Optimization of the specific kinetic energy of the pre-grooved stun grenade fragments based on HyperMesh, LS-DYNA and Matlab

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Abstract. Large-scale fragments formed by packaging shell of stun grenade are easy to cause irreversible damage to human body in close range. In order to reduce the specific kinetic energy of shell fragments as much as possible, the pre-grooving method is proposed to optimize the safety of packaging shell. According to the process of fragment forming, flying and impacting, the shell breaking model, fragment dispersion model and average specific kinetic energy calculation model are established respectively. The non-grooved shell and inner grooved shell are simulated by the joint simulation method of HyperMesh, LS-DYNA and Matlab. The fragment mass distribution, initial velocity and average specific kinetic energy are obtained and compared. The results show that under the same main charge parameters, the mass distribution of fragments is more concentrated and the large mass fragments are less in the inner grooved shell than in the non-grooved shell; the average initial velocity of fragments in the inner grooved shell is lower than that in the non-grooved shell; the attenuation of average specific kinetic energy in the inner grooved shell is faster than that in the non-grooved shell, which is safer than that in the non-grooved structure.

1. Introduction
Stun grenade is a kind of non-lethal ammunition which produces the strong sound and dazzling flash by the explosion of special charge to stimulate the ears and eyes of living targets, making them temporarily deaf and blind [1]. The large fragments formed in the process of explosion are easy to cause irreversible damage to people. To evaluate fragment safety, the simulation model of the whole process of formation-dispersion-impact should be established, which can guide weapon use, optimize weapon performance, and save research and development cost.

At present, there are relatively few studies on the simulation of the safety characteristics of Stun Grenade by scholars, while there are relatively more studies on the lethality fragments, especially on the numerical simulation of the power field of the lethality prefabricated fragment warhead. Many mature simulation models and methods of lethality fragments have been proposed, such as Liang Anding [2], Li Yuan [3,4], Li Xiangyu [5], Liu Chen [6], Hong Xiaowen [7], Shen Jingtian [8]. Based on the LS-DYNA and AUTODYN platform, the modeling, simulation evaluation, efficiency optimization and rapid calculation of various warhead fragment fields were researched. However, the
above research relies on the LS-DYNA and AUTODYN post-processing software, which only obtains the fragment field characteristics in the initial period of explosion. It cannot directly obtain the motion characteristics of the whole process of fragment formation and dispersion\(^9\), nor directly obtain the specific kinetic energy used to evaluate the safety characteristics of stun grenade. With the joint simulation method of finite element and independent programming, the deficiency of FEM can be improved, such as the modeling complexity, the large amount of calculation and the difficulty of automatic simulation. And with the relevant simulation calculation model established, the average specific kinetic energy of fragments can be obtained more flexibly and efficiently.

Therefore, according to the formation mechanism, motion law and impact target principle of detonation fragments, shell breaking model, fragment dispersion model and average specific kinetic energy calculation model are respectively established. With joint simulation method of HyperMesh, LS-DYNA and Matlab, the average specific kinetic energy of fragments of the shell without grooves and internal grooves can be simulated and solved. Among them, the breaking model is established by the fluid-solid coupling method of FEM, which is used to obtain the shock wave pressure time history curve, initial velocity of fragments, mass distribution in the initial period of explosion; the fragment dispersion model is established by aerodynamics, which is used to obtain velocity decay situation of fragments and the whole three-dimensional flying trajectory. After comparing the simulation results of the above two models with the test results, the calculation model of the average specific kinetic energy of fragments is established and solved based on the Monte Carlo subdivision projection simulation (MC-SPS for short). By this method, the vertical target distribution and average specific kinetic energy of natural fragments or prefabricated fragments at any distance from the explosion center can be obtained, and the safety radius can be evaluated. The flow chart of joint simulation based on HyperMesh, LS-DYNA and MATLAB is shown in figure 1.

