Simulation study on the influence of liquid level on anti-jet penetration ability of single-cell composite structure

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Abstract. The liquid composite armour produces transverse interference to the shaped charge jet through the backflow of liquid in the inner cavity, which affects the subsequent penetration ability of the jet. Within this article, a single-cell structure filled with water is taken as the research target. Through numerical simulation, the process of shaped charge jet penetrating the single-cell structure at different liquid levels is reproduced, and the parameters of the remaining jet after penetration, the interference of jet, and the deformation and energy absorption of shell are obtained. The results showed that the liquid level of liquid-filled single-cell structure has a significant influence on the anti-jet penetration ability of the single cell structure. When the liquid level was 60mm to 65mm, the water-filled single-cell structure has the best interference effect on the incoming shaped charge jet.

1. Introduction

With the development of weapon systems, the survivability of armoured vehicles such as tanks is becoming weaker and weaker. It is well known that the high-speed metal jet formed by the shaped charge is the enemy of armour, the anti-jet penetration performance of composite structures has become the focus of researchers and scholars in the field of armor protection this year. Because of its effective anti-jet penetration ability and low collateral damage, liquid composite armour is usually fitted to armoured vehicle as an additional armour. The liquid composite armour consists of a metal cover plate, the filled liquid, a metal shell and the fixed device. It uses the propagation of the shock wave in the liquid and the reflection on the inner wall of the structure to make the radial convergence of liquid, thus causing transverse interference to the incoming shaped charge jet.

Previously, in the research on the interaction between the projectile and the liquid-filled structure, most scholars focused on the expansion and collapse of cavity and the deformation and destruction of containers[1], and their original intention was to prevent the tank and other liquid-filled structures from being damaged. Interestingly, when the size of the liquid-filled structure is reduced to a certain extent, the small size liquid-filled structure can be used as a protective device, which can be interfered with the high-speed jet with high penetration capacity. Thus, a new type of composite armour began to be used in the military.

Up to now, there have been few studies on the resistance of liquid-filled structure to jet impact. In terms of experiments, J. J. White [2], Andersson [3], et al. demonstrated that the closed structure full of liquid has a good interference effect on the jet. E.S. Lee [4] explored the penetration process of jet
particles in water through high-speed photography and X-ray experiments. In terms of theoretical analysis, Held [5] modified Szendrei equations and obtained the remaking equations of jet penetration in water. Gao, Zhang and Guo et al. [6-10] analysed the propagation and reflection of shock wave in the liquid-filled structure and the process of liquid interfering the shaped charge jet under the action of shock wave, and their theory method can be used to calculate the influence velocity interval and residual penetration depth of the jet. Zhao, Shan, Cai, et al. [11-15] also did some research on numerical simulation. They analyzed the effect of size effect, parameters of liquid material and parameters of shell material on the armor resistance of liquid-filled composite structure through LS-DYNA or Autody.

At present, scholars’ research on the anti-jet penetration of liquid composite structure is limited to full-filled composite structure. In this paper, the anti-jet penetration performance of non-full liquid composite structure was studied, and a cylindrical unit in the liquid composite armour is selected as the research object, which called single-cell composite structure. The single-cell composite structure is composed of cover plate, filled liquid and shell. The diameter of the inner cavity of the single cell composite structure is 30mm, the height of the inner cavity is 70mm, the material of the cover plate and shell is 45 steel, the thickness is 5mm, and the filling liquid is water. By studying the interference caused by the single-cell composite structure at different liquid level to the shaped charge jet, we can obtain the influence law of liquid level on the anti-jet penetration ability of single-cell composite structure, and obtain the optimal liquid level range for the single-cell composite structure in this paper. The work in this paper will more clearly demonstrate the interaction between the liquid composite structure and the jet, and promote the structural design of liquid composite armour.

2. Model Construction
The fluid-solid coupling method was used to establish the simulation model in LS-DYNA. Among them, Euler mesh was used for explosive, air, liner and water, and Lagrange mesh was used for the shell of single-cell composite structure.

