23^{RD} INTERNATIONAL SYMPOSIUM ON BALLISTICS
TARRAGONA, SPAIN 16-20 APRIL 2007

IMPACT ON GLASS LAMINATES

S. J. Bless, T. Chen, and R. Russell

Institute for Advanced Technology, The University of Texas at Austin

Laminated glass armor was struck with fragment-simulating projectiles. Impacts were observed with high-speed photography, and one target was carefully disassembled. Rapid propagation of damage in the impact zone is consistent with failure wave observations. A map of the post-test damage was prepared. There are at least ten different damage patterns. Regarding penetration resistance: structural failure of the inner plastic plate is apparently a critical phenomenon.

INTRODUCTION

Use of laminated glass armor on military vehicles has become widespread in recent years. Scientific studies of impact damage on glass have focused chiefly on the impact behavior of glass as a material. Examples are early time formation of cone cracks [1], edge-on impacts onto glass plates [2], penetration through “semi-infinite” glass blocks [3], and impact on single plates [4]. However, up until now, there have not been reports available on impact damage to laminated glass of the type usually used in military windows by the types of projectiles that are common threats to such windows.

Two targets were tested: a four-layer target and a seven-layer target. Glass layers were bonded with about 0.6 mm of polyurethane. The four-layer target was 267 mm square, and the total thickness of glass layers was 31 mm, backed by 5.8 mm of polycarbonate. The edges of the glass were taped, but the tape was removed on one side to facilitate high-speed photography. The targets were held in place with a steel clamp on the plastic layer surface. The seven-layer target is shown in Fig. 1. Both targets were fabricated by Secur*Glass in Dallas, Texas. The glass used in this target was commercial soda-lime glass.

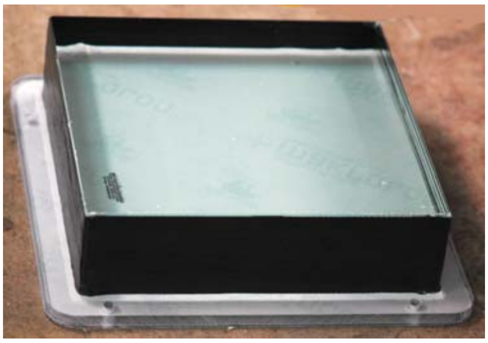

Fig. 1. Seven layer glass target. Glass outside dimensions are 304 × 285 mm. The seven-layer target contained 76 mm of glass on 12.7 mm of polycarbonate.

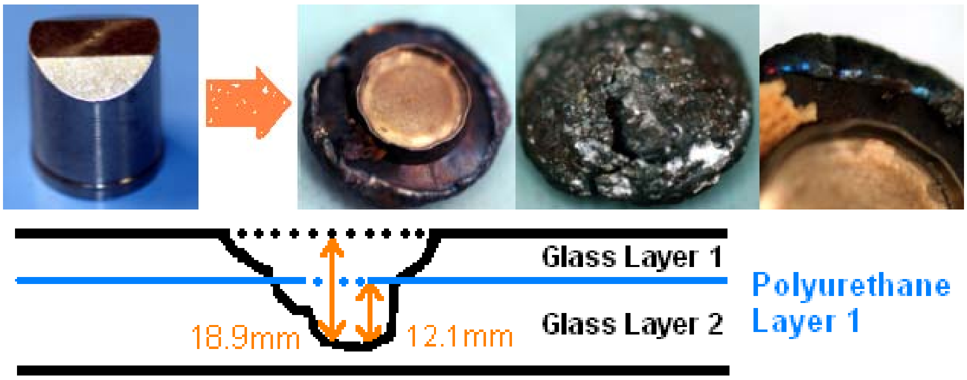

Fig. 2. Original and recovered FSP from shot into seven-layer target.

Our study was aimed at characterizing damage from 0.50 fragment-simulating projectiles (FSP). This projectile diameter is 12.7 mm and the mass is 13.4 g. At the impact velocities used here, 879–1110 m/s, the FSP projectiles were massively deformed by the impacts, as shown in Fig. 2.

HIGH-SPEED PHOTOS

The first experiment was on the four-layer target impact velocity was 880 m/s. High-speed pictures were taken of the damage, using a turning mirror so that both the edge view and the rear view were visible. A time-of-arrival screen was placed on the impact surface, and t = 0 was defined as impact. The projectile did not perforate the target; in fact it was expelled. From the damage pattern, penetration appears to have been through the second glass plate.

