DAMAGE EVOLUTION IN BALLISTIC IMPACT OF GLASS PLATES

S. J. Bless, R. Russell, D. T. Berry, and S. Levinson

Citation: AIP Conference Proceedings **1195**, 1453 (2009); doi: 10.1063/1.3295085
View online: http://dx.doi.org/10.1063/1.3295085
View Table of Contents:
http://scitation.aip.org/content/aip/proceeding/aipcp/1195?ver=pdfcov
Published by the AIP Publishing

CP1195, *Shock Compression of Condensed Matter - 2009,*
edited by M. L. Elert, W. T. Buttler, M. D. Furnish, W. W. Anderson, and W. G. Proud

DAMAGE EVOLUTION IN BALLISTIC IMPACT OF GLASS PLATES

S. J. Bless, R. Russell, D. T. Berry, and S. Levinson

Institute for Advanced Technology, The University of Texas at Austin

Abstract. High-velocity impact onto a layered glass target produces a very extensive damage pattern exhibiting many distinct morphologies. High-speed photography reveals failure waves and cracks that move at acoustic velocities. These prompt features evolve into a complex final damage pattern that includes needle fragments around the penetration cavity, radial cracks at mid distance, and dicing cracks near the edges.

Keywords: Glass, transparent armor
PACS: 62.20.mm, 81.05.Kf.

INTRODUCTION

Glass laminate armor has become a subject of intense interest in recent years [1]. Consequently, efforts have begun to develop better constitutive models for glass [2,3]. This is a challenging task, since the dynamic properties of glass differ in many ways from other brittle materials [4] in that shocks are dispersive at low stresses. Since glasses exhibit very high tensile strength, they can permanently densify under shock loading, and failure waves can initiate at free surfaces. Historically, most scientific investigations of glass penetration have involved thick targets [5] or plane stress configurations [6,7].

Actual ballistic windshields are constructed of laminated glass. The major design problem is associated with adequate multi-hit resistance. As shown by Bless and Chen [8], even when one impact only penetrates partway through a target, the impact damage is pervasive. There are a large number of damage patterns, which are generally symmetric around the impact, and which vary systematically through the thickness of the target. Figure 1 is a damage map from Bless and Chen [8] for a seven-layer soda-lime glass laminate. Descriptions of the multitude of damage patterns can be found in their paper.

EXPERIMENTS

A Cooke high-speed image converter camera was used to photograph damage evolution from impact onto a four-layer + polycarbonate and one-layer + polycarbonate glass target.

The four-layer target was comprised of 5.8 + 5.8 + 9.66 + 9.66 mm of soda-lime glass, backed by 5.8 mm of polycarbonate. The layers were bonded with a 0.7 mm thickness of polyurethane. The target was 267 mm square. The impactor was a .50-caliber, fragment-simulating projectile (FSP) (13.4 g, 12.7 mm HRC30 steel cylinder) at 879 m/s. The FSP penetrated only through the second layer and was expelled from the target, being flattened but having lost only 1 g of mass. The high-speed camera viewed the target both through the side and from the rear via a mirror.

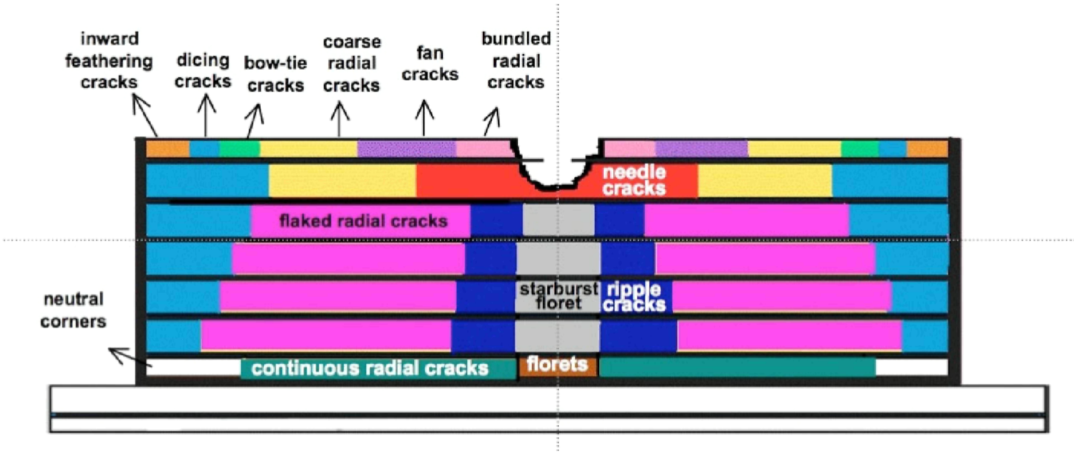

Figure 1. Damage zones in a seven-layer glass target, from [8].

