The Optimization the Latching Mechanism Design Based on Progressive Damage Analysis

YANG Yang¹, LIU Ning¹, SUN Qilong¹, WANG Xiaoxue¹ and CHEN Juwei¹

¹Beijing Institute of Space Long March Vehicle, Beijing, China 100076

sunnybuaa@foxmail.com

Abstract. The rocket latching force is an important parameter, prevent the rocket from falling off and affect the launch of the rocket. In order to obtain the optimal engineering design of the latching bar, this paper predicts the damage failure of two kinds of latching bar, based on the continuous damage theory and the Johnson-Cook constitutive model. Compared with the experimental data, the relative error accuracy of the ultimate strength simulation for rocket latching force is reached 5%.

1. Introduction

The latching mechanism is used to prevent the rocket falling off and ensures that the relative position of the rocket in canister does not change during the transportation and preparation phases. After the rocket is fired and the thrust is generated, the rocket explodes against the latching force. The practice verification shows that the rockets deviation of the impact point angle caused by the deviation of the off-track velocity with uniformly latching force can be reduced [1-3]. The basial latching mechanism used in the rocket launcher has four kinds: friction-latching mechanism, spring-latching mechanism, lever-latching mechanism and shear pin latching mechanism [4-6].

This paper focus on the shear pin latching mechanism, wherein the key component for the latching force is the latching bar. The latching force FL provided by the latching bar needs to meet the following conditions.

Static / Quasi-static: \( F_L > n_s F_s \); (1)
Dynamic: \( F'_L < n_d F_d \). (2)

where \( F_s \) is the maximum load in the transportation and other ground conditions, \( n_s \) is the safety factor corresponding to \( F_s \), \( F_d \) is the motor thrust in launch conditions and \( n_d \) is the corresponding safety factor corresponding to \( F_d \).

The equation (1) denotes that the latch bar can be adapted to the ground condition, the equation (2) denotes that the latch force does not affect the launch. In order to ensure the uniform latching force, it is necessary to analyze the effect of structure parameters and determinate structural design of the latching bar.

In order to obtain the optimal engineering design of the latching bar, this paper predicts the damage failure of two kinds of latching bar. The progressive damage theory in static / quasi-static is applied to
predict the damage load of the 7A04 aluminum alloy latching bar, and simulation data is consistent with the experimental results. According to experimental data, the motor thrust is enough to over the dynamic damage load of the latching bar, and the stresses and strains of the other part in latching Mechanism should be analyses either.

2. Static / Quasi-static Constitutive Model
Considering the response of a typical metal specimen during a simple tensile test, the stress-strain response, such as that illustrated in figure 1. The material response is initially linear elastic, $a\rightarrow b$, followed by plastic yielding with strain hardening, $b\rightarrow c$. Beyond point $c$ there is a marked reduction of load-carrying capacity until rupture, $c\rightarrow d$. The deformation during this last phase is localized in a neck region of the specimen. Point $c$ identifies the material state at the onset of damage, which is referred to as the damage initiation criterion. Beyond this point, the stress-strain response $c\rightarrow d$ is governed by the evolution of the degradation of the stiffness in the region of strain localization. In the context of damage mechanics $c\rightarrow d$ can be viewed as the degraded response of the curve $c\rightarrow d'$ that the material has followed in the absence of damage.

![Figure 1. Typical uniaxial stress-strain response of a metal specimen.](image)

the specification of a failure mechanism consists of four distinct parts:

- the Elasticity law ($a\rightarrow b$ in figure 1),

$$\varepsilon_e = \frac{\sigma}{E(1-D)}$$

where $E$ is Young's modulus of the undamaged material; $\nu$ is Poisson's ratio; $D$ received the status of an internal state variable: $0 \leq D \leq 1$ (0 for the undamaged state and 1 for failure).

- the Plasticity law ($b\rightarrow c$ in figure 1),

In order to model plasticity two kinds of strain hardening are usually considered: (a) the isotropic hardening related to the density of dislocations or flow arrests; (b) the kinematic hardening related to the state of internal microstress concentrations, the corresponding back stress defines the center of the elastic domain in tension compression (or in three dimensions).

This model can be described as

$$\left|\frac{\sigma}{1-D} - X\right| - R - \sigma_y = 0$$

- a damage initiation criterion ($c$ in figure 1),

The microcracks are initiated by the accumulation of microstresses accompanying incompatibilities of microstrains or the accumulation of dislocations in metals. The damage threshold can be defined as
where $\varepsilon_{pd}$ is the damage initiation criterion strain.

- a damage evolution law (e.g., $c\rightarrow d$ in figure 1).

