BALLISTIC IMPACT ON COMPOSITES

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Abstract

Composite structures are sometimes subjected to impacts thatl result in partial penetration or complete perforation. Tests are conducted to determine the velocity required to achieve complete penetration for a given projectile and a model is required for data reduction purposes, to understand the effect of various parameters and to extrapolate for other test conditions. Here, a systematic approach for developing engineering models for composite structures is presented and the models obtained are used to analyze experimental results.

1 Introduction

Extensive studies of the effects of impacts on composite materials in recent years resulted in a large number of publications that deal mostly with low velocity non-penetrating impacts [1]. The penetration of fabric armor was treated in recent review articles [2,3] and will not be considered here. This article focuses on penetrating impacts that can occur at both low and high velocities. General experimental observations are included in section 2. Following Zukas [4], mathematical models are divided into three broad categories: empirical models, approximate analytical models, and numerical models. Engineering models are usually based on basic assumptions regarding the interaction between the projectile and the target. These models are shown to capture the main features observed in experimental results while remaining simple.

2 Experimental Dtermination of the ballistic limit

Many experimental studies have been conducted to determine the ballistic limit of various laminated composites. Initially the projectile of mass M has a velocity V_i and that velocity is varied in order to determine the ballistic limit V_b. That is the lowest velocity that results in total penetration of the laminate. Knowing V_i and the residual velocity V_R for several tests, a data reduction procedure is needed to estimate V_b.

2.1 Assumption 1: Constant penetration force

Using an energy approach, several authors [5-10] considered $U_R = \frac{1}{2} M V_R^2$, the residual kinetic energy of the projectile to be equal to the initial kinetic energy $U_i = \frac{1}{2} M V_i^2$ minus the penetration energy U_P

$$U_R = U_i - U_p \tag{1}$$

Usually, U_P is assumed to be constant. Sun and Potti [5] state that U_P is the penetration energy required for penetrating the laminate during a static test. Eq. (1) implies that plotting U_R versus U_i, the experimental results can be fitted by a straight line with a unit slope and a horizontal intercept U_P. Then, the ballistic limit is estimated using $\frac{1}{2} M V_b^2 = U_P$.

Eq. 1 can be derived by considering the bullet as a rigid body subjected to a resisting force F. Using Newton's law, the equation of motion is

$$-F = M v \frac{dv}{dx} \tag{2}$$

Robins (1742) and Euler (1745) assumed that the resistance to penetration is a constant $(F = c_o)$ proportional the cross-section of the projectile [11]. Integrating the equation of motion, we recover Eq. 1 with $U_P = c_o h$ where h is the thickness of the laminate. Therefore, the two approaches (energy balance approach and the constant penetration resistance) are equivalent and the penetration energy is the same as the static penetration energy as stated by Sun and Potti [10]. Unfortunately, experimental data often shows that, while U_R is a linear function of U_i, the slope of the line is generally less than one so that curve fitting experimental results by Eq. 1 leads to significant errors in estimating the ballistic limit.

Another problem with Eq. 1 is the assumption that the penetration resistance is the same as the static penetration energy. A number of investigators show that the absorbed energy defined as

$$U_{abs} = U_i - U_R \tag{3}$$

increase with U_i. Roach et al [12] show that the dynamic penetration energy can be times higher than the static penetration. Lee et al [13] measured the energy required for perforation of 5-ply laminates of Spectra fabric reinforced composites with vinylester and polyurethane resin matrices. Three types of tests were conducted using the same FSP geometry for the penetrator: (1) quasi-static puncture; (2) dropweight impact (3.78 m/s, 12.3 kg); (3) ballistic impact (220-260 m/s, 1.1 g). Results indicate that the energy absorbed for full penetration during ballistic impacts is nearly twice that absorbed during dropweight impact tests. Similarly, in the experiments conducted by Mines et al [14] on glass-polyester composites, the perforation energy measured during ballistic impacts was significantly larger than the static penetration energy. The elastic moduli of Spectra composites vary significantly with strain rate [15], which is advanced as an explanation for the increased energy absorption during high velocity impacts.