Figure 3 shows the first frame after impact, at t = 2 μs. At this time, the projectile cannot be more than part way through the first plate. In the edge view, failure waves are

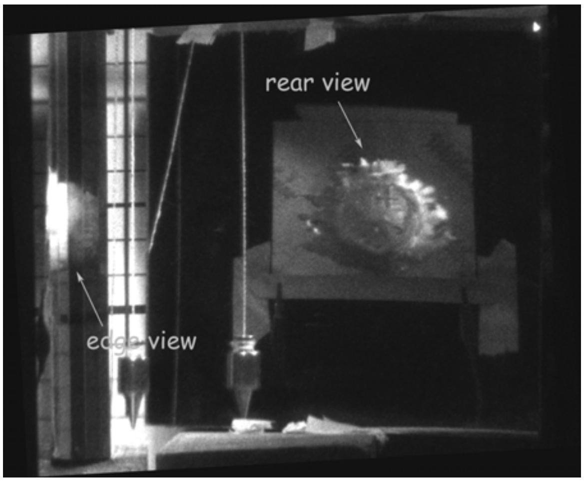

Fig. 3. Impact damage in target.

visible in the first and second plates. These appear to be propagating radially outward in the first plate, but from front to back in the second plate. From the rear view, the failure wave in the front plate can be seen to be jagged, as if the wave emanates from a network of radial cracks. In the second plate, the leading edge of the failure wave appears to be smooth. (In other experiments, the wave in the second plate appeared to propagate through the plate, front to back, instead of radially outward from the center). In the inner plates there appears to be a central column with six spokes around it. In the edge impact view, the damage in the second and third plates is clearly less extensive because there is less light scatter.

Failure continues to spread in all layers. Figure 4a shows the edge view at 8 μs. Between 2 μs and 8 μs, the failure-wave speed in the first plate has an average speed of 3.45 mm/μs. This is too fast to be a single crack, but is commensurate with failure wave speeds observed in flyer plate tests [5]. By 26 μs, the edge view shows the front plate failure has spread to about 107 mm, but it is clear the failure zone is no longer uniform. The rear view at 26 μs shows very fine radial striations in the second plate, which suggests needle cracks. The inner plates are still less reflective, and the failure in both the third and fourth plates is moving slowly and well behind the failure in the first two plates.

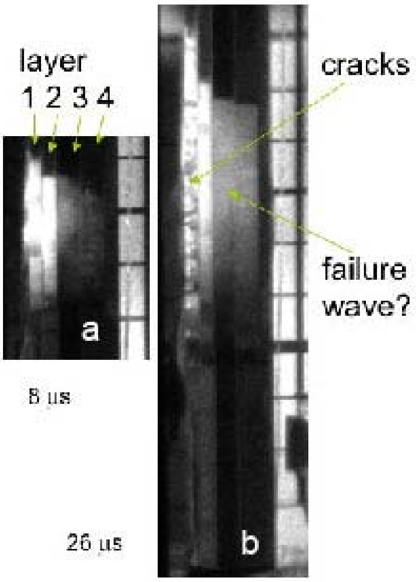

Fig. 4. Edge view, (a) 8 μs and (b) 26μs.

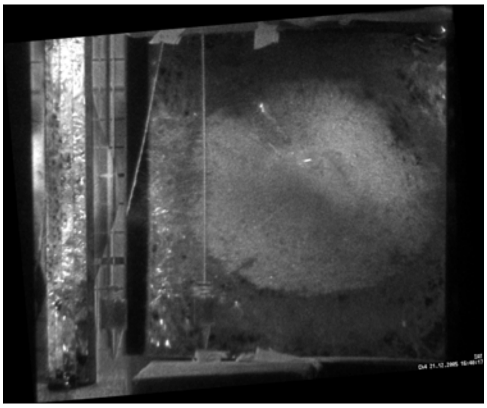

Fig. 5. View of target at 300 μs.

When this target was recovered, all of the layers were flat, but there was a gap between the fourth glass layer and the polycarbonate, into which many glass particles had become wedged. The last high-speed camera frame, at 300 µs, shows the plastic has bulged by about 6 mm (Fig. 5). This bulge recovers, but the transient excursion allowed glass blocks to fall out of the fourth plate. The rear view at that times shows the outer regions of the first plate are cracked into a mosaic pattern, which was also seen in the recovered target.

DAMAGE

The nature of the impact damage was revealed in the experiment on the seven-layer target. It was struck at 1120 m/s. Subsequently, the target was carefully disassembled in order to reveal the damage.

Every section of all seven layers of this target was damaged by the impact; however, the plastic did not bulge. Ten different damage morphologies were identified; undoubtedly these could be divided into several more subcategories. Figure 6 is a map showing, roughly, where the different types of damage occurred within this target.

The excavated crater extended to only about two-thirds the depth of the second layer. Particles ejected form the crater had nano-scale damage features indicating very rapid crack growth with multiple branching [6].

