INL/CON-21-64719-Revision-0

Dimensionless parameters to categorize the failure modes of ductile plate perforation

May 2022

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Zherui Guo

Idaho National Laboratory

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Zherui Guo

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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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Title: Categorizing ballistic perforation mechanisms of ductile metallic plates using dimensionless parameters

Authors (names are for example only): Zherui Guo

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(FIRST PAGE OF ARTICLE)

In this work, two dimensionless parameters were derived organically from impact mechanics equations to remove the need for empirical constants. These two dimensionless parameters effectively collapse the ballistic performance of ductile metal plates along two distinct loci, depending on the projectile geometry and the corresponding failure mode. Projectiles that initiate ductile hole enlargement via cavity expansion fall along a linear curve, while shear-plugging failure modes tend to fall along a cubic curve. Results were demonstrated for various projectiles of different calibers impacting aluminum and Ti-6Al-4V alloys. The main advantage of the approach in this work is to drastically reduce the number of features for input into machine learning algorithms.

INTRODUCTION

Forrestal and colleagues [1] first derived a dynamic cylindrical cavity expansion (CCE) formulation to model the ballistic perforation of rate-independent ductile target plates impacted by conical- and ogival-nosed projectiles. The CCE equations were used to model and predict the ballistic limit velocity V_{bl} of 7.62-mm APM2 armor-piercing rounds perforating 5083-H116 aluminum alloy plates [2]. Since the ballistic performance of the aluminum alloy plates was more dependent on the target strength than on inertia, perforation results were well-predicted using a quasi-static CCE formulation. The crucial parameter is the quasi-static cavity expansion strength σ_s, which is the stress required to open a cavity from zero radius. The predictive V_{bl} equation is given as

(1)

where ρ_p is the projectile density, L is the projectile shank length, l is the nose length, T is the target plate thickness, and k_1 is an empirical nose shape factor. Ryan et al. extended the application to predict the performance of several aluminum alloys against small arms armor-piercing (AP) projectiles, namely 7.62- and 12.7-mm APM2, and 14.5-mm BS41 rounds [3]. For each alloy and caliber, a separate empirical nose coefficient k_1 obtained via curve-fitting was required.

Similarly, a prior scaling law effort by Guo & Forrestal et al. [4] showed that for fragment-simulating projectiles (FSPs), which result in target plate failure via shear-

[1] National & Homeland Security, Idaho National Laboratory. Idaho Falls, ID, USA.

plugging, the ballistic performance data collapses along a concave curve using dimensionless parameters. The shear plugging formulation is based on the dynamic compressive strength σ_0 of the target alloy, which can be approximated via high-strain, quasi-static, uniaxial compression stress-strain curves at a true strain of approximately 40% [5]. For an FSP with diameter D, length L impacting a target with density ρ_t, the V_{bl} can be predicted with the equation

(2)

We show in this work that all the ballistic performance data for both AP rounds and FSPs fall along two distinct curves on a single plot, with the shape of the curves dependent purely on the shape factor of the projectile and consequently, the target failure mode response. This method has shown success for aluminum plates, and we further show preliminary success for Ti-6Al-4V plates under similar ballistic impact conditions. The results show potential for optimisation of machine learning algorithms by vastly reducing the number of inputs/features required for ballistic performance prediction of target plates.

DERIVATION OF DIMENSIONLESS EQUATIONS

Dimensionless CCE Parameters for AP Round Impact

In a recent work, Guo & Chen showed that the ballistic experimental data could be collapsed along a singular linear curve using two dimensionless parameters [6]. In contrast to prior work, these dimensionless parameters were derived organically from Forrestal et al.'s original dynamic CCE model without the need for empirical constants (Fig. 1). The mass of the projectile is first expressed as

(3)

For a target plate of certain uniform thickness T, we can introduce the term

(4)

The term A_d is defined as the target's areal density i.e. the plate mass m_t divided by its planar area A_t. Squaring both sides, multiplying by the target density ρ_t, and substituting Equations 3 and 4 gives

(5)

Dimensionless Shear-Plugging Parameters for FSP Impact

The ballistic impact data for FSPs can be collapsed in the same fashion as for the CCE model. Multiplying both sides by the density ratio and changing variables with Equation 5 yields

(6)

We can see that the CCE and shear-plugging ballistic data can be collapsed with two dimensionless parameters i.e.

(7)

with σ being some representative target strength term, namely the cavity-expansion strength σ_s for the CCE model, and the dynamic compressive strength σ_0 (via shear strength) for the shear-plugging model.

