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PENETRATION ANALYSIS OF CERAMIC ARMOR WITH COMPOSITE MATERIAL BACKING

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This paper is concerned with the further development of the multi-stage penetration mechanics model of ceramic armor originally proposed in 1989 by Ravid & Bodner and revised in 1999. The 2D analysis relies on the treatment of the initial shock stage (1987), and on the model of 1983 for a rigid projectile penetrating a viscoplastic target. After the shock stage that leads to shattering of the ceramic layer, continued penetration of the projectile into fragmented ceramic, held in place by the backing plate and by inertial effects, is an important part of the process. The final stage involves deformation and penetration of the backup plate which can consist of Aramid or high density Polyethylene in polymeric matrices. The performance of such laminate backing materials under impact loading has been studied which included detailed examination of their straining and failure. These physical considerations are incorporated into the final penetration stage of the current analysis of ceramic armor.

INTRODUCTION

During the past decade, considerable attention has been given to the mechanical behavior of ceramics under impact and thermal loadings. These investigations have encompassed the full range of dimensional scales, and some of the results have been applied to ceramic armor. In the simplest case, this armor consists of a frontal layer of coramic tiles backed by plates of a ductile metal or of composite materials. Present practice for the support plate tends to the use of Aramid or high density Polyethylene in polymeric matrices. Examination of the behavior of such backing plates is therefore a necessary part of the investigation.

The acquired information is intended to be used in computer simulations of the ballistic event and also in the development of analytical models of the process. Both approaches encounter difficulties due to uncertainties in understanding essential physical mechanisms such as the conditions and process of dynamic failure of ceramics, the ballistic resistance of fragmented ceramic held in place by a support plate, and the performance of the backing plate as an integral component of the armor system.

The present paper is a continuation of the development of the analytical models of [1] and [2] for the ballistic penetration of ceramic armor. Emphasis here is given to a detailed examination of the performance of laminated composite backup plates that are currently in use.

ANALYTICAL MODEL

In [1] and [2], the initial stage of impact is characterized by shock waves developed in the ceramic frontal layer and in the projectile as described in [3]. When the shock wave in the ceramic reaches the interface with the backup plate, rarefaction waves are generated which propagate backwards towards the impact surface. The shock compressed ceramic is more dense than the original state but had experienced damage in the form of micro-cracks developed by the initial wave. These effects influence the velocity of the rarefaction wave in opposing manners. After a short delay, the rarefaction wave is followed by breakup of the ceramic whose front can be considered to be a “shatter wave”. The velocity of the shatter wave is estimated to be $c_o/2$ where c_o is the velocity of bulk elastic waves and is approximately equivalent to that of the Rayleigh surface wave for maximum crack propagation.

The shatter wave velocity should also be influenced by the bonding at the interface and by the impedance mismatch effect on the intensity of the reflected wave. A factor F on the velocity $c_o/2$ is taken to be,

$$F = \frac{P_{H1} - P_{H2}}{P_{H1}} \tag{1}$$

where P_{H1} is the Hugoniot pressure in the ceramic due to projectile impact, and P_{H2} is the Hugoniot pressure delivered to the backup plate due to “impact” of the ceramic on it (at twice the initial particle velocity in the ceramic). Typical values for F are in the range 0.65–0.90.

Complete breakup of the ceramic is presumed to occur when the front of the shatter wave reaches the forward extent of the “inelastic zone” of comminuted (pulverized) ceramic surrounding the imbedded projectile. Penetration of the projectile during the shock stage is calculated from [3] up to a time T_1 when shock effects are diminished. After T_1, penetration continues according to the analysis of [4] and projectile erosion, as determined in [3], is assumed to continue at the same rate until breakup. Subsequent to breakup, continued penetration is resisted by fragmented ceramic pieces held in place and constrained by the backup plate and by inertial effects. The effective strength of the fragmented ceramic σ'_{0c} is estimated by an empirical equation,

$$\sigma'_{0c} = 0.2\,\sigma_{0c}\left\{1 - \exp\left[\frac{-m\sigma_{0b}}{0.2\,\sigma_{0c}}\left(\frac{H_b}{H_c}\right)^2\right]\right\} \tag{2}$$

In eq. (2), σ_{0b} is the in-plane strength of the backup layer of thickness H_b, and H_c is the ceramic thickness between the current projectile front and the interface. The modifying term in (2) depends on the relative inelastic bending moduli of the two components of the armor. For strong support, the effective strength would be 0.2 of the compressive strength of intact ceramic σ_{0c}, which was indicated in a few exploratory tests. Alternatively, weak backing of the fragmented ceramic would lead to low effective strength. The quantity m is intended to indicate the quality of bonding and is taken to be unity for optimum bonding.

