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, f 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 conducted extended penetrator of the double bomb core numerical simulation on the angle of attack and exsertion of the process [6]. N.J.Lynch[7] and Han Yong-yao[8] done a certain amount of research on tube body on the contribution of penetration depth. Han [4] and Fang [9] have done a certain research on the extended penetrator of the rod in the front tube in after.

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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.

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 $Y_p = \sigma_{bc}^D$, 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 $p_1=p_s+p_i$. p_s is static resistance, and p_i is dynamic resistance. The tube in the middle is not only affected by p_1 in penetration, but also by p_2 , the force needed to take out the "target core", $p_2 = \sigma_{bt}^D$. 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 diameter, the crater opening stage completes and the static resistance reaches R_t at the moment.

5 When the thick rod the front end of the penetrator is penetrating, the latter part can be equivalent to it with the same diameter and quality. In a similar way, when the middle tube is penetrating, the thin rod behind it equals to it with the same quality. Assume the penetration of the entire penetrator is a continuous process, namely the end conditions of one stage are start conditions of the one after it.

C. Basic Penetration Model Building

Based on the assumption of one-dimensional movement, we only consider the part of the movement when the penetrator moves in the target along the penetration direction. When the tube or rod hits the target with the speed v at the time t, the rod length or the tube length is $l = l(t)$, the velocity is $v = v(t)$, the velocity at the crater bottom is $u = u(t)$, the movement speed relative to the crater bottom is $(v-u)$, then the equation for the penetrator length change is

$$dl/dt = -(v-u) \tag{2.1}$$

The penetrator slows down with the influence of Y_p , its movement equation is

$$\rho_p l \, dv/dt = -Y_p \tag{2.2}$$

In this equation: ρ_p is the density of the projectile body, Y_p is the maximum compressive stress which the penetrator can withstand. The relation between u , the velocity at the crater bottom and, x the penetration depth is

$$u = dx/dt \tag{2. 3}$$

The motion equations of residue at the crater bottom in the rod penetration. According to Zhao Guozhi, if we assume that only a small part of the residue produced by the rod hitting remains at the crater bottom, then the quality and speed of this part changes slowly with the passing time.

As shown in Figure 1, taking the control volume as research subject is similar to the method adopted by Han[4], to establish the momentum conservation equation at the direction of x . Set the movement speed at the plane surface $x=x_i$, namely the penetration speed is u , the speed of the tube is v_t , the speed of the rod is v_r ; the outside diameter of pipe is r , the diameter ratio is μ , the crater diameter is D_c , then the momentum conservation equation at the direction of x is:

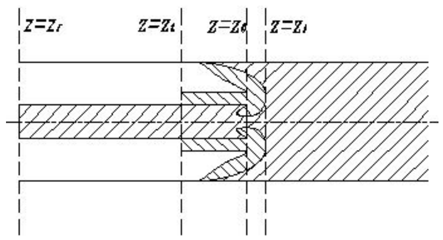

Figure1. Schematic illustration of extended penetrator penetrating the target

$$\begin{aligned} &Y_p\pi + \rho_p\left(v_t-u\right)\left(v_t-u+u_f\right)\pi\left(1-\mu^2\right)r^2 + \\ &\rho_p(v_r-u)(v_r-u+u_f)\pi\mu^2r^2 + \frac{1}{2}\rho_t u^2\pi\mu^2r^2 - p\left(\frac{\pi D_c^2}{4}\right) = 0 \end{aligned} \tag{2.4}$$

In the above equation, Y_p is the dynamic yield strength of the projectile body, ρ_p is the density of it, and u_f is the degree of reflux of the projectile materials. $p=p_s+p_i$. p_s is static resistance, and p_i is dynamic resistance. Their expressions are as follows:

$$p_s = \frac{2}{3}\sigma_{st}\left(1+\ln\frac{2E_t}{3\sigma_{st}}\right) + \frac{2\pi^2}{27}E_{tt} = R_t \quad p_i = \rho_t\left(\frac{D_c}{2}\frac{du}{dt} + \frac{3}{2}u^2\right) \tag{2.5}$$

In the above equation, E_{tt} 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.

$$D_c = D_{c1}\sqrt{1+\frac{1/4(1-(\mu/D_{c1}))\rho_t u^2}{R_t}} \tag{2.6}$$

In the above equation, the expression of D_{c1} is by

$$D_{c1} = \sqrt{r_1^2 + \frac{(1-\mu^2)S}{\sqrt{T+T^2}}\ln[1+2T+2\sqrt{T+T^2}\,]}$$ among

which

$$r_1 = \sqrt{\frac{(1+\mu)^2}{4} + \frac{2(1-\mu^2)\ S}{1+T}} \qquad S = \frac{1/2\rho_p(v-u)^2}{R_t}$$

$$T = \frac{1/2\rho_t u^2}{R_t} \tag{2.7}$$

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

$$(v_t-u)(1-\mu^2)r^2 + (v_r-u)\mu^2 r^2 = u_f\pi\left(\frac{D_c}{2}-r\right)^2 \tag{2.8}$$

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

$$dl_t/dt = -(v_t-u) \qquad dl_r/dt = -(v_r-u) \tag{2.9}$$

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

$$\rho_p l_t\, dv_t/dt = -Y_p \qquad \rho_p l_r\, dv_r/dt = -Y_p \tag{2.10}$$

The penetration depth variation is:

$$dx/dt = u \tag{2.11}$$

Initially, $v_{t0} = v_0$, $l_{t0} = l_0$, 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_t are 1860 MPa and 5077 MPa respectively, ρ_p and ρ_t are $17.6 g\cdot cm^{-3}$ and $7.85 g\cdot cm^{-3}$), 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.

