BALLISTIC LIMIT BEHAVIOR OF POLYMERS TRANSPARENT MATERIALS UNDER HIGH VELOCITY IMPACT

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ABSTRACT

The purpose of this work is to present a new analytical model for predicting the perforation characteristics of multi–layered transparent polymer materials. In type polycarbonate and impacted by rigid steel conical tip projectiles in the range of 100–970 m/s of impact velocity. Analytical model has been presented for all energy absorbing mechanism. It was assumed that the energy is equated as loss of the kinetic energy of the projectile and assumed to be classified into three types which include elastic work, petaling work done and dishing work done. The analytical predictions were in good agreement with existing experimental results.

***Keywords**: Ballistic limit, energy balance, multi–layer*

INTRODUCTION

This research work deals with materials that have the dual properties of being visually transparent and resistant to penetration by high energy projectiles and fragments. These materials, albeit loosely defined, have received considerable attention in military research and development establishments mainly for protection of the eyes of military personnel as well as the face and head a variety of military as well as civilian applications for these materials have evolved over the years, automotive windshields for very important people, lectern protection, and goggles for military tank crews and other hazardous military operation [1].

Investigation on transparent armored materials under impact on ceramic materials, glass and polycarbonate was reported by Straßburger [2]. Hard front layer of transparent ceramic materials were subjected to projectile of 7.62 mm x 51 AP steel with a total mass of 9.5 g. The impact velocity was kept constant at nominally 850 ± 15 m/s. It was reported that the protective strength increased proportional with thickness. The materials efficiency in term of strength was observed in the thickness range from 1 to 2 mm.

The importance of penetration and perforation into targets in both, military and civilian application has made it the subject of many investigations. This research work is aim to present an analytical model for ballistic velocity impact and this modal used for predicting the energy absorbed mechanisms by using three types of observed energies which includes elastic work, petaling work done and dishing work done. These energies have been presented for a typical polycarbonate materials impacted with spherical projectile.

This paper reports experimental work to investigate and model the ballistic impact of polycarbonate. The structure of the paper is as follows. First the ballistic rig and experimental techniques used are described briefly. Theoretical analysis of the impact behaviour of polycarbonate is reported elsewhere [3], as is the characterization of the deformation and fracture behaviour of the material [4, 5]. To avoid ambiguity, we define the following terms. The distal face of the plate is that parallel to, and farthest away from the impact face. An analytical model was presented for perforation of sandwich panels with honeycomb core [6].

Analytical models

The theoretical model of the penetration and perforation of three rigid projectile (conical) against polymer polycarbonate target plate clamped at its outer periphery will be based on the conservation of the total energy where the loss of the kinetic energy of the projectile $\Delta K.E$ is equated to the total work done in the deformation of the W_T, and assumed to be classified into three types which are:-

The elastic work W_E
The work done in dishing W_D
The work done petaling W_P

$$\Delta K.E = W_T$$
(1)
$$W_T = \frac{1}{2} m V_b^2$$
$$W_T = W_E + W_D + W_P$$

(m being the mass of the projectile, V_b is the ballistic projectile velocity) , this work is comprised of the following.

Elastic work W_E

Which is the elastic energy stored in the target plate during the penetration process. That for a clamped circular plate of radius a, subjected to a central concentrated load P, the central deflection (w_c) may be written as.

$$w_c = \frac{PR^2}{16\pi D} \quad (2)$$

$$D = \frac{Eh^3}{12(1-\upsilon^2)} \quad (3)$$

Thus, the central deflection can be written as:

$$w_c = \frac{P}{\left(4\pi Eh^3 / 3\left(1-\upsilon^2\right)R^2\right)} \quad (4)$$

Assuming,

$$K = \frac{4\pi Eh^3}{3(1-\upsilon^2)R^2} \quad (5)$$

Equation (4) reduces to

$$w_c = \frac{P}{K} \quad (6)$$

Note that K is the structural stiffness of the plate.

