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BRIEF TECHNICAL NOTE

Perforation of 7075-T651 Aluminum Armor Plates with 7.62 mm APM2 Bullets

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Abstract We conducted an experimental and analytical study to better understand the mechanisms and dominant parameters for 7.62 mm APM2 bullets that perforate 7075-T651 aluminum armor plates. The 7.62-mm-diameter, 10.7 g, APM2 bullet consists of a brass jacket, lead filler, and a 5.25 g, ogive-nose, hard steel core. The brass and lead were stripped from the APM2 bullets by the targets, so we conducted ballistic experiments with both the APM2 bullets and only the hard steel cores. These projectiles were fired from a rifle to striking velocities between 600 and 1,100 m/s. Targets were 20 and 40-mm-thick, where the 40-mm-thick targets were made up of layered 20-mm-thick plates in contact with each other. The measured ballistic-limit velocities for the APM2 bullets were 1% and 8% smaller than that for the hard steel cores for the 20 and 40-mm-thick targets, respectively. Thus, the brass jacket and lead filler had a relatively small effect on the perforation process. Predictions from a cylindrical cavity-expansion model for the hard steel core projectiles are shown to be in good agreement with measured ballistic-limit and residual velocity data. The results of this study complement our previous paper with 5083-H116 aluminum target plates in that the ultimate tensile strength of 7075-T651 is about 1.8 times greater than that of 5083-H116. We also present a scaling law that shows a square root relationship between ballistic-limit velocity and plate thickness and material strength.

Keywords Aluminum armor plates · 7.62 mm APM2 bullets · Experimental study · Perforation equations · Validation

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Introduction

For this paper, we study the perforation of 7075-T651 aluminum armor plates with 7.62 mm APM2 bullets. The results of this study complement our recent paper with 5083-H116 aluminum target plates [1].

We conducted perforation experiments with the full 10.7 g, APM2 bullets and only the 5.25 g, hard steel cores from the full bullet. Our data shows that the perforation process is dominated by the hard steel core. Predictions from our cylindrical cavity-expansion model [1] are in good agreement with the hard steel core data, so these closed-form perforation equations are able to show the relevant problem parameters. Other papers concerned with 7.62 APM2 bullets are discussed in [1].

In the next sections, we describe the targets and projectiles, present the perforation data, and compare measurements with predictions. In addition, we present a scaling law that shows a square root relationship between the ballistic-limit velocity and plate thickness and material strength for both 7075-T651 and 5083-H116 aluminum targets.

Projectiles

The 7.62 mm APM2 Bullet

Figure 1 shows the dimensions and the parts that make up the APM2 bullet. The 7.62 mm-diameter, 10.7 g, APM2 bullet consists of a brass jacket, an end cap, lead filler, and a 5.25 g, ogive-nose, hard steel core. The steel core has density ρ_p=7,850 kg/m^3, hardness R$_c$ 63, and ψ = CRH= 3.0 (caliber-radius-head).

The Hard Steel Core Projectile

As previously mentioned, we will present predictions from a cylindrical cavity-expansion model for the hard steel core projectile. Our perforation model [1] is for a rigid, ogive-nose, rod projectile. Note that the shank of the steel core of the 7.62 mm APM2 bullet shown in Fig. 1 is truncated towards the end cap, so we find an equivalent shank length L [1] that matches the measured mass of the steel core. Properties for the equivalent hard core projectile include:

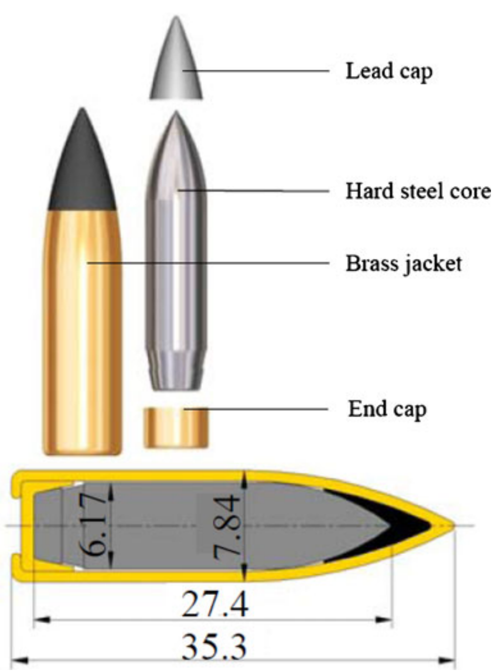

Fig. 1 Geometry and dimensions of the 7.62 mm APM2 bullet (in mm)