2.2 Assumption 2: Kinetic Energy Absorbed by Ejecta

In order to explain the inadequacy of Eq. 1, consider that after penetration the projectile plus an equivalent mass of ejecta m is moving with a residual velocity V_R. Using the work-energy principle

$$\frac{1}{2}(M+m)V_R^2 = \frac{1}{2}M V_i^2 - U_P \tag{4}$$

By definition, the residual velocity is zero when the initial velocity is equal to the ballistic limit V_b, so, according to Eq. 1, the penetration energy is $U_p = \frac{1}{2}M V_b^2$. Then, Eq. 1 can be written as

$$U_R = \left(U_i - U_p\right) / \left(1 + \frac{m}{M}\right) \tag{5}$$

Eq. 5 shows that when the residual kinetic energy is plotted versus the initial kinetic energy, the data should plot on a straight line with a slope that is less than or equal to one. Therefore, in this model, the kinetic energy absorbed by the material removed during perforation is the reason why the slope of the line is less than one in a U_R versus U_i plot. Eq. 5 can be written as

$$V_R = \alpha\left(V_i^p - V_b^p\right)^{1/p} \tag{6}$$

with p=2 and $\alpha = 1/\sqrt{1+(m/M)}$. Eq. 6 is the well-known Lambert-Jonas equation (see Zukas [4]) that is used to fit experimental data for impacts on metals and other materials. The parameter p is usually equal to 2 for rigid projectiles. Eq. 6 was used by Kasano [16] in a study of perforation of carbon fiber reinforced composites by a steel ball projectile. Larsson [17] reported α values of 0.7920, 0.7926, 0.8825, and 0.8427.

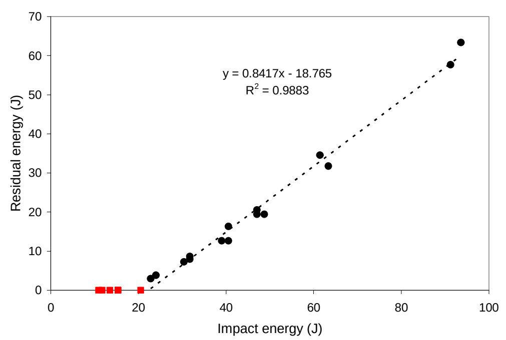

Fig. 1.a: Experimental data from Lee and Sun [7,8]

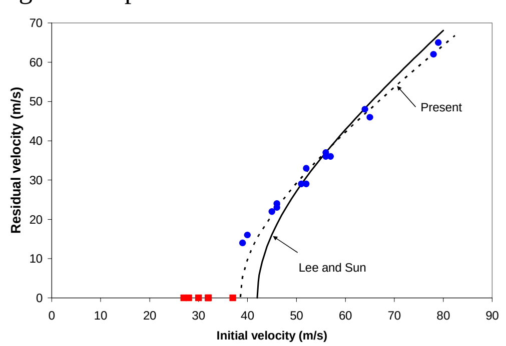

Fig. 1.b: Experimental data from Lee and Sun [7,8]

Eq. 6 was also mentioned by Lee and Sun [7,8] but α was immediately taken to be one and Eq. 1 is recovered. Fig. 1 shows the data presented by Lee and Sun [7]. Round symbols represent experimental results for penetrating impacts that were fitted by a straight line in Fig. 1.a with a high coefficient of correlation. Square symbols represent results for non-penetrating impacts. In this case $\alpha = 0.9174$ and V_b= 38.55 m/s. Assuming a unit slope as in that Ref. 7, leads to a poor fit of the entire data (Fig 1.b) and an over-estimation of the ballistic limit with V_b=42 m/s. With the present approach, the estimated ballistic limit (38.55 m/s) is higher than the highest velocity for non-penetrating impacts and lower than the lowest velocity for penetrating impacts in the experiments. The ballistic limit obtained by previous authors (42 m/s) is higher than that of two of the penetrating impacts in the experiments.