Now, according to Castigliano's Theorem [8], the deflection w_c is equal to the derivative of plate strain energy U with respect to central concentrated load P, i.e.,

$$w_c = \frac{\partial U}{\partial P} \quad (7)$$

and since there is no other load but P acting on the plate, the derivative becomes an ordinary one, i.e.,

$$w_c = \frac{dU}{dP} \quad (8)$$

or

$$dU = w_c dP \quad (9)$$

From equation (6)

$$dP = K dw_c \quad (10)$$

Substituting into equation (8)

$$dU = Kw_c dw_c \quad (11)$$

Integrating equation (11) to a limiting maximum deflection w_{max} the maximum elastic deflection w_c

$$\int_0^U dU = K \int_0^{w_{\max}} w_c dw_c \quad (12)$$

The following expression for the strain energy stored in the target plate is obtained,

$$U = \frac{Kw_{\max}^2}{2} \quad (13)$$

by assuming a linear elastic structure,

$$w_{\max} = \frac{P_0}{K} \quad (14)$$

where $P_0 = \pi\sigma_y h^2$ is the plastic collapse load of the structure [9] and σ_y is the mean dynamic flow stress of the target plate material taken to be twice the value of the static flow stress to account for high strain rate effects.

From equations (13) and (14) and equating the strain energy to the elastic work W_E resulted,

$$w_E = \frac{P_0^2}{2K} = \frac{3\pi\sigma_y^2}{8E} hR^2(1-\upsilon^2) \quad (15)$$

The Work Done in Dishing W_D

The work out to obtain the expression for work done in dishing, i.e. bending and stretching is presented below. The plate is considered to be of infinite radius and subjected to a radial bending moment per unit circumferential length M_r a hoop bending moment per unit circumferential length M_θ and a membrane stretching force per unit circumferential length N_r, the corresponding strains are;

$$W_D = \frac{\pi}{4}\sigma_y h w_0^2 e^{-2r}[1+2r] + \frac{\pi}{2}\sigma_y h^2 w_0 e^{-r}[2+r] \quad (16)$$

The Petaling work done:

The beginning of the petaling process during perforation is always associated with fracture initiation. Immediately after contact by the projectile nose, a star–shaped crack is formed. The hoop stress is thus responsible for further radial extension of the cracks.

The work done in the petaling process can be expressed as

$$m_1 = \frac{\rho h B l}{2}$$

(17)

Where m_1 is the mass of the cantilever petal

With ρ as the mass density of the target if the length of the crack is "c", then B, the width of the root

$$B = 2\pi c \quad (18)$$

Where the circular geometry of the base has been linearized, If $l = c$

$$m_1 = \pi\rho h c^2 \quad (19)$$

The mass ratio parameters it,

$$k = \frac{m_1}{3m} = \frac{\pi\rho h c^2}{3m} \qquad (20)$$

The second stage of motion, rigid–body rotation of the petal about their fixed end takes place. The balance of energy for this stage is [7]

$$\frac{m}{2}\left(V_i^2 - V_f^2\right) = \frac{\pi}{2}\sigma_y c h^2\left(\theta_2 - \theta_1\right) - \frac{m}{4}\frac{k}{\left(1+k\right)^2}V_i^2 + \frac{\pi c^2 h\rho}{12}\cos^2\theta_2 V_f^2 \qquad (21)$$

$$W_P = \frac{\pi}{2}\sigma_y c h^2\left(\theta_2 - \theta_1\right) - \frac{m}{4}\frac{k}{\left(1+k\right)^2}V_i^2 + \frac{\pi c^2 h\rho}{12}\cos^2\theta_2 V \qquad (22)$$

The total work done is the sum of the above mentioned individual expressions.

