# Damage analysis of explosion blast wave to rocket structure and payload

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# Damage analysis of explosion blast wave to rocket structure and payload

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**Abstract.** The explosion of rocket poses a serious threat to the payload in it. LS-DYNA software is used to analyze co-bottom explosion of the third stage in flight. The damage mechanism of explosion to the structure of the rocket body and the storage tank is mainly studied, and effect of shock peak overpressure, positive pressure time and specific impulse on the payload is evaluated. The results show that: the model can reflect the destruction mechanism of rocket structure explosion. Secondly, the closer the payload is to the explosive core, the more destructive the blast wave will be to it. What's more, overpressure value is much larger than the upper limit of overpressure criterion, which will cause serious damage to the payload. The results may provide a reference for the safety protection design of the payload in the rocket.

## 1. Introduction

The research on the harmfulness of propellant explosion to the personnel and facilities around the launch site is highly valued at home and abroad, but the research on the harmfulness of the payload is very little. The payloads of satellites, manned spacecrafts, and so on are integrated with various electronic devices, which are high-tech and expensive. At the same time, the rocket blast wave can easily cause serious damage. In addition, once the payload carrying nuclear energy explode, the damage of the payload structure will cause nuclear leakage, which will also cause secondary damage to the personnel and facilities around the launch site. Therefore, the research on the harmfulness of blast wave to rocket structure and payload is important and far-reaching for improving the protection ability of payload.

Through accident statistics and scaling test, foreign researchers, NASA has established an experience-based rocket explosion model [1]. Risk of explosion accident is evaluated by combining experimental data and numerical simulation[2], and the factors influencing explosion intensity were studied[3]. The safe distance of explosion was determined[4], and the equivalent of liquid rocket in different distances and angles were studied[5]. The TNT equivalent model and TNO multi-energy model are mainly used to simulate the explosion of liquid propellant. The peak pressure and attenuation process of shock wave were studied[6]. Also, the prediction of far field overpressure by empirical formula is improved[7] and the distance of safety fortification is divided[8].

A third-stage model of a certain rocket is simulated to obtain the damage mechanism of blast wave to rocket structure and the damage effect to payload, and it may provide effective reference for the safety protection design of the payload.

## 2. Empirical formula for blast wave of liquid propellant

In practical engineering application, the parameters of air blast wave are mainly characterized by peak overpressure, positive pressure time and specific impulse[9]. For the convenience of calculation, some empirical formulas are gradually formed based on a large number of experiments.

### *2.1. Determination of explosive yield of liquid propellant*

The equivalent of explosion is greatly influenced by propellant type, mixing degree and ignition time[10]. According to the energy similarity principle, TNT equivalent method is adopted and the equivalent conversion formula is

$$W_{\mathrm{T}} = Y \cdot W_0 \qquad (1)$$

Where, $W_{\mathrm{T}}$ represents mass equivalent to TNT, kg. Y stands for explosion equivalent coefficient, dimensionless. $W_0$ is the total mass of the liquid propellant, kg.

Refer to American research results of liquid propellant equivalent, the upper limit of the equivalent coefficient is 0.6 both on the launch pad and outside the launch pad for liquid hydrogen/oxygen propellant[11].

### *2.2. Empirical formula for blast wave characteristic parameter*

The formula of the peak pressure $\Delta P$ of the air blast wave is given by Chen Xinhua[10], and the unit is MPa.

$$\Delta P = \frac{0.0824}{Z} + \frac{0.265}{Z^2} + \frac{0.6865}{Z^3} \qquad (2)$$

Where, Z is defined as proportional distance, and $Z = \frac{R}{\sqrt[3]{W_T}}$, m·kg$^{-1/3}$. R is the distance to the detonation, and $W_{\mathrm{T}}$ is the mass of TNT.

The formula for calculating positive pressure time is

$$\frac{t_+}{\sqrt[3]{W_T}} = 1.35\times10^{-3}\left(\frac{r}{\sqrt[3]{W_T}}\right)^{1/2} \qquad (3)$$

The shock wave is the integral of air blast wave overpressure curve to the positive pressure time, that is

$$i_+ = \int_0^{t_+} \Delta P(t)\mathrm{d}t \qquad (4)$$

## 3. The establishment of rocket explosion numerical model

The Suppose a rocket is flying 10s, storage in the third stage of rocket is broken caused by the rapid pressure increase, which causes a large amount of leakage of liquid oxygen, an explosion.