The data of Jenq et al [18] leads to $\alpha = 0.9066$ and a ballistic limit of 71.82 m/s. In Ref. 18 it was assumed that m=0 and Eq. 1 was used to estimate the ballistic limit V_b from each data point. This approach leads to the erroneous conclusion that the ballistic limit varies between 68.8 and 91.1 m/s as the impact velocity increases from 68.6 to 172 m/s. Similar errors are made by others.

Table 1: Data from Gu and Xu (2004)

V_i (m/s)	V_R Exp. (m/s)	V_R Cal. (m/s)
291	210	204
295	225	210
298	204	214
299	231	216
383	325	328
386	316	338
390	329	337
505	479	473
531	502	503
650	641	635
658	638	643

Gu and Xu [19] presented experimental results for the ballistic penetration of braided composites. The initial and residual velocities of the projectile (Tables 1) were fitted by Eq. 6 with $\alpha = 1.034$ and $V_b = 214\ m/s$. Another set of experimental results on the same type of composites was presented by Gu and Ding [20]. The data presented in that reference (Table 2) was fitted by Eq. 3 with $\alpha = 1.011$ and $V_b = 189\ m/s$. In both cases, the residual velocities calculated using Eq. 3 are in good agreement with the measured values. Values of that are slightly larger than one are often encountered. There does not appear to be much significance to the fact that it is larger than one except that it is obtained from curve fitting experimental results.

Table 2: Data from Gu and Ding.

V_i (m/s)	V_R Exp. (m/s)	V_R Cal. (m/s)
241	158	152
253	168	170
256	170	175
263	182	185
279	224	208
287	206	219
326	276	269
328	279	271
378	326	331
385	342	339
391	343	346
523	486	493
532	501	503
661	647	641
670	648	650

Using Eq. 5 we find that that the absorbed energy

$$U_{abs} = \left(U_i\, m + U_p\, M\right) / \left(M + m\right) \tag{7}$$

increases linearly with the impact energy. This result has been observed experimentally by several authors. Wonderly et al [21] presented experimental results for the perforation of glass fiber/vinyl ester and carbon fiber/vinyl ester composites. The absorbed energy $U_{abs} = U_i - U_R$ was shown to be a linear function of the initial kinetic energy U_i. From that data we extract $\alpha = 0.9463$ and $V_b = 108.9\ m/s$ for the glass fiber/vinyl ester composites and, for the carbon fiber/vinyl ester $\alpha = 0.9543$ and $V_b = 99.52\ m/s$. In both cases, the ballistic limits determined by this procedure is larger that the initial velocities of all the non-penetrating impacts and lower than the initial velocities of all the penetrating impacts.

2.3 Assumption 3: Penetration force increases linearly with the square of the velocity

It is well-known that during dynamic event strain rate effects are significant with polymer matix composites. Then it is logical to assume that the penetration resistance will increase with the velocity of the projectile. Poncelet (1829) assumed that the penetration resistance is a function of velocity in the form [11]

$$F = c_o + c_2 v^2 \tag{8}$$

In this case, integrating the equation of motion gives

$$c_o + c_2 V_R^2 = \left(c_o + c_2 V_R^2\right) \exp\left[-\frac{2c_2 h}{M}\right] \tag{9}$$

Using the Taylor series expansion $e^x = 1 + x$, this expression gives

$$U_R = \left(1 - \frac{2c_2 h}{M}\right) U_i - c_o h \tag{10}$$

In Eq. (10), $c_o h$ represents the static penetration energy. Plotting the residual kinetic energy U_R versus the initial kinetic energy U_i will result in a straight line with a slope that is less than one. Eq. 10 can also be written in the form of the Lambert-Jonas equation (Eq. 6) but in this case, $\alpha = \sqrt{1 - \frac{2c_2 h}{M}}$. With this model, the energy required to penetrate the target during ballistic penetration

$$U_b = c_o h \Big/ \left(1 - \frac{2c_2 h}{M}\right) \tag{11}$$

is higher than the static penetration energy since denominator on the right hand side of Eq. 11 being less than one. In addition, Eq. 10 also imply that the energy absorbed during the penetration event increases linearly with the impact energy.