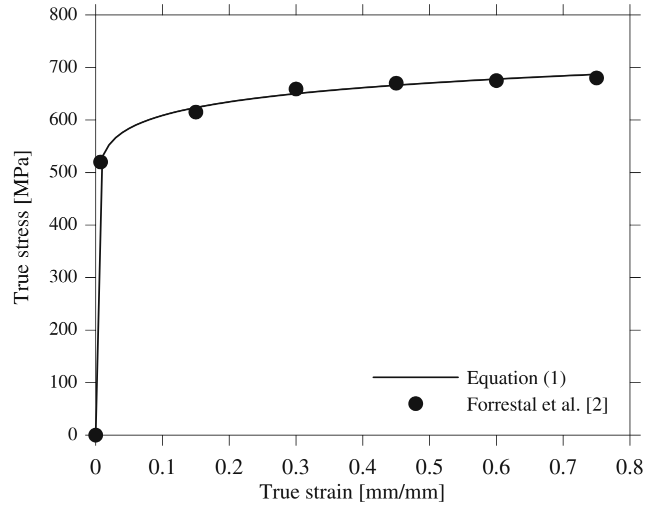

Fig. 2 Compression stress-strain data and power-law fit with E=71.1 GPa, ν=1/3, Y=520 MPa, n=0.060, and ρ_t=2,810 kg/m^3

mass m=5.25 g, diameter $2a$=6.17 mm, CRH=3.0, nose length l=10.2 mm, and shank length L=16.8 mm.

7075-T651 Aluminum Target Plate

For this study, we obtained 20-mm-thick plates. The supplier provided inspection certification sheets with tensile data. Data included the ultimate tensile strength σ_u= 582 MPa, yield strength defined by 0.2% offset σ_o= 520 MPa, and an elongation at failure of 11%. We also conducted tensile tests in the rolling direction of the plates and obtained similar results. Thus, our results are in good agreement with the inspection sheets.

For input to our cavity-expansion perforation model, uniaxial compression data [2] were curve-fit with

$$\sigma = \begin{cases} E\varepsilon \ , & \sigma < Y \\ Y\left(\frac{E\varepsilon}{Y}\right)^n, & \sigma \geq Y \end{cases} \qquad (1a, b)$$

where σ is the true stress, ε is the true strain, E is the Young's modulus, Y is the yield stress, and n is the strain-hardening exponent. Figure 2 shows this power-law data fit from equations (1a,b) with E= 71.1 GPa, Y= 520 MPa, and n=0.060. The value of Y was taken as σ_o=520 MPa from the suppliers inspection sheet.

The 7.62 mm APM2 Bullet and Hard Steel Core Experiments

A 7.62-mm-diameter, 63-mm-long, smooth-bore Mauser gun that used adjusted ammunition fired these projectiles. The APM2 bullets fit the gun bore, and the 6.17-mm-diameter cores were encased in a 7.62-mm-diameter, 0.3 g plastic sabot. Square target plate configurations with a side length of 300 mm and thicknesses of 1×20 mm and 2×20 mm were firmly clamped to a frame by two beams. This provided a fixed boundary for the horizontal sides of the targets, while the vertical sides remained free. The in-plane distance between each impact point and the target boundary was 100 mm, and a maximum of four shots were allowed in each target before it was replaced. All layered plates were in direct contact with each other, so plate spacing was not considered in this study. Striking and residual velocities were measured with laser optical devices that were shown to be accurate to within 1% and 2%. In addition, the overall perforation process was photographed with a high-speed video camera operating at 50,000–100,000 frames per second. Both the experimental procedures and measurements used in these tests are described in more detail in [1].