### *3.1. Computational models and algorithms*

The third stage 1:1 model of a certain rocket is established, which is shown in Fig.1. Total amount of propellant was 18.4t, and the density of TNT explosive was 1.63x10$^3$kg /m$^3$. Air field is a 500cm×500cm×2100cm rectangle and TNT is a Φ100cm×216cm cylinder. While, payload is a Φ365cm×345cm solid cylinder and tank is a Φ140cm×580cm cylindrical shell. The skin of the rocket is composed of five thin-walled structures, and the thickness is 0.2cm. The explosive center is 410cm from the reference surface, and the storage box center is 440cm from the reference surface.

The minimum size was 5cm and the maximum size was 50cm, and the whole model was divided into 932267 grids[11]. The unit type is three-dimensional SOLID164, the multi-material ALE algorithm is used. TNT and air are modeled by euler grid, while the storage tank, payload and rocket skin are modeled by lagrangian grid. Fluid-solid coupling algorithm is used between two grids.

Four sets of observation points, 16 points in total, at different heights of A, B, C and D were selected in the area near payload, whose location and number are shown in Fig.2.

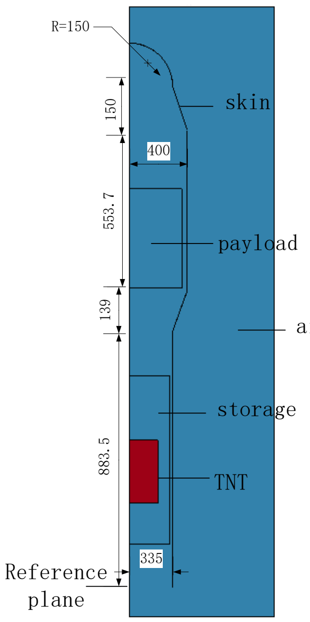

Fig.1. 1/4 rocket model of the third-grade

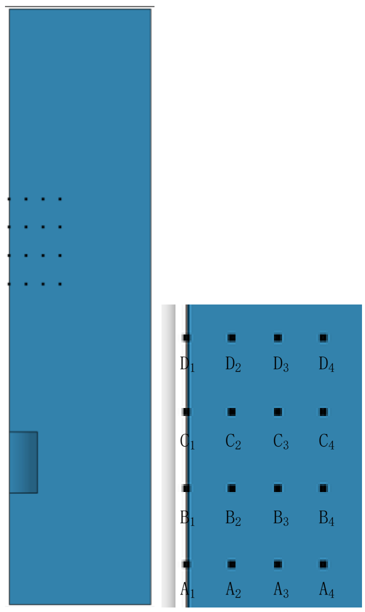

Fig.2. Gauges and partial enlarged chart

*3.2. Material model and parameters*

The air is described by MAT_NULL material model and linear polynomial equation of state EOS_LNIEAR_POLYNOMIAL, while TNT is described by MAT-HIGH-EXPLOSLVE-BURN material model and the relationship between detonation pressure P and unit volume internal energy and relative volume V is described by JWL equation of state. Aluminum alloy and Johnson-cook constitutive model were used to describe the tank, load and skin. The equation of state was described by Gruneisen. Detailed parameters are set out in literature [12].

## 4. Structural failure analysis of rocket explosion

*4.1. Structural damage analysis of rocket*

As shown in Fig.3, blast wave spreads outward in the form of spherical[13]. When time is 0.319ms, the blast wave spreads into the skin structure of the body, causing structural deformation of the rocket body. The structural damage of rocket gradually extends to the upper and lower sides, and the structural damage area gradually increases. When time is 3.394ms, blast wave propagates to the payload and damages it. According to the basic theory of material mechanics, the peak overpressure exceeds the yield limit of the material and result in plastic deformation and failure.

*4.2. Failure analysis of tank structure*

As is shown in Fig.4(a)、(d)、(g), when time is 0.49ms, material damage began to appear on the wall surface of the rocket tank.. When time is 0.83ms, the bottom of the storage tank, due to the strong impact of blast wave, exceeds the stress limit that the material can withstand, and there are four obvious damaged areas, as shown in fig.4(b), (e) and (h). As the shock wave propagates, the damaged area gradually increases, and finally the central area and the marginal area are also damaged, as shown in fig. 4(c), (f), and (I).