$$W_T = W_E + W_D + W_P \qquad (23)$$

$$W_T = \frac{3\pi\sigma_y^2}{8E}hR^2(1-\upsilon^2) + \frac{\pi}{4}\sigma_y h w_0^2 e^{-2r}\left[1+2r\right] + \frac{\pi}{2}\sigma_y h^2 w_0 e^{-r}\left[2+r\right] + \frac{\pi}{2}\sigma_y c h^2\left(\theta_2-\theta_1\right) - \frac{m}{4}\frac{k}{\left(1+k\right)^2}V_i^2 + \frac{\pi c^2 h\rho}{12}\cos^2\theta_2 \qquad (24)$$

$$\frac{1}{2}mV_b^2 = \frac{3\pi\sigma_y^2}{8E}hR^2(1-\upsilon^2) + \frac{\pi}{4}\sigma_y h w_0^2 e^{-2r}\left[1+2r\right] + \frac{\pi}{2}\sigma_y h^2 w_0 e^{-r}\left[2+r\right] + \frac{\pi}{2}\sigma_y c h^2\left(\theta_2-\theta_1\right) - \frac{m}{4}\frac{k}{\left(1+k\right)^2}V_i^2 + \frac{\pi c^2 h\rho}{12}\cos^2\theta_2 \qquad (25)$$

$$V_b = \sqrt{\frac{3\pi\sigma_y^2}{4mE}hR^2(1-\upsilon^2) + \frac{\pi}{2m}\sigma_y h w_0^2 e^{-2r}\left[1+2r\right] + \frac{\pi}{m}\sigma_y h^2 w_0 e^{-r}\left[2+r\right] + \frac{\pi}{m}\sigma_y c h^2\left(\theta_2-\theta_1\right) - \frac{1}{2}\frac{k}{\left(1+k\right)^2}V_i^2 + \frac{\pi c^2 h\rho}{6m}\cos^2\theta_2} \qquad (26)$$

This equation gives the ballistic limit velocity of a target function of its polycarbonate properties.

RESULTS AND DISCUSSION

The theoretical ballistic limit velocity equation (26) is plotted as the solid line figure (1) and it shows good correlation with the experimental results of Land Koff and Goldsmith [7] for multi-layer polycarbonate targets. The overall trend is that the ballistic limit velocity of a target increases as its total thickness increases. The effect of layering on the ballistic limit velocity can be more clarified in figure (1). The ballistic limit velocity is greatly dependent on the total work done in deforming the target. That has suggested that the total work done to be plotted against the total thickness of the target as shown in figure (2). This trend can be understood if the total work done is decomposed into the work done in the different types of failure as equation (23) by using three types of observed energies which are: elastic work, plastic work done in dishing and work done by petaling work done.

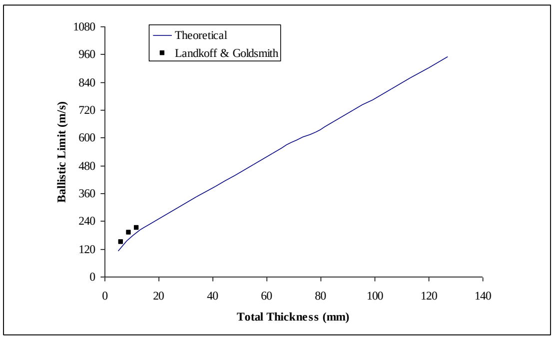

Figure 1: Theoretical ballistic limit velocities for PC versus thickness

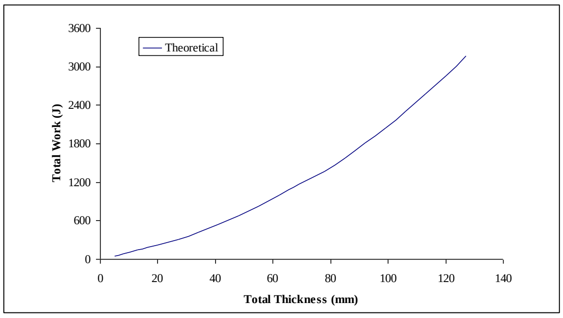

Figure 2: The effect of target thickness on the total work done for PC target

CONCLUSIONS

The polycarbonate targets showed their unique failure form resembling the failure form that resembles what was already reported for multi–layer thin metallic targets. Perforation energy is consumed by elastic work, dishing work and petaling work. Moreover, the perforation energy is found to rise with target thickness in a power series function form. The ballistic impact behavior of polycarbonate, when impacted by projectile, is based on the analytical method. The ballistic limit results were compared with experimental work done by Land Koff and Goldsmith.

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