We conducted a large number of tests with these projectiles and two different plate thickness configurations. The ammunition was adjusted so that the projectiles impacted the targets at striking velocities in a range from just below to well above the ballistic-limit velocities. The measured striking velocity V_s and residual velocity V_r data for the tests are given in Table 1. Table 2 presents the ballistic-limit velocities V_{bl} obtained from the data in Table 1 together with data for AA5083-H116 from [1]. Figure 3 shows typical, high-speed video images of the perforation process for a 20-mm-thick plate impacted by the APM2 bullet. Note that the brass jacket and lead cap are completely stripped from the hard core by the target. Figure 4 shows some high-speed video images of the perforation process for a 20-mm-thick plate impacted by the hard steel core. Figure 5 shows pictures of some cross-sections of the target plate configurations. As also discussed by Gooch et al. [3], Figs. 3 and 4 show considerable back surface plate spall.

The most important results of our study are shown in Fig. 6 that display the residual velocity versus striking velocity curves. Data for the APM2 bullets and hard cores were curve-fit to the data with the least squares method and the Lambert-Jonas empirical equation [4, 5]

$$V_r = \left(V_s^p - V_{bl}^p\right)^{1/p} \quad (2)$$

where p is the empirical constant used to best fit the data with the least squares method. The measured ballistic-limit velocities for the APM2 bullets were 1% and 8% smaller than that for the hard steel cores for the 1×20 mm and 2×20 mm plate configurations, respectively. Thus, the brass jacket and lead filler had a relatively small effect on the perforation process even though the masses of the APM2 bullet and hard steel core are 10.7 g and 5.25 g, respectively.

Figure 7 compares our cylindrical cavity-expansion, model predictions discussed in [1] and data for the hard steel core projectile. Predictions used the material parameters given in Fig. 2 and assume that the layered plates are monolithic with a single equivalent thickness. Predictions with C=0 neglect radial target inertia and only include target strength. Thus, the closed-form, cavity-expansion equations give a reasonable good first order estimate and display the dominant problem parameters.

A Scaling Law for the 7.62 mm APM2 Bullet and Aluminum Armor Plates

Results of this study with 7075-T651 aluminum plates and our previous paper [1] with 5083-H116 aluminum plates

Table 1 Test data—AA7075-T651 target plates

Test nr.	APM2 bullet		APM2 bullet—core only		APM2 bullet		APM2 bullet—core only	
	20mm targets		20mm targets		2×20mm targets		2×20mm targets	
	V_s [m/s]	V_r [m/s]	V_s [m/s]	V_r [m/s]	V_s [m/s]	V_r [m/s]	V_s [m/s]	V_r [m/s]
1	824.6	561.8	715.7	357.1	885.9	0.0	984.1	0.0
2	694.0	315.3	670.3	190.6	931.5	0.0	1094.3	465.6
3	661.8	232.6	654.0	140.5	933.8	192.8	1025.9	219.5
4	610.9	0.0	667.0	198.9	929.7	173.6	989.2	183.5
5	616.4	0.0	641.8	76.9	900.5	0.0	1009.2	293.2
6	628.9	51.0	614.0	0.0	898.8	0.0		
7	641.0	151.3	597.5	0.0	909.2	0.0		
8	649.5	204.0	640.5	129.2	920.5	180.8		
9	782.4	509.4	625.7	0.0				
10	874.9	650.9	867.8	579.7				

Table 2 Ballistic-limit velocities obtained from data

Projectile type	AA5083-H116 target plates [1]			AA7075-T651 target plates	
	1×20mm [m/s]	2×20mm [m/s]	3×20mm [m/s]	1×20mm [m/s]	2×20mm [m/s]
APM2 bullet	492	722	912	628	909
APM2 core only	513	767	1,025	633	984

suggest that the perforation resistance is dominated by plate thickness and material strength. Thus, if we neglect the small contribution of radial target inertia, equation (5) in [1] suggests that

$$V_{bl} = K[\sigma_s h]^{1/2}, \tag{3}$$

where K is a constant, h is the plate thickness, and σ_s is the quasi-static, radial stress required to open a cylindrical cavity from zero initial radius. This quasi-static radial stress σ_s is given by

