Assessment of Ballistic Performance for Transparent Material

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***Abstract*—A finite element method was used to investigate the ballistic behavior of Polymethylmethacrylate (PMMA) under impact loading by spherical steel projectile with different ranges of velocities. Three different target thicknesses were used in the experimental and the numerical works. A mathematical model has been used for the ballistic limit based on the experimental results. It has been found that projectile velocity and target thickness play an important role in the ballistic behavior of PMMA. A good agreement was found between the numerical, experimental, and the analytical result.**

***Index Terms*—ballistic impact, Finite Element method, PMMA.**

I. INTRODUCTION

The ballistic behavior of transparent materials (ceramic and glass) was studied. Different kinds of layered composite materials were compared from the ballistic strength viewpoint. Layered composites from soda-lime silicate float glass and also sandwiches with sapphire top layer were prepared. Their ballistic strength against two kinds of (AP) ammunition were studied. A test technique and (BMES) criterion have been used to assess the ballistic performance depth of penetration (Klement, et al., 2008).

To describe the performance of polyurethane elastomeric polymer and numerical results of the penetration mechanism and depth-of-penetration a simple linear viscoelastic model has been applied to AUTODYN-2D. The perforation and penetration of the lead antimony bullet against glass-faced polyurethane elastomeric polymer resin has been studied. The resulting craters in the resin contained elongated bullet core material that had a considerable quantity of porosity. Analysis of the simulation model and the high speed photography and of penetrating a viscoelastic resin exhibited that during the primary phases of penetration, the projectile is turned inside out. Besides, the geometry of the cavity was described by the elastic relaxation of the resin that led to compression of the core material (Hazella, Edwardsa and Longstaffa, 2009).

Research on transparent materials under impact on glass, ceramic materials and polycarbonate was studied (Straßburger, 2008). A front layer of transparent materials was impacted by a projectile with 9.5 g in mass. The impact velocity was 850 ± 15 m/s. It has been found that the resistance strength increased proportional with material thickness. With two different thicknesses the materials efficiency in terms of strength has been observed.

The mechanical behavior (static and dynamic) of commercial polymethylmethacrylate (PMMA) have been studied (Rittel and Brill, 2008). It has been found that PMMA shows brittle failure and brittle ductile transition which is similar in its rule to that noticed in brittle material.

This study deals with transparent materials that have resistance to penetration by high velocity impactor fragments. These materials, although generally defined, have got considerable care in military investigations and industrial establishments especially for protection of the head and face area for both civilians and military personnel. The transparent materials have been used widely over the years in, defense and buildings industries, automotive, and aerospace (Laible, 1980).

This work aims to investigate numerically the ballistic behavior and the failure modes of PMMA plates under impact by a steel spherical projectile in the speed range of 78–900 m/s and compare the results with analytical and experimental ones.

II. EXPERIMENTAL WORK

A. *Preparation of Test Specimens*

Polymethylmethacrylate (PMMA) is a type of resins known for its low cost and moderate characteristics, so the specimens have been prepared using plates from this transparent material. The material targets were prepared to 100 x 100 mm in dimensions. A according to the standard size (ANSI/ASTM D 638-77), tensile test specimens were prepared as well (Abbud, et al., 2010). Tensile test was conducted on INSTRON test machine at 10 mm/min cross head speed. The mechanical properties for the PMMA are outlined in Table I.

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B. *Ballistic Test*

All tests were conducted using the test device illustrated schematically in Fig. 1. The device consisted of a barrel of 7.85 mm bore diameter and 480 mm in length. Time counter system consisting of two measuring velocity devices has been installed in front and behind the target. Each device consists of two wire grid units connected to a time counter. This system is responsible about counting the time between the wire grid units before and after the target. Spherical rigid projectile 7.8 mm in diameter and 2.05 g in mass was used. Different velocities have been used by changing the weight of gun powder charges. Targets have been installed between two rigid fixed plates. The projectile initial velocity and the residual velocity were calculated by dividing the distance between two wire grid units by the counted time.