![Flow chart of joint simulation based on HyperMesh, LS-DYNA and MATLAB.](image)

**Figure 1.** Flow chart of joint simulation based on HyperMesh, LS-DYNA and MATLAB.
2. Modeling

2.1. Shell breaking model

2.1.1. Model analysis and establishment. The structural principle of stun grenade is shown in figure 2, which is mainly composed of six parts: firing mechanism, delay ignition tube, connecting receptacle, propellant, main charge and cylindrical shell. The diameter of shell is 38mm, which is made of hard PVC. The mass of main charge is 60g [1]. The shell geometry model of non-grooved structure and inner groove structure are shown in figure 3(a) and figure 3(b). Four circumferential grooves and two axial grooves are used in the internal groove structure. The depth and height of grooves are 1mm and 2mm respectively. The firing mechanism of models are simplified properly.

![Figure 2](image1.png)

**Figure 2.** The structural principle of stun grenade.

![Figure 3](image2.png)

(a) non-grooved structure (b) inner groove structure

**Figure 3.** The shell geometry model of non-grooved structure and inner groove structure.

The shell breaking process is modeled symmetrically by $1/4$ finite element method based on ALE fluid-solid coupling, as shown in figure 4. Single point initiation is adopted for the explosive, and the blasting point is as shown in the figure, and the blasting height (bottom of shell) is 1m from the ground. The grid is divided by hexahedral solid element of eight nodes. The main charge and air are divided by multi-material Euler algorithm. And the shell is divided by Lagrange algorithm, which is coupled with multi-material element. The symmetrical constraint condition is set at the symmetrical interface, and the non-reflecting boundary is set on the outer surface of $1/4$ cylinder.
2.1.2. Material constitution and failure criterion.

**Main charge:** the constitutive model of HIGH_EXPLOSIVE_BURN is adopted. Its JWL state equation is as follows:

\[
p = A \cdot \left(1 - \frac{W}{R/V}\right) e^{R/V} + B \cdot \left(1 - \frac{W}{R/V}\right) e^{R/V} + \frac{E_{0e}}{V}\]

Where: \( p \) is the pressure; \( V \) is the ratio of the volume of the detonation product to the initial volume of the explosive; \( E_{0e} \) is the internal energy of the detonation product; \( A, B, R_1, R_2, \omega \) are the characteristic parameters of JWL state equation. The parameters of the model are as follows: the density of main charge \( \rho = 836.8 \text{ kg/m}^3 \); detonation velocity \( D = 6545 \text{ m/s} \); Chapman-jouget pressure \( P_{CJ} = 21 \text{ GPa} \); \( A = 371 \text{ GPa} \); \( B = 1.43 \text{ GPa} \); \( R_1 = 4.15 \); \( R_2 = 0.95 \); \( \omega = 0.3 \); \( E_{0e} = 1 \text{ GJ/m}^3 \); \( V_0 = 1.00 \).

**Air:** the null material constitution and the state equation of linear polynomial are used to establish the air. The state equation is as follows:

\[
p = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + (C_4 + C_5 \mu + C_6 \mu^2) E_0 \]

Where, \( C_0 - C_6 \) is the state equation parameter related to gas properties; \( C_0 = C_1 = C_2 = C_3 = C_6 = 0, C_4 = C_5 = \gamma - 1 \); \( \mu = \rho / \rho_0 - 1 \); \( \rho, E_0, \gamma \) are the initial density, density, initial internal energy and adiabatic index of gas respectively. The model parameters of air materials are \( \rho_0 = 1.2929 \text{ kg/m}^3 \), \( E_0 = 0.25 \text{ MPa} \), and \( \gamma = 1.4 \).