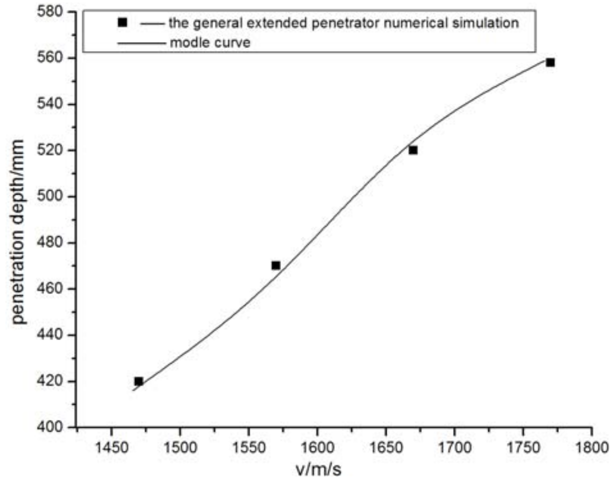

Figure 2. Theoretical calculations and numerical simulation results

III. NUMERICAL SIMULATION STUDIES

A. Finite Element Model and Material Param

TABLE I.
MATERIAL PARAMETERS OF PENETRATOR AND TARGET

Type	$\rho/g\cdot cm^{-3}$	μ	A/MPa	B/MPa	C	n	m	T_{melt}/K	T_{room}/K
93W	17.6	0.28	1506	177	0.008	0.12	1.0	1450	294
LC4	2.77	0.33	426	265	0.015	0.34	1.0	775	294
RHA603	7.85	0.22	792	180	0.016	0.12	1.0	1520	294
steel45	7.83	0.22	350	30	0.014	0.26	1.03	1760	294

3D numerical simulation is carried out for the penetration course by LS-DYNA, which calculates penetration merit for several 93W alloy extended penetrator contrasted to baseline rod normal penetrating RHA603 armor steel target. The penetrators and the targets both adopt the Johnson-Cook material model, Gruneisen equation of state is used in the calculation. Erosion algorithm is adopted while calculating the contact of penetrators and targets: ERODING _SURFACE_TO_SURFACE. It can be used together with the failure criterion of bias stress tensor: when the element effective plastic strain achieved the failure strain or when the element pressure reaches the minimum failure pressure, the element becomes invalid. We use the Language law for the grid division. Penetrators and targets element types are both SOLID164, the grid cell shape is eight-node hexahedron.Given the symmetry of the problem, we use 1/2 of models during the simulation of penetrators and targets. Basic material parameters as shown in table 1.

B. Numerical Simulation Results and Analysis

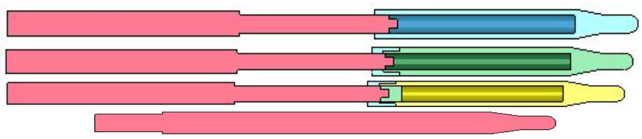

Figure 3. Several extended simulation structure

In this article, numerical simulation of four penetrators, at the speed of 1470m/s-1770m/s is conducted and analyzed. In Figure 3, we can see the structure of the four penetrators respectively: extended penetrator, extended penetrator with connectors, extended penetrator with connectors and plugs, and baseline rod. In order to 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.

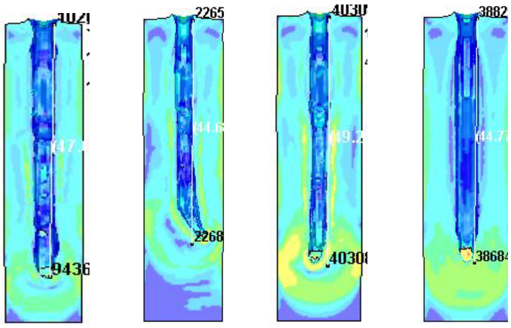

Figure 4. Penetration depth at the speed of 1570m/s

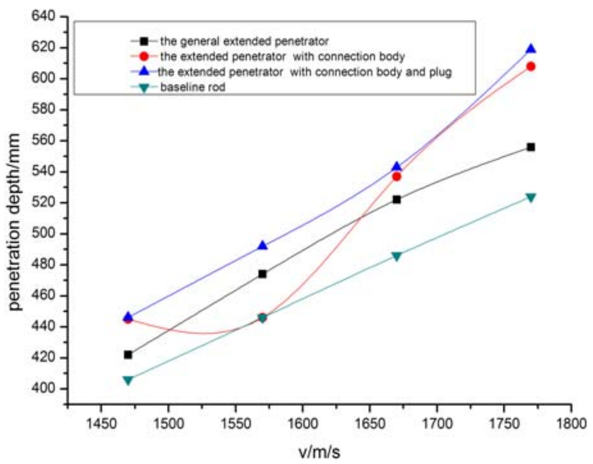

Figure 5. Penetration depth curve

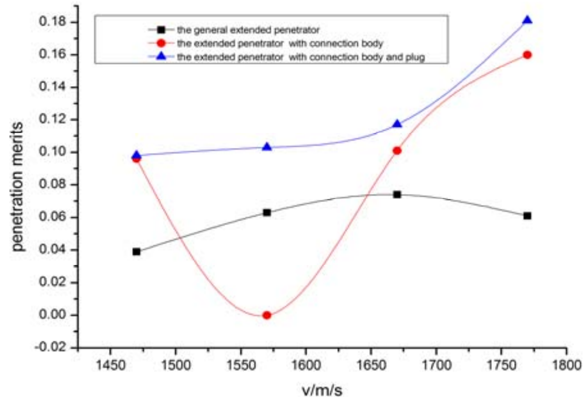

Figure 6. Penetration gain curve

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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