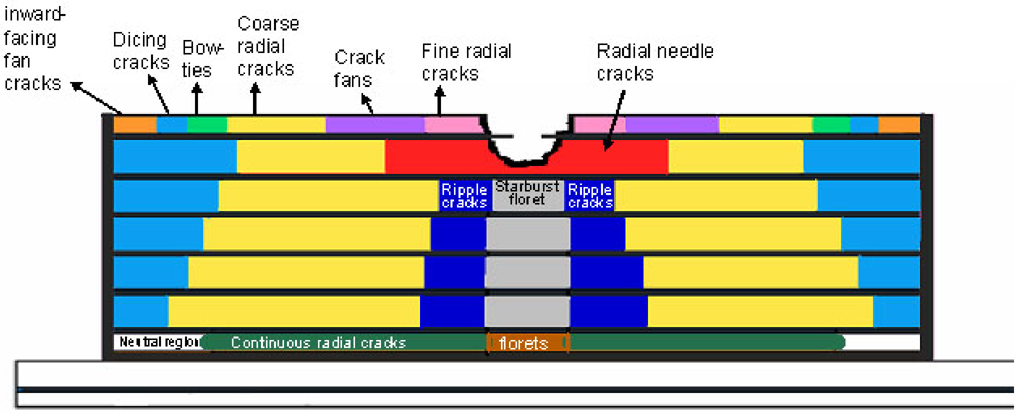

Fig. 6. Map of damage within target. Dimensions in this figure are all scaled the same, so damage extent can be inferred from the total target thickness (about 96 mm).

The region around the impact zone in the front plate consisted of tight bundles of radial cracks, between which there was relatively little damage. The same region in the second layer was comprised of tightly packed needle cracks, whose lateral dimension was typically a few tenths of a millimeter, and whose length was several mm. (These needle cracks were apparently observed by the high-speed camera viewing the four-layer target.) Directly beneath the impact, the third, fourth, fifth, and sixth layers contained a central crack surrounded by spokes, shown in Fig. 7; this is also similar to the high-speed photograph in Fig. 3.

However, in the last layer of glass, as viewed through the plastic layer, the central damage pattern appeared homogeneous and composed on many millimeter-scale starburst patterns—termed *florets*—shown in Fig. 8.

In the first and second layers, there was a transition zone beyond the central damage pattern. In the first layer, it was comprised of fan cracks, which pointed radially outward (Fig. 9). In the second layer, it was comprised of needle cracks aligned in the azimuthal direction—called *ripple cracks*—in Fig. 7).

Fig. 7. Damage pattern under the impact cavity in layer 3.

Fig. 8. Central damage pattern in the last layer of glass, viewed through the polycarbonate.

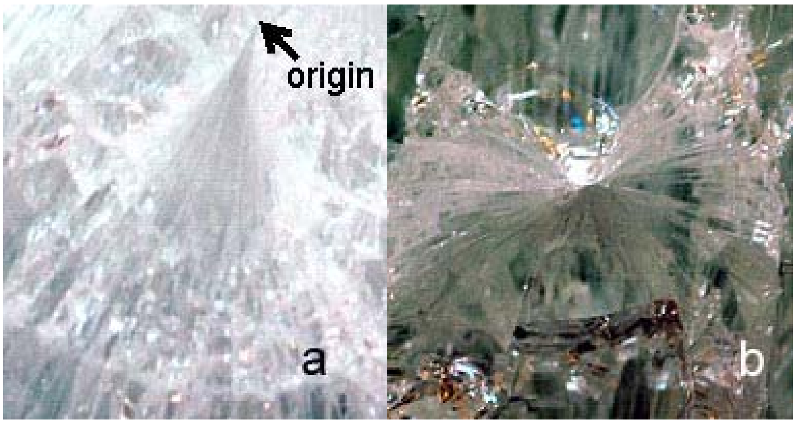

Fig. 9. Fan crack. In the first plate, Fan cracks surround the central damage zone and spread radially outward. (a) Near the edges, they are often paired, into “bowties.” (b) They also appeared on the edges of the target plates.

The outer regions of all the glass layers were characterized by coarser radial cracks. In the upper layers, the radial cracks were rippled. In the lower layers there were often tiled (e.g., blocks of glass separated by radial cracks were also split in two in a plane parallel to their surface). In the last layer only, the radial cracks were straight and continuous, although they were broken up by transverse cracks and cracks that were parallel to the rear surface, shown in Fig. 10.

In all plates, the glass nearest the edges displayed a dicing type fracture. Dicing cracks were roughly equi-axial, ran through the thickness, and did not have flat surfaces.

