Residual velocity of hard bullet after penetrate through aluminum 7075-T651 plate

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Abstract

This paper presents a prediction of residual velocity of 7.62 mm APM2 bullets penetrated through aluminum alloy 7075-T651 plates. The striking velocities of bullets are in the range of 616-824 m/s. A series of numerical analyses of bullet impact on aluminum plate were performed in this study and compared to the test results reported in the literature. Moreover, this paper also investigates the efficacy of the existing closed-form perforation equations for rigid and ogive nose projectiles. The results of 2D axisymetric finite element (FE) models performed in this study agree very well with the test results for the striking velocity above 780 m/s. However, the closed-form equation yields more accurate predicted residual velocity of the bullet for the lower striking velocity, i.e. 600-700 m/s. Although the analytical model generally gives good prediction of the residual velocity of bullet, the model was developed for only rigid projectiles against aluminum target. In order to evaluate the performance of composite armor threatened from both soft and hard bullet, a sophisticated FE model is still a more competitive approach.

1. Introduction

In 1945 Bishop et al. [1] studied on the quasi-static expansions of cylindrical and spherical cavities to estimate forces on conical nose punches pushed into metal targets. The dynamic cavity-expansion was then developed later for the penetration and perforation problems. It was noted that the spherical cavity-expansion has been employed for penetration problems whilst the cylindrical cavity-expansion has been used for perforation problems. Since late 80's a team of researchers [2-5] has investigated and tested on the perforation of aluminum plates with conical and ogive noses projectiles. Until 2008, Forrestal and Warren [6] discussed a comprehensive spherical cavity-expansion and penetration problems. The cylindrical cavity –expansion approach and a series of closed-form equations for ballistic limit and residual velocities for rigid projectiles which perforate aluminum targets are presented in [7].

Since there has been a majority of available test data on the perforation of aluminum plates [2-5], this study therefore attempts to verify FE results with those test data in terms of residual velocity of bullet. Apart from a comparison between test data and FE results, the results obtained from empirical solutions were also validated in this study.

2. Perforation model

This section summarizes the assumptions and formulas employed to calculate the residual velocity of bullet which perforates aluminum target. The perforation equations presented in this paper are summarized from [7]. The two main mechanisms found in the experiment are that; firstly, both the conical [3] and ogive noses [6] high strength projectile were visible undeformed. Secondly, the plate perforation process was dominated by ductile hole-growth mechanism in which the cylindrical cavity-expansion model can be employed to describe this behavior. From the mechanisms observed from the tests, the assumptions of the model are that the closed-form solution can only be applied for the rigid projectiles. The analysis is simplified to one-dimensional motion in the radial plate direction. Eqs. (1) - (7) presented in this paper are employed to calculate ballistic limit velocity of target and residual velocity of bullet.

$$B=\frac{1}{2}\left\{\frac{1}{(1-\nu)\sqrt{1-\alpha^2}}\ln\left[\frac{1+\sqrt{1-\alpha^2}}{\alpha}\right]+\gamma^2-2\ln[\gamma]-1\right\} \quad (1)$$

$$\alpha^2=\frac{\sqrt{3}(1-2\nu)}{2(1-\nu)}\left(\frac{\rho_t V^2}{Y}\right) \quad (2)$$

$$\gamma^2=\frac{2(1+\nu)Y}{\sqrt{3}E} \quad (3)$$

$$\sigma_s = \frac{Y}{\sqrt{3}}\left\{1+\left[\frac{E}{\sqrt{3}Y}\right]^n \int_0^b \frac{(-\ln x)^n}{1-x}dx\right\}, b = 1-\gamma^2 \quad (4)$$

$$V_{bl} = \left(\frac{\sigma_s}{\rho_t B_0 N(\psi)}\right)^{1/2}\left[\exp\left[\frac{2h}{(L+k_1 l)}\frac{\rho_t}{\rho_p}B_0 N(\psi)\right]-1\right]^{1/2} \quad (5)$$

$$N(\psi) = 8\psi^2 \ln\left(\frac{2\psi}{2\psi-1}\right)-(1+4\psi)$$
$$\psi = \frac{1}{4}\left[\left(\frac{l}{a}\right)^2+1\right] \quad (6)$$

$$V_r = \sqrt{V_s^2 - V_{bl}^2}\exp\left[-\frac{h}{(L+k_1 l)}\frac{\rho_t}{\rho_p}B_0 N(\psi)\right] \quad (7)$$

where V = cavity-expansion velocity
Y = initial yield stress of target
ν = poisson's ratio of target
ρ_t = density of target
ρ_p = density of projectile
E = Young's modulus of target
σ_s = quasi-static radial stress required to open the cylindrical cavity
h =thickness of target
V_r = residual velocity of bullet
V_s = striking velocity of bullet
V_{bl} = ballistic limit velocity
a, l, L = dimension of the conical and ogival nose bullets as shown in Fig. 1.

