Analysis of Anti-jet Penetration Characteristics of Axial Single-cell / Multi-cell Closed Structure

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Abstract. To analyze the mechanical properties of jet penetration on a single-cell / multi-cell liquid composite closed structure, the motion equation of jet penetrating a metal target is established, and the energy equation of the penetration system is derived. The simulation results show the radial convergence effect of the liquid in the single-cell increases with the increase of the height of the inner cavity of the closed structure. The radial convergence effect of liquid in multi-cell also has the same phenomenon, but the phenomenon of liquid disjunction appears, which leads to the convergence of liquid into segments. The pressure in the single-cell liquid appears at the bottom of the cell, but the multi-cell liquid appears in the last cell. The pressure distribution of the single-cell is concentrated on the bottom of the cell, and the pressure distribution is circular. The pressure distribution of multi-cell is more uniform, and there is no obvious concentrated distribution phenomenon. The energy of the closed cell structure increases with the increase of the height and the number of the cell.

1. Introduction

The analysis of penetration performance of jet and anti-penetration performance of target plate is a hot research topic in military academies and weapon equipment units at home and abroad in recent years. The research contents include penetration and anti-penetration theory, protection structure, anti-penetration material, charge structure and the use of penetration warhead. Chen Chuang deduces the double virtual origin calculation model according to the improved PER theory, so that the virtual origin theory redefined by Dipersio and Simon can more accurately describe the penetration process of jet[1-2]. Ceramic, rubber, fabric fiber, explosive, diesel oil and other different structural shapes of composite armour appeared one after another[3-4].

In the study of liquid composite armor, many scholars have done research. For example, Gao Zhenyu has carried out a study on the anti-jet penetration performance of liquid composite armor with periodic cell structure[5]. Zhao Changfang and others have studied the effects of liquid sound velocity, density, dynamic viscosity, size effect and structure shape on the penetration resistance of liquid composite cells to jet penetration[6-10]. Zhang Xian carried out the analysis of jet penetration into liquid compound cell structure liquid jet[11]. However, the above-mentioned problems are all based on the analysis and research of single-cell or transverse multi-cell structure. Few people consider the problem from the direction of axial multi-cell structure, and few of them consider the problem from the angle of energy. Based on these problems, the simulation of the axial multi-cell structure is carried out in this paper. Through the comparative analysis of the mechanical properties and energy absorption characteristics of the single-cell and the multi-cell, the anti-penetration performance of the multi-cell is verified. Further enrich the research knowledge of liquid composite armor.
2. Theoretical Analysis

2.1 Equation of motion of jet penetrating metal target

The jet velocity formed by the detonation wave collapsing charge cover after explosive detonation is very high, which is much higher than the critical penetration velocity \( v_{j\text{min}} \) of the jet penetrating the target plate. The case can be described by the PER model (quasi-steady penetration model). That is, both the jet and the target are treated as fluids, modeled by the Bernoulli equation is

\[
\frac{1}{2} \rho_j (v_j - u)^2 = \frac{1}{2} \rho u^2
\]

(1)

Where, \( \rho_j \) is jet density, \( u \) is penetration velocity, \( \rho_t \) is metal target density.

However, when the jet head velocity \( v_j \) is less than \( v_{j\text{min}} \), the strength of metal plate must be considered. The equation of penetrating target of Eichelberger-Pack-Evans Bernoulli is

\[
\kappa \rho_j (v_j - u)^2 = \rho u^2 + 2Z
\]

(2)

Where, \( \rho_t \) is the density of the target plate, \( \kappa \) is constant (continuous jet \( \kappa = 1 \), fracture jet \( \kappa = 2 \)), \( Z \) is deformation impedance \( Z = \sigma_m - \sigma_j \), \( \sigma_m \) and \( \sigma_j \) is usually 1-3 times the static axial stress of metal target and jet.

2.2 Energy conservation equation of penetration system

According to the law of energy conservation, the total energy of the system remains unchanged. Assuming that the total energy of jet molding is \( E^0_j \), the system of jet invading cell structure at time \( t \) is analyzed. The kinetic energy of the jet is \( E^k_j \) and the internal energy is \( E^i_j \) and the strain energy is \( E^s_j \), the kinetic energy of the liquid is \( E^k_l \) and the internal energy is \( E^i_l \) and the strain energy is \( E^s_l \), the kinetic energy of the cell is \( E^k_c \) and the internal energy is \( E^i_c \), and the strain energy is \( E^s_c \). If gravity, environmental pressure and other forms of lost energy are not taken into account, and the system is adiabatic from the outside world, then the energy conservation equation is

\[
E^0_j = (E^k_j + E^i_j + E^s_j) + (E^k_l + E^i_l + E^s_l) + (E^k_c + E^i_c + E^s_c)
\]

(3)

The simplest method with errors is to use the average of two extreme values of velocity to represent kinetic energy and the average of two extreme values of temperature to represent internal energy. The subscript of the extreme value is \( *_{\text{max}} \) and \( *_{\text{min}} \), respectively. For strain energy, the sum of body variation energy and distortion energy of isotropic material can be expressed, and the superscript sum can be used to write the strain energy. In addition, subscript \( *_j \) is the energy parameter of the jet, \( *_l \) is the energy parameter of the liquid, \( *_c \) is the energy parameter of the cell, \( *_{\text{head}} \) is the head of the jet, \( *_{\text{tail}} \) is the tail of the jet; and \( m \) is the mass, \( C \) is the specific heat capacity, and \( T \) is the temperature.

