Simplified Model and Numerical Simulation of Tube-Rod Extended Penetrator

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Abstract—Through the research and analysis of tube-rod extended penetrator vertically penetrating limited thick target, a simplified model of tube-rod extended penetrator vertically penetrating semi-infinite thick target is proposed based on hydrodynamics and penetration mechanics. At the speed of 1470-1770m/s, numerical simulation of tube-rod extended penetrator vertically penetrating limited thick target is conducted with the usage of LS-DYNA. The theoretical calculations and numerical simulation results agree with each other greatly. The tube-rod extended structure has been optimized through numerical simulation. The extended structure with connectors forms lateral drift reflux in penetration, which reduces the penetration efficiency. This adverse effect is alleviated by connectors plus plug plan, with a maximum efficiency gain of 18.1%

Index Terms—extended penetrator, simplified model, numerical simulation, Connectors, reflux

I. INTRODUCTION

In this paper, through a practical case study, the application of RE to the shape matching of a car is explained in detail. In order to solve the problems of large L/D rod penetrator including fire, flight and impact, we proposed the extended structure which with a small shell core can also achieve a long penetrator. In impact speed and the L/D reaches a certain value, the depth of penetration of long rod penetrator will have a limit value and segmented rods is not subject to this limitation [1,2]. Penetration of segmented rods is a cumulative effect, that is, it is the sum of segments consisting of penetration effect. Frank and Zook[3] theoretically concluded each aspect ratio L/D=1 on a segmented rod in deep larger merit than the long rod. In all telescopic penetrator, the extended penetrator is one of the most promising and therefore receive widespread attention [4]. V.A.Veldanov et al. [5] have carried out study on the inside to outside diameter ratio of tube in the tube penetration for the experiment and numerical simulation. Edmond


II. SIMPLIFIED PENETRATION MODEL AT THE JUNCTION OF ROD AND TUBE

A. Penetration Description

At the speed of 1500-2000m/s, the penetration of the special-shaped penetrator can be roughly divided into four stages:

1. Crater opening stage: When the front thick rod hits the target, two reverse compression wave propagated in the rod and target respectively. The compression wave in the rod becomes very weak and can be ignored quickly while exceeding 2-3 times of the projectile diameter. Due to the high-temperature and high-pressure target and the plastic deformation and destruction of the rod close to the collision, the eroded material splashes out along the crater surface. Due to plastic flow and splash of the target, the crater is formed on the target, namely the crater opening stage.

2. Front-end thick rod penetration stage: When broken material and penetration speed totally discharge in reverse direction, penetration enters into the steady stage. The rod hits the target with a high speed, and the crater is deepening. Part of the broken projectile and target residue remain in the crater, and the rest discharge in reverse direction out of the crater along the sides of the rod. The thick rod becomes shorter and disappears with the processing of penetration and that is the end of this stage.

3. Intermediate tube penetrating stage: When the thick rod is completely broken, the tube in the middle starts its penetration. The residue of the tube discharges in reverse direction inside and outside of the tube. The “core” in the center of the tube breaks and discharges by a constant tensile stress. When the back-end thin rod hits the target, this stage ends.

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4 Back-end thin rod penetration stage: When the middle tube breaks and thin rod hits the target, the back-end rod continues to penetrate. The length of the thin rod is shortening and the energy of it continues to decline. When the material speed at the bottom of the crater is reduced to zero, the penetration ends completely.

B. Basic Assumptions in Penetration

1 Penetrator vertically penetrating the target can be seen as a one-dimensional quasi-steady movement. The physical quantity changes slowly over time, therefore, before and after some moment, the physical image of the movement is basically the same.

2 The target has a bilinear hardening constitutive relation, extended penetrator is made of ideal rigid-plastic material; and both materials are incompressible in penetration. If the maximum compressive stress the penetrator can withstand is \( Y_p \), then \( Y_p = \sigma_{icD} \), namely the extended penetrator material is more dynamic compressive.

3 Based on the cavity expansion theory [10], \( p_1 \), the resistance given to the front-end tube in penetration by opening the target material, consists of two parts, namely \( p_1 = p_{s1} + p_{i} \). \( p_{s1} \) is static resistance, and \( p_{i} \) is dynamic resistance. The tube in the middle is not affected by \( p_1 \) in penetration, but also by \( p_{s1} \), the force needed to take out the “target core”, \( p_2 = \sigma_{icD}^{D} \). So the force of tube is \( p = p_1 + p_2 \).