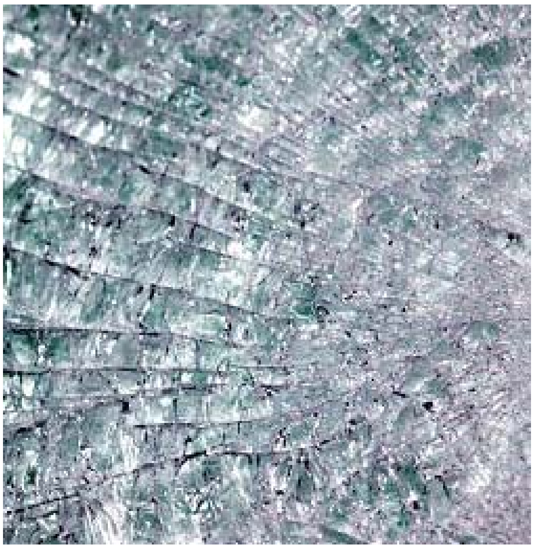

Fig. 10. Region of continuous radial cracks in last glass plate.

DISCUSSION

The similarity of many of the damage processes observed in the high-speed camera in the four-layer target and observed upon disassembly of the seven-layer target suggests that generally the same damage patterns occurred in both targets, and may indeed be relatively universal for dimensionally similar impacts.

It would appear that the inner damage zones in the outer plates are driven by hoop stresses. The region of crack fans corresponds to when an acoustic wave reflecting from the boundaries of the target arrives at a crack front that started at impact and is spreading at about 1.5 mm/μs, the maximum crack velocity in soda-lime glass [7]. The region of coarser radial cracks in all of the plates except the last must also be driven by the hoop stress field, but the fact that the lateral faces of these cracks are curved indicates that the crack speed was not approaching its maximum value where cracks branch. The continuous straight radial cracks in the last plate may be characteristic of a rapid bending failure from center loading.

Fan cracks are probably symptomatic of sudden changes in stress state that cause the cracks to branch. They point radially outward near the center, and in both transverse directions (bowties) near edges, and inward near corners. This directionality probably indicates the direction of principle compressive stress.

It is remarkable that even the heavily fractured glass in this target experienced almost no displacement. Large pieces of fractured glass could be removed from the target and seemed to possess considerable structural integrity. This was in contrast to the four-layer target, which possessed very little structural integrity. Considering that the design criteria for glass armor almost always requires multiple hit protection, the loss of structural integrity due to transient deflection of the plastic may be one of the most important processes that leads to target defeat.

ACKNOWLEDGMENTS

The research reported in this document was performed in connection with Contract number DAAD17-01-D-0001 with the US Army Research Laboratory. The views and conclusions contained in this document are those of the authors and should not be interpreted as presenting the official policies or position, either expressed or implied, of the US Army Research Laboratory or the US Government unless so designated by other authorized documents. Citation of manufacturers or trade names does not constitute an official endorsement or approval of the use thereof. The US Government is authorized to reproduce and distribute reprints for government purposes notwithstanding any copyright notation hereon.

REFERENCES

[1] E. Strassburger, P. Patel, J. W. McCauley, D. W. Templeton, “High-Speed Photographic Study of Wave and Fracture Propagation in Fused Silica,” presented at the 22nd Int’l Symp. Ballistics, Vancouver, Canada, 14–18 November, 2005.

[2] J. E. Field and A. D. Hayes, “The Fracture of Materials of High Elastic Moduli,” *Proc. 7th Inst. Conf on High-speed Photography*, Zurich, CH, 1965.

[3] C. E. Anderson, Jr., S. Chocran, and J. D. Walker, “Analysis of Time-resolved Penetration of Long Rods into Glass Targets,” presented at the 29th Int’l Conf. and Exposition on Advanced Ceramics and Composites, Cocoa Beach, FL, Jan 23, 2005.

[4] N. K. Bourne, “On the Impact and Penetration of Soda Lime Glass,” *Int. J. Impact Engng*., 32, 62–69, 2006.

[5] S. J. Bless and N. S. Brar, “Failure Waves and Their Effects on Penetration Mechanics in Glass and Ceramics, in High Pressure Shock Compression of Solids,” Springer-Verlag, in print 2007.

[6] T. Chen and S. Bless, “Ballistic Damage in Transparent Armor,” presented at the ASME Applied Mechanics and Materials Conference, June 3–7, Austin, TX, 2007.

[7] S. J. Bless and A. M. Rajendran, “Initiation and Propagation of Damage Caused by Impact on Brittle Materials,” *Fracture and Fragmentation of Brittle Solids,* eds. L. Davison & D. E. Grady, Springer-Verlag, 1994.