Measurement of damage velocities in impacts of transparent armor

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Abstract. A series of impact experiments were conducted to examine the response of transparent material to ballistic impact. The experiments consisted of impacting 15 mm of borosilicate glass bonded to 9.5 mm of Lexan. The projectile was a 0.30-cal hard steel bullet designed specifically for the experiments. High-speed imaging of the impact event and post-test analysis quantified damage propagation and the rate of propagation.

1. Introduction

A bullet must crack and comminute glass before it can penetrate transparent armor. Additionally, transparent armor is typically designed to provide protection against multiple impacts. Therefore, rate of damage and extent of damage are important metrics that must be replicated in an accurate numerical model of bullet-glass interaction. There have been several studies that have quantified damage in glass resulting from impact. In particular, a series of edge-on-impact (EOI) experiments have been conducted by Strassburger and colleagues to investigate the fracture/failure response of brittle materials, of which references [1-4] are typical. In the EOI experiments, Cranz-Schardin high-speed cameras are used to visualize dynamic fracture during approximately the first 20 µs after impact. The projectile (either flat-nosed or a hemispherical nose) impacted the edge of the target for the EOI experiments. Anderson and colleagues investigated the response of a borosilicate glass to rod penetration [5-6]. The reverse ballistics technique was used; high-speed photography recorded damage propagation, and flash radiography recorded penetration versus time. The cameras for both types of experiments were typically run at 1,000,000 frames/s.

Anderson and Holmquist conducted numerical simulations of the reverse ballistic experiments using a computational glass model [7] to assess how well the simulations could replicate details of the experiments, including failure propagation. However, it was determined that it would be advantageous to have experimental data that was more directly relevant to the application of impacts into transparent armor. Therefore, the present work focused on measuring damage propagation in borosilicate glass bonded to a polycarbonate substrate impacted by a hard-steel, conical-nose projectile. The projectile impacted at the center of, and normal to, the target.

2. Experimental Setup

The targets consisted of 15 mm of a borosilicate glass (Borofloat®33) bonded to a 9.52-mm-thick Lexan using 25-mil TPU PE399 polyurethane. Borofloat®33 glass has the following properties: $\rho = 2.22$ g/cm^3; $E = 62.3$ GPa; $\nu = 0.20$; $c_L = 5.61$ km/s; and $c_s = 3.41$ km/s, where c_L and c_s are the longitudinal and shear wave velocities, respectively. The targets measured 30.5 cm by 30.5 cm; the target was supported in an aluminum frame with a 29.5-cm square opening. The targets were marked with a 25.4-mm square grid to facilitate quantitative measurements of damage extent.

The conical-nosed bullets had a diameter of 7.62 mm and a length of 22.86 mm, including the 7.62-mm-long conical nose. The bullets were fabricated from 4340 steel, hardened to Rockwell C53. Chronographs were used to measure the impact velocity; a high-speed camera was used to determine the residual velocity if the bullet perforated the target.

3. Impact Results

Residual velocities versus impact velocities are shown in figure 1. The V_{50} for the threat/target combination was determined to be 628 ± 28 m/s. The vertical dashed lines provide the region of mixed results of no perforation and perforation. The Lambert equation provides an estimate for the residual velocity for a specific impact velocity. The Lambert equation has the form:

$$V_r = \begin{cases} 0 & V_r \le V_{50} \\ a\left(V_s^{\,p} - V_{50}^{\,p}\right)^{1/p} & V_r \ge V_{50} \end{cases} \tag{1}$$

where V_r is the residual velocity and V_s is the impact (striking) velocity. The parameters were determined by a nonlinear regression fit to the experimental data: a = 0.739; p = 3.155. Equation (1), using these parameters, is plotted as the dashed curve in figure 1.

