ON THE NORMAL PERFORATION OF THICK METALLIC PLATES BY A SHARP NOSE RIGID PROJECTILE*

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The normal perforation of thick metallic plate by sharp nose rigid projectile is studied in the present paper based on the general penetration resistance, which contains the terms of damping effect and the dummy mass of projectile induced by the deceleration effect. The terminal ballistic formulae with four dimensionless parameters are introduced, i.e., the impact function *I*, geometry function *N*, the damp function ξ and the dimensionless target thickness χ. Theoretical predictions of perforation dependent/independent of the damping function ξ, show good agreement with the individual published test data of different projectiles and impact velocities as well as different targets.

INTRODUCTION

Dynamic cavity expansion model has been taken as one of the most effective theoretical models in predicting the ballistic effect of dynamics of rigid projectile. Penetration resistance includes not only the static strength term of target material and flow stress term, but also the damping effect of target material. The effect of dummy mass caused by hypervelocity impact becomes more and more distinct, while it is always omitted in the formulation of dynamic cavity expansion theory because of mathematical simplification. The general formula of penetration resistance is

$$\sigma = a + bv + cv^2 + e\dot{v} \tag{1}$$

Where a, b, c and e are material coefficients and v is the velocity of cavity expansion.

Based on the dynamic cavity-expansion model, the normal perforation of thick metallic plate by sharp nose rigid projectile is studied in the present paper. Besides the impact function I, geometry function N and dimensionless thickness of target χ, the fourth dimensionless parameter, i.e., the damping function ξ is introduced to predict ballistic limit and residual velocity. Theoretical predictions of the model show good agreement with the individual published test data.

THE THIRD DIMENSIONLESS NUMBER

The resulting axial resistant force on the projectile nose can be integrated from the normal compressive stress and the tangential stress, which are formulated from the dynamic cavity expansion analysis. We have

$$F_x = \frac{\pi d^2}{4}\left[AYN_1 + B\rho V^2 N_2 + \left(C\sqrt{\rho Y}\cdot V + D\rho d\cdot\dot{V}\right)N_3\right] \tag{2}$$

Where Y and ρ are yielding stress and density of target material, respectively. A, B, C and D are dimensionless material constants of target. N_1、N_2 and N_3 are three dimensionless parameters relating to nose shape of projectile and friction [1].

Based on the general expression of penetration resistance, Chen et al.[1] introduced the third dimensionless parameter, i.e., the damping function, ξ, besides the impact function I and geometry function N of projectile introduced early [2,3],

$$\xi = \frac{C^2}{4AB} \tag{3}$$

Only three dimensionless numbers, i.e. the impact function I, geometry function of projectile N and damp function ξ, are dominant parameters to determine the dimensionless depth of penetration (DOP) into a target impacted by a rigid projectile.

$$\frac{X}{d} = \frac{2}{\pi} N \left\{ \ln\left(1 + 2\sqrt{\xi \frac{I}{N}} + \frac{I}{N}\right) - \int_{\sqrt{\xi}}^{\sqrt{I/N}+\sqrt{\xi}} \frac{2\sqrt{\xi}\, d\overline{U}}{\left[\overline{U}^2 + (1-\xi)\right]} \right\} \tag{4}$$

An actual equation of dimensionless DOP only exists in the case of $\xi < 1$, therefore the corresponding dimensionless penetration depth can be obtained

$$\frac{X}{d} = \frac{2}{\pi} N \left\{ \ln\left(1 + 2\sqrt{\xi \frac{I}{N}} + \frac{I}{N}\right) - \frac{2\sqrt{\xi}}{\sqrt{1-\xi}} \left[\tan^{-1} \frac{\sqrt{I/N} + \sqrt{\xi}}{\sqrt{I-\xi}} - \tan^{-1} \frac{\sqrt{\xi}}{\sqrt{I-\xi}} \right] \right\} \tag{5}$$