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

$$\gamma^2 = \frac{2(1+\nu)Y}{\sqrt{3E}}. \tag{4b}$$

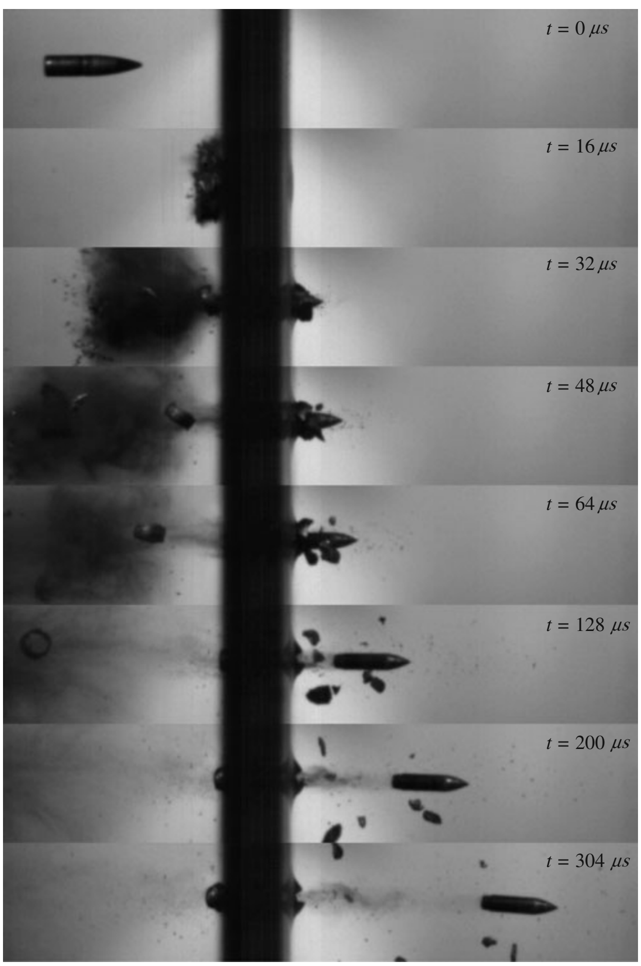

Fig. 3 High-speed video images showing the perforation process of a monolithic 20-mm-thick, 7075-T651 plate impacted by a APM2 bullet (V_s=629 m/s and V_r=51 m/s)