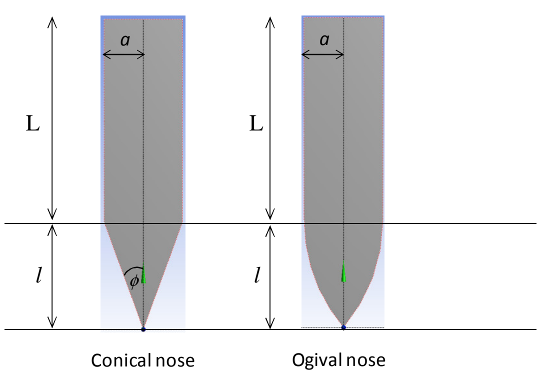

Fig. 1 Geometries of conical and ogival noses

3. Test and FE model description

The test data employed to validate the FE model in this study is obtained from [8]. The bullet used in the tests was 7.62mm AP M2 in which the dimension is shown in Fig. 2. The test target was 20 mm thickness of 7075-T651 aluminum armor plates. The test plates were 300 mm square in which the maximum of four shots were allowed for each test target. The striking velocities of bullets recorded during the experiment were in between 600 m/s to almost 900 m/s. Only seven test data are extracted from [8] and employed to validate the FE analyses performed in this research.

In this study, a total of five sets of FE models were analyzed and compared to the tests results so as to determine the FE mesh size sensitivity and the suitable FE modelling approach. Three of them are modelled using Smoothed Particle Hydrodynamics (SPH) whilst the last two sets of FE analyses are modelled using a traditional Lagrange element formulation. For the SPH modelling, both 2D- and 3D analyses were performed in this study.

The SPH technique is a mesh-free FE solver that can be used for solving computational continuum dynamics problem. There is no numerical grid so that the problem of grid tangling does not exist in the simulation. On the other hand, a severe distortion of FE mesh for the highly deformed FE problems may exist in the lagrangian solution. However, more complex constitutive model can be applied to the lagrange FE formulation. A brief summary of SPH and Lagrange FE techniques can be found in [9]. A comparison of the FE results using SPH and Lagrange formulation was also presented in [9]. It is noted that the comparison was for the high velocity impact of long rod at 1600 m/s which is much higher than the velocity range investigated in this research.

There are five categories of FE models performed in this study. These are both SPH and Lagrange FE formulations. Although, both 3D- and 2D axisymetric SPH FE analyses were performed, only 2D- axisymetric FE analyses using Lagrange formulation was performed in this research. Descriptions of each FE model category are presented in Table. 1. It can be seen in Table. 1 that the particle sizes are 0.05 mm and 0.125 mm for categories 1 and 2, respectively, whilst the 3D SPH analysis in category 3 employed larger particle size of 0.25 mm. The reason of using a bigger particle size in 3D SPH analysis is to reduce large computation time. In analysis cases using Lagrange element formulation, there were two categories in which the element sizes are 0.125 mm and 0.075 mm.

Fig. 3 presents the set up of FE model using SPH techniques performed in categories 1, 2 and 3. For the model categories 4 and 5, the dimension and boundary of the model are the same as those of model categories 1 and 2. Fig. 4 presents the lagrangian mesh of bullet used in model categories 4 and 5.

Table. 1 Descriptions of each FE model category

Categories of FE models	Element formulation	Analysis type	Element or particle size, mm
1	SPH	2D	0.05
2	SPH	2D	0.125
3	SPH	3D	0.25
4	Lagrange	2D	0.125
5	Lagrange	2D	0.075

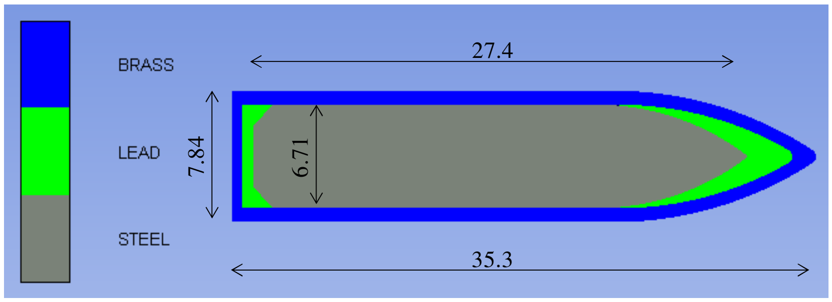

Fig. 2 Composition and geometry of 7.62 mm AP M2 bullet (unit : mm)