PERFORATION OF THICK PLATES BY SHARP-NOSED PROJECTILE

The normal perforation of thick metallic plate by sharp-nose rigid projectile is studied based on the general penetration resistance and above three dimensionless parameters. For a projectile with sharp nose, plugging stage is usually omitted and only penetration (or hole enlargement) dominates in the whole perforation process. Perforation occurs when the nose tip of projectile reaches the rear surface of the target. We define $\chi = H/d$ is the dimensionless thickness of plate and H is the target thickness. The residual or exit velocity of the projectile is assumed to be V_r. The boundary effect of rear free surface is negligible, eq.(5) is re-written as

$$\chi = \frac{2}{\pi} N \left\{ \ln\left(\frac{1 + 2\sqrt{\xi \frac{I}{N}} + \frac{I}{N}}{1 + 2\sqrt{\xi \frac{I_r}{N}} + \frac{I_r}{N}} \right) - \frac{2\sqrt{\xi}}{\sqrt{1-\xi}} \left[\tan^{-1} \frac{\sqrt{\frac{I}{N}} + \sqrt{\xi}}{\sqrt{1-\xi}} - \tan^{-1} \frac{\sqrt{\frac{I_r}{N}} + \sqrt{\xi}}{\sqrt{1-\xi}} \right] \right\} \tag{6}$$

Where $I_r = \dfrac{M_m V_r^2}{A N_1 d^3 Y}$ is the impact function corresponding to the residual velocity V_r.

Ballistic limit is achieved at critical perforation with zero residual/exit velocity, i.e., $V_r = 0$. In that case, we have,

$$\chi = \frac{2}{\pi} N \left\{ \ln\left(1 + 2\sqrt{\xi \frac{I_{BL}}{N}} + \frac{I_{BL}}{N}\right) - \frac{2\sqrt{\xi}}{\sqrt{1-\xi}} \left[\tan^{-1} \frac{\sqrt{I_{BL}/N} + \sqrt{\xi}}{\sqrt{1-\xi}} - \tan^{-1} \frac{\sqrt{\xi}}{\sqrt{1-\xi}} \right] \right\} \qquad (7)$$

where $I_{BL} = \dfrac{M_m V_{BL}^2}{A N_1 d^3 Y}$ corresponds to the ballistic limit V_{BL}. From eqs.(6) and (7), it can be formulated as follows.

$$\begin{aligned} &\ln\left(1 + 2\sqrt{\xi \frac{I_r}{N}} + \frac{I_r}{N}\right) - \frac{2\sqrt{\xi}}{\sqrt{1-\xi}} \left[\tan^{-1} \frac{\sqrt{\frac{I_r}{N}} + \sqrt{\xi}}{\sqrt{1-\xi}} - \tan^{-1} \frac{\sqrt{\xi}}{\sqrt{1-\xi}} \right] \\ &= \ln\left(\frac{1 + 2\sqrt{\xi \frac{I}{N}} + \frac{I}{N}}{1 + 2\sqrt{\xi \frac{I_{BL}}{N}} + \frac{I_{BL}}{N}} \right) - \frac{2\sqrt{\xi}}{\sqrt{1-\xi}} \left[\tan^{-1} \frac{\sqrt{\frac{I}{N}} + \sqrt{\xi}}{\sqrt{1-\xi}} - \tan^{-1} \frac{\sqrt{\frac{I_{BL}}{N}} + \sqrt{\xi}}{\sqrt{1-\xi}} \right] \end{aligned} \qquad (8)$$

In general, the ballistic limit V_{BL} and residual velocity V_r may be solved with Eq.(7) and Eq.(8), respectively. Some special simplified cases in engineering application will be further given in next Section.

SPECIAL CASES OF PERFORATIONS

Case of $\xi = 0$

Without considering the damping effect in the perforation process, the simplified ballistic limit and residual velocity are obtained from eqs.(7) and (8) respectively when $\xi = 0$, which have the same forms as those in [4].

$$V_{BL}^2 = \frac{A N_1 Y}{B N_2 \rho} \left[\exp\left(\frac{\pi \chi}{2N}\right) - 1 \right] \qquad (9)$$

$$V_r = \sqrt{\frac{\left(V_0^2 - V_{BL}^2\right)}{\exp\left(\frac{\pi\chi}{2N}\right)}} \tag{10}$$