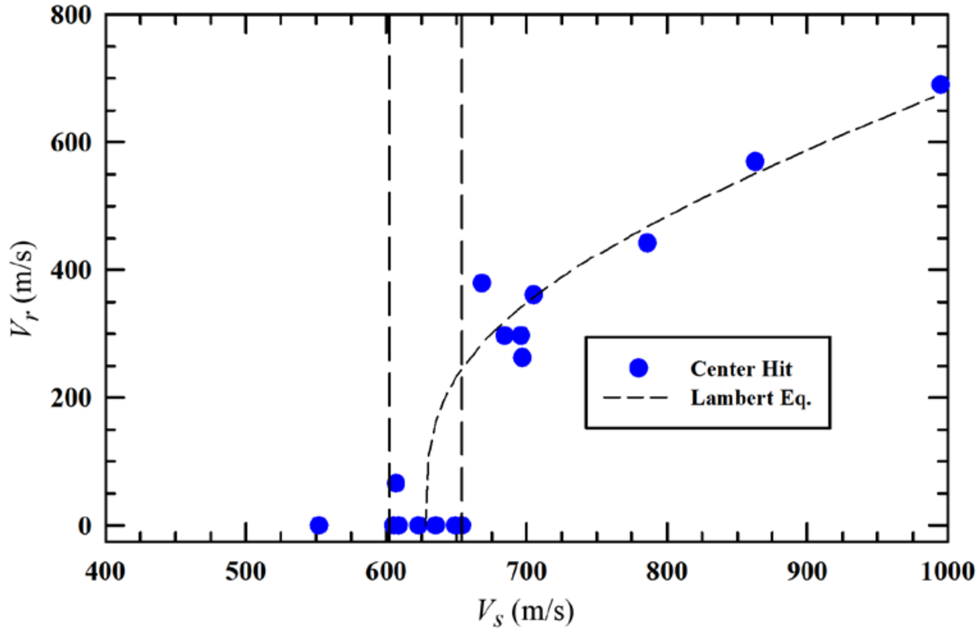

Figure 1. Residual velocity vs. impact velocity.

4. Crack Velocity

A high-speed video camera (a Vision Research Phantom v711) was placed just underneath the muzzle of the gun for recording damage propagation in the target. A white backdrop was placed approximately 60 cm behind the target and illuminated with two 1000 W lamps to provide strong backlighting; thus, the damaged glass appeared dark. The camera ran at 210,000 frames/s with an exposure time of 1 μs. Since the pixel resolution was 128 x 128, only one quadrant of the target was imaged. The camera recorded long enough so that the final (post-test) damage pattern was imaged.

Crack growth was measured outward from the impact point. A circle was drawn to fit the extent of the crack in each camera frame, see figure 2(a). The circle radius was determined from camera calibration, and the velocity calculated from the inter-frame time and circle radius. Figure 2(b) displays a typical crack radius versus time result; crack tip position is nearly linear with time. Table 1 provides the results for 14 tests. The crack velocity, 1.92 ± 0.03 mm/μs, is an average of the 14 tests. It is observed that the measured crack speed is independent of the impact velocity, and whether the bullet perforated or was stopped by the target. Thus, it is concluded that this crack velocity is a "property" of the glass.