Penetration of the projectile through fragmented ceramic is considered to be operative until the front of the inelastic zone surrounding the projectile reaches the interface. At this condition, motion of the backup plate is initiated with a velocity field corresponding to simple radial flow emanating from a point on the centerline as in the initial bulging mode of the model of [4]. For this stage, shear strength and frictional effects in the comminuted ceramic forward and moving with the projectile and in the laminated backing plate are ignored so that material displaced by the combined projectile bulges into the backing plate and leads to an equivalent volume bulge of that plate's outer surface. This mode is illustrated in Fig. 1 where the volume of material within the sector angle 2ψ for the spherical cap shaped bulge of the backup plate equals that for the bulge in the ceramic plate with sector angle 2β. As a consequence, the average velocity for each layer i of the backup plate with radial extent $\eta_i R$, $\overline{V}_i$, can be related to the current projectile velocity V and the radial flow geometry by,

$$\overline{V}_i = \frac{V}{3\eta_i^2}\frac{\left(1-\cos^3\psi\right)}{\left(1-\cos\psi\right)} \tag{3}$$

where

$$\eta_i = \eta_b + \left(\eta_{bb} - \eta_b\right)\left[(i-1)/N\right] \tag{4}$$

and the layers are numbered from i=1 to N, R is the projectile radius, and η_b,η_{bb} are shown in Fig. 1. According to the model of [5] for the behavior of fabric subjected to a transversely applied velocity, the average resisting force that each fabric layer, assumed elastic, would exert in the direction of the applied velocity would be

$$F_i = \left(E\,\varepsilon_i\right)\left[Y\left(\frac{\eta_i R}{\sin\psi}\right)\psi\right]S\cos\theta_i \tag{5}$$

where E is Young's modulus, ε_i is the strain, Y is the number of yarns of fabric per unit length, S is the cross section of the yarn, and θ_i is the angle between the force induced in the deformed yarn and the direction of projectile motion. It is also assumed that the force is constant over the effected length of each layer.

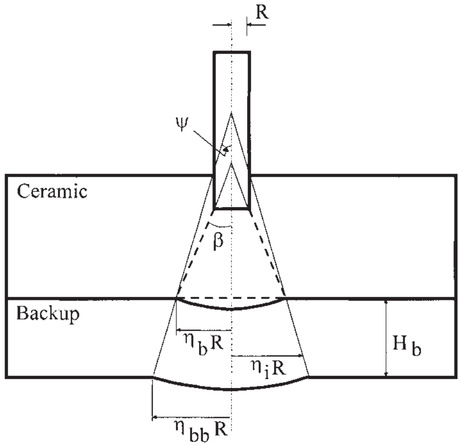

Fig. 1: Bulging of backup plate.

An essential point in the model for the behavior of the laminated backup plate is that the resisting force in each layer, eq. (5), could be expressed in terms of the velocity of each layer, $\overline{V}_i$, , which in turn is a function of the current projectile velocity and the current geometry, eqs. (3),(4). The relevant equations are given in [6] and reproduced in [51, [7] and other papers. In the present notation they are,

$$\overline{V}_i = c\sqrt{\varepsilon_i\left(2\sqrt{\varepsilon_i(1+\varepsilon_i)} - \varepsilon_i\right)} \tag{6}$$

where c is the longitudinal elastic wave velocity in the yarn. A practical value of c to be used for a strong fabric surrounded by a polymer matrix is.

$$c' = \left(c/\sqrt{2}\right)(1-P)^{1/2} \tag{7}$$

where the factor $1/\sqrt{2}$, is based on the work of [8] and P is the fraction of added mass of polymer. The $(1\text{–}P)^{1/2}$ term is approximately that obtained by calculating an effective modulus based on the law of mixtures. The angle θ_i is determined from [6] to be a function only of the strain ε_i so it could also be expressod in terms of V and the current geometry from (6) and (3),

$$\sin\theta_i = \frac{\sqrt{2\varepsilon_i\sqrt{\varepsilon_i(1+\varepsilon_i)} - \varepsilon_i^2}}{\sqrt{\varepsilon_i(1+\varepsilon_i)}} \tag{8}$$

The total resisting force of the backup plate could be obtained by summing F_i for all the layers of fabric. However, the resisting force of each layer multiplied by its velocity $\overline{V}_i$, is summed and enters the overall work rate balance equation of [4] for determination of the current penetration velocity.

Continued penetration leads to a condition where the spherical cap geometry of the bulge of the ceramic layer changes to a bulge advancement mode as described in [4]. To simplify the calculation of ψ for subsequent penetration, the ratio (cosψ/cosβ) is held constant at the value existing at the transition. The velocity field described by (3), (4) remains unchanged. With further penetration, the projectile front reaches the original position of the rear surface of the ceramic layer. At this condition, the projectile and the comminuted ceramic material forward and moving with it are considered to act together as a rigid projectile having the current momentum. Penetration of the backup plate by the effective projectile would again be governed by the work rate balance equation of [4] using the preceding equations for the resisting force and velocity of each layer of fabric. During this final stage, the angles β and ψ are taken to be constant at the onset values. Failure of a layer of fabric is governed by a limiting strain criterion where the strains are obtained from eqs. (6) and (3). Until failure, each layer would contribute to the work rate balance equation.

