Numerical Simulation of the Protection System of Explosive Reaction Armor

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***Abstract*—There are some extreme conditions in the process of metallic jet penetrating the explosive reaction armor (ERA), such as high instantaneity, large deformation, et al. Based on the smoothed particle hydrodynamics (SPH) method, the generalized density approximate formula is proposed and the Held criterion is introduced. Then the numerical SPH model of metallic jet penetrating the explosive reaction armor is built to study its protection mechanics. The calculation result meets well with the theoretical value. The influences of some parameters, such as thickness of plate and attacking angle, on the protecting effect of explosive reaction armor are analyzed, aiming at providing references for the related engineering application.**

Keywords-numerical simulation;ERA; protection mechanics; SPH; generalized density approximate

I. INTRODUCTION

The explosive reaction armor (ERA) [1], which consists of a sandwich explosive and two plates, can considerably decrease the penetration and damage effects of the metal jet by cutting it continuously under the explosion of the sandwich explosive and the movement of plates [2]. Most research on the explosive reaction armor (ERA) at present is based on the simulation using the finite element software, such as LS-DYNNA [3-5]. Some relevant experiments are also conducted to study the protection effect of the ERA [6-8]. However, the numerical methods based on finite element mesh need to estimate expansion of the detonation products before calculation, and then dimension of background mesh can be set. The excessive mesh domain will lead to the great increase of calculation amount while the smaller one may cause the larger calculation result error. Meanwhile, another question in the application of finite element software for the simulation of ERA is the impact detonation of the sandwich explosive.

However, the defects of finite element methods mentioned above can be properly solved by the smoothed particle hydrodynamics (SPH) method [9]. So the numerical simulation model of the explosive reaction armor (ERA) under the impact of metal jet is built using the SPH method to study the protection mechanism of the ERA.

II. NUMERICAL MODEL

A. Governing Equations

The formation of metal jet and impact detonation of the ERA is the high-velocity process that involves material strength. In this process, the behavior of structure shows some characteristics like the fluid. The hydrodynamic governing equations with material strength, as in (1), are adopted in this paper to simulate the entire process of metal jet formation and impact detonation of the ERA.

$$\begin{cases} \dfrac{d\rho}{dt} = -\rho \dfrac{\partial \boldsymbol{v}^b}{\partial \boldsymbol{x}^b} \\ \dfrac{d\boldsymbol{v}^a}{dt} = \dfrac{1}{\rho}\dfrac{\partial \boldsymbol{\sigma}^{ab}}{\partial \boldsymbol{x}^b} \\ \dfrac{de}{dt} = \dfrac{\boldsymbol{\sigma}^{ab}}{\rho}\dfrac{\partial \boldsymbol{v}^a}{\partial \boldsymbol{x}^b} \\ P = P(\rho, e) \end{cases} \tag{1}$$

Where P, ρ, e, $\boldsymbol{v}^a$, $\boldsymbol{x}^b$, $\boldsymbol{\sigma}^{ab}$, and t are pressure, density, internal energy, velocity, coordinate, total stress tensor and time, respectively. The total stress tensor $\boldsymbol{\sigma}^{ab}$ is defined as [9] $\boldsymbol{\sigma}^{ab} = -P\delta^{ab} + \Gamma^{ab}$, where Γ is the viscous shearing stress.

B. Generalized Density Approximation

The process of metal jet formation and detonation of the ERA involve the interaction between materials with high density ratio, so the density approximation is a key component in the SPH particle approximation of the governing equations. Reference [10] presents the concept of "Compositing Density" to deal with the interaction between materials with different density and introduce it into the numerical simulation of underwater explosion. Based on this work, the concept of "Generalized Density Approximation", which is defined as (2), is presented and applied in the SPH discretization of continuity equation during the interaction between materials with high density ratio. The correlation between interaction particles is determined by their densities, and then the format of density approximation is defined. The density correlation coefficient η of particle i and its interacting particle j is defined as $\eta = \left|\rho_i / \rho_j - 1\right|$. If η exceed some value, the continuous density approximation is adopted, otherwise the summarized density approximation is applied. Then the error caused by the discontinuous density between different materials can be obviously reduced and the mass conservation is ensured.

$$\begin{aligned} \rho_i^{t+1} &= \delta(\rho_i, \rho_j)^t \cdot \rho_i^t \Big(1 + \sum_{j=1}^{N} \frac{m_j^{\ t}}{\rho_j^{\ t}} \upsilon_{ij}^{bt} \cdot \frac{\partial W_{ij}^{\ t}}{\partial x_i^b} \cdot dt\Big) + \\ & [1 - \delta(\rho_i, \rho_j)^t] \cdot \sum_{j=1}^{N} m_j^{t+1} W_{ij}^{\ t+1}, \delta(\rho_i, \rho_j) = \begin{cases} 1, & \left|\rho_i / \rho_j - 1\right| > \xi; \\ 0, & \left|\rho_i / \rho_j - 1\right| \le \xi. \end{cases} \end{aligned} \tag{2}$$

Where $\delta(\rho_i, \rho_j)$ is the density correlation function, the reference coefficient ξ varies at different conditions. In this paper, ξ is defined as $\xi = 0.2$.