2.4 Assumption 4: Penetration force increases linearly with the velocity

In modeling the perforation of composite structures, it is often assumed assumed that the resisting force increases linearly with the velocity pf the projectile

$$F = c_o + c_1 v \tag{12}$$

In this case, integrating the equation of motion (Eq.) gives

$$-\frac{h}{M} = \frac{V_R - V_i}{c_1} + \frac{c_0}{c_1^2}\left\{\ln\left(1 + \frac{c_1}{c_o} V_i\right) - \ln\left(1 + \frac{c_1}{c_o} V_R\right)\right\} \tag{13}$$

Using the Taylor series expansion $\ln(1 + x) = x - \frac{x^2}{2}$ which gives less than 3% error when x<0.3, Eq. 11 reduces to Eq. 1 with $U_P = c_o h$. Therefore, the effect of the velocity on the penetration force are negligible as long as $c_1 V_i < 0.3 c_o$.

2.5 Assumption 5: The Penetration force varies with v and v²

Resal (1895) assumed that the penetration resistance is a function of velocity of the form [11]

$$F = c_1 v + c_2 v^2 \tag{14}$$

Integrating the equation of motion gives

$$c_1 + c_2 V_R = \left(c_1 + c_2 V_i\right) \exp\left[-\frac{c_2 h}{m}\right] \tag{15}$$

A Taylor series expansion of the exponential function reveals that

$$V_R = V_i\left(c_1 - \frac{c_2 h}{m}\right) - \frac{c_1 h}{m} \tag{16}$$

In other words, the residual velocity increases linearly with the initial velocity of the projectile.

3 Effect of laminate thickness and projectile diameter on the ballistic limit

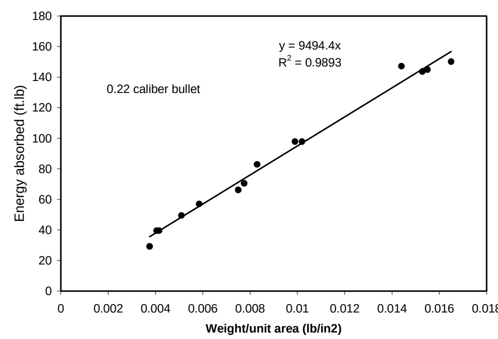

Figure 2: Energy absorbed versus areal density (Data from Ref. 22)

Assuming that the penetration resistance (force F) is constant, the penetration energy should then be proportional to the thickness of the laminate. Gupta and Davids [22] studied the penetration resistance of fiberglass-reinforced plastics against small-caliber projectiles. Their experimental results (Fig.) indicate that the energy absorbed increases linearly with the areal density or the thickness of the laminate. If the penetration resistance is constant, the $U_{abs} = U_b$ so the kinetic energy at the ballistic limit is a linear function of the thickness of the laminate. Iremonger and Went [23] studied the penetration of nylon 6,6 / ethylene vinyl acetate composite laminates by fragment simulating projectiles (FSPs). In their experiments, the ballistic velocity was proportional to the square root of the thickness which means that U_b is also proportional to h. Bartus and Vaidya [24] performed ballistic impact tests on of polypropylene (PP)/E-glass composites using flat ended and conical-tipped cylindrical projectiles. The penetration energy increased linearly with the areal density of the plate and for each thickness, a significant scatter of the results was shown probably for the first time. The penetration energy for conical tipped projectile was 27% lower than that for flat ended projectile due to different failure modes. Jacobs and Van Dingenen [25] studied the ballistic penetration of composites with Dyneema fiber reinforcement by FSPs. Results indicated that the energy absorbed during perforation is proportional to the area density of the laminate and also to the cross-sectional area of the projectile. Lin and Bhatnegar [26] showed that for composites with Spectra fiber reinforcement, U_b is proportional to both the areal density (or h) and d, the diameter of the projectile.

Hoo-Fatt et al [27] and Lin and Hoo Fatt [28] provided data on the ballistic limit of glare laminates as a function of thickness or equivalently as a function of the areal density w. A least square fit of the data (Table 3) gave $V_b^2 = 273.1w + 8898$. The ballistic limit calculated using this expression is in good agreement with the experimental data.