EXAMPLES

Some numerical exercises were performed for the ceramic armor combinations described in [2]. The properties of the projectile, the ceramic outer plate, and those of the backup plate of Kevlar fibers in a polymer matrix are listed in Tables I and II. The examples consist of three different thicknesses of the ceramic layer, 8.5, 9 and 10 mm, and backed respectively by 28, 26 and 20 layers of Kevlar K770 laminate to provide for an equal areal density of 50 kg/m^2. Areal density of each Kevlar layer was 560 gram/m^2 with the matrix and 470 gram/ m^2 without the matrix.

Numerical exercises were carried out for each case for impact by a 7.62x54 mm API projectile at 870 m/s. Results of the penetration velocity-time history for each case are shown in Fig. 2. All three cases led to no perforation (similar to the results of the ballistic tests), but the one with the 10 mm ceramic (case 3 of Table II) indicated the best relative performance with no breakage of any of the layers of the backup plate.

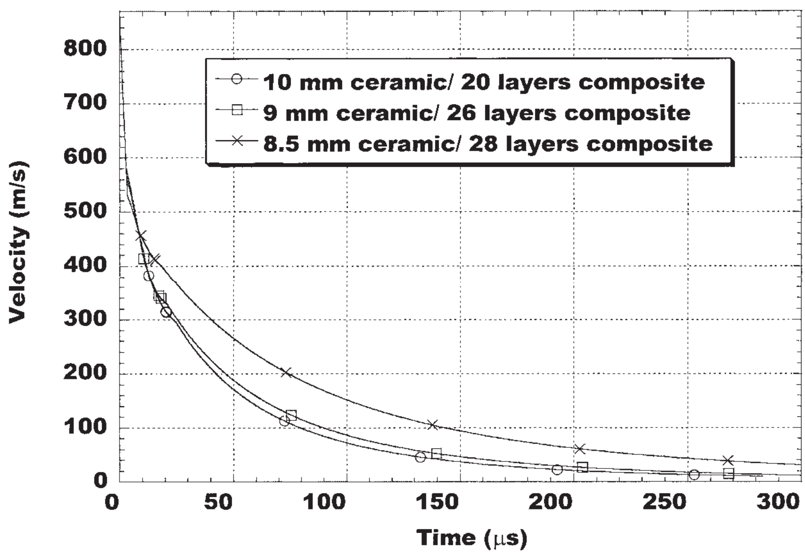

Fig. 2: Calculated penetration velocities for the three cases as functions of time.

Table I. Material properties

Symbol	Units	Material Properties			
		Penetrator	$A\ell_2O_3$,98%	K 770 laminate	Kevlar Yarns
$\sigma_0(\dot{\varepsilon}_0 = 1\,s^{-1})$ flow stress	MPa	1765	2844	290 (average)	-
ρ density	gr/cc	7.85	3.80	1.4	1.4
C $\dot{\varepsilon}$ coefficient	n.d.	0.025	0.04	0.02	-
ε_{max} failure strain	%	4	1	-	3.8
E Young's modulus	GPa	213	274	-	60
ν Poisson ratio	n.d.	0.31	0.22	0.45	-
c_o bulk sound velocity	km/sec	4.55	10	(c) 2.07	(c) 6.55
α_1 shock wave constant	n.d.	1.45	1.3	-	-
Γ Gruneissen coefficient	n.d.	2.03	2.3	-	-
Cross section of yarn : $0.23\ mm^2$ ‖ yarns/m : 670 ‖ resin mass fraction : 0.125					

$\sigma_y = \sigma_0[1 + C\log(\dot{\varepsilon}_{eff}/\dot{\varepsilon}_0)]$ ‖ Factor on shatter velocity : 0.70.

Table II. Ballistic test target ad calculated results

Case	Layer 1		Layer 2		Number of K770 broken layers (calculated)
	Material	Thickness (mm)	Material	Thickness (mm)	
1	$A\ell_2O_3$ (98%)	8.5	K770	12.7 28 layers	12
2	$A\ell_2O_3$ (98%)	9	K770	11.4 26 layers	2
3	$A\ell_2O_3$ (98%)	10	K770	8.7 20 layers	0

projectile: 7.62x54 mm T API-B32/0°N
total actual length of AP core: 29.9 mm
equivalent cylinder length: 23.5 mm

hard core diameter = 6.1 mm
hard core weight 5.39 gm
impact velocity: 870 ± 5 m/s
areal density of armor = 50 kg/m^2

DISCUSSION

The modification suggested in this paper of the analytical model for ballistic penetration of ceramic armor [2] leads to improved understanding of the response behavior of laminated backup plates. Those plates provide the support for fragmented ceramic to have effective resistance to ballistic penetration. They also serve to absorb kinetic energy of the residual effective projectile in the final stage of the penetration process. In that respect, the backup plate acts as a viscous medium, even for elastic fibers, since the resistance depends upon the imposed penetration velocity.

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