TABEL I
Mechanical Properties of PMMA

Material	Density ρ (kg/m^3)	*E* (MPa)	Yield Stress σ_y (MPa)	Tensile Strength (MPa)	Poisson's Ratio υ
PMMA	1190	3280	53.8	48.3	0.28

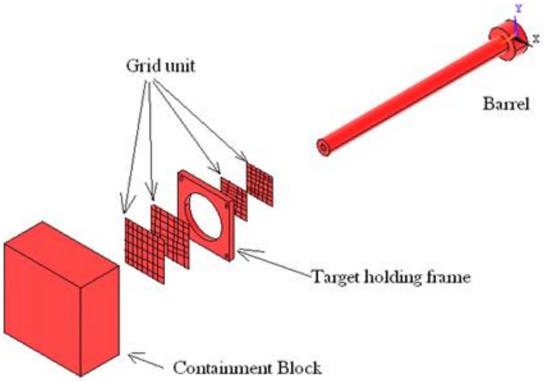


Fig. 1. Schematic drawing of the ballistic test device, re drawn based on the original scheme (Abbud, et al., 2010).

III. ANALYTICAL MODEL

The analytical model of the penetration and perforation of a hard projectile on a PMMA plate fixed at its rim will depend on the conservation of energy principle where the reduction of the kinetic energy of the projectile ($\Delta K.E$) is equal to the work done on the deformation of the W_E,

$$\Delta K.E = \frac{1}{2}\left[m\left(V_i^2 - V_r^2\right)\right] = W_E \tag{1}$$

Where m is the mass of the rigid projectile, V_i and V_r are the initial and residual projectile velocities respectively W_E is the elastic work stored in the target panel during the penetration phase. (Al–Ghabban, 1996) showed that for a clamped circular plate of radius (R), subjected to a central concentrated load (P), the central deflection (W_E) may be written according to (Timoshenko and Goodier, 1982);

$$W_E = \frac{p_o^2}{2k} = \frac{3\pi\, \sigma y^2}{8E} hR^2\left(1 - v^2\right) \tag{2}$$

$$\frac{1}{2}\, mV_b^2 = \frac{3\pi\, \sigma y^2}{8E} hR^2\left(1 - v^2\right) \tag{3}$$

$$V_b^2 = \frac{2}{m}\left\{\frac{3\pi\, \sigma y^2}{8E} hR^2\left(1 - v^2\right)\right\} \tag{4}$$

Therefore the ballistic limit (V_b) is

$$V_b = \frac{2}{m}\left\{\frac{3\pi\, \sigma y^2}{8E} hR^2\left(1 - v^2\right)\right\}^{\frac{1}{2}} \tag{5}$$

Where, P_o is plastic failure load of the material, σ_y is yield stress, E is modulus of elasticity, h is target thickness, R is target radius and υ is poisson's ratio.

IV. NUMERICAL MODELING

A 3D finite element modeling has been conducted for the impact pair with sufficient number of element to ensure highest possible degree of accuracy. Spherical rigid projectile was modeled with material in ANSYS-AUTODYN Library adopting the mechanical properties of the material in the experimental work. Hardened steel has been used for defining the behavior of projectile in the simulations. The projectile was considered as rigid material model and built by solid elements. So, the effect of element number and size on the projectile modeling is not significant in terms of residual velocity and deformation. A finite element model of a PMMA plate has been used 56661 brick element is shown in Fig. 2. All the periphery elements have been constrained. The PMMA plate is 100x100 mm size with three different thicknesses (4, 5 and 6 mm).

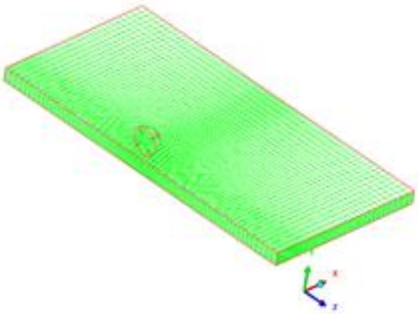


Fig. 2. Finite element model for projectile and PMMA target.

