BEHAVIOR FORMS OF GLASS AND OTHER TRANSPARENT MATERIAL TARGETS UNDER HIGH SPEED IMPACT LOADING

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ABSTRACT

The failure forms associated to high speed loading tests on Glass, Polymethylmethacrylate and Polycarbonate targets are presented. Targets of the three indicated transparent materials were subjected to high velocity impact, at normal incidence, by spherical steel projectiles in the 100 m/s to 950 m/s velocity range. Each type of the targets studied showed its unique trend in its failure forms. The failure forms observed seems to be related to the mechanical properties of the tested material. Polycarbonate targets showed failure forms quite similar to those shown by ductile metallic targets of similar thickness. However, the glass and the polymethylmethacrylate targets showed totally different forms. Based on the high velocity impact test results, a mathematical model that couples the terms of the work done in causing the failure forms to the projectile kinetic energy dropped during the target perforation is suggested.

Keywords*; Glass performance, Transparent materials, Performance of materials under impact conditions*

1- INTRODUCTION:

Existing transparent shielding panel systems are typically comprised of many layers of several materials which only have in common the transparency differing in the other physical properties. Such systems can be engineered to provide different levels of protection against high speed projectiles or fragments by changing variables such as the plate material, thickness of plies, interlayer thickness, and the number of plies. Laible R. [1] includes a chapter with technical information of "Transparent Armor". This chapter included a literature survey on the subject that contains 19 references of David H. Rose [2] reported to the existing transparent shields. These systems are typically comprised of many layers separated by polymer interlayer. Such systems are engineered to provide different levels of protection by changing the layers variables. Texas Armoring Corporation [3], and Sierracin/ TransTech [4] reported that the glass-clad polycarbonate products are able to accommodate almost any threats from explosion sharpness. This paper deals with the failure forms shown by three main constituents of any transparent shields, namely Glass, Polymethylmethacrylate and Polycarbonate, when subjected to high speed impact by a spherical projectile. The energy required to defeat a target of each of the mentioned materials is estimated accordingly.

2- EXPERIMENTAL SET-UP

2.1- Test specimens preparation

Test specimens were prepared using panels of the three transparent materials, Glass, Polymethylmethacrylate and Polycarbonate. Glass is a familiar group of ceramics. Mainly it is noncrystalline silicates containing other oxides, namely CaO, Na_2O,K_2O and Al_2O_3, which influence the glass properties. The test specimens were chosen from common commercial window type glass with no further heat treatment. Polymethyl-methacrylate is a kind of polymers known for its fair mechanical properties, low cost and transparency. Polycarbonates are probably the most common plastics used for transparent armor applications. Their low cost, easy forming and molding and excellent protection against small high speed fragments made them common to all transparent shielding applications. The three materials panels were machined either to (100*100 mm) high velocity impact test target dimensions or to the standard (ANSI/ASTM D 638-77) tensile test specimen dimensions according with the type of the required test. Tensile tests were carried out on (INSTRON 1195) test equipment at the rate of 10 mm/min.

Material	Modulus of Elasticity (GN/m²)	Poisson Ratio	Thickness (mm)	Density (g/cm³)	Tensile Stress (MN/m²)
Glass	*69*	*0.23*	*4* *6* *8* *12*	*2.5*	*69*
Polymethylmetha-crylate	*3.28*	*0.36*	*4* *5* *6* *10*	*1.19*	*72.3*
Polycarbonate	*2.38*	*0.28*	*2.5* *5*	*1.2*	*62.8*

Table (1): Characteristics of the transparent material targets used in this work.

2.2- The high velocity tests:

High velocity tests were carried out using the high velocity-testing rig shown schematically in figure 1. Basically, the rig consists of a two-clamped base on which a gun barrel with 7.85 mm of nominal bore and 480 mm of length was mounted. In the fire's line of the projectile, two specially designed velocity measurement units were positioned in front and behind the target holding frame. Each unit consisted of two spaced shorting grids connected to an electronic time counter. Time counting started when the projectile cuts the wires of the first grid and is stopped when the projectile cuts the wires of the next grid. Steel spherical projectiles of 85-87 HRB hardness, with 7.8 mm of diameter and a mass of 2.05 g, were propelled up to 950 m/s velocity using commercial powder gun charge. Various projectile velocities were obtained by manipulating the weight of powder gun charge. Tested targets were clamped between two steel constraining plates with 70 mm aperture center and firmly tightened. The striking velocity and the residual mean velocity were estimated dividing the distance between two consecutive grids by the counted time, respectively. The perforation energy was then calculated, assuming a non-deformable projectile and the conservation of energy, using the following relationship:

