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Predicting the perforation of ceramic-faced light armors subjected to projectile impact

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ABSTRACT

An analytical model is presented herein for the perforation of ceramic-faced light armors subjected to impact by flat-ended projectiles at normal incidence using energy balance method. The backing plates of ceramic-faced light armors consist of either metals or fiber reinforced plastic (FRP) laminates. It is assumed that during ballistic impact the kinetic energy of a projectile is dissipated by deformation (mushrooming) and erosion of the projectile, compression/fragmentation and shear failure of the ceramic facing tile as well as perforation of metal or FRP backing plate. Various equations are obtained and compared with available experiments. It transpires that the present model predictions are in good agreement with the test data for the perforation of ceramic-faced light armors under impact by flat-faced projectiles in terms of ballistic limit and residual velocity. It also transpires that, to a first approximation, the present model can also be applied to ceramic-faced light armors struck normally by non-flat missiles.

1. Introduction

Ceramic-faced light armors have now been widely used in defense industry due to its high specific strength and excellent ballistic performance. High strength ceramic facing tile is designed to break/defeat an incoming projectile by deformation (mushrooming) and erosion of the projectile, ceramic cone (conoid) formed in the ceramic plate to spread the loading over a large area of the backing plate.

In the past fifty years or so many researchers have conducted theoretical investigation into the perforation of ceramic/metal light armors or ceramic/FRP composite armors subjected to impact by flat-nosed projectiles and suggested many analytical models. Florence [1] proposed an analytical model for predicting the ballistic limit velocity of a ceramic-faced light armor struck transversely by a rigid flat-ended missile using the conservation of energy. Woodward [2] suggested a simple one dimensional approach to modeling ceramic composite armor defeat and Reijer [3] formulated a series of equations to describe the time histories of various parameters in the penetration process. Zaera and Sanchez-Galvez [4] examined the ballistic perforation of ceramic/metal light armor by employing the A-T model to describe the projectile penetration process of the ceramic facing tile and the model proposed by Woodward [2] to depict the energy absorption of the backing plate. The model predictions were found to be in good agreement with the test results for the perforation of AD995/5083 aluminum alloy or AD995/6082 aluminum alloy light armors struck by 20 APDS in terms of residual velocity, residual mass of projectile and ballistic limit. On the basis of the work done by Zaera and Sanchez-Galvez [4], Feli et al. [5] described the deformation of projectile by using the model proposed by Walker and Anderson [6] and modified the semi-cone angle in their model. It was shown that the modified model can be used to calculate the residual velocity more accurately as compared to the model suggested by Zaera and Sanchez-Galvez [4]. On the other hand, Naik et al. [7] proposed an engineering model for the perforation of ceramic/FRP composite armors under impact by flat-ended projectiles based upon energy balance method and stress wave theory. Various energy absorbing mechanisms in the perforation process were delineated and the model predictions were shown to be in reasonable agreement with the experimental results for the perforation of alumina/FRP composite armors subjected to impact by a flat-nosed projectile in terms of residual velocity.

However, it should be noted here that the failure mechanisms considered in the analytical models mentioned above are not comprehensive and, in particular, the values of some explicit parameters or the method for determining the parameter values are not given. As such the applicability of some existing models is quite limited.

The objective of this paper is to suggest an analytical model to predict the perforation of ceramic-faced light armors struck normally by flat-ended projectiles using energy balance method. The backing plates are made of either metals or fiber reinforced plastic (FRP) laminates. Various equations are derived based upon the assumption that the main energy absorbing mechanisms are