V. RESULTS AND DISCUSSION

A. *Ballistic Behavior*

Generally, the fracture mechanism of PMMA plates is similar to the brittle fracture mechanism observed in the typical hard ceramic systems. A conoid fracture mode is obvious in the exit side of PMMA.PMMA illustrated a change of style of failure from brittle kind cracking to localized as the impact velocity increases. At moment of impact , the zone of impact suffers high radial and hoop stress leading to radial and circumferential cracks form over the PMMA plate causing finally the fracture of the target material in that region in a star shape. As the projectile penetrates the material with driving impulse, affected areas exhibit radial cracks makes some concentric cracks around the projectile. The projectile residual velocity V_r depends on a power function of the striking velocity and the ballistic limit as follows:

$$V_r = \sqrt{V_i^2 - V_b^2} \qquad (6)$$

The experimental and analytical ballistic limit velocity V_b in (5) shows good agreement with the experimental results as shown in Fig. 3.

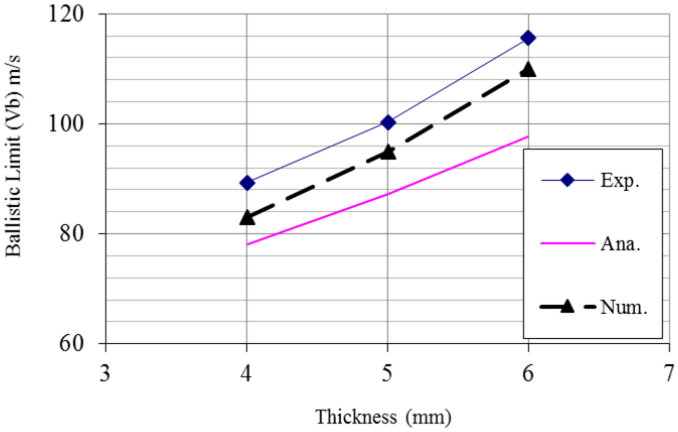


Fig. 3. Ballistic limit for PMMA.

Fig. 4, Fig. 5 and Fig. 6 illustrate the striking velocity for PMMA plates against the residual velocity for target thickness 4, 5, and 6 mm respectively. The residual velocities for numerical and experimental results have been compared versus empirical equation by Recht and Ipson (1963). It was noticed that the results were in good correlation.

B. *Image Analysis*

Fig. 7 shows the induced damage in the PMMA material where the red color area around the projectile represent 100% damage with radial cracks extended through the target. The localized damage diameter depends entirely on projectile velocity for specific target thickness, the higher projectile velocity the bigger localized damage diameter. Furthermore, the length of the extended radial cracks is inversely proportional with projectile velocity, besides these cracks directions depend on the projectile velocity as well.

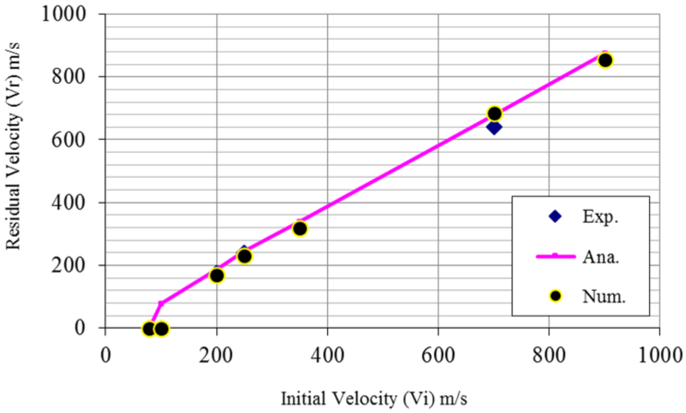


Fig. 4. Initial velocity versus residual velocity (4 mm target thickness).