**Shell:** The PLASTIC_KINEMATIC constitutive and principal strain tensile failure criteria of elastic-plastic material are adopted. The Cowper Symonds model is used for the strain rate of the material, and its yield stress expression is as follows:

\[
\sigma_Y = \left[ 1 + \left( \frac{\dot{\varepsilon}}{C} \right) \right]^{\frac{1}{P}} (\sigma_0 + \beta E_p \varepsilon_p^{eff})
\]

In the formula, \( \sigma_0 \) is the initial yield stress, \( \dot{\varepsilon} \) is the strain rate, \( C \) and \( P \) are the Cowper Symonds strain rate parameters, \( \varepsilon_p^{eff} \) is the effective plastic strain, \( E_p \) the plastic hardening modulus, its value is given by the following formula:

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**Figure 4.** The shell breaking model of 1/4 finite element based on fluid-solid coupling method.
\[ E_p = \frac{(E_{\text{tan}}E)}{(E-E_{\text{tan}})} \]  \hspace{1cm} (4)

Where, \( E_{\text{tan}} \) is tangent modulus and \( E \) is elastic modulus.

Relevant parameters of shell material model are \( \rho_0 = 1050 \text{kg/m}^3 \), elastic modulus \( E=2 \text{GPa} \), Poisson's ratio \( \nu = 0.3 \), initial yield stress \( \sigma_0 = 40 \text{MPa} \), tangent modulus \( E_{\text{tan}} = 20 \text{MPa} \), \( \beta = 1 \) and the elongation at break of material is 150%.

2.2. Dispersion model

2.2.1. Model analysis and establishment. When the shell is broken, with the continuous attenuation of the shock wave, the thrust on the fragments will gradually weaken until it no longer plays a significant role. At this time, each fragment can be regarded as the motion of the center of mass under the action of air resistance, gravity and rotation moment. It is assumed that the flight path of the center of mass is always in the same plane, that is, the azimuth angle is constant, and the air resistance direction is always in the opposite direction of the velocity vector of the fragment mass center.

According to Newton's second law, the transformation relationship of velocity, acceleration and included angle, the ordinary differential equations of the velocity, horizontal angle, horizontal displacement and vertical displacement of the jth fragment in its two-dimensional plane can be derived by force decomposition along the tangent and normal directions of the point [10]:

\[
\begin{align*}
\frac{dv_j}{dt} &= \frac{1}{2} C_d \rho \bar{S} v_j^2 - g \sin \theta_j \\
\frac{d\theta_j}{dt} &= -g \frac{\cos \theta_j}{v_j} \\
\frac{dx_j}{dt} &= v_j \cos \theta_j \\
\frac{dy_j}{dt} &= v_j \sin \theta_j
\end{align*}
\]  \hspace{1cm} (5)

Where, \( C_d \) is the air resistance coefficient, which can be solved according to the logistic fitting curve and resistance law [11]; \( \rho \) is the density of fragment material, which is 1050 \( \text{kg/m}^3 \); \( \bar{S} \) is the average windward area of irregular fragment, which can be solved according to MC-SPS; \( g \) is the local gravity acceleration.

The initial conditions of each fragment can be obtained according to the results of shell breaking model. In addition, the constraint condition needs to be set to \( y_{j,n} \geq 0 \).

2.2.2. Model solution. For the solution of equation (5), the fourth-order and fifth-order Runge-Kutta (RK4 for short) algorithm can be used preferentially because the equation (5) is a nonlinear Non-stiff ordinary differential equation. RK4 method uses difference instead of integral. On the premise of knowing the derivative and initial value of the equation, the discrete numerical solutions of each variable of ordinary differential equations with high accuracy can be obtained by programming iteration. With RK4 method, the motion parameter matrix of each fragment in the two-dimensional plane can be obtained finally according to the initial conditions and constraint condition.

2.2.3. Coordinate transformation from 2D trajectory to 3D trajectory. According to the nodes coordinates of fragment element and its spatial transformation relationship, the two-dimensional
trajectory \((x_{jn}, y_{jn})\) can be transformed into three-dimensional trajectory \((x'_{jn}, y'_{jn}, z'_{jn})\) by rotating a certain angle \(R_{jy}\) around the coordinate axis Y, and the transformation relationship of coordinate matrix is as follows:

\[
(x'_{jn}, y'_{jn}, z'_{jn}) = (x_{jn}, y_{jn}, 0) \cdot \begin{bmatrix}
\cos R_{jy} & 0 & -\sin R_{jy} \\
0 & 1 & 0 \\
\sin R_{jy} & 0 & \cos R_{jy}
\end{bmatrix} \tag{6}
\]