C. Detonation of the ERA

The most representative criterion of jet impact detonation of the ERA is the Held criterion [11-12], which is presented by M.Held based on his relevant study for multiple years. It is defined as:

$$k \le \upsilon_0^2 d \quad (3)$$

Where k is the critical detonation constant; υ_0 is the velocity of jet impacting on the target; d is the diameter of metal jet. The material of metal jet is set as copper in the paper, so k is defined as $k = 35\text{km}^3/\text{s}^2$ [11] in the simulation. When the detonation criterion is satisfied, the sandwich explosive of the ERA explodes.

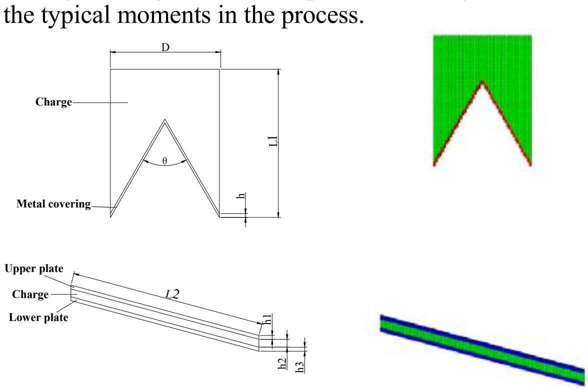
III. MODEL OF SIMULATION

The explosive reaction armor (ERA) mainly consists of the upper plate, the sandwich explosive and the lower plate. When the metal jet caused by the shaped charge impacts on the upper plate, the sandwich explosive will be detonated under the extremely high thermal effect. Then the upper and lower plates move oppositely under the explosion shock wave and the elastic wave forms, which will make great damage to the metal jet and obviously reduce its penetration effect to the main armor. Fig.1 (a) shows the simplified model of metal jet attacking the ERA, and the corresponding particle simulation model built by the SPH method is shown in Fig.1 (b).

As shown in Fig.1 (a), D is the diameter of the shaped charge, L1 is the charge length, h is the thickness of the metal cover, θ is the cone angle of the metal cover, L2 is the length of the ERA, h1,h2 and h3 are the thickness of the upper plate, the sandwich explosive and the lower plate. The values of parameters mentioned above are shown in Tab.1.

IV. SIMULATION RESULTS

The calculation model is built using the SPH method to simulate the process of metal jet attacking the ERA. During the initial simulation the penetration angle, which is defined as the angle between metal jet and the upper plate, is set as 90 degrees. Fig.2 shows the particle velocity distribution at the typical moments in the process.