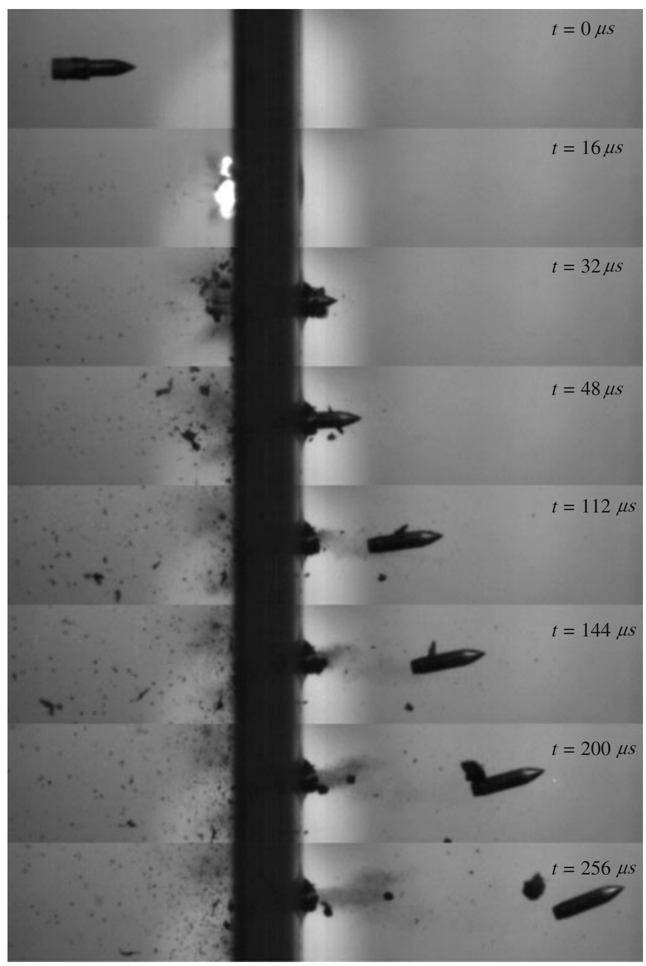

Fig. 4 High-speed video images showing the perforation process of a monolithic 20-mm-thick, 7075-T651 plate impacted by only the hard core of the APM2 bullet (V_s=642 m/s and V_r=77 m/s)