Table 3: Glare laminates Lin and Hoo Fatt [28]

Areal density (N/m^2)	Exp. Ballistic limit (m/s)	Calc. Ballistic limit (m/s)
36.65	136	137
43.41	150.5	144
61.15	155.5	160
91.92	182	182
124.46	209	207

Bhatnagar et al [29] studied the ballistic performance of vinyl ester composite with glass and Spectra fibres subjected to 22 caliber FSPs. In one series of experiment, the front layer had glass reinforcement while the back layer had spectra fiber reinforcement. In a second set of experiments the position of the two layers was reversed. Fig. shows that the order in which those layers are placed has a significant effect on the ballistic limit.

Lin and Batnagar [30] and Bhatnagar [29] presented results for spectra reinforced composites that showed a linear variation of the ballistic velocity V_b with the areal density of the laminate. The same trend was observed for Kevlar-Polyester [31,32], for both Kevlar and graphite laminates [33] and for Kasano [16]. Abdullah and Cantwell [34] have performed ballistic impact tests on Fiber-Metal Laminates (FML) and presented results showing that the ballistic limit increases almost linearly with the thickness of the laminate.

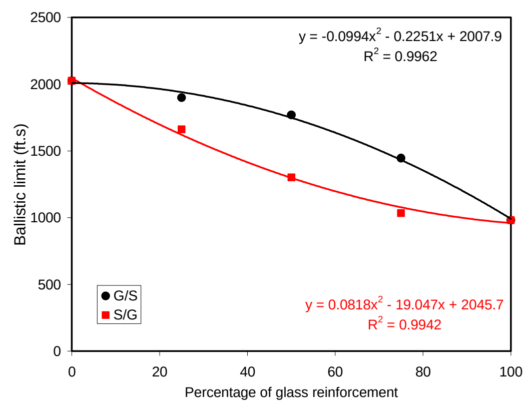

Fig. 3: The ballistic limit depends on which type of fibers is located on the front face of the laminate (Data from Bhatnagar et al [29])

4 Effect of projectile density on the ballistic limit

Czarnecki [35,36] conducted a series of ballistic tests on graphite-epoxy (AS4/3501-6) laminates with either 32 or 128 plies. The stacking sequences were $[(0/90/+45/-45)_4]_S$ and $[(0/90/+45/-45)_{16}]_S$ respectively. Square 7 x 7 in. specimens were clamped around the edges and support conditions were assumed to be between ideally simply supported and clamped. These specimens were impacted by 0.5 in. spheres made out of aluminum, steel, or tungsten. The tests on 32-ply laminates showed that the ballistic limits for ½ in. diameter spherical projectiles made out of aluminum, steel, and tungsten were 625, 371.3 and 281.9 ft/s respectively. If the penetration energy U_p is constant, as assumed in Eq. 1, the ballistic limit should be inversely proportional to the square root of the density of the projectile. A least square fit through the experimental data shows that this is true and that $V_{50} = 1550.4/\sqrt{\rho}$.

The experimental results show that the slope of the line in the U_R versus U_i graph is 0.82 which leads to an m/M ratio of 0.2195. With aluminum projectiles, the slope is 0.63 which indicates that there might be another phenomenon involved here: deformation of the projectile.

5 Empirical models for predicting the ballistic limit

Empirical approaches are use to draw inferences as to the effect of parameters such as projectile diameter and laminate thickness on quantities of interest such as the penetration energy or the ballistic limit. Caprino et al [37, 38] postulated that the penetration energy is related to the laminate thickness t, the fiber volume fraction v_f, and the diameter of the projectile D by

$$U_p = K(t.v_f.D)^{\alpha} \qquad (17)$$

where K and α are constants to be determined from the experimental data. The exponent α was found to be 1.40 for CFRP and 1.30 for GRP. Eq. (3.1) is similar to the formulas proposed by deMarre in 1886 (see [4]) and the modified deMarre equation

$$\frac{MV^2}{D^3} = \alpha \frac{t^{1.4}}{D^{1.5}} \qquad (18)$$

$$\frac{MV^2}{D^3} = \alpha (t/D)^{\beta} \qquad (19)$$

Reddy et al [9, 39] proposed a more complicated expression for the quasi-static penetration energy.