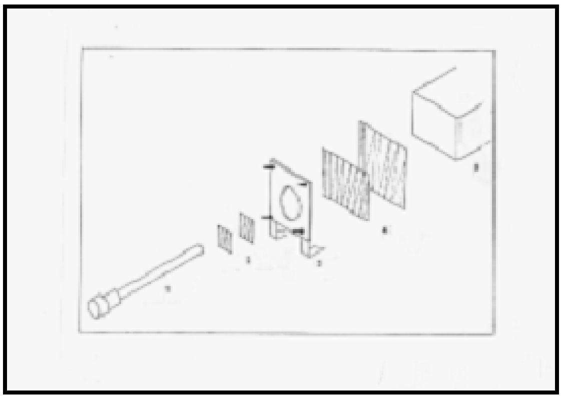

Figure 1- Schematic drawing of the high velocity-testing rig where (1) presents the gun, (2) are the pre-impact velocity measurement grids, (3) is the target holding frame. (4) are the post-impact velocity measurement grids, and (5) is the projectile containment box.

$$E = \frac{1}{2} \times m \times \left(V_i^2 - V_r^2\right) \qquad (1)$$

where

E – perforation energy (Joules)

m - Mass of the projectile (Kg)

V_i - incident velocity m/s

V_r - residual velocity m/s

After impact, damage was assessed using optical microscopy.

3- RESULTS AND DISCUSSION

The damage caused by the high speed impact on the Glass, Polymethyl-methacrylate and the Polycarbonate targets was assessed using an optical microscope. An image of one of the failure patterns obtained can be seen in figure 2.

3.1- Impact Damage Characteristics for Glass Targets

For the glass targets, star shaped cracks were noticed to be formed upon the first projectile-target contact, followed by circular cracks forming a spider net like shape, figure 2, denoting a stress field in the hoop and radial directions exceeding the yield stress of the glass even if the projectile kinetic energy is not sufficient to drive it through the glass thickness. When the incident velocity of the projectile increases such that (and consequently its kinetic energy) it is sufficient to cross the target, the glass is fractionized and the fragments are projected ahead, keeping the specimen completely shattered. Thickness in glass targets is found irrelevant to its penetration resistance as glass is shattered upon the first projectile- target contact

Figure2- The post impact damaged areas of a 5mm thickness glass target struck by a 7.8 mm diameter spherical projectile driven at a very low velocity.

3.2- Impact Damage Characteristics for Polymethylmethacrylate Targets

Figure 3 shows photography of the post impact damaged areas of a 5mm thickness Polymethylmethacrylate target struck by a 7.8 mm diameter spherical projectile driven at 250 m/s velocity.

Here again star shaped cracks are initiated upon projectile-target incident impact.

Figure3- The post impact damaged areas of a 5mm thickness Polymethylmethacrylate target struck by a 7.8 mm diameter spherical projectile driven at 250 m/s velocity.

The area of impact presents high stresses both in the radial and hoop directions, with the hoop stresses much higher than the maximum tensile stress permitted by the material. This stresses are the eventual cause of the fracture of the material, with a star shape form, in the vicinity of the point of impact. If the kinetic energy of the projectile is sufficient to move it through the target material, radial cracks and several concentric cracks around the projectile tip are formed. On further projectile progress, the cracked zone is pushed forward in front of the progressing tip forming a conical cross section shape. Finally the projectile emerges from the rear side of the target pushing a plug of a diameter greater than the diameter of the projectile.

The total energy dissipated by the penetration process in Polymethylmethacrylate targets is mainly consumed in crack growth work,

$$E = W_{Crack} \qquad (2)$$

where W_{Crack} is derived according [5] and defined in appendix.

Figure 4 shows the relation of the projectile consumed energy, obtained by applying equation [1], versus the polymethylmethacrylate target thickness and the results obtained experimentally. The graphic indicates that perforation energy rises linearly with target thickness. The experimental results are generally in good agreement with the theoretical model.