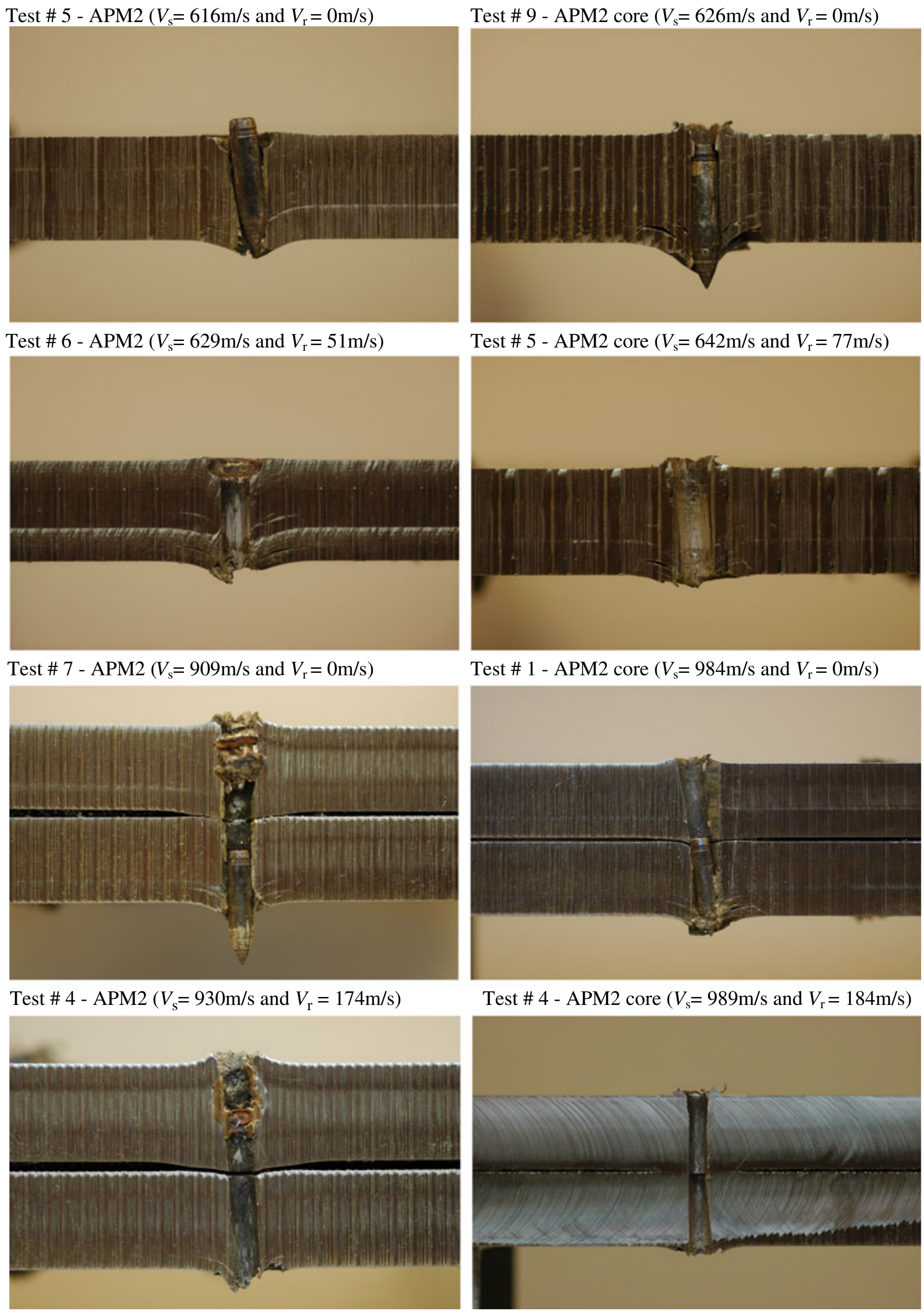

Fig. 5 Pictures of cross-sections of monolithic and double-layered target plates perforated by 7.62 mm APM2 bullets (*left*) and sabot-mounted hard cores only (*right*)

Figure 8 shows a linear fit to the 5083-H116 and 7075-T651 data with equation (3). For 5083-H116, σ_s=1.12 GPa, and we have three data points for h=20, 40, and 60 mm. For 7075-T651, σ_s=1.85 GPa, and we have two data points for h=20 and 40 mm.

Summary and Discussion

In this study, we present results from a large number of perforation experiments with 7075-T651 target plates struck by 7.62 mm APM2 bullets. The 7.62-mm-diameter, 10.7 g,

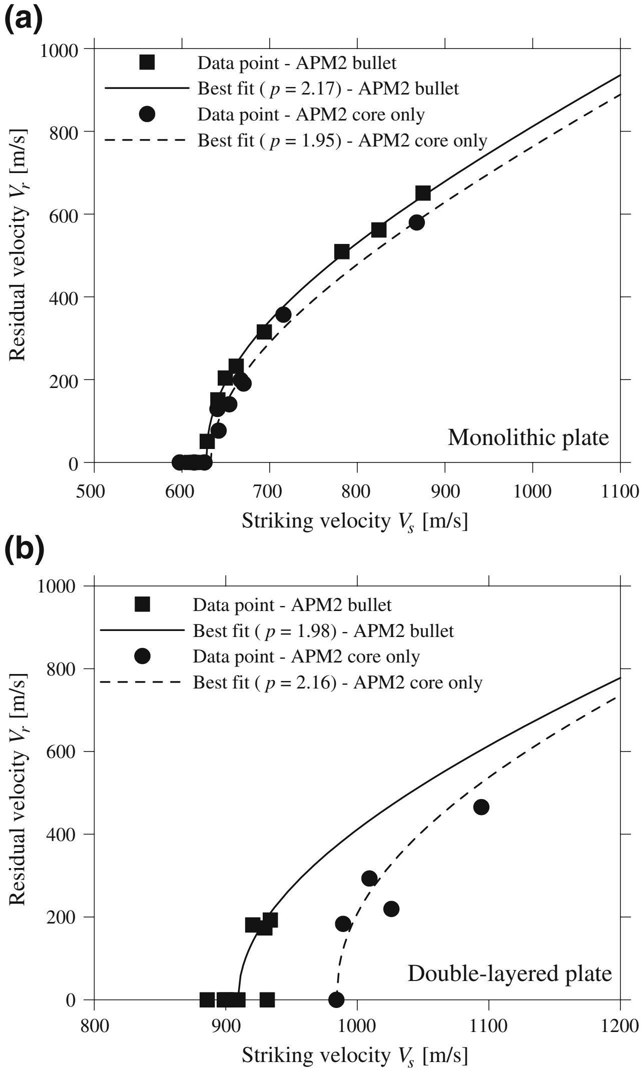

Fig. 6 Striking versus residual velocity for (**a**) monolithic (20-mm) and (**b**) double-layered (2×20-mm) target plates impacted by APM2 bullets and hard cores only

APM2 bullet consists of a brass jacket, lead filler, and a 5.25 g, ogive-nose, hard steel core. The brass and lead were stripped from the APM2 bullets by the targets, so we conducted experiments with both the APM2 bullets and only the hard steel cores. Targets were 20 and 40-mm-thick, where the 40-mm -thick targets were made up of layered plates in contact with each other. Residual velocity versus striking velocity data showed that the brass jacket and lead filler had a relatively small effect on the perforation process. We compared the hard steel core, perforation data with a closed-form, cylindrical cavity-expansion model and showed reasonable good agreement. In addition, we present a scaling law that shows a square root relationship between ballistic-limit velocity and plate thickness and material strength for both 7075-T651 and 5083-H116 aluminum targets. Results of this study identify the dominant problem parameters.