The total energy of the jet \( E^0_j \), which is similar to the initial kinetic energy of the jet, is expressed as the average velocity.

\[
E^0_j = \frac{1}{2} m_j (v^0_{j\text{head}} + v^0_{j\text{tail}})
\]

(4)

At time \( t \), the energy equation of the jet is

\[
E^k_j = \frac{1}{8} m_j (v_{j\text{max}} + v_{j\text{min}})^2
\]

(5)

\[
E^i_j = \frac{1}{2} C m_j (T_{j\text{max}} + T_{j\text{min}})
\]

(6)

\[
E^s_j = \frac{1}{24E} \left( (1 - 2u) \sum_{i=x, y, z} (\sigma^i_{j\text{max}} + \sigma^i_{j\text{min}})^2 + (1 + u) \sum_{i=1, 2, 3} (\sigma^i_{j\text{max}} + \sigma^i_{j\text{min}} - (\sigma^i_{j\text{max}} + \sigma^i_{j\text{min}})^2 \right)
\]

(7)

The energy equation of the closed cell is

\[
E^i_c = 0
\]

(8)
The energy equation of the liquid is

\[
E_i^m = \frac{1}{2}m_i(v_i + v_{min})^2
\]

The combined formula (4)-(13) passes the formula (3) through the summation of the upper, subscript, and obtains

\[
\frac{1}{2}m_j(v_{jhead} + v_{jtail}) = \sum_{r=j,c,d} \left[ \frac{1}{8}m_r(v_r + v_{rmin})^2 + \frac{1}{2}C_r m_r(T_r + T_{rmin}) \right] + \sum_{r=j,c,d} \frac{1}{24}E \left\{ (1-2\nu) \left[ \sum_{i=x,y,z} (\sigma_{i max} + \sigma_{i min})^2 + (1+\nu) \sum_{i,k=1,2,3} (\sigma_{i max} + \sigma_{i min}) - (\sigma_{i max} + \sigma_{i min})^2 \right] \right\}
\]

3. Result and Discussion of Simulation

In order to get the mechanical phenomenon of jet penetrating single-cell / multi-cell structure, the finite element method based on fluid-solid coupling is used to simulate and analyze. To achieve the comparison between single-cell and multi-cell, the wall thickness of circular cell structure, the radius of outer circle and the height of outer wall remain unchanged, and only the partition plate is added in the closed cell to realize the stratification of liquid. Simulation model and material parameters reference to [5].

3.1 Pressure
After the jet penetrating into the liquid compound closed structure, the shock wave will move transversely and reflect on the wall of the closed structure, which will drive the liquid movement and produce the radial convergence, so that interferes the penetration behavior of the jet. Compared with the (a) in Figure. 1, it is found that the radial convergence effect of the liquid in the single-cell increases with the increase of the inner cavity height of the closed structure. The radial convergence effect of the liquid in the multi-cell also has the same phenomenon, but the liquid separation phenomenon occurs, which leads to the convergence of the liquid into segments. In addition, the pressure in the single-cell liquid appears at the bottom of the cell, and the pressure in the multi-cell liquid appears in the last cell. In combination with the simulation results (b) in Figure.1, the single-cell is concentrated on the bottom in a pressure distribution and is distributed in an annular shape; the pressure distribution of multi-cell is more uniform, and there is no obvious centralized distribution phenomenon. In contrast, the inter-layer of the multi-cell plays an important role in enhancing the stability of the cell, and it can make the liquid form the multi-stage convergence effect and produce the high-speed turbulence, which better interferes with the continuous penetration ability of the jet.

3.2 Energy

The energy consumption of the jet is another index to evaluate the anti-jet penetration performance of the liquid composite target. The more the absorbing energy of the liquid composite target, the more the penetration ability of the jet decreases. As can be seen from Figure. 2, the energy of the cell structure increases with the increase of the lumen height of the single-cell and the increase of the number of multi-cell. It can be found that the energy of the single-cell is higher than that of the multi-cell. According to the theoretical analysis above, the energy is divided into kinetic energy, internal energy and strain energy. But, the single-cell is fixed in the simulation, and the simulation process is adiabatic, so there is only strain energy. It is shown that the deformation of the single-cell is larger than that of the multi-cell, which is consistent with the above-mentioned analysis, and further proves the advantages of the multi-cell structure.

4. Conclusion

Through the comparison and analysis of the simulation results, the inter-layer of the multi-cell plays a strengthening role and further improves the force stability of the closed cell, and the multi-stage convergence effect of liquid formation can better interfere with the residual penetration ability of the jet. The deformation of the single-cell is larger than that of the multi-cell, so the strain energy of the single-cell is larger, which further proves the mechanical properties of the multi-cell subjected to jet penetration. Compared with references [5-11], the axial multi-cell has more excellent anti-penetration characteristics. The research work in this paper lays a foundation for the further development of the
liquid composite multi-cell structure.

Acknowledgments
This work was supported by Xiangtian University National College students Innovation Project (201810530018).

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