## 5. Damage effect analysis of blast wave characteristic parameters on payload

*5.1. Blast peak overpressure*

As is shown in Fig.5, blast wave decays exponentially, eventually stabilizing the pressure in the atmosphere. This is because there is always an irreversible energy loss caused by air shock compression during the propagation of blast wave. The greater the intensity of blast wave is, the greater the irreversible energy loss is.

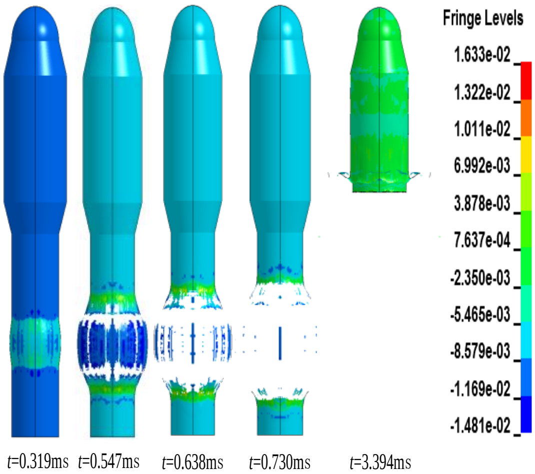


Fig.3. Pressure contour at different times of rocket explosion

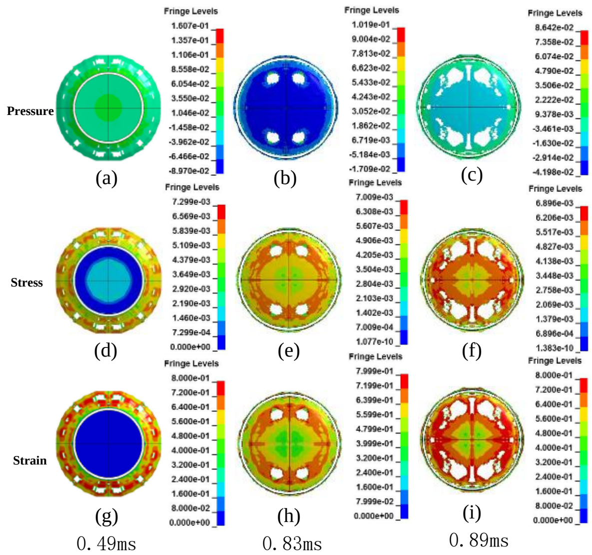


Fig.4. Pressure, stress and strain contours of tank cross section

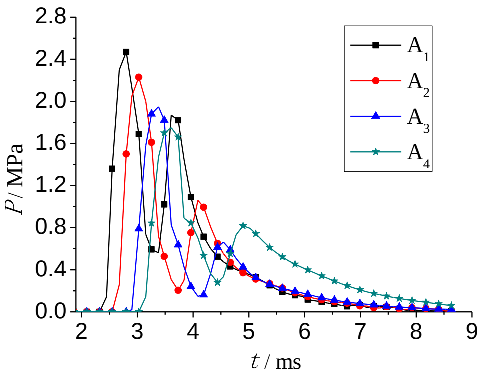


Fig.5. Pressure-time curve of blast wave

The peak pressure decreases with the increase of distance. As the distance increases, the pressure attenuation decreases and the pulse width increases. This is because the average energy per unit mass of air keeps falling as the shock wave spread[14].

## *5.2. Blast wave duration*

Positive pressure time of air blast wave is also one of the important parameters to measure the damage degree of blast wave to the target. Generally, the longer the positive pressure time is, the stronger the damage to the target will be. For the observation points of different columns, time of positive pressure of blast wave decreases with the increase of the proportional distance, and the closer to the observation point, the longer the time of positive pressure will be, the greater the damage to the load will be. As is shown in figure 6, the positive pressure action time of blast wave on the payload is between 5.3 and 7.4ms.

## *5.3. Specific impulse*

The specific impulse is the integral of blast overpressure on positive pressure time, which is another characteristic parameter to measure the damage degree of blast wave to the target, whose value directly determines the damage degree of blast wave to the target[15]. Generally, the larger the impulse is, the stronger the damage to the target will be. In general, for observation points of different columns, the specific impulse decreases as the proportional distance increases. As is shown in Figure.7., the specific impulse to payload varies between 1627 and 3550 N·S·m$^{-2}$.

