Simulation analysis on explosion safety of intense light stun grenades

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Abstract. To evaluate the explosion safety of intense light stun grenades, an explosion simulation model was established for their explosion bodies based on a LS-DYNA simulation platform. In this way, both the distribution rules and velocity variations of fragments can be analyzed. As indicated by the simulation results, their fragments are proven to be non-uniformly distributed as far as their sizes are concerned; and, low-velocity fragments with a large mass produced in the middle of the explosion body are the major sources of damage. Moreover, the corresponding radius of safety turns out to be 2.33m approximately. In a word, such an investigation provides a scientific basis for the R&D and applications of intense light stun grenades.

1. Introduction

Explosive energy produced from explosion bodies of intense light stun grenades stimulate people with strong noise and dazzling flash, resulting in temporary deafness and blindness, causing people to lose their capacity for resistance. Thanks to their advantages, such as high striking power and a good effect of dispelling, they have been extensively applied in forced dispelling and military assault, etc. by police departments and armies in different countries [1-2]. To minimize the lethality of their fragments and ensure safety in use, an intense light stun grenade with an ovaly structured projectile body is designed herein, as shown in figure 1. For the purpose of analyzing and verifying the safety of these stun grenades, not only should in-depth analysis be made on mass distribution and velocities, etc. of the fragments, but their radius of safety should be evaluated as well.

In terms of arms and ammunition design in modern times, it is common that the finite element method is selected to perform an explosion simulation. For instance, Yu Zhitong et al. [6] carried out a finite element simulation specific to blast loading and fragment emission processes of the payload, followed by analysing the dispersion regularity of pre-fabricated fragments. Fan Zhuangqing et al. [7] carried out a simulation analysis on the propagation characteristics of cabin explosion loads, which makes a reliable reference for damages and protection of naval vessels. At the early phase of the research, a non-linear finite element application, LS-DYNA, was selected by the research group to simulate the blast wave overpressure of an intense light stun grenades based on an ALE algorithm, to analyze their wounding properties, and to demonstrate the validity of such simulation.
Figure 1. Overall structure of an intense light stun grenade.

(1. Connecting bracket; 2. Secondary ignition-delay; 3. Lower cover; 4. Ignition and safety mechanism; 5. Ring-pull locking buckle; 6. Primary separating igniter tube; 7. Flash pyrotechnic composite)

2. Analysis on the operating principle
The intense light stun grenade is composed of a firing device, a safety mechanism, a connecting bracket and an explosion body (see figure 1). Its operating principle can be described as follows. Once its safety pin is pulled out and the stun grenade is thrown out, a pin plate overturns to ignite a primary separating igniter tube; after a delay, the primary separating igniter tube catches fire and high-temperature and high-pressure gases thus generated will separate the connecting bracket from the explosion body, so that the explosion body can be ejected; simultaneously, ignition powder inside the secondary ignition-delay body is ignited. Subsequent to a following delay, the secondary ignition-delay body ignites, making a flash pyrotechnic composite excited and exploded. In this way, the shell of the explosion body is broken into pieces, producing dramatically loud noise and strong flash.

Since the intense light stun grenade is provided with a double delay tube serial ignition member, the connecting bracket has been separated at a low velocity prior to explosion of the blast body. In this manner, the lethality incurred by the stimulated emission of the connecting bracket as a whole can be utterly eliminated. As a consequence, shell fragments turn into a major source of lethality of the stun grenade. For this reason, this paper conducted a simulation analysis on the explosion processes of the blast body. Compared with various finite element analysis platforms, LS-DYNA has some unique advantages, such as the capability to analyze non-linear dynamic problems such as explosion, structural impacts and shock [9]. In this consideration, it was selected as the simulation platform for this study.

3. Construction of the simulation model
3.1. Fundamental assumption
Due to the complex explosion process and limitations of the computing resources, the following assumptions were made:

(1) The flash pyrotechnic composite was assumed to demonstrate a linear transient detonation;
(2) The propagation and reflection processes of stress waves inside the shell were ignored, so was the superposition of minor stress waves during propagation;
(3) No mass loss or deformation was assumed to exist in the shell fragments as driven by detonation.

3.2. Construction of the physical model
Considering that the blast body is an axisymmetric structure, a 1:4 physical model was established herein.
(1) A cross section of the blast body was created. The blast body was made of ABS materials; as for its 2-D cross section and dimension, please refer to figure 2 below.

(2) A cross section of air and explosive was established; the blue part is made of flash pyrotechnic composite. The shot elevation is 33.7mm, and the weight of the explosive reaches 28g. Moreover, the red part refers to air.

(3) A 1:4 physical model was generated. The rotated physical models generated are respectively presented in figures 4 & 5.