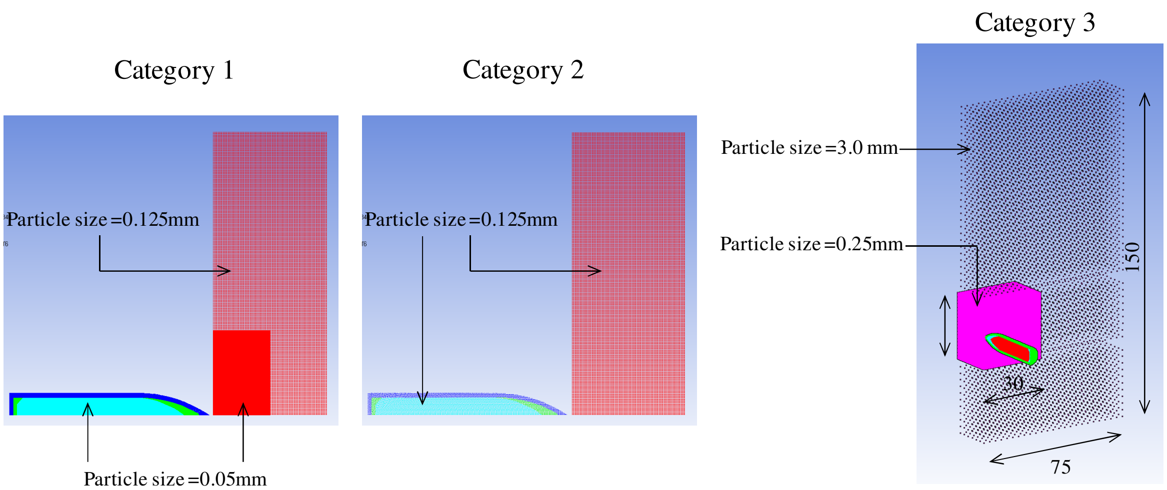

Fig. 3 FE models using SPH formulation in model categories 1, 2 and 3

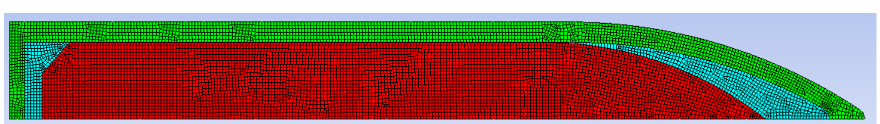

Fig. 4 Lagrangian mesh of 7.62 mm APM2 bullets

4. FE results

Fig. 5 shows that the results from 3D SPH analysis does not agree well with the test results for the striking velocity range between 616.4 m/s to 694 m/s. For this velocity range, an empirical method and FEM using 2D SPH yields more accurate results compared to those of 3D SPH. It is noted that the mesh sizes of 3D SPH analyses are bigger than those of 2D SPH analyses. It is not possible in this study to use the same mesh size for 2D SPH and 3D SPH analyses due to limited computation resources. In the same bullet velocity range, FE analyses using 2D Lagrange overestimate the bullet resistance of the aluminum plate.