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Notation

C_v	heat capacity of metal plate
D, q	empirical constants chosen to describe rate sensitivity of a metal material
d_0	initial diameter of projectile
d_p	diameter of projectile after deformation/mushrooming
E_b	energy absorbed by backing plate
E_c	energy absorbed by ceramic facing plate
E_{cc}	energy absorbed by ceramic facing plate with compression failure
E_{cs}	energy absorbed by ceramic facing plate with shear failure
E_k	initial kinetic energy of projectile
E_{kb}	kinetic energy of residual projectile when it strikes backing plate
E_{kr}	kinetic energy of residual projectile
E_p	energy absorbed by projectile
F_{cc}	ceramic compressive force resistive to projectile motion
F_{cs}	shear force a ceramic plate can withstand when shear failure occurs
h_b	thickness of backing plate
h_c	critical thickness of the ceramic plate between shear and compress
h_{c0}	thickness of ceramic facing plate
k_1	ratio of projectile deformed diameter to its initial diameter
k_2	ratio of penetration velocity to initial velocity
l_0	initial length of projectile
l_e	erosion length of projectile
l_{eq}	equivalent length of non-flat-nosed missile
m_p	initial mass of projectile
m_b	lugging mass of the backing plate
m_r	mass of residual projectile after erosion
n	shear strain hardening exponent
ρ_b, ρ_c, ρ_p	densities of backing plate, ceramic facing plate and projectile
u	penetration velocity of projectile
v_0	initial velocity of projectile
v_r	residual velocity of projectile
v_s	velocity of residual projectile when it impacts backing plate
Y_p	dynamic yield strength of projectile
α	thermal softening coefficient
β_c	empirical constant, defined in Eq. (8)
β	empirical constant, defined in Eq. (12)
ζ	heat transfer coefficient of metal plate
ξ	empirical constant used in Eq. (16)
σ_e	linear elastic limit of FRP laminates in through-thickness compression
HEL	Hugoniot elastic limit of ceramic
τ_0	quasi-static shear strength when shear strain $\gamma = 1$
τ_s	shear strength of ceramic
γ	shear strain of metal plate
$\gamma_{m}^{\cdot}$	average shear strain rate
γ_f	critical shear strain when adiabatic shear occurs
δ	reduction of cross-section area
e_f	true fracture strain of projectile material
θ	semi-angle of ceramic cone as defined in Fig. 1

projectile deformation (mushrooming) and erosion, ceramic compression (crushing) and shear failure, backing plate perforation. The analytical model is compared with available test data as well as some existing models and discussed.

2. Formulation of an analytical model

Consider a flat-ended projectile of length l_0 penetrating into a ceramic-faced light armor at impact velocity v_0, the initial kinetic energy of the projectile can then be expressed as

$$E_k = \frac{1}{2} m_p v_0^2 = \pi {d_0}^2 \rho_p l_0 {v_0}^2 / 8 \tag{1}$$

where m_p, d_0 and ρ_p are the mass, initial diameter and density of the projectile, respectively. From the energy balance, one obtains

$$E_k = E_p + E_c + E_b + E_{kr} \tag{2}$$

where E_p, E_c and E_b are the energies absorbed by the projectile, the ceramic facing tile and the backing plate, respectively; E_{kr} is the kinetic energy of the residual projectile. The expressions for various energy parameters will be constructed in the following sections.

2.1. Energy dissipation of projectile

On the basis of the experimental observation, it is assumed that when a projectile strikes a ceramic-faced light armor the deformations (thickening/mushrooming) and erosion of the projectile occur before it penetrates into the backing plate, and the kinetic energy loss of the projectile is mainly related to the energy associated with the erosion of the projectile itself. Hence, one obtains

$$E_p = \pi {d_0}^2 Y_P \cdot l_e / 4 \tag{3}$$

in which Y_p is the dynamic yield strength of the projectile, l_e is the erosion length of the projectile.

2.2. Energy dissipation of ceramic facing tile

A ceramic facing tile under impact by a blunt projectile can fail, depending upon its thickness relative to the projectile diameter, in two modes: direct formation of ceramic cone; first penetration/compression and then followed by ceramic cone formation. The former ceramic tile is defined as thin whilst the latter as thick. Fig. 1 shows schematic diagram of a typical cone formed in a ceramic plate struck normally by a flat-faced projectile as observed experimentally by Wilkins et al. [8]. Damage can also occur in ceramic plate when it contacts the bullet, and part of its kinetic energy is absorbed by ceramic. It should be mentioned here that failure mechanisms of

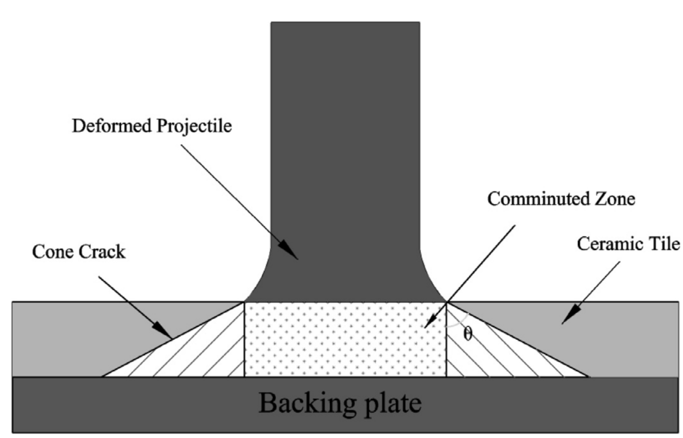

Fig. 1. Schematic diagram of a typical ceramic cone.