The dynamic compressive strength σ_0 of aluminum alloys was found to correlate strongly with the cavity expansion strength σ_s [5], with a ratio of $\sigma_s/\sigma_0 \approx 2.75$. This relation essentially allows the FSP ballistic impact data to be collapsed along the same dimensionless axes as the AP round ballistic data. As long as the representative strength term in Equation 7 for the respective perforation model can be related to a common strength term via simple linear scaling, the data can be similarly collapsed. The overall results are plotted in the next section (Figure 1).

RESULTS

Along with the AP and FSP impact data obtained from existing literature, ballistic perforation data was also plotted on the same axes of dimensionless parameters for conical-nosed long steel rods [7] and hard spheres [8] impacting aluminum plates. The choice of σ_s as a common strength term is arbitrary – σ_0 could be the common strength term and the results would have been similar. Since the CCE and shear-plugging models neglect effects such as projectile fragmentation, plate bending, or projectile wave propagation, the complex dynamics of different material pairs and geometries will certainly result in deviation from the predictions. Nonetheless, the data exhibit two general trends: a linear curve for sharper-nosed projectiles, and a cubic curve for flat/round-nosed projectiles. That the shear-plugging cubic curve lies below the CCE curve does not imply that a particular plate performs better against AP rounds than FSPs. Rather, the plot gives a general locus of the failure mode being initiated.

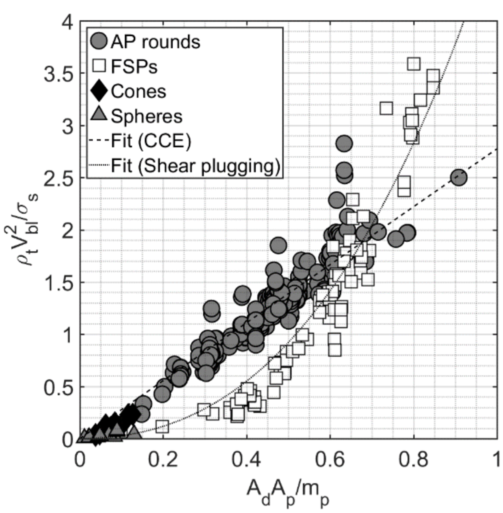

Figure 1. Collapsed ballistic limit data using dimensionless parameters for aluminum target plates.

As a preliminary study, ballistic data for Ti-6Al-4V alloy plate perforation [9–14] was plotted in the same fashion using the two dimensionless parameters (Figure 2). Guo & Chen [6] previously noted that the experimental V_{bl} of a 20-mm M602 round (data from Fanning [10]) against a Ti-64 plate was much lower than predicted. The impact of M602 rounds on high hard armor steel plates was previously shown by Squillacioti [15] to have a reduced ballistic performance due to shear plug formation, especially at normal incidence – the same phenomenon may be occurring for Ti-64 plate perforation to result in a drastically reduced ballistic limit. Figure 2 shows this data point lying near the shear-plugging cubic locus, further suggesting that the M602 may result in adiabatic shear failure rather than ductile hole expansion. Post-mortem data or images were not available to verify this hypothesis, although this may be a good starting point for future work.

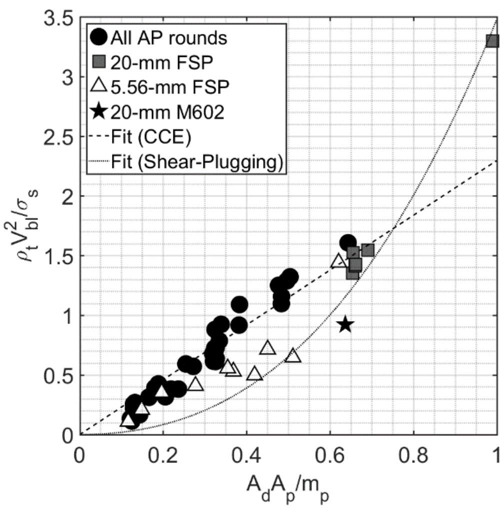

Figure 2. Collapsed ballistic limit data using dimensionless parameters for Ti-6Al-4V target plates.

CONCLUSIONS

In this work, two dimensionless parameters were derived from the impact mechanics of their respective failure modes instead of obtaining empirical constants from experimental data. Using the two dimensionless parameters, the ballistic performance of aluminum alloy plate targets can be collapsed along two broad curves: a linear curve for sharper-nosed projectiles that initiate ductile expansion failure modes, and a cubic curve for flat-nosed projectiles that initiate shear-plugging modes. These scaling efforts can drastically reduce the number of parameters required for ballistic performance predictions, and can potentially optimize machine learning algorithms via physically-meaningful reduction of features.

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