Study on Separation Dynamics of Explosive Bolt and Test Verification

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Abstract. In order to simulate the dynamic process after the separation of explosive bolt, and to analyze whether the impact force of the explosion could cause the damage of the explosive bolt box structure. The explicit dynamic method of ABAQUS was adopted in this paper to carry out simulation analysis on the process of the explosive bolt passing through the corner piece and hitting the buffer block after unlocking, and to evaluate the strength and deformation of the bolt box under impact load. The verification test of explosive bolt was carried out to evaluate the reliability of the design, and the test results indicated that the designed explosive bolt box achieves a successful acceptance of the explosive bolt of the separation with design margin, the structure of the box does not have obvious deformation under the impact load, and the strength design of the explosive bolt box meets the use requirements.

1. Introduction

The explosive bolt, cutting pyrotechnic and release actuator are used in aerospace models for separation, and the explosive bolt is the most widely used due to its stable connection and high reliability [1, 2]. Wu simulated the process of PETN exploding and its effect to the explosive bolt box by nonlinear dynamic finite element analysis software LS-DYNA [3]. Yang used explicit dynamic simulation method to analyze the separation process by Dytran software, and the shock response spectrum (SRS) at different measurement points was investigated [4]. The total process of the explosive bolt passing through the flake spring and striking the cushion block was simulated dynamically with ABAQUS by Wang [5].

During the process of separating and unlocking the explosion bolt, extraneous materials are generated due to the action of the pyrotechnics, and the explosion bolt rod would obtain a higher separation speed. If the structural strength design of the explosive bolt box body is insufficient, or the buffer block cannot absorb the separation energy, the structure of the box may be broken after being impacted by the bolt rod, which may cause the separation of products to enter the aircraft, and seriously lead to the failure of the flight test. Therefore, in the design of explosive bolt box, not only the strength of the box body is sufficient, and the structure would not be damaged due to pyrotechnic impact during the separation process, the bolt rod and the separated products should be reliably stored. In the past design process, most of the mature design experience was used for reference, and combined with the multi-round tests for verification, the analysis of the separation process of explosive bolt box is relatively lack, which affects the design and development process.

In this paper, the dynamics simulation analysis method was used to simulate the separation process of the explosive bolt. The storage performance of the explosive bolt box is evaluated, and the separation test of the explosive bolt has been validated for the structural design and the simulation results.
2. Design of Explosive Bolt Box Structure

Conventional explosive bolt box is designed with corner piece, buffer block and other structures. Through the cushioning action of the corner piece and the buffer block, the separation energy of the bolt rod caused by the action of the pyrotechnic product can be absorbed, and the bolt box caused by the impact can be avoided. In addition to the above structure, another typical explosive bolt box structure is provided with flake spring on both sides of the box body, the flake spring could absorb a part of the impact energy in the process of bolt rod separation, and can also play a role in the bolt rod rebound clamping, avoid bolt in the separation of protruding separation surface. Typical explosive bolt box structures are shown in figure 1.

![Figure 1. Schematic of the explosive bolt box structure.](image)

The working process of the explosive bolt box is briefly described as follows: the explosive bolt rod is cut off under the action of pyrotechnical products and generates a certain separation speed, the nut moves in the box. By properly designing the structure of the corner piece and the buffer block, it can fully absorb the separation energy of the bolt rod assembly, and finally stop moving in the box, so as to realize the storage of bolt rod and nut.

3. Dynamics Simulation Analysis

Explosive bolt involves a lot of structures in the separation process, and the motion process is complicated. It is difficult to accurately simulate the entire separation process and structural strength by means of engineering analysis. Therefore, the ABAQUS was used to simulate the whole separation process by dynamics simulation analysis method in this paper, the strength of the box body and components was evaluated, whether the box body structure met the design requirements at the maximum separation speed was analyzed.

3.1. Explicit Dynamics Simulation Analysis Method

The dynamic equation an object under the action of external force $F$ can be expressed as:

$$Ma + Cv + Ku = F$$

In equation (1), $M$, $C$, $K$ are the mass, damping and stiffness matrices of the object. The speed of the object at time $t_n$ is:

$$a_{(n)} = M^{-1} ( F_{(n)} - Ku_{(n)} - Cv_{(n)} )$$

For the above equations, the solution to the dynamics is to use the central difference method, which assumes that the acceleration of the motion of the object is constant over a time step, i.e.
Substituting equation (3) and equation (4) into equation (2), the acceleration at time $t_n$ could be solved.

### 3.2. Impact Speed Analysis

When the explosive bolt is normally separated, the impulse $I$ generated by the pyrotechnics is 5.25 Ns. According to the momentum theorem, the initial speed of the bolt and the nut before the separation is 0. After the separation, the bolt and nut are moved to the inside of the box at the same speed.

$$I = mv$$  \hspace{1cm} (5)

In equation (5), $I$ is the impulse that generated by the separation and locking of pyrotechnics, $m$ is the mass of bolt and nut, a total of 89g, and $v$ is the initial speed after the separation of bolt and nut.

It can be calculated that the initial speed of the bolt and nut is 59 m/s (100% speed) under the designed impulse of 5.25 Ns. The separation speed is 71 m/s (120% speed) considering a certain design margin.