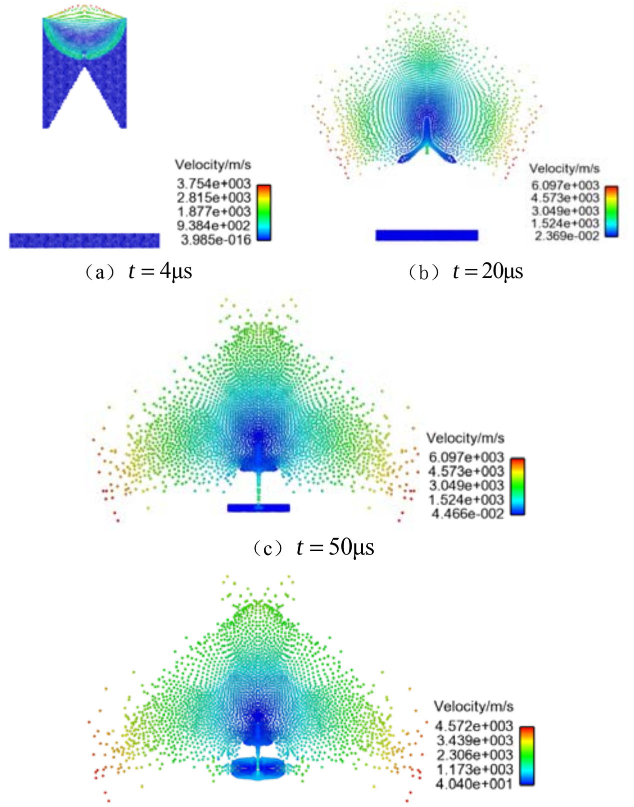


（a）Simplified model （b）SPH particle model

Figure1. Calculation model of the metal jet attacking the ERA

TABLE I. VALUES OF PARAMETERS FOR THE CALCULATION MODEL

Parameter	D	L1	h	L2	h1	h2	h3	θ(°)
Value (mm)	56	76	2	100	2	4	2	60



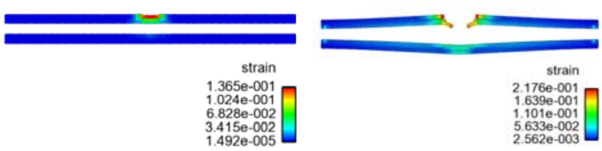
（a） $t = 4\mu s$ （b） $t = 20\mu s$

（c） $t = 50\mu s$

（d） $t = 76\mu s$

Figure2. Particle velocity distribution at typical moments in the process of metal jet attacking explosive reactive armor

It is seen in Fig.2 that the SPH numerical model built in this paper can effectively simulate the complete process from metal jet formation to detonation of the ERA. After the explosion of the shaped charge, detonation products move along the normal direction of charge and impact on the metal cover. Under the continuous impact of detonation products, particles of metal cover moves to the central line and form a metal jet with high pressure, velocity and density finally. After that, the metal jet impacts on the upper plate and cause shock wave in it. When the detonation criterion is satisfied, the sandwich explosive explodes. Then the upper and lower plates move oppositely and make continuous damage to the metal jet [2].



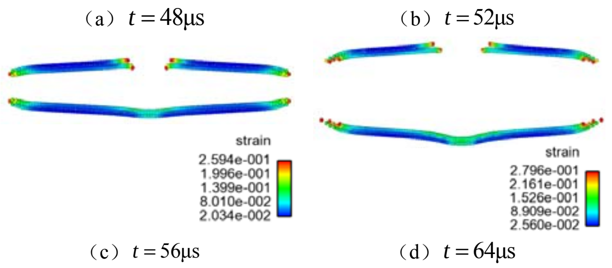


Figure3. Equivalent plastic strain distribution of upper and lower plates of explosive reactive armor at typical moments

In order to clearly observe the movement and deformation of the upper and lower plates after detonation of the ERA, Fig.3 shows the equivalent plastic strain distribution of the upper and lower plates at typical moments in the process of metal jet attacking the ERA. It can be observed that the upper and lower plates move oppositely under the detonation of sandwich explosive. The upper plate disturbs the penetration of metal jet, at the same time it is greatly damaged by the metal jet, and some crevasse appears on it.

The Gurney theory [13] used to be applied to calculate the velocity of upper plate in the process of metal jet attacking the ERA, and the result was verified by the experimental data. The velocity-time history curves of the upper plate are obtained using the Gurney theory and SPH method, respectively. The comparison is shown in Fig.4 to verify the simulation result of this paper.

As shown in Fig.4, the velocity-time history curve of the upper plate obtained in this paper meets pretty well with the curve calculated by the Gurney theory, which indicates the accuracy and reliability of the numerical simulation in this paper.

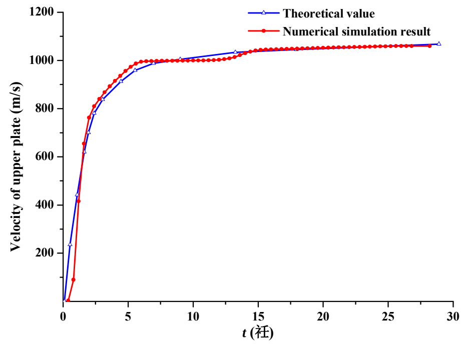


Figure4. Velocity-time history curves for upper plate of explosive reactive armor in the process of metal jet attacking explosive reactive armor

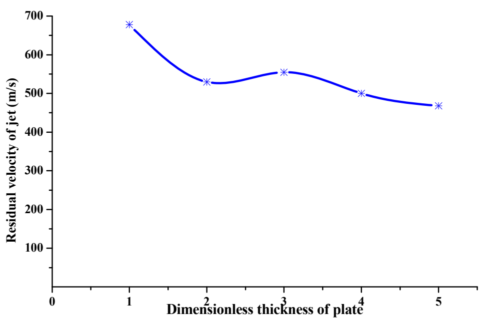


Figure5. Residual velocity of the jet head changing with thickness of upper plate

V. INFLUENCES OF DIFFERENT PARAMETERS ON THE PROTECTION SYSTEM OF ERA

A. Influence of the Thickness of Plates on the Protection Effect of the ERA

The upper plate, sandwich explosive and lower plate are main components of the ERA. Generally, the increase of sandwich explosive can greatly improve the protection effect of the ERA, while at the same time this will bring some damage to itself and the surrounding structures. So the increase of sandwich explosive is not an ideal measure to improve protection effect. Considering the mass of sandwich explosive is fixed, then the proper increase of the thickness of upper plate may improve the protection capability of the ERA and the shock resistance of itself.