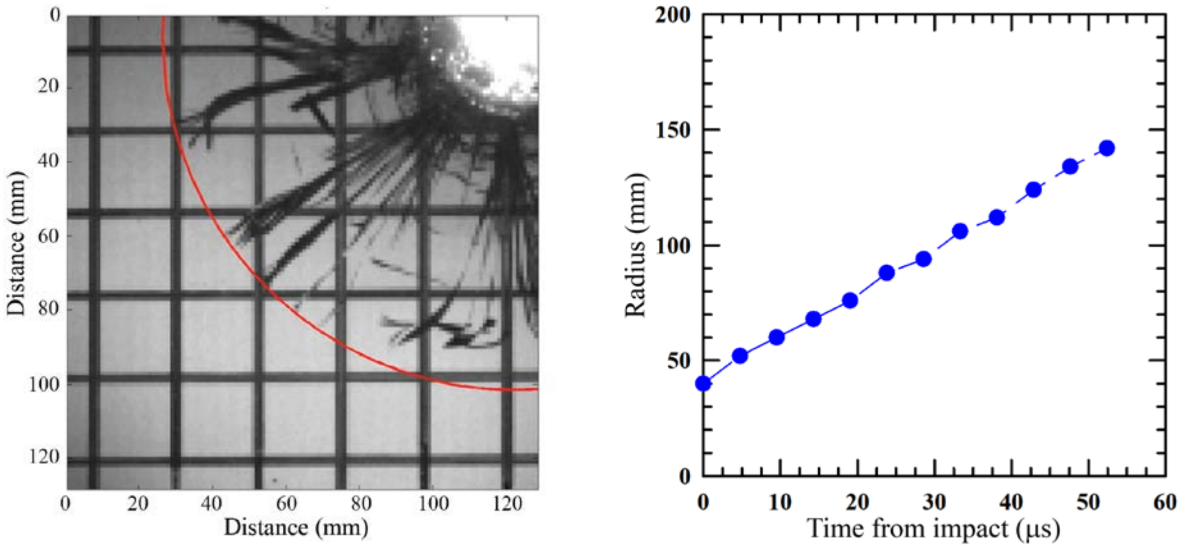

Figure 2. a) Measurement technique; **b)** Radius vs. time.

Table 1. Crack velocities.

Shot No.	V_s (m/s)	V_r (m/s)	Crack Vel. (mm/μs)
15	609	0	1.90
14	684	297	1.89
13	863	570	1.95
102	241	0	1.88
101	615	258	1.92
156	626	0	1.89
180	759	317	1.89
179	963	564	1.94
162	631	0	1.93
170	732	286	1.95
174	993	632	1.96
189	541	0	1.91
184	696	342	1.95
186	875	541	1.92

Quinn [8] tabulates crack velocities for various glasses; crack velocities of 1.68 and 1.80 mm/μs are reported (two different sources) for borosilicate crown glass (BK-7), which are lower than the velocity measured here. However, BK-7 glass has a lower modulus and higher density than Borofloat®33, implying that the crack speed for BK-7 glass should be lower than that for Borofloat®33. Quinn also states that crack velocities are usually 0.5 – 0.6 times the Rayleigh wave speed, which is a little slower than the shear wave velocity. The shear wave velocity for Borofloat®33 is 3.48 mm/μs, which implies that the crack velocity should be between approximately 1.74 and 2.09 mm/μs. Strassburger *et al.* [4] used the edge-on-impact experimental technique on various transparent materials, and they report a crack velocity of 2.03 mm/μs for Borofloat®33. It is concluded that the crack velocity calculated for these experiments is in good agreement with values reported in the literature.

5. Time Evolution of Damage

A MATLAB script was written to estimate the amount of damaged glass versus time. The algorithm used a contrast detection scheme to determine damaged glass; the algorithm also included as damaged glass an estimate of the area under the impact flash. The analysis did not differentiate between comminuted glass and cracks.

An example of the normalized damage as a function of time is displayed in figure 3, for an impact velocity of 786 m/s. It is estimated that the bullet perforated the target by 100 μs, so it is seen that the glass continues to accumulate damage long after the bullet has perforated the target.

The glass has to be comminuted for the projectile to penetrate, i.e., it is comminuted glass that "flows" around the projectile as it penetrates. Therefore, a procedure was developed to examine the first 150 μs of data from the camera images, which is when the bullet is still interacting with the target. The normalized damage area was converted to an equivalent area (e.g., cm^2) versus time based on image size and camera scale factor. Since the damage zone propagates approximately in a circular pattern, an equivalent radius of damage versus time was derived. Since differentiation of experimental data tends to be rather noisy, a 6^{th}-degree polynomial was used to fit the radius versus time results. The time derivative of the polynomial provided the damage rate versus time. The maximum rate, which typically occurs at impact, is plotted versus impact velocity in figure 4. The vertical dash-dot line represents the ballistic limit for this target/projectile combination. Although there is scatter in the data, there appears to be some velocity dependence on the damage rate, going from approximately 0.8 mm/μs at 500 m/s to 1.2 mm/μs at 1000 m/s. In all the experiments, the damage velocity decreases fairly rapidly from this maximum. For example, by 50 μs after impact, the damage velocity has decreased to 0.3 mm/μs for the 1000-m/s impact, and 0.5 mm/μs for the 500-m/s impact.