### 3.3. Analysis of Action of Flake Spring

The function of the flake spring is to block the nut when the bolt rod and the nut move toward the inside of the box during the separation process, absorb a part of the separation energy, slow down the movement speed of the rod and the nut. After the buffer block has absorbed the energy, the explosive nut does not move in the opposite direction to protrude the separation surface by the angle that the flake spring is opened. The flake spring is spring steel, and the mechanical properties at 20 $^\circ$C are shown in the table 1.

| E/GPa | $\mu$ | $\sigma_b$/MPa |
|-------|-------|---------------|
| 206   | 0.29  | 1570          |

The initial speed calculated in last section is used as the separation speed of the bolt rod. The separation process of the two structural design forms with or without flake spring is simulated by ABAQUS software. The movement speed of the bolt rod and the nut was extracted from the simulation analysis results. It can be seen from the curve of the movement speed of the bolt and the nut shown in figure 2 that there is no significant differences in the movement speed of the bolt rod and the nut under the two structural forms. It is indicated that the flake spring does not fully absorb the energy of the bolt during the movement of the bolt and does not affect the bolt rod movement track.

At the same time, the movement process of the bolt and the nut is analyzed after the buffer block absorb the separation energy. In both cases, the energy of the bolt rod and the nut is absorbed by the buffer block and the corner piece. The rebound speed of the bolt rod and nut decreased from 6.5 m/s to 5.9 m/s, and neither of the two structural forms the bolt and nut would not protrude from the separation surface in the end.
3.4. Stress Analysis of Explosive Bolt Box
The explosive bolt would generate impact load during the separation process. During the use process, the damage of the box structure must be avoided. Therefore, a buffer block is installed inside the box, and the buffer block should effectively absorb the impact energy by bolt, nut and corner piece.

The finite element simulation software was used to simulate and analyze the stress situation of the explosive bolt box under the condition of 100% and 120% speed. The explosive bolt box material is aluminum alloy. The mechanical properties are shown in table 2. The stress of the box is shown in the figure 3.

Table 2. Material properties of explosive bolt box.

| E/GPa | μ   | σ₀/MPa | σ/s/MPa |
|-------|-----|--------|---------|
| 70    | 0.3 | 280    | 220     |

According to the calculation results, the most severe stress area of the box is the contact position between the bottom and the buffer block. At the end of impact separation, the equivalent stress at this position is 221 MPa at 100% speed and 255 MPa at 120% speed, none of situations exceeded the strength limit of the box material. The strength of the box of the explosive bolt box is designed to meet the requirement of use, and has a certain of design margin.

3.5. Deformation Analysis of Explosive Bolt Box Buffer Structure
From the simulation calculation results in figure 4, the buffer block inside the box is the main part to absorb the bolt and nut movement energy. In order to ensure that the box does not damage due to
excessive impact, the buffer block needs to be able to absorb all the energy and leave a certain amount of compression. By simulating the deformation of the buffer block at 100% speed with flake spring, 100% speed without flake spring and 120% speed without flake spring, the buffer block still has a certain compression margin at the maximum design speed, and there is no crushing phenomenon. It is shown that the design form and thickness of buffer block structure meet the design requirements.

![Figure 4. Deformation of explosive bolt box buffer in different structural forms.](image1)

3.6. The Verification Test

According to the above simulation analysis, the design of the box structure and buffer block can absorb the separation energy, and the bolt rod does not protrude the separation surface after the separation is completed. Although the flake spring can absorb certain of energy, the box structure is too small, so the actual installation of the flake spring would have difficulties. Considered the actual product design, the flake spring was not to install finally.

The verification test of the explosive bolt box was carried out according to the above structure. The air gun was used to load the impact, and the compressed air was used to make the projectile produce the set speed. When the projectile hits the bolt rod, the separation speed generated by the explosion of the pyrotechnic product is simulated.

![Figure 5. Results of verification test with different speed.](image2)

The test simulated the separation, impact and storage of the explosive bolt box, and tests were carried out in two working conditions of 100% speed and 120% speed. Under all tests the bolt rod did not protrude from the separation surface, and no obvious deformation was found in the box structure, indicating the reliability of the box structure design. After the test, the compression of the buffer block is basically consistent with the simulation results, and a certain amount of compression is still maintained.

4. Conclusion
In this paper, explicit dynamic analysis method is used to simulate the whole process of the impact of the corner piece on the buffer block after the separation of the explosive bolt, and the strength of the explosive bolt box under the impact load is evaluated. According to the separation speed designed air gun impact test, test results verified the effectiveness of the explosive bolt box structure strength design and simulation results.

a) According to the simulation and test results, the corner piece and the buffer block in the explosive bolt box are the main parts to absorb the explosion separation energy. The spring flake has little effect on absorbing the explosion separation energy.

b) At 100% speed, the maximum stress on the explosive bolt box is 221 MPa, which is not larger than the strength limit of the box material, and there was no obvious gap between the bolt box and cover plate. At 120% speed, there is no obvious deformation of the box and the cover plate of the bolt, which verifies the structural design of the bolt box.

c) The high-speed impact generated by the air gun can better simulate the separation speed generated by the explosion of the separation bolt. Compared with the deformation of the buffer block in the bolt box after the actual explosion separation and air gun test, the amount of deformation is basically the same. It is indicated that the air gun test can use to replace the actual explosive bolt separation test, and it can reduce test expenses and development schedule.

d) Using ABAQUS explicit dynamics method, the whole process of explosive bolt separation can be simulated realistically, and the simulation results are consistent with the test results. The process of the simulation simplifies the design process, and saves part of the test costs, which can provide a reference for subsequent design of explosive separation works.

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