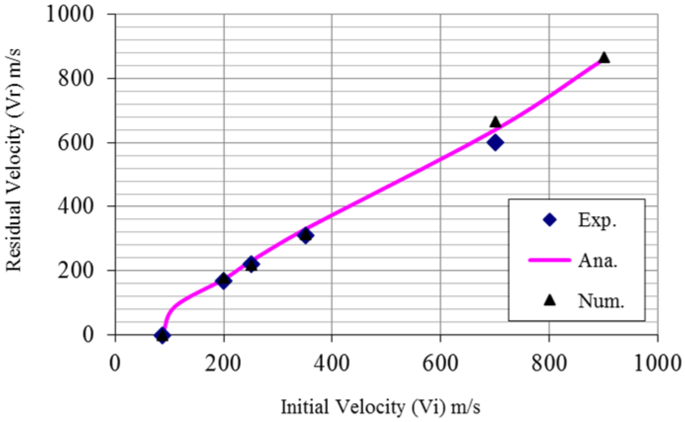


Fig. 5. Initial velocity versus residual velocity (5 mm target thickness).

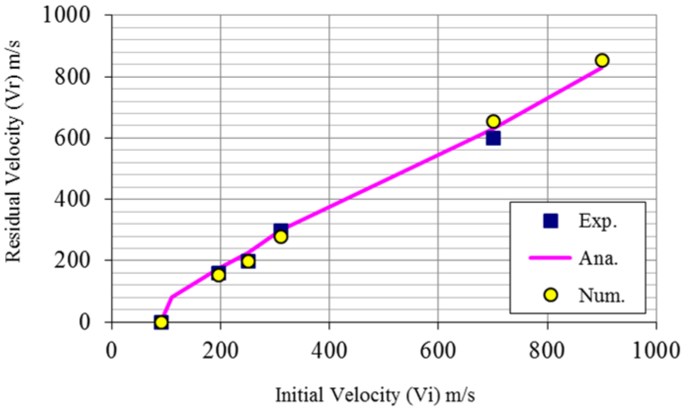
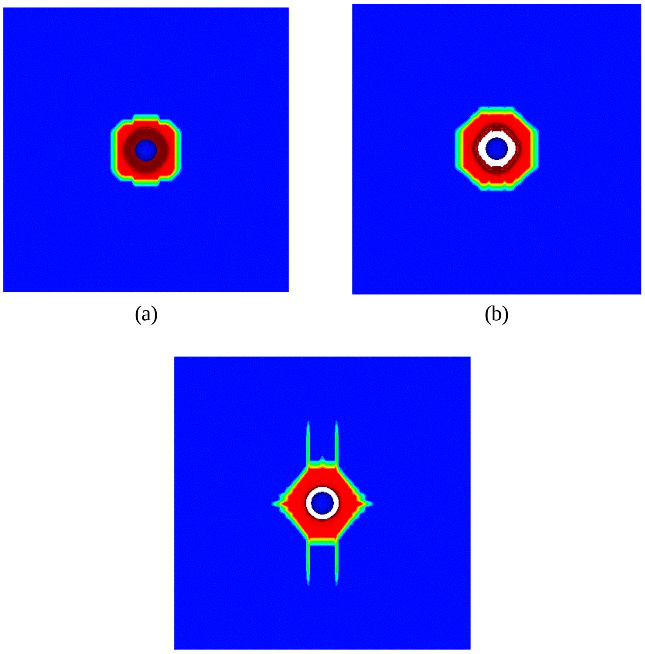


Fig. 6. Initial velocity versus residual velocity (6 mm target thickness).

Fig. 8 illustrates the comparison between the experimental photocopies and the finite element images.



(a) (b)

(c)

Fig. 7. Finite element images for 4mm target thickness, (a) 800 m/s projectile velocity, (b) 600 m/s projectile velocity and (c) 250 m/s projectile velocity.

(a) (b)

Fig. 8. PMMA target Damage for 100 m/s velocity and 4 mm target thickness; (a) Numerical result and (b) Experimental result.

VI. CONCLUSION

This work showed that the use of finite element method helps a lot in the representation and analysis of the behavior of transparent materials that are exposed to high velocities load with very high accuracy, which is difficult to obtain in practice. Whereby they can trust this method to reduce the time, effort and money too, especially when there is no laboratory abilities. The projectile velocity and the target thickness play a significant role in the localized damage zone, length and directions of the extended cracks. A good agreement was found between the numerical experimental and analytical result.

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