6 Localized projectile-target interaction models

As already mentioned, many authors modeled the penetration of projectiles into targets based on assumptions on the resisting force. Robins and Euler assumed that the penetration resistance is constant, Poncelet assumed that the penetration resistance consists of a constant term and a term proportional to the square of the speed of the projectile. Resal assumed that the penetration resistance depends on v and v^2. A number of authors make similar assumptions on the normal stress between the projectile and the target.

Wen [41, 42] assumed that the normal pressure applied on the projectile is given by

$$\sigma = \sigma_e \left[1 + \beta v \sqrt{\rho_t / \sigma_e}\right] \qquad (20)$$

and developed formulas for calculating the penetration resistance for several types of projectiles. In Eq. 20, σ_e is the static linear elastic compression limit in the through-thickness direction, β is a constant having a value of 1.5 for a hemispherical projectile, ρ_t is the density of the target and v is the velocity of the projectile. Wen [41] considered cylindrical projectiles with either conical or ogival noses and in [42, 43] projectiles with truncated, conical, flat, ogival and hemispherical ends were considered. These models were used by Ulven et al [44]. He, Wen and Qin [45] used the model for projectiles with conical tips.

Abdullah and Cantwell [34, 46] used Eq. 20 to predict the ballistic limit of fiber-metal laminates (FMLs). The same assumption (Eq. 20) was made by Ben-Dor et al [47-49] in their study of the penetration of fiber-reinforced plastics. Wang and Chou [50] assumed that the surface of the projectile is subjected to a constant normal stress σ_1 and to a tangential frictional stress $\mu\sigma_1$ (Coulomb friction). Ben-Dor et al [51-54] assumed that the normal pressure on the projectile followed a Poncelet-type dependence and neglected frictional effects. Jones and coworkers studied the penetration of rigid projectiles in isotropic targets. Jones and Rule [55] assumed that the normal pressure followed a Poncelet type of dependence and Coulomb type friction. Jones et al [56] discussed the use of more complex frictional laws. Ben-Dor [57] determined a class of projectile-target interaction laws for which the Lambert-Jonas equation (Eq. 7) is satisfied.

The model developed by Zhu et al [29] for penetration of Kevlar laminates by conical-tipped indentors also belongs to this category. The penetration process is divided into three stages: indentation, perforation, and exit of the projectile. During indentation motion of the projectile is resisted by uniform pressure p_m and the resistive force is obtained by multiplying that pressure p_m by A_p, the projected area of the projectile. The means pressure p_m is said to be proportional to the yield stress of the material and to be best determined through experiments. For the perforation phase, a damage factor defined as $d_m = N_b / N_t$ where N_b is the number of broken fibers and N_t is the total number of unbroken fibers in front of the contact region is introduced $\left(P = p_m A_p (1 - d_m)\right)$. In the exit stage, a frictional force P_μ determined through static tests provides the only resistance to the motion. The damage factor varies through the penetration process as successive layers fail. Fiber failure is predicted by a maximum strain criterion and the total strain in the fiber depends on the global deformation of the plate and on the local deformation near the indentor. Global deformation is predicted using the first order shear deformation theory and the local damage model includes bulging and delamination.

7 Other engineering models models

Several models attempt to combine the effect of local interaction between the target and the projectile and the overall deformation of the target. For example, Langlie and Cheng [58] proposed a simplified analytical model for the impact penetration process in thick fiber reinforced composites (Fig. 2). The resisting force is represented by a nonlinear spring (spring 1). The deformation of the target remains very localized in a small region surrounding the impacted area and consists mainly of transverse shear deformation. As the deformed zone expands, the effective mass of the target increases and the effective stiffness represented by the linear spring 2 decreases with time.