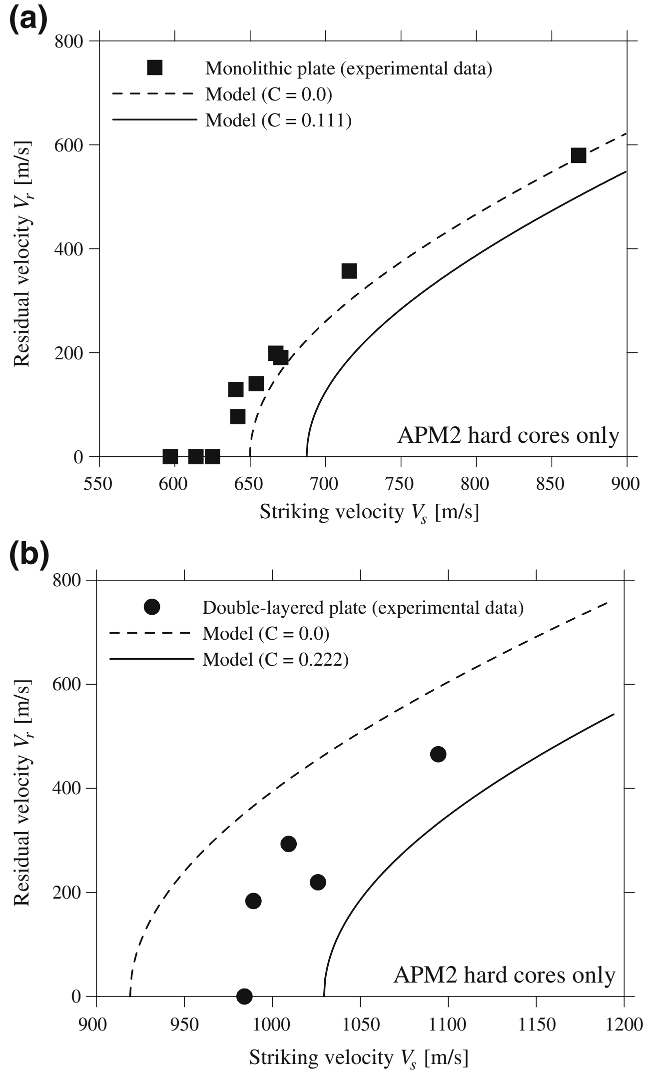

Fig. 7 Comparison of predicted and measured striking velocity versus residual velocity for the hard core only of an APM2 bullet (**a**) h=20 mm and (**b**) h=40 mm

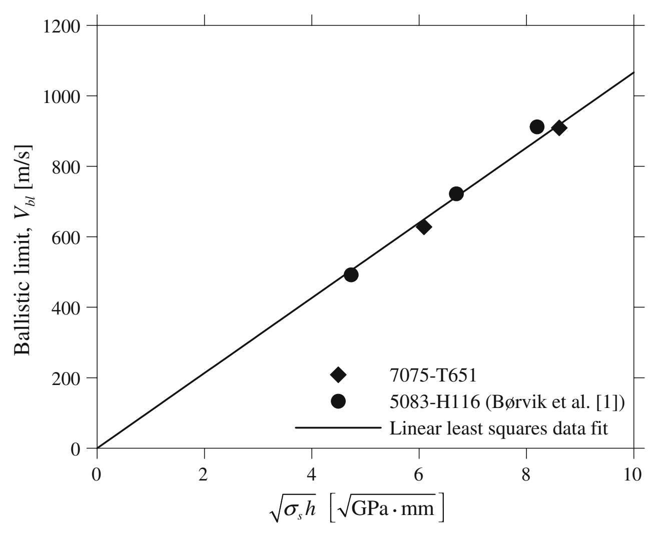

Fig. 8 Scaling law for 7.62 mm APM2 bullets and aluminum armor plates

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