Case of $I/N \to 0$

Usually a sharp nose projectile has a large value of geometry function N, while it perforates a metallic plate at a relative low impact velocity, i.e., with a small impact function I. Thus, we have $I/N \to 0$ [4]. It indicates that the value of damping function ξ is smaller for most of experimental results in the next section, i.e., $\xi < 0.1$. With Comparing to I and N, the influence of damping function ξ on the penetration capability is consistent and smaller, and its deviation from early analysis is lower than 15%. Thus, it may be further simplified as,

$$V_{BL} = \sqrt{\frac{AN_1Y}{BN_2\rho}}\left[\frac{\xi}{1-\xi}\sqrt{\xi} + \sqrt{\frac{\pi\chi}{2N}}\right] \tag{11}$$

$$\left[\frac{I_r}{N} - \frac{2\xi\sqrt{\xi}}{(1-\xi)}\sqrt{\frac{I_r}{N}}\right] = \left[\frac{I}{N} - \frac{2\xi\sqrt{\xi}}{(1-\xi)}\sqrt{\frac{I}{N}}\right] - \left[\frac{I_{BL}}{N} - \frac{2\xi\sqrt{\xi}}{(1-\xi)}\sqrt{\frac{I_{BL}}{N}}\right] \tag{12}$$

If $\xi < 0.01$, the effect of damping function ξ is regarded as completely ignored, and much simpler formulae can be conducted from eqs.(11) and (12)

$$V_{BL} = \sqrt{\frac{\pi\chi AN_1Y}{2\lambda\rho}} \tag{13}$$

$$V_r = \sqrt{V_0^2 - V_{BL}^2} \tag{14}$$

EXPERIMENTAL ANALYSIS

Experimental data from [5,6,7,8] are compared with the present analytical predictions on ballistic limit and residual velocity.

Figs.1-4 show the experimental results and corresponding theoretical predictions. For an impact at higher velocity, a projectile always perforates a target plate with reserving most of the kinetic energy. In other words, with further increasing the impact velocity, residual velocity of projectile will be rather close to the impact velocity which being as an asymptote. Therein, the individual modeling of ballistic performance always approach the test results as well at higher initial impact velocity. However, it is nearby the ballistic limit that obvious difference may exist between the various theoretical predictions and test results.

The present discussion focuses on the ballistic limit. According to Figs.1-4, it improves the target resistance against penetration by introducing damping function ξ, and thus, the ballistic limit increases while the residual velocity decreases a little bit with comparing to that in Chen and Li [4]. However, after accounting for the dummy mass, the ballistic limit may decrease and even become smaller than the prediction of Chen and Li [4], while being more close to the test results. The dummy mass is beneficial for improving the ballistic performance of projectile. In general, the damping function ξ conflicts with the dummy mass M_m and compensate for each other in a penetration. A theoretical prediction which takes into account ξ and M_m simultaneously may become more appropriate in practice. It is worth mentioned that dummy mass has little influence on the residual velocity and can be neglected for perforation of metallic target by sharp nose projectile, which is determined by eq.(8). According to the definition of I and N, the ratio of I/N (including I_r/N and I_{BL}/N) is independent of modified mass of projectile.

The general formula of penetration resistance, which contains the terms of damping effect and dummy mass of projectile, had been proposed in 50s of last century, and the damping coefficient C can be defined by dynamic cavity expansion theory.

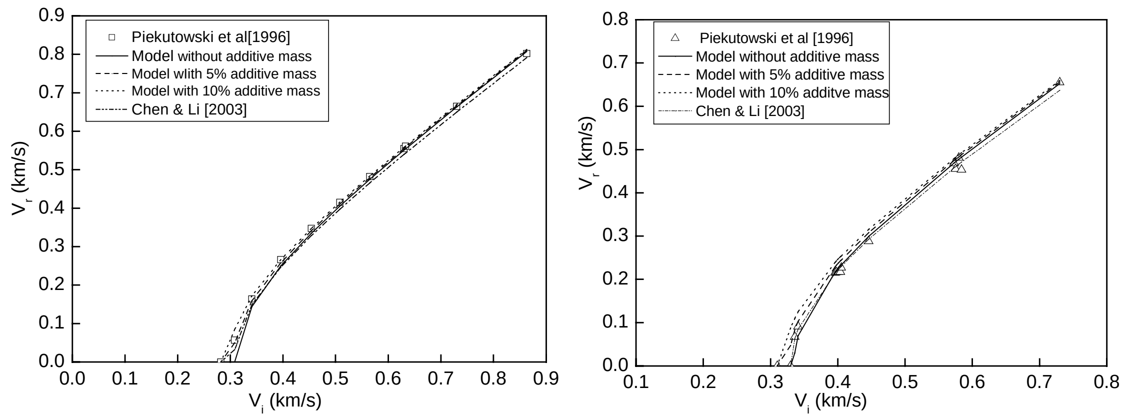

Figure 1. Prediction of residual velocity and test data [5]