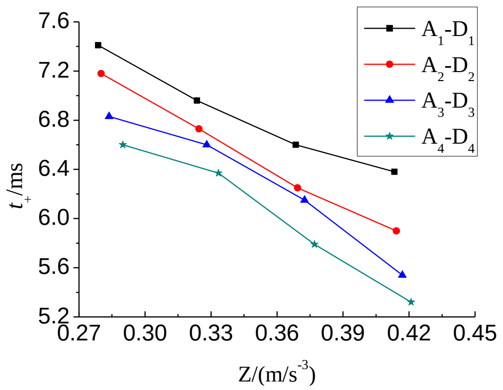


Fig.6. Positive pressure time varies with proportion distance

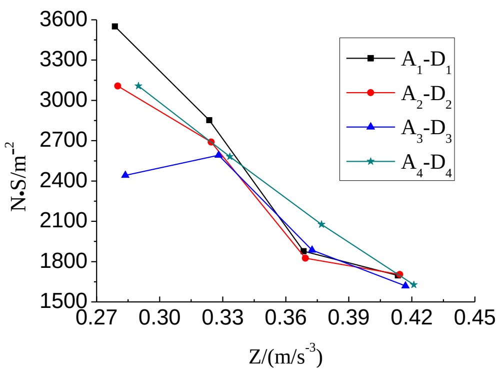


Fig.7. Specific impulse varies with proportion distance

*5.4. Numerical simulation results and error analysis*

Literature [16] shows that when the proportional distance is less than 3, the distribution of peak overpressure is relatively dispersed. The reasons for this phenomenon mainly include two aspects. On one hand, the empirical formula is obtained by fitting the measured results of the explosion test. The test results are affected by various factors, such as the shape of TNT, the height of explosion and the diffusion of explosive products. On the other hand, the sensor is subject to both high speed impact and thermal effect, which produces parasitic effect and causes signal distortion, resulting in inaccurate measurement data of near field of explosion.

The peak overpressure of the blast wave obtained by numerical simulation is between 1.53 and 2.47mpa, which is in the same order of magnitude comparing with 4.1 to 10.6mpa obtained by empirical formula (2). On the other hand, table 1 shows the overpressure data of the liquid hydrogen and oxygen explosion of about 1t in literature[5], which is slightly less than the simulation results. It shows that the numerical simulation results of the near-field blast wave have certain reliability.

According to the empirical formula (3), the positive pressure time is 15.88 ~ 19.52ms, while time is 5.32~ 7.41ms obtained from the numerical simulation, which is very close to the time 3.55ms obtained from the liquid hydrogen and liquid oxygen explosion test in table 1. Usually positive pressure time of liquid blast wave is longer than the solid TNT[7], the time of TNT is between a few milliseconds and a few milliseconds[8]. Therefore, the simulation results have certain credibility.

According to the blast wave overpressure criterion, when the peak overpressure is greater than 0.1Mpa, it will cause a very serious damage to the exposed people. While, when the peak overpressure is greater than 0.2Mpa, blast wave will be extremely damaging to the construction of large steel structures. The minimum peak overpressure of the simulation results is 1.53Mpa, which is far more than the limit of the structure and the exposed people. So the explosion of third-stage rocket will be very harmful to the payload.

## 6. Conclusion

In this paper, the three-dimensional finite element model of the third-stage liquid hydrogen and oxygen rocket was established. The destruction process of the rocket structure and the effect of blast wave on the payload are studied. The following conclusions are drawn:

(1) The three-dimensional model established in this paper can accurately reproduce the dynamic destruction process of rocket explosion, and can reflect the mechanism of the explosion structure of the rocket.

(2) The blast wave of different observation points decays approximately exponentially, and peak overpressure decreases with the increase of proportional distance. The time of positive pressure decreases with the increase of the proportional distance, and the closer the observation point to blast center, the longer time is. In general, specific impulse decreases with the increase of the proportional distance. As a result, the closer payload is to the blast center, the stronger damage to the payload will be.

(3) According to the blast wave overpressure criterion, the burst explosion mode of third-stage rocket will be very harmful to the payload. Necessary safety measures are required for effective load.

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