Among them, the rotation angle \(R_{jy}\) can be calculated according to the quadrant position of the nodes coordinates and the right-hand rule, and its expression is as follows:

\[
R_{jy} = \begin{cases}
\arcsin \frac{z_{j}}{\sqrt{x_{j}^2 + z_{j}^2}}, & x_{j} \geq 0, z_{j} \leq 0 \\
\pi - \arcsin \frac{z_{j}}{\sqrt{x_{j}^2 + z_{j}^2}}, & x_{j} \leq 0, z_{j} \leq 0 \\
\pi + \arcsin \frac{z_{j}}{\sqrt{x_{j}^2 + z_{j}^2}}, & x_{j} \leq 0, z_{j} \geq 0 \\
2\pi - \arcsin \frac{z_{j}}{\sqrt{x_{j}^2 + z_{j}^2}}, & x_{j} \geq 0, z_{j} \geq 0
\end{cases} \tag{7}
\]

According to equations (6) and (7), the final trajectory of each fragment in three-dimensional space can be obtained.

2.3. Calculation model of average specific kinetic energy

Because of the irregular shape of fragments and the continuous rotation of the flight process, the windward area of fragment impacting the target is a random quantity. Therefore, the average specific kinetic energy of fragments is usually represented by the quotient of fragment kinetic energy and average windward area. The expression is as follows:

\[
e_{nj} = \frac{E_{nj}}{A_{nj}} = \frac{m_{nj}v_{nj}^2}{2A_{nj}} \tag{8}
\]

Where, \(E_{nj}\) is the kinetic energy of the jth fragment; \(A_{nj}\) is the average windward area of the jth fragment; \(m_{nj}\) is the mass of the jth fragment; \(v_{nj}\) is the velocity of the jth fragment. For spherical, cubic, cylindrical, rhombus and other regular fragments, the solution method of the windward area has been described in the literature of terminal effect \([12,13]\). But for the irregular shape fragment, the windward area needs to be solved based on Monte Carlo subdivision projection simulation (MC-SPS for short).

MC-SPS method is to obtain the average windward area \(A_{j}\) by translation, random rotation, projection and triangulation of the node coordinates of N times. When the N tends to infinity, the mean value can be approximated as the average windward area. The schematic diagram of MC-SPS is shown in figure 5. And the area of the plane projection nodes needs to be solved by triangulation algorithm.
3. Result analysis and discussion

3.1. Mass distribution

Based on the shell breaking model, the breaking situation of non-grooved structure and inner grooved structure can be solved at different time, as shown in figure 6. It can be seen from the figure that the two kinds of shells have been completely broken at 200us. The number, coordinate, velocity, volume of elements and nodes can be output as the initial condition of the dispersion model. After sorting by elements search algorithm of the same fragment, the number, quality, velocity of fragments can be obtained. The mass distribution of non-grooved structure and inner grooved structure are as shown in figure 7. It can be seen from the figure that the mass distribution of non-grooved structure presents a ladder like exponential distribution. The number of fragments with large mass is relatively less, and the number of fragments with small mass is relatively more; while the mass distribution of the inner grooved fragments shows a gentler exponential distribution. From the number of fragments, there are 2 fragments larger than 1g in non-grooved structure, while 1 fragment larger than 1g in non-grooved structure. The number of fragments with inner groove structure more than 1g is less than that without groove structure.

Figure 5. Schematic diagram of translation, random rotation and plane projection of fragment coordinates.

Figure 6. The breaking situation of non-grooved structure and inner grooved structure at different time.

(a) Original node (b) Node after translation (c) Node after rotation (d) Node after projection
3.2. Fragment initial velocity

According to the shell breaking model, the tracking elements on different fragments are set up to observe the initial velocities of the shells, and the velocity-time history curves are shown in figure 8. Among them, the velocity of non-grooved structure fragments is between 58m/s-173m/s, while that of inner grooved structure fragments is between 68m/s-122m/s. The average fragment velocities of non-grooved structure and inner grooved structure are respectively 117m/s and 82m/s at 250us. It can be seen from the results that the initial velocity of the inner grooved structure fragment is lower than that of the non-grooved structure fragment.