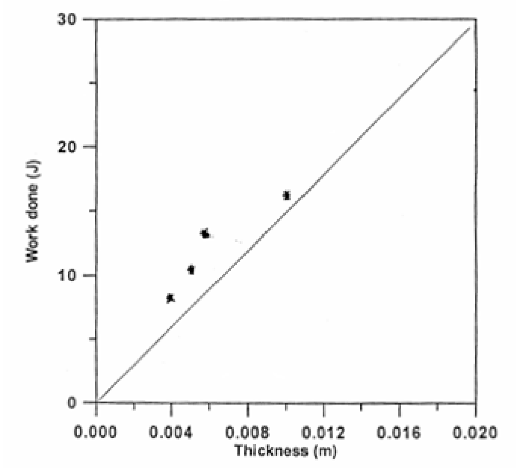

Figure 4- Projectile consumed energy versus poly-methylmethacrylate target thickness compared to experimental results.

The second stage is marked by the onset of the plastic thinning of the material under the action of the moving projectile. If there is an enough material to resist its movement, a star shape crack in the target material is formed at its tip. Further movement causes crack growth and folding of the resulting (petals) outwards and permitting eventually the projectile to exit through the rear side of the target.

3.3- Impact Damage Characteristics for Polycarbonate Targets

In figure 5, a 2.5 mm thickness Polycarbonate target impacted by 256 m/s velocity projectile is shown. From the obtained results, the event sequence during penetration process is schematically simulated in figure 6.

Upon first impact, target plate acts as an elastic circular plate clamped at edges when acted by a concentric force. This force drives the target up to most possible elastic deflection permitted by the material.

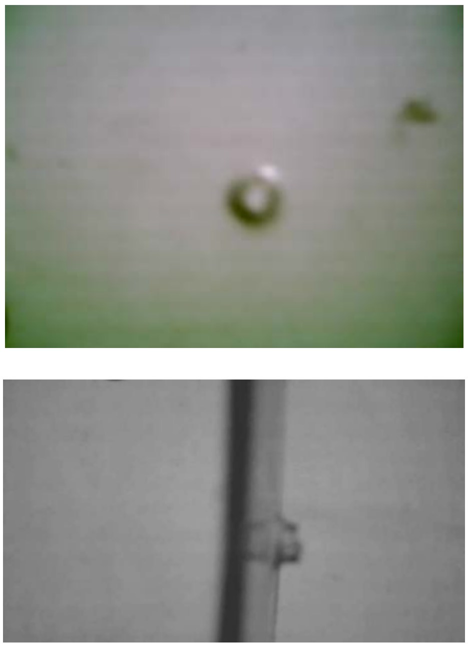

Figure 5- 2.5mm thickness Polycarbonate target struck by a 7.8 mm diameter spherical projectile driven at 256m/s velocity .
Top - front view; bottom - side view.

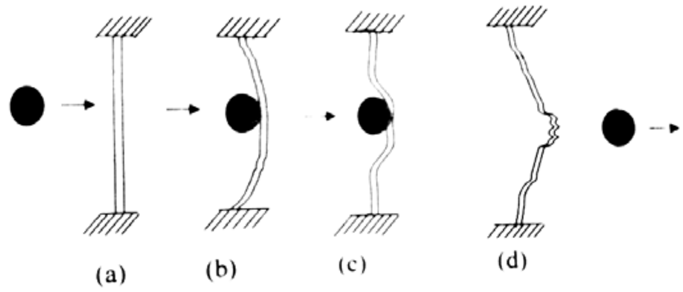

Figure 6- The event sequence during penetration process of polycarbonate targets

The total energy dissipated by the penetration process in Polycarbonate targets is consumed in elastic work, indentation work, and finally dishing (bending and stretching) work,

$$E= W_{Elastic} + W_{Indentation} + W_{Dishing} \qquad (3)$$

$W_{Elastic}$, $W_{Indentation}$, and $W_{Dishing}$ were derived for thin metallic targets by [6] as is presented in the appendix.