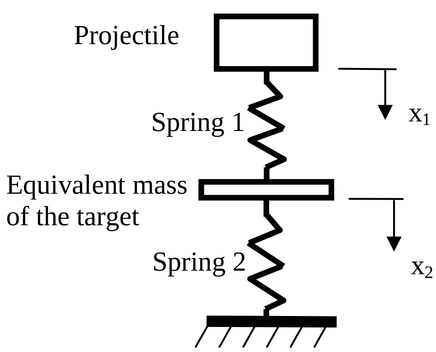

Fig. 4: Simplified model from Langlie and Cheng [58]

Another approach consists of accounting for all energy-dissipating mechanisms. For example, Cantwell and Morton [59] considered that to perforate a composite beam energy is dissipated through four mechanisms: bending deformation of the target, contact deformation, delamination, and shear out.

$$U = U_f + U_c + U_d + U_s \qquad (21)$$

Where the subscripts f, c, d, and s stand for flexural, contact, delamination and shear respectively. Each term on the right hand side of Eq. 21 is estimated using some insight from experiments. With this approach, perforation energies were predicted with good accuracy for a limited number of cases for which experimental results were available. Similar approaches were used Ref. [60-63].

8 Evolution of projectile velocity using various models

When the penetration resistance is given by Eq. 8, the equation of motion for the projectile can be written in non-dimensional form as

$$\bar{v}' + 1 + \varepsilon \bar{v}^2 = 0 \qquad (22)$$

where $\bar{v} = v / V_i$ is the non-dimensional velocity, $\tau = c_o\, t / M$ is the nondimensional time and $\varepsilon = \left(c_2 V_i^2\right) / c_o$. Fig. 5 shows that even when the effect of velocity on the penetration resistance is important, the velocity appears to decrease almost linearly with time.

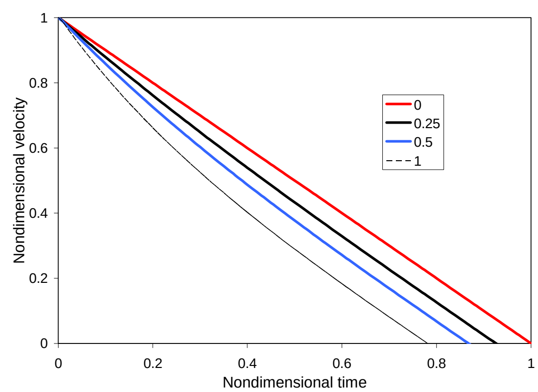

Fig. 5: Evolution of the projectile velocity time for four values of the parameter ε in Eq. 22: 0, 0.25, 0.5 and 1.0

Similarly, when the penetration resistance is given by Eq. 12, the equation of motion for the projectile can be written in non-dimensional form as

$$\bar{v}' + 1 + \varepsilon\, \bar{v} = 0 \qquad (23)$$

where $\bar{v} = v / V_i$ is the non-dimensional velocity, $\tau = c_o\, t / \left(M V_i\right)$ is the nondimensional time and $\varepsilon = \left(c_1 V_i\right) / c_o$. Fig. 6 shows that here also, even when the effect of velocity on the penetration resistance is important, the velocity appears to decrease almost linearly with time.

These results show why both assumptions are used successfully by various researchers to analyze penetrating impact. There is no significant qualitative difference and, provided that the proper constants are used, numerical results agree with experimental results.

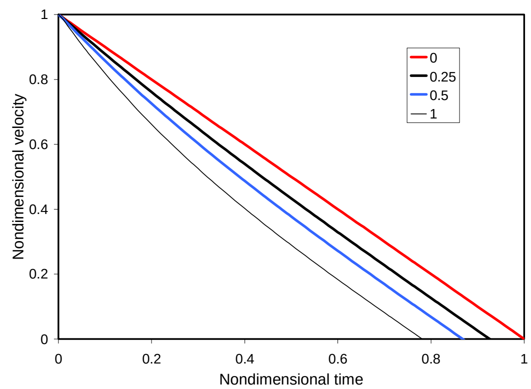

Fig. 6: Evolution of the projectile velocity time for four values of the parameter ε in Eq. 23: 0, 0.25, 0.5 and 1.0

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