![Figure 8. The breaking situation of non-grooved structure and inner grooved structure at different time.](image)

(a) the initial velocity of non-grooved structure  (b) the initial velocity of inner grooved structure

3.3. Vertical target distribution and average specific kinetic energy

Base on the calculation model of average specific kinetic energy, the vertical target distribution and average specific kinetic energy can be obtained at different distances from the explosion center. The results of non-grooved structure at 1m, 3m, 5m and 7m are shown in figure 9. It can be seen that 13 fragments hit the target at 1 m, and the rest of the fragments hit the ground at less than 1 m due to the negative and large initial firing angle; at 1m, the average specific kinetic energy of the maximum fragment can reach 17.455J/cm², the minimum fragment is 0.0044J/cm², and the average specific kinetic energy of the maximum fragment and the minimum fragment is greatly different. In the same way, the results of the inner grooved structure can be analyzed.

The average specific kinetic energy thresholds of non-grooved and inner grooved fragments at different distances are shown in Table 1 and table 2. According to the theory of Terminal Effect [13], the minimum specific kinetic energy of abrading skin is 9.8J/cm². So the safety threshold value of specific kinetic energy should not be higher than this value. From table 1 and table 2, it can be seen that six of the non-grooved fragments exceed this threshold value, while two of the inner grooved...
fragments exceed this value. That is to say, the safety risk of the non-grooved fragments at 1m is relatively larger; the average specific kinetic energy of the maximum fragments of the inner grooved structure at 1m, 3m, 5m and 7m is smaller than that of the non-grooved structure; when the distance from the detonation center exceeds 5m, the average specific kinetic energy of all fragments decreases to below 9.8J/cm²; however, the attenuation of the maximum fragment average specific kinetic energy with distance increasing is more significant, and the safety of the inner grooved structure is higher than that of the non-grooved structure.

![Images](a) 1m  (b) 3m  (c) 5m  (d) 7m

**Figure 9.** The vertical target distribution and average specific kinetic energy of non-grooved structure.

**Table 1.** The average specific kinetic energy thresholds of non-grooved fragments at different distances.

| Distance (m) | Maximum fragment average specific kinetic energy (J/cm²) | Minimum fragment average specific kinetic energy (J/cm²) | Over abrading standard number |
|--------------|-------------------------------------------------------|--------------------------------------------------|-------------------------------|
| 1            | 17.46                                                 | 0.0044                                           | 6                             |
| 3            | 10.83                                                 | 0.0272                                           | 5                             |
| 5            | 9.67                                                  | 0.2689                                           | 0                             |
| 7            | 8.44                                                  | 0.0376                                           | 0                             |

**Table 2.** The average specific kinetic energy thresholds of inner grooved fragments at different distance.

| Distance (m) | Maximum fragment average specific kinetic energy (J/cm²) | Minimum fragment average specific kinetic energy (J/cm²) | Over scratch standard number |
|--------------|----------------------------------------------------------|--------------------------------------------------------|------------------------------|
| 1            | 15.23                                                    | 0.0225                                                 | 2                            |
| 3            | 10.24                                                    | 0.0561                                                 | 1                            |
4. Conclusion

1. The shell breaking model, fragments dispersion model and average specific kinetic energy calculation model are established by the joint simulation of the finite element method and independent programming, which can be used to solve the mass distribution, fragment velocity and average specific kinetic energy of any regular or irregular shaped fragment.

2. The hidden danger of natural fragments based on PVC material is larger, and the attenuation of the maximum specific kinetic energy of fragments at 7 m distance is not obvious. For the inner grooved shell, the mass distribution is more concentrated, the initial velocity of fragments is lower, and the average specific kinetic energy attenuation is faster, which is safer than the non-grooved shell.

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