In order to analyze the influence of the thickness of upper plate on the protection effect of the ERA, the thickness of upper plate h1 is set as 2mm, 4mm, 6mm, 8mm and 10mm, respectively in the simulation of metal jet attacking the ERA.

Fig.5 shows the residual velocity of jet head changing with the thickness of upper plate, where the dimensionless thickness of plate ε is defined as the ratio of thickness of upper plate h1 and thickness of sandwich explosive h2, namely $\varepsilon = h1/h2$. It can be observed that the residual velocity of jet head falls down with the increase of the thickness of upper plate at the beginning; while the reducing tendency become smooth when ε exceeds 2.0. It can be concluded that under the fixed mass of sandwich explosive, the proper increase of the thickness of upper plate can improve the protection effect of the ERA; when exceeding some range, increase of the thickness makes no great significance.

B. Influence of the Penetration Angle on the Protection Effect of the ERA

Fig.6 shows the shape and velocity distribution of jet at the typical moment under vertical (penetration angle equals 90 degrees) and oblique (penetration angle equals 70 degrees) penetrations, respectively. It can be seen that compared with vertical penetration, the metal jet gets a transverse velocity after impacting on the upper plate and the moves sideward in the process of jet attacking the ERA. At the same time, the velocity of jet is reduced lower, so the penetration capability of metal jet is weakened much more in the oblique penetration.

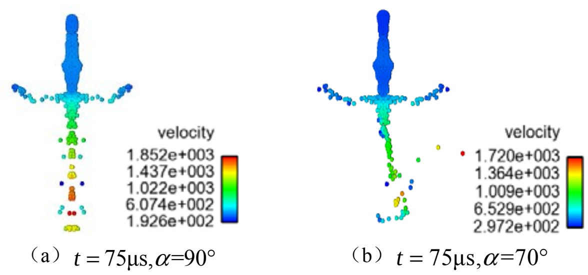


Figure6. Shape and velocity distribution of metal jet at typical moment

under different penetration angles

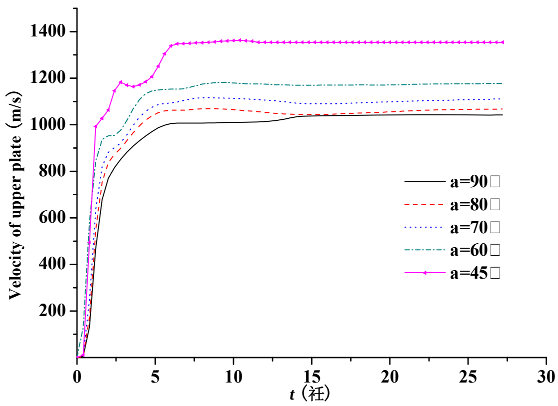


Figure7. Velocity-time history curves of the upper plate under different attacking angles

The velocity-time history curves of the upper plate under the penetration angle of 90°, 80°, 70°, 60° and 45° are shown in Fig.7. It can be observed that the decrease of penetration angle has little influence on the initial accelerating process of the upper plate. However, in the later period, the acceleration of upper plate increases with the decrease of penetration angle, which leads to the increment of the terminal velocity of upper plate. That is to say, the decrease of penetration angle is propitious to improve the protection effect of the ERA.

VI. Conclusions

The smoothed particle hydrodynamics (SPH) method is applied to simulate the process of metal jet attacking the explosive reaction armor (ERA). The protection mechanism of the ERA is analyzed and the main conclusion is as follows:

1) The SPH numerical model built in this paper can effectively simulate the entire process from metal jet formation to impact detonation of the ERA, and the simulation result meets well with the theoretical value;

2) The detonation of sandwich explosive of the ERA generates the shock wave with high pressure and velocity, which will reduce the penetration velocity of metal jet to a much lower value and even cause the opposite movement of the jet, so it has better protection effect than the common armor;

3) Under the fixed mass of the sandwich explosive, the increase of the thickness of upper plate can improve the protection effect of the ERA in a certain extent, while exceeding some range, increase of the thickness makes no great significance;

4) The proper decrease of the penetration angle can be also propitious to improve the protection effect of the ERA.

Acknowledgment

R.B.G. thanks the support of the Program for New Century Excellent Talents in University of Ministry of China (Grant No. NCET100054), the Program of Science Foundation for Distinguished Young Scholars (Grant No. 51222904) and the Lloyd's Register Educational Trust (The LRET) through the joint center involving University College London, Shanghai Jiaotong University and Harbin Engineering University.

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