4 In the early period of crater re-opening stage, when the projectile touches the target, the static resistance given to the penetrator by the target equals to the pressure applied to the surface by the static punching, that is the HB value, or the hardness of the material. When the depth of penetration exceeds 1 time of the projectile body, \( Y_1 \), the movement equation is

\[
\frac{dv}{dt} = -\left(v - u + u_{f}\right)\left(1 - \mu^{2}\right) + \frac{1}{2} \rho \Delta u^{2} \pi R^{2} - p R = 0
\]

In the above equation, \( Y_1 \) is the dynamic yield strength of the projectile body, \( \rho \) is the density of it, and \( u_{f} \) is the degree of reflux of the projectile materials. \( p = p_{s1} + p_{i} \), \( p_{s1} \) is static resistance, and \( p_{i} \) is dynamic resistance. Their expressions are as follows:

\[
p_{s1} = \frac{2}{3} \sigma_{ic} \left(1 + \ln \frac{2E}{3\sigma_{ic}}\right) + \frac{2\pi}{27} E_{u} = R_{p}, \quad p_{i} = \rho \left(\frac{D_{c} du}{2} + \frac{3}{2} u^{2}\right)
\]

In the above equation, \( E_{u} \) is the target hardening modulus. The expression derived by M Lee [10] two-phase expansion theory can be used to get the \( D_{c} \) value.

\[
D_{c} = D_{c1} \sqrt{1 + \frac{1}{4} \left(1 - (\mu/D_{c1})\right) \rho \Delta u^{2}}
\]

In the above equation, the expression of \( D_{c1} \) is by
D_{t} = \sqrt{r_{i}^2 \left(\frac{1-d^2}{T^2}\right) + 2(1-\mu^2) S} \frac{\ln[1+2T+2\sqrt{T+T^2}]}{\sqrt{T+T^2}}

which

\eta_i = \sqrt{\frac{(1-\mu^2)}{4} + \frac{2(1-\mu^2) S}{1+T}} \quad S = \frac{1}{2} \rho_i (v-u)^2

T = \frac{1}{2} \rho_i u^2

(2.7)

In addition, we can know based on the law of conservation of mass:

\left(\frac{v_i - u}{(1-\mu^2)}\right) r^2 + \left(\frac{v_r - u}{\mu^2}\right) \mu^2 r^2 = u \frac{D_{r}}{2} - r^2

(2.8)

The length variation of the tube and rod is as follows:

dl_i/dt = -(v_i - u) \quad dl_r/dt = -(v_r - u)

(2.9)

The speed variation of the tube and rod is as follows:

\rho_r \rho_i dl_i/dt = -Y_{p} \quad \rho_r \rho_i dl_r/dt = -Y_{p}

(2.10)

The penetration depth variation is:

dx/dt = u

(2.11)

Initially, \( v_{i0} = v_0 \), \( l_{i0} = l_0 \), among which, \( v_0 \) and \( l_0 \) are the initial velocity and the initial length of the penetrator.

D. The Model and Numerical Calculation Results

In Figure 2, the curve represents the model calculation results (in which \( Y_{p} \) and \( R_{p} \) are 1860 MPa and 5077 MPa respectively, \( \rho_{p} \) and \( \rho \) are 17.6 g cm\(^{-3}\) and 7.85 g cm\(^{-3}\)), the black boxes represent the numerical simulation results of the general extended penetrator. The errors between numerical simulation and model calculation are 1.9 %, 2.5%, 1.4%, 1.1% respectively. It can be concluded that the simplified model can reflect the penetration depth of the tube-rod extended penetrator.

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compare their performance effectively, the quality the four projectiles core in the simulation of are all 3.2kg. Their kinetic energy while hitting the target is the same with the same muzzle velocity.

As can be seen in Figure 4, since the energy of baseline rod is concentrated in the process of penetration, it produces relatively smooth crater walls with large diameter of after penetration, causing too much energy consumption of penetration depth units and reducing the depth of penetration. Other three extended penetrators forms rough crater walls and their diameters are smaller than the baseline rod. However, the energy consumption of penetration depth unit is reduced with a fixed amount of energy, which provided the preconditions for the increase in penetration merit.

In the speed of 1570m/s, compared with the baseline rod, the extended penetrator with connectors produced the worst depth merit, the merit is almost zero and its penetration is less deeper than the extended structure. While at the other three speeds, the penetration of the extended penetrator with connectors is deeper than the general extended ones. This is because the uneven erosion of the material reflux hits the target first and causes the deflection of the penetrator.

It can be seen from Figure 5 and Figure 6 that, there is a linear increase in the penetration depth of the baseline rod with the increasing speed; the gain rate of the extended penetrator increases first and then decreases; the gain of extended penetrator with connectors is greater than the general extended one, except influenced by the lateral drift reflux at the speed of 1570m/s. We can see from the simulation results that the extended penetrator with connectors and plugs relieves the influence by the lateral drift reflux at the speed of 1570m/s. As the speed increases, its penetration gain shows an upward trend. At the speed of 1770m/s, the gain of the extended penetrator with connectors and plugs gain reaches 18.1%.

**IV. CONCLUSIONS**

It can be found through the above model calculation and numerical simulation results that: Numerical simulation and simplified theoretical model agree with each other quite well, demonstrating that the built model can describe the tube-rod extended penetrator penetrating the limited thick target. This provides a basis for further study of the penetration mechanism of extended penetrators. The extended penetrator with connectors and plugs can relieve the bad influence by the lateral drift reflux and increase the gain stably compared with the extended penetrator with connectors. The maximum gain of the extended penetrator with connectors and plugs can reach 18.1% in the simulation speed range.

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