3. Dynamic Constitutive Model

The Johnson-Cook criterion (available only in Abaqus/Explicit) is a special case of the ductile criterion in which the equivalent plastic strain at the onset of damage, $\bar{\varepsilon}_D$ is assumed to be of the form

$$\bar{\varepsilon}_D = [d_1 + d_2 \exp(-d_3 \eta)] \left[ 1 + d_4 \ln \left( \frac{d_{pl}}{\varepsilon_0} \right) \right] (1 + d_5 \hat{\theta})$$

(6)

where $d_1$-$d_5$ are failure parameters and $\hat{\varepsilon}_0$ is the reference strain rate. This expression differs from the original formula published by Johnson and Cook in the sign of the parameter $d_3$. This difference is motivated by the fact that most materials experience a decrease in $\bar{\varepsilon}_D$ with increasing stress triaxiality; therefore, $d_3$ in the above expression will usually take positive values. $\hat{\theta}$ is the nondimensional temperature defined as

$$\theta \equiv \begin{cases} 0 & \text{for } \theta < \theta_{\text{transition}} \\ \frac{\theta - \theta_{\text{transition}}}{\theta_{\text{melt}} - \theta_{\text{transition}}} & \text{for } \theta_{\text{transition}} \leq \theta \leq \theta_{\text{melt}} \\ 1 & \text{for } \theta > \theta_{\text{melt}} \end{cases}$$

(7)

where $\theta$ is the current temperature, $\theta_{\text{melt}}$ is the melting temperature, and $\theta_{\text{transition}}$ is the transition temperature defined as the one at or below which there is no temperature dependence on the expression of the damage strain $\bar{\varepsilon}_D$. The material parameters must be measured at or below the transition temperature.

4. Experimental Design

The carrying forces of the latching bars with two different characteristic parameters were examined in the test to obtained the latching force, and the test diagram was shown in figure 2. By the loading bulk, the loading was concentrated on the middle part of the latching bar, and the breaking force value, fracture displacement and fracture morphology of the latching bar were recorded. Two kinds of bars are tested and the structural and material characteristics of the latching bars were shown in figure 3 and table 1. The materials of all the part in the test system were steel, except the latching bar.

![Figure 2. The carrying capacity test of the latching bar.](image-url)
Figure 3. The structural characteristics of the latching bar.

Table 1. The structure parameters of latching bar.

| Number of scheme | Quantity | Radius of weakening groove/mm | Type of weakening groove | Material             |
|------------------|----------|-------------------------------|-------------------------|---------------------|
| Scheme 1         | 3        | 7.5                           | 90°                     | 7A04 aluminum alloy |
| Scheme 2         | 3        | 7.5                           | R=2mm                   | 7A04 aluminum alloy |

5. Numerical Simulation
The numerical model was established as shown in figure 4, including three parts, i.e. the base, loading bulk and latching bar. In the model, the bottom of the base was fixed as the boundary condition and only loading direction freedom of loading bulk was free. The real contact relationships between the latching bar, the base and the loading bulk were defined. The simplified loading rod model was used to simulate the test loading device. The latching bar was defined as the ductile metals, and the materials properties was according to the reference [5], wherein the stress triaxiality and the damage initiation criterion has been defined. Assume other parts in this test was linear elasticity materials.

Figure 4. The numerical model of test.
The result of carrying capacity of the latching mechanism was given, as shown in figure 5 and figure 6. The failure mode of different latching bars was yield failure mainly. The latching force was related to type of weakening groove and the dimension of the latching bar directly.

By comparison, it was considered that the latching force of the two schemes were both satisfied the condition (1), and meanwhile the damage phenomenon was different for the two type of weakening groove. Though all the load-displacement curve had two peaks, the maxmum peak load with Scheme 1 was the second one and the maxmum peak load with Scheme 2 was the first one. It was implied that the displacement related to the peak load was smaller in the Scheme 2. Thus, the latching force of Scheme 2 it was more suitable for the environmental requirements because of its uniform and better properties. Therefore, Scheme 2 was selected.

The prediction of failure load of latching bar was consistent with the experimental results, but the prediction of displacement was affected by the systematic error of the experimental machine.

In order to check the adaptation of latching bar for condition (2), the dynamic behavior of whole mechanism was simulated by applying the "J-C Constitutive". The FEM model established for the local structure as shown in figure 7, wherein the red flat-plate and white bulk were represented part of the launch canister body and rocket respectively.

![Figure 5](image1.png)

**Figure 5.** The load-displacement curve of latching bar with V weaken groove.

![Figure 6](image2.png)

**Figure 6.** The load-displacement curve of latching bar with circle weaken groove.
According to the calculation results as shown in figure 8, the maximum of stress is 361.8 MPa, which was small enough to meet the condition (2).

By the practice verification, the new latching mechanism can adapt to the environment of rocket explodes and the simulation was correct.

6. Conclusion
In this paper, the damage load of the rocket latching bar was simulated based on the strength failure model, and the conclusion is obtained as followed.

1) The failure mode of latching bar was yield failure mainly. The equivalent plastic strain is the key parameter to judge the damage initiation criterion. When the equivalent plastic strain of the structural member reaches the material limit, the structural damage is occurred.

2) The displacement related to the peak load was smaller in the Scheme 2. Thus, the latching force of Scheme 2 it was more suitable for the environmental requirements because of its uniform and better properties.

3) In this paper, the prediction of failure load of latching bar based on the nonlinear damage constitutive was consistent with the experimental results, but the prediction of displacement is affected by the systematic error of the experimental machine.
4) By the practice verification, the new latching mechanism can adapt to the environment of rocket explodes and the simulation was correct.

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