establish the base during the impact process in the finite element modelling. And the damage constitutive is used to model other components. The aluminium material damage constitutive is adopted to establish the model of the cover plate. The steel material dynamic damage constitutive is adopted to establish the explosive bolts during the transitory separation. The low-strength alloy steel dynamic damage constitutive is adopted to establish the fast-compressed cushioning parts. The material properties is as shown in Table 1. The shell elements are used in the buffer parts, and the hexahedral entity units are used in other structure. The cover plate and the base are connected with bolts, and the base is fixed to simulate real installation. The initial velocity of the explosive bolt is set to be 50 m/s based on the initial impulse of the separation.

![Figure 3. The explosive separation device and the finite element model.](image)

### Table 1. Material properties of explosive bolt box.

| Parts            | E/GPa | μ  | σs/MPa | σb/MPa | Rou/g/cm³ |
|------------------|-------|----|--------|--------|-----------|
| explosive bolt box | 71    | 0.3| 250    | 380    | 2.7       |
| explosive bolts  | 200   | 0.3| 885    | 1080   | 7.8       |
| cover plate      | 68.6  | 0.3| 117    | 315    | 2.7       |
| buffer parts     | 200   | 0.3| 300    | 615    | 7.8       |

The impact force curve of the explosion bolt to the bolt box is as shown in Figure 4. The impact force of the explosion bolt is shown as the purple curve and the impact of the explosive bolt to the buffer parts is shown as the blue curve in Figure 4. The impact force can be completely transmitted to the buffer parts on account of the good stiffness of the explosive bolt. It can be seen from the analysis that after the separation, the explosive bolt moved forward at a speed of 50 m/s, and the maximum impact force of the explosive bolt on the base is about 69.6 kN. The impact process can be described as the following course. Firstly, the movement of the shock buffer parts and the explosive bolt will be
continuous until the impact energy was completely exhausted. The large upward deformation will appear while the buffer parts was compressed, and then the large deformation will be discovered on the cover plate. Finally a large gap will be generated between the base and the cover plate. The deformation comparison of the explosion separation device between the ground test and the simulation results is as shown in Figure 5. The deformation comparison of the components is as shown in Figures 6-8. The actual deformation of the cover plate is 4.94 mm in the simulation, and the deformation is about 5 mm in the ground test, which confirms the accuracy and effectiveness of the simulation of the damage of the explosive separation device based on the metal dynamic damage constitutive. The simulation results are in good agreement with ground test experiment.

Figure 4. Impact force curve of explosion bolt on bolt box (maximum value is 2×34.8kN).

Figure 5. Deformation of the bolt box after explosive separation.

Figure 6. Deformation of the cover plate after explosive separation.
4. Conclusions

- The traditional method, based on the elasto-plastic constitutive, is unable to simulate the damage of each component in the separation. The traditional strength check can be calculated by the elasto-plastic constitutive relation for large deformation, while the damage simulation can only be obtained by the progressive damage fracture.

- The large deformation of the buffer parts is the immediate cause for the deformation of the cover plate. The structural improvement method was proposed to change the structural form of the buffer parts so that the deformation direction was changed from squeezing the cover plate to squeezing the base, which could effectively reduce the deformation of the cover plate and improve the structural sealing property.

- The damage of various components of the explosion separation device was accurately simulated in ABAQUES based on the dynamic damage constitutive of the metal materials. The research will be a great reference for the structural design improvement.

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