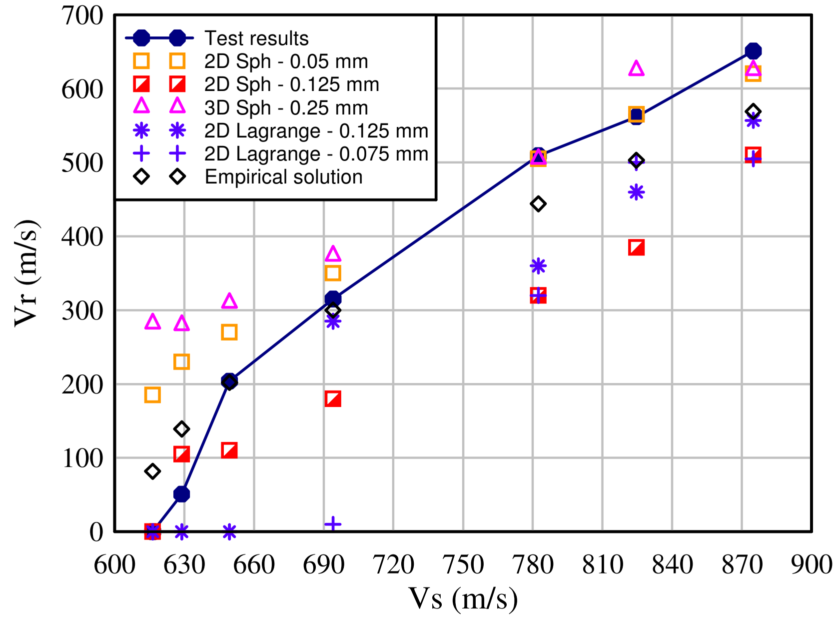

Fig. 5 Comparison of numerical and empirical results to the test results

Table. 2 Comparison of the FE results to the test results

Test results	Test No.	1	2	3	4	5	6	7
	Vs (m/s)	824.6	616.4	694	628.9	649.5	782.4	874.9
	Vr (m/s)	561.8	0	315	51	204	509.4	650.9
Category 1	Vr (m/s)	565	185	350	230	270	505	620
	% error	0.6	N/A	11.1	351	32.4	-0.9	-4.7
Category 2	Vr (m/s)	385	0	180	105	110	320	510
	% error	-31.5	N/A	-42.9	105.9	-46.1	-37.2	-21.6
Category 3	Vr (m/s)	625	282	374	280	310	505	625
	% error	11.2	N/A	18.7	449	52	-0.9	-4.0
Category 4	Vr (m/s)	460	0	285	0	0	360	557
	% error	-18.12	N/A	-9.5	N/A	N/A	-29.3	-14.4
Category 5	Vr (m/s)	500	0	10	0	0	320	505
	% error	-11	N/A	-96.8	N/A	N/A	-37.2	-22.4
Empirical solution	Vr (m/s)	503	81.9	300	139.2	202.1	444	569
	% error	-10.5	N/A	-4.8	173	-0.9	-12.8	-12.6

For a higher bullet velocity range i.e., 782 m/s to 824 m/s, both 2D and 3D SPH analyses (categories 1 and 3) give good prediction of the residual velocity of bullet compared to the test results. This research also shows that both 2D and 3D FE analyses using Lagrange element formulation are not suitable to predict the residual bullet velocity as shown in Fig. 5. All test data and FE results are summarized in Table. 2.

5. Conclusion

FE analyses using traditional Lagrange and SPH techniques were performed in this research so as to verify the accuracy of each FE technique employed to predict residual velocity of bullet after penetrate through aluminum 7075-T651 plate. In addition, a set of empirical formulas were also used to calculate the residual velocity of bullet. This research confirms the efficacy of these empirical models, however, it is noted that they are applicable for the calculation of residual velocity of rigid projectile penetrated through aluminum target only. From a series of FE analyses using Lagrange and SPH techniques performed in this research, a 2D SPH modeling with a mesh size of 0.05 mm is recommended for a prediction of residual bullet velocity after penetrate through aluminum 7075-T651 plate.

7. References

[1] Bishop, R., Hill, R. and Mott, N. F. (1945). The theory of indentation and hardness, *Proceedings of the Physical Society*, vol. 57(3), pp. 147-159.

[2] Forrestal, M. J., Rosenberg, Z., Luk, V. K. and Bless, S. J. (1987). Perforation of aluminum plates with conical-nosed rods, *Journal of Applied Mechanics*, vol. 54(1), pp. 230-232.

[3] Rosenberg, Z. and Forrestal, M. J. (1988). Perforation of aluminum plates with conical-nosed rods - Additional data and discussion, *Journal of Applied Mechanics*, vol. 55(1), pp. 236-238.

[4] Forrestal, M. J., Luk, V. K. and Brar, N. S. (1990). Perforation of aluminum armor plates with conical-nose projectiles, *Mechanics of Materials*, vol. 10(1–2), pp. 97-105.

[5] Piekutowski, A. J., Forrestal, M. J., Poormon, K. L. and Warren, T. L. (1996). Perforation of aluminum plates with ogive-nose steel rods at normal and oblique impacts, *International Journal of Impact Engineering*, vol. 18(7–8), pp. 877-887.

[6] Forrestal, M. J. and Warren, T. L. (2008). Penetration equations for ogive-nose rods into aluminum targets, *International Journal of Impact Engineering*, vol. 35(8), pp. 727-730.

[7] Forrestal, M. J. and Warren, T. L. (2009). Perforation equations for conical and ogival nose rigid projectiles into aluminum target plates, *International Journal of Impact Engineering*, vol. 36(2), pp. 220-225.

[8] Forrestal, M., Børvik, T. and Warren, T. (2010). Perforation of 7075-T651 aluminum armor plates with 7.62 mm APM2 bullets, *Experimental Mechanics*, vol. 50(8), pp. 1245-1251.

[9] Hayhurst, C. J., Clegg, R. A., Livingstone, I. H. and Francis, N. J. (1996). The application of SPH techniques in Autodyn-2D to ballistic impact problems, paper presented in *the 16th International Symposium on ballistics*, San Francisco.