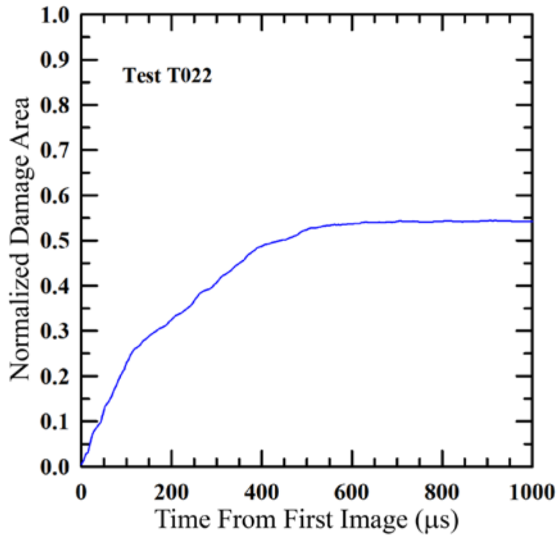

Figure 3. Normalized damage vs. time.

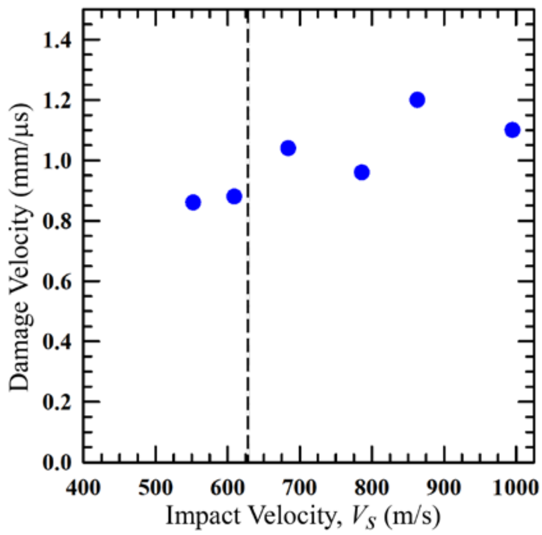

Figure 4. Damage velocity vs. impact velocity.

The damage velocity determined from these experiments can be compared to that measured by Strassburger *et al.* [3], in the EOI experiments on Borofloate®33 glass. They measured 2.03 mm/μs for a sphere impact, and 4.15 mm/μs for a cylinder impact. These velocities are considerably higher than measured in the current experiments.

The 4.15 mm/μs is considerably faster than the shear wave velocity; thus, this damage rate may be associated with the propagation of the shock originating from the impact, which is approximately 5.6 mm/μs at for the impact velocities here. In contrast, there is essentially no shock associated with the impact of the sphere or the pointed bullet since rarefaction waves are immediately generated at the free surface. There are differences in the geometry of the projectiles, as well as differences in the geometry of the experiments (edge-on impact versus direct impact normal to the glass surface). Additionally, the damage propagation speeds in the EOI experiments were obtained by very-high-speed imaging during the first 20 μs after impact (20 images with 0.2 to 2.0 μs between images). In the ballistic experiments described here, the time resolution is 4.76 μs between images, with the added complication that the impact flash tends to obscure the extent of damage for the first several frames. Thus, it is not clear if the difference between the damage velocities is due to geometric considerations, time resolution, or some combination of the two.

6. Summary

A series of impact experiments into a simple transparent armor system was conducted. The transparent armor consisted of 15 mm of a borosilicate glass bonded to a 9.52-mm-thick polycarbonate substrate. One of the objectives of the experiments was to quantify the damage that develops in the glass as a result of penetration and perforation. It was found that crack speed was independent of the impact velocity; cracks propagated at 1.92 ± 0.03 mm/μs. The maximum speed at which a highly damaged zone propagates from the impact point was found to vary between 0.8 mm/μs and 1.2 mm/μs; there appears to be a slight increase in the damage velocity as a function of impact velocity. Although the crack speed determined during this study is in very good agreement with the work of others, the damage velocity is less than reported by Strassburger *et al.* [3], and it is not clear whether the differences are due to the geometry of the experiments, geometry of the projectiles, and/or time resolution differences between the two investigations.

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