Due to the axial symmetry of the model, the 1/4 model has been established, which can improve the calculation speed, Figure 1. The Ø56mm uncased standard shaped charge was used in the simulation and the X-ray test. The shaped charge is an uncased cylinder with 56mm diameter and 73mm length, the cone liner is made using copper at a 60°angle and a 0.8mm thickness.

![Figure 1. Finite element model of jet penetrating single-cell composite Structure.](image)

3. Material Models

3.1. Explosive
The type of explosive used in the calculation is JH-2. The material type is High Explosive Detonate Model, and the Equation-of-State Form is JWL EOS. The JWL equation of state [17] defines pressure as a function of relative volume, \( \bar{V} \), and internal energy per initial volume, \( E \), as

\[
p(\bar{E}, \bar{V}) = A \left(1 - \frac{\omega}{R_1 \bar{V}}\right) e^{-R_2 \bar{V}} + B \left(1 - \frac{\omega}{R_1 \bar{V}}\right) e^{-R_2 \bar{V}} + \frac{\sigma E}{\bar{V}}
\]

(1)

Where \( \omega, A, B, R_1 \) and \( R_2 \) are user defined input parameters.
Table 1. Parameters of explosives in simulation.

| $\rho_0$ (g cm$^{-1}$) | $D$ (cm s$^{-1}$) | $E_0$ (GPa) | $P_C$ (GPa) | $A$ (GPa) |
|-------------------------|------------------|-------------|-------------|-----------|
| 1.695                   | 0.8425           | 9.5         | 29.66       | 854.5     |
| $B$ (GPa)               | $R_1$            | $R_2$       | $\omega$   | $V_0$     |
| 20.493                  | 4.6              | 1.35        | 0.25        | 1         |

3.2. Copper

The liner material is red copper. The Johnson-Cook strength model and the Gruneisen EOS are adopted for the copper. The Johnson-Cook equation can be expressed as

$$p = \rho_0 C^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2}\right) \mu - \frac{a}{2} \mu^2 \right] + \left(\gamma_0 + a\mu\right)E, \quad \mu > 0$$

(2)

$$p = \rho_0 C^2 \mu + \left(\gamma_0 + a\mu\right)E, \quad \mu \leq 0$$

(3)

Where $\mu = \rho\rho_0^{-1} - 1$, $\rho$, $\rho_0$, $C$, $\gamma_0$, $a$ can be obtained by experiment.

Table 2. Parameters of liner material in simulation.

| $\rho_0$ (g (cm$^3$)$^{-1}$) | $G$ (GPa) | $T_m$ (K) | $T_i$ (K) | $\gamma_0$ |
|-----------------------------|-----------|-----------|-----------|------------|
| 8.960                       | 47.7      | 1360      | 293       | 1.99       |

| $C$ (m·s$^{-1}$) | $S_1$ | $S_2$ | $S_3$ |
|-----------------|------|------|------|
| 3940            | 1.49 | 0    | 0    |

3.3. 45# Steel

The Johnson-Cook strength model and the Gruneisen EOS are adopted for the 45# steel.

Table 3. Parameters of shell material in simulation.

| $\rho_0$ (g (cm$^3$)$^{-1}$) | $G$ (GPa) | $T_m$ (K) | $T_i$ (K) | $A$ (GPa) | $B$ (GPa) |
|-----------------------------|-----------|-----------|-----------|-----------|-----------|
| 7.83                        | 77        | 1760      | 294       | 350       | 300       |

| $C$ (m·s$^{-1}$) | $S_1$ | $S_2$ | $S_3$ | $\gamma_0$ | $A$ |
|-----------------|------|------|------|-------------|---|
| 4569            | 1.49 | 0    | 0    | 2.17        | 0.46 |

4. Verification of simulation method

Fluid-solid coupling method was used to calculate the process of jet penetrating single-cell composite structure. Figure 2 described the shape of the jet at 30µs and 50µs, as well as the interference after the jet penetrated the single-cell liquid composite armor. Figure 3 showed the jet morphology at different time taken by two pulse X-ray machines [7].

Figure 2. The simulation results of jet molding.
Figure 3. X-ray test results of jet molding.