The earliest frame is 2 μs after impact, and the two views are shown in Figure 2. At this time, the projectile should be partway through the first layer of glass. The first two layers of glass are lit by internal failures that reflect light. The width of the damage zone, as seen in either view, is about 48 mm, which is about the size of the cavity in the glass after the shot. The similar width of the damage zone in the two plates suggests that the initial damage, which is driven by compression, passes through the interface. The damage in the second plate is not uniform—it is significantly more intense in the half of the plate that is against the front plate. This strongly suggests that the damage in the second plate is traveling as a plane wave and it was nearly simultaneously initiated at the first plate–second plate boundary. This is similar to what was observed in rod penetration of glass plates [9].

In frame 2, at 8 μs, shown in Fig. 3, the damage has spread, having an average speed of 3.45 mm/μs. The damage in the second plate has only spread to 52 mm diameter—which is almost the same as the eventual channel in that plate—and the third and fourth plates have become translucent, indicating that they are highly stressed but not fractured. In fact, they are never penetrated by the projectile.

In the third frame, at 26 μs, shown in Figure 4, the spreading failure zone in the first plate has broken up into bundled cracks. This feature is present in recovered targets—in the area next to the penetration cavity in the first plate, the radial cracks form in bundles, and then branch into fans.

At later times, it is difficult to distinguish the layers. In order to better follow the evolution of damage in the strike face and obtain more and higher-resolution frames at early times, a target was constructed with a single 12.7 mm layer of soda-lime glass bonded with polyurethane onto a single 28 mm sheet of polycarbonate. Exterior dimensions of the glass were 300 × 300 mm. Two shots were conducted against this configuration, using the same .50 FSP but at 1153 m/s. Photos of a reference grid were taken so that high-speed pictures could be rectified to remove distortions from camera angle and refraction from the polycarbonate backing plate. Figure 5 shows the pattern at 30 μs, after the crack fans have formed.

Features in Fig. 5 were tracked up to that frame. The leading edges of the crack fans are propagating a little faster than the crack speed in glass (1.5 mm/μs), and they experienced a faster surge during the actual branching that led to the crack fan. At later times, it becomes very difficult to track features.

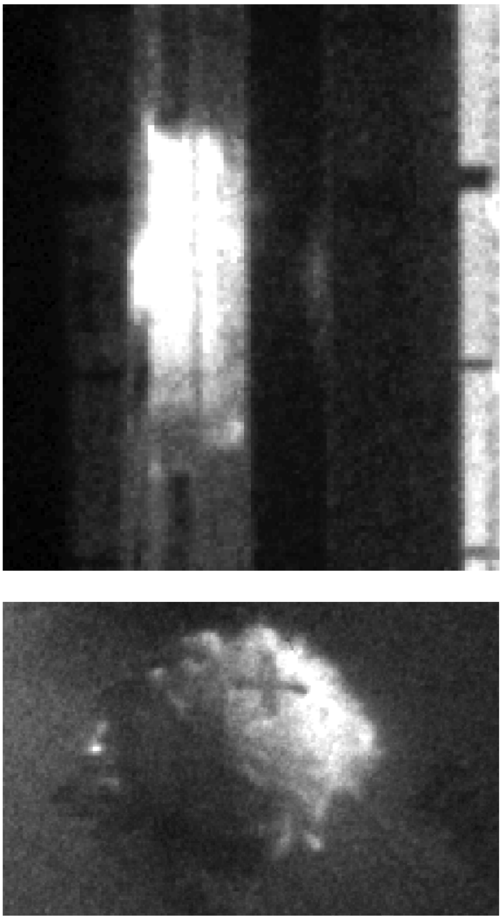

Figure 2. Upper, side view. Lower, rear view.

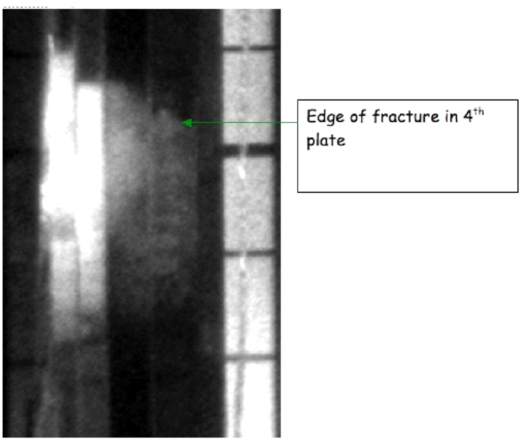

Figure 3. Second frame, at 8 μs.