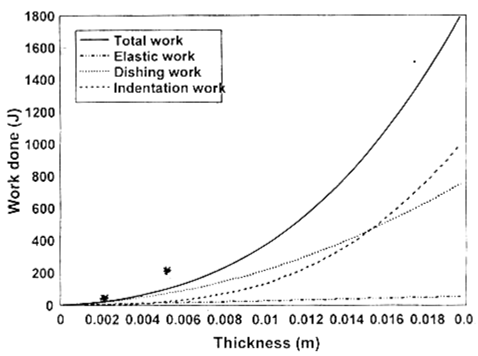

Figure 7- Projectile consumed energy versus polycarbonate target thickness compared to experimental results.

In the figure 7, showing the relation of both the total energy consumed and the different portions of dissipated work vs target thickness, it is possible to observe that the perforation energy rises with the increasing target thickness in a power series form. It is worth noting the order of magnitude of the consumed energy needed to defeat the polycarbonate targets compared to that needed to defeat the polyme-thylmethacrylate targets. As shown in figure 4, the superiority of polycarbonate targets are clearly manifested. Experimental results are close to the theoretical model for low thickness targets.

CONCLUSIONS

A set of high velocity impact tests were conducted on three types of transparent material targets, namely glass, polymethylmethacrylate and polycarbonate in order to assess experimentally their behavior under such harsh loading. The following conclusions may be derived from the results:

- The threshold perforation energy needed to defeat glass targets was found irrelevant to the target thickness. Glass showed the weakest behavior under high velocity impact of the three studied materials as its targets were shattered into a jet of small glass fragments constituting an additional threat.
- Polymethylmethacrylate targets were found to fail mainly by crack forming. Perforation energy was found to rise linearly with target thickness.
- Polycarbonate targets showed their unique failure form resembling the failure form that resembles what was already reported for thin metallic targets. Perforation energy is consumed by elastic work, indentation work and dishing work. Moreover, the perforation energy is found to rise with target thickness in a power series function form. Polycarbonate is found most suitable of the three tested materials for defeating high velocity impact and maintaining safety at the same time.

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Appendix

The work consumed in cracking is given by the following equation

$W_{cracking} = 2\ p\ n\ h\ [\ a\ s_y F(n)]^2 / E_e$

where

n- crack petal number estimated from experimental results.

h- target thickness .

a- crack length estimated from experiment-tal results.

s_y- tensile stress.

F(n)- Function of petal number as shown in figure A.1.

E_e- Modulus of elasticity.

The work consumed in elastic energy stored in clamped edge circular target during penetration process is given by the following equation,

$W_{Elastic} = 3\ p\ s_y^2\ h\ R^2\ (1 - n^2)\ / 8\ E_e$

where ;

R- Target diameter

n- Poisson's' ratio

Other symbols are as previously indicated

The work consumed to form a spherical indentation by the projectile in target plate is given by the following equation,

$W_{Indentation} = 2\ p\ h^3\ s_y\ / 3$

where all symbols are as previously indicated

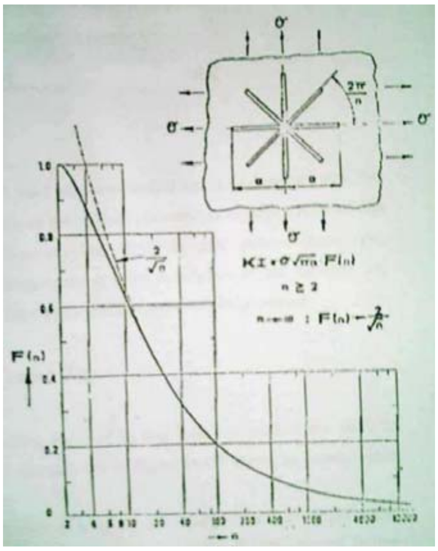

Figure A.1- F(n) in terms of number of cracks (n) for a symmetrical crack pattern

Dishing include plastic bending and stretching of the target plate. The work done in dishing is given by,

$W_{Dishing} = p\ h\ s_y\ w_o^2\ e^{-2r} [1+2\ r]\ / 4 + p\ h^2\ s_y\ w_o\ e^{-r} [2+ r]\ / 2$

where the final effected target area is assumed to have an exponential bulge profile given by:

$w = w_o\ e^{-r}$

Here w_o is the bulge height, *r* is the effected area radius, both estimated from experimental results.