The X-ray test results are compared with the simulation results, as shown in table 4.

| Comparison     | Velocity of the tip of formed jet (m·s⁻¹) | Velocity of the tail of formed jet (m·s⁻¹) |
|---------------|------------------------------------------|------------------------------------------|
| Simulation    | 6328                                     | 1230                                     |
| X-ray test    | 6510                                     | 1189                                     |
| Relative error| 2.8%                                     | 3.4%                                     |

According to the comparison results of the X-ray tests and simulation, the relative error of the shaped of jet molding is within the acceptable range. Therefore, the simulation model and the simulation method in this paper are reliable.

5. Analysis of numerical simulation results

In this work, a series of simulations are carried out for the process of jet penetrating single-cell composite structures with a liquid level height vary from 0mm to 70mm. From 0mm to 70mm, the interval size is set to 5mm, and there are 15 working conditions in total. For the simulation of each working condition, we calculated the fracture position, necking position and head velocity of the residual jet, and the statistical results are shown in figure 4.

It can be seen that when the liquid level height is from 0 to 15mm, the single-cell composite structure has no effect on jet almost. When the liquid level height is from 20mm to 25mm, the single-cell composite structure has slight interference to the jet. When the liquid level height is 30mm to 55mm, the single-cell composite structure has moderate interference on the jet. When the liquid level height is from 60mm to 70mm, the single-cell composite structure caused a serious interference effect on the jet. It can be intuitively seen from figure 4 that the liquid level height is 60mm, the interference velocity of the jet is the largest, and the fracture points are evenly distributed.
According to the simulation results, we divided the interference of single-cell composite structure on jet into four degrees: no obvious interference, light interference, moderate interference and obvious interference. We selected four liquid level height from the four interference-degree range respectively to compare the interaction between the jet and the liquid at a certain time.

By comparing Figures 5, 6, 7 and 8, we can find that when the liquid level height increases, the interaction range between the liquid and the jet increases at 50μs. In addition, the deformation of the shell increases with the rise of the liquid level.
Figure 7. The interaction between jet and a single-cell composite structure with a liquid level of 45mm at 50μs.

Figure 8. The interaction between jet and a single-cell composite structure with a liquid level of 60mm at 50μs.

Figure 9 shows the shaped of residual jet and the velocity range of the interfered jet after the jet passed through the single-cell composite structure with a liquid level of 0mm, 15mm, 30mm, 45mm, 60mm and 70mm, while figure 10 shows the deformation of shell of single-cell composite structure. It can be seen that, before reaching the optimal liquid level height, the interference effect of the composite structure on the jet is strengthened, and the deformation of the shell is increased with the increase of the liquid level height.

Figure 9. The shape of the jet at 100μs(From top to bottom, the liquid level height is 0mm, 15mm, 30mm, 45mm, 60mm, 70mm).

Figure 10. Deformation of shell of single-cell composite structure at 100μs(From left to right, the liquid level height is 0mm, 15mm, 30mm, 45mm, 60mm, 70mm).

Figure 11 shows the kinetic energy travel curve of the shell of single-cell composite structure with different liquid level height. The peak of the kinetic energy curve of the shell of the single-cell structure with the liquid level height of 60mm and 65mm is lower than that of the shell of the full-filled single-cell composite structure. This proves that the shell deformation of single-cell composite structure is small when the filling liquid is less, which is beneficial to ensure the integrity of the structure and prolong the
interaction time between liquid and jet. However, too little filling liquid in single-cell structure composite structure is not conducive to interference of shaped charge jet. Therefore, it is very important to find out the optimum liquid level height for each liquid composite structure.

Figure 11. The Kinetic energy travel curve of the shell of single-cell composite structure with different liquid level height(60mm-blue, 65mm-green, 70mm-black).

6. Conclusion

Through the above analysis, we can get the following conclusions:

A. For single-cell composite structures with cavity diameter of 30mm and cavity height of 70mm, the interference effect of single-cell composite structures on jet is best when the liquid level height is 60mm to 65mm.

B. It is crucial to find out the optimum liquid level height for each kind of single-cell composite structure.

C. The pressure in the single-cell composite structure full filled with water is the largest, resulting in the maximum deformation of the shell.

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