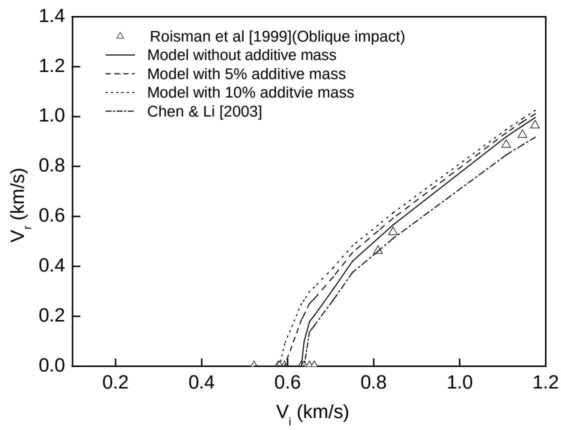

Figure 2. Prediction of residual velocity and test data [6]

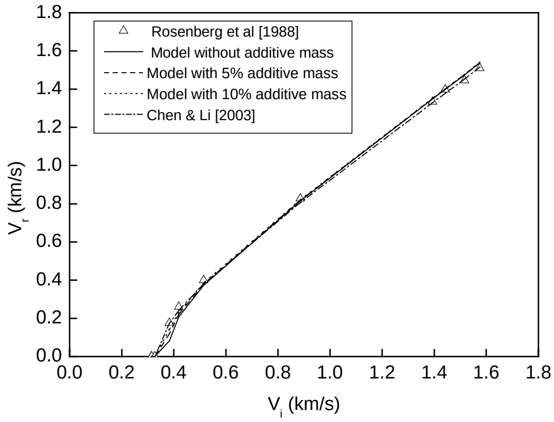

Figure 3. Prediction of residual velocity and test data [7]

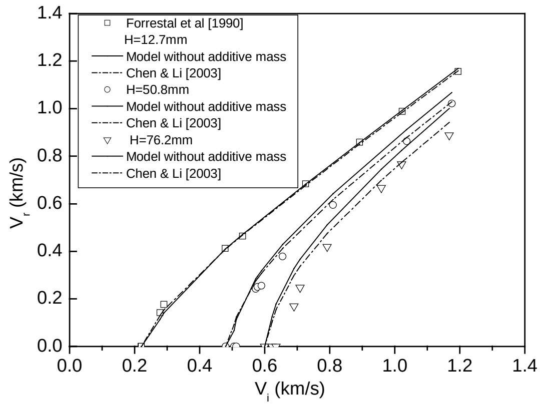

Figure 4. Prediction of residual velocity and test data [8]

However, the dummy mass coefficient D has not yet been discussed in detail up to now. Through fitting the test data, we may evaluate the influence of dummy mass term on penetration/perforation reversely. As shown in Figs. 1-4, accompanied with the damping effect, the residual velocity and ballistic limit lead to good predictions of experimental results if the mass of projectile increase by 5%-10%. In other words, the dummy mass may contribute to the mass of projectile from 5% to 10%. Thus the value of D can be deduced by $M_{\mathrm{m}} = \left(M + \pi\rho d^3 / 4 \cdot DN_3\right)$ and varies between 1 and 2.

CONCLUSIONS

The normal perforation of thick metallic plate by sharp nose rigid projectile is studied in the present paper based on the general penetration resistance, which contains the terms of damping effect and the dummy mass of projectile induced by the deceleration effect. The terminal ballistic formula with four dimensionless parameters is introduced, i.e., the impact function *I*, geometry function *N*, the damp function ξ and the dimensionless target thickness χ. Theoretical predictions of perforation dependent / independent of the damping function ξ, show good agreement with the individual published test data of different projectiles and impact velocities as well as different targets. At the same time, the contribution of dummy mass caused by deceleration effect to penetration/perforation performance is quantitatively estimated.

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