3.3. Mesh generation
Since the projectile body configuration is symmetrical, a tetrahedral mesh was selected here to realize a mesh generation for the blast body, the explosive, and the air. The total number of meshes is approximately 400,000, as shown in figures 6 & 7.
3.4 Material models and the equations of state

The explosion process of the blast body is concerned with three materials: the blast body, air, and the flash pyrotechnic composite. In this case, the models should be separately built.

3.4.1 Flash pyrotechnic composite. A *MAT_HIGH_EXPLOSIVE_BURN material model was selected for flash pyrotechnic composite; and, the corresponding equation of state was written into *EOS_JWL. Such an equation can accurately describe energy characteristics, pressure and volumes of detonation gas products under the action of detonation drive, which can be expressed as follows:

\[
P = A \left(1 - \frac{\omega}{R_1 V}\right) \exp\left(-R_1 V\right) + B \left(1 - \frac{\omega}{R_2 V}\right) \exp\left(-R_2 V\right) + \frac{\omega E}{V}
\]

(1)

Where, \(A, B, R_1, R_2\) and \(\omega\) are constants; and, \(P\) refers to pressure of detonation products, \(V\) to their relative specific volumes and \(E\) to a constant in direct proportion to explosion heat.

Since the formula of the flash pyrotechnic composite cannot be found in the JWL material parameter manual, it is acquired by means of fitting based on a state equation of condensed explosives [10].

According to the equation K,

\[
\begin{align*}
p &= \frac{A}{\sqrt{\nu}} \\
e &= \frac{A}{(k-1)\sqrt{\nu}}
\end{align*}
\]

(2)

The parameter \(\nu\) in \(p = A/\sqrt{\nu}\) is denoted by a relative specific volume in JWL, that is \(\nu = \nu_vV\); then, \(p = A/(\nu_v V) = M\nu_v / V = M/\nu_v\), where \(M = Ap_0^k\) and it is a constant.

By virtue of detonation wave front parameters below,

\[
\begin{align*}
\rho_u &= \frac{k+1}{k}\rho_e \\
v_u &= \frac{k}{k+1}\nu_s \\
\rho_u &= \frac{1}{k+1}\rho_s D^2
\end{align*}
\]

(3)
There exists
\[ A = p_n v_{hi} = \left( \frac{k}{k + 1} \right) \rho_0 D^2 \]

Furthermore, the equation of state was obtained for the flash pyrotechnic composite through fitting; and, relevant parameters are listed in table 1.

Table 1. State equation parameters of flash pyrotechnic composite.

| Parameter | A (GPa) | B (GPa) | R₁ | R₂ | ω |
|-----------|---------|---------|----|----|---|
| Value     | 2.95    | 0.019   | 4.85 | 1.34 | 0.51 |

3.4.2. Air. *MAT_NULL* was selected as the material of air; and, the corresponding equation of state was *EOS_LINEAR_POLYNOMIAL*. For relevant parameters, please refer to table 2.

Table 2. Parameters of air material model.

| Parameter | Density \( \rho \) (kg/m³) | \( c_0 \) | \( c_4 \) | \( c_1 \) | \( e_0 \) |
|-----------|----------------------------|---------|---------|---------|---------|
| Value     | 1.29                       | -1E5    | 0.4     | 0.4     | 2.5E6   |

3.4.3. Blast body. Its plastic material model of kinematic hardening involves the following parameters (see table 3).

Table 3. ABS material model parameters.

| Parameter | Density \( \rho \) (kg/m³) | Elastic modulus E (GPa) | Poisson's ratio | Yield strength (MPa) |
|-----------|----------------------------|-------------------------|----------------|---------------------|
| Value     | 1020                       | 2.2                     | 0.394          | 63                  |

The ultimate plastic strain was designed to be 0.06.

In LS-DYNA, the solving time and the solving step were respectively set at 0.5ms and 100; moreover, the symmetric boundary conditions of YZ and XY were applied and the initiation point was set at the center of flash pyrotechnic composite. Once the K file had been generated, the operation was implemented.

4. Result analysis

4.1. Analysis on the distribution regularity of fragments

The fragmenting simulation of the blast body is presented in figure 8 under the circumstance that the explosion time ranges between 0.05ms and 0.45ms.
As can be observed from figure 8, the explosion of the blast body produced large quantities of fragments. Due to the complex structures, the fragments of diverse parts of the blast body had different sizes and different dispersion directions. To be specific, they can be described as follows:

1. Fragments of the end cover were generally large-sized and they dispersed in an axial direction of the blast body;
2. Fragments of its upper part were mostly and dispersed upwards at a 45-degree angle with the axial direction of the blast body;
3. Fragments of its middle part were usually large; as a connecting part, the shell here was rather thick, the fragments dispersed circumferentially in a direction perpendicular to an axial direction of the blast body;
4. Fragments of the bottom were comparatively small; to be specific, while those of the arc bottom dispersed downwards at a 45-degree angle with the axial direction of the blast body approximately, those of the flat bottom dispersed in an axial direction of the blast body.

4.2. Analysis on fragment velocity

PREPOST was used to process and analyze the fragment velocity. Regarding the time-variation curves of the total kinetic energy of blast body, they are presented in figure 9b.

Clearly, the blast body was subjected to shock waves produced from the explosion at 0.035 ms; within 0.005 ms, the kinetic energy abruptly increased to its maximum value; and within 0.1 ms subsequently, the explosive continuously produced shock waves during explosion and small fragments of the blast body disappear rapidly, which gave rise to kinetic energy loss. Therefore, a balance was achieved eventually and the kinetic energy reached its peak once more. In this event, explosion of the main part of flash pyrotechnic composite was completed; due to the disappearance of the small fragments, the kinetic energy of the blast body began to decline gradually.

Fragments were randomly selected from different parts for the velocity analysis. The corresponding results are shown in figures 9c-f. Apparently, the fragment velocities changed in different ways during explosion of the different blast body parts. The maximum velocity was found in an upper part of the blast body and reached 132 m/s; and, the velocity distribution of fragments in the upper part was rather extensive. Regarding the velocity at the minimum level, it was 10 m/s. In the middle part, fragments were large-sized and their velocities were comparatively low. On average, the fragment velocity here...
was 45m/s. As for the end cover and the bottom, the velocities were primarily distributed in an axial direction of the blast body. In detail, the velocity began to dramatically rise at about 0.05ms and reached its peak at 0.1ms; after that, it went up or down gently or remained unchanged.

**Figure 9.** Kinetic energies and velocities of the fragments.

(a: Parts of the blast body; b. Time variation curve of total kinetic energy of the blast body; c. Time variation velocity curves of some fragments from an end cover; d. Time variation fragment velocity curves of the middle part; e. Time variation fragment velocity curves of the upper part; f. Time variation fragment velocity curves of the bottom part)

4.3. Safety radius evaluation of the fragments

The lethality sources of the blast body were derived from the low-velocity fragments of the large masses. In this paper, a fragment (mass: \( M_f = 2.15 \text{ tMg} \); and, maximum initial velocity: \( V_0 = 97.6 \text{ /ms} \)) of the greatest mass was selected from the simulation results with the goal of evaluating its safety radius.

Specific kinetic energy of the fragment can be expressed in the following equation:

\[
e_f = E_f / S_f
\]

In equation (4), \( E_f \) stands for the kinetic energy of the fragment, and \( S_f \) for a contact area between the fragment and the skin.

Since the fragment moved in an erratically, \( S_f \) is generally processed in line with a uniform orientation theory and calculated according to an average contact area of the fragment, that is, according to \( 1/4 \) of the area. Therefore, the surface area of the fragment can be derived from the following equation.

\[
S_f = \frac{1}{4} \frac{S_r M_f}{M_f}
\]

Where, \( M_f \) represents mass of the blast body and \( S_f \) is its surface area.

Then, a relational expression between initial velocity of the fragment and the specific kinetic energy can be written into the following equation:
Where, $e_{\min}$, equal to 9.8J/cm$^2$, is the minimum specific kinetic energy enough to leave a scratch mark; and, $v_{\min}$ is the least initial velocity high enough to leave such a scratch mark.

It was assumed that the ammunition exploded close to the sea level, that is $H(y)=1$. Under the circumstance that fragments in motion still remain cylindrical, their attenuation coefficient $\alpha$ can be expressed in the following equation:

$$\alpha = \frac{C_x \rho_0 H(y) S_y}{2M_f}$$

(7)

Where, $C_x$, as a coefficient of air resistance of the cylindrical fragment, is equal to 1.17; and, $\rho_0$ represents air density.

Based on an equation of motion of fragments below,

$$V = V_0 \exp(-\alpha x)$$

(8)

By substituting structural parameters of the blast body given in figure 2, the safety radius of the stun grenade was calculated to be 2.33m approximately.

5. Summary

Through a simulation analysis on explosion of intense light stun grenade, it has become clear that the size distribution of fragments generated by diverse parts of the blast body is non-uniform. For example, fragments of the end cover and the middle part are rather large. Subsequent to the explosion, the total kinetic energy gradually attenuates. Regarding fragments of the upper part, they have the maximum velocity, but are small in size. In addition, fragments of the middle part are major sources of lethality and their velocity is comparatively low. By means of estimation and calculation, the safety radius of the entire stun grenade was found to be 2.33m. In a word, the proposed simulation evaluation method can be used as a beneficial reference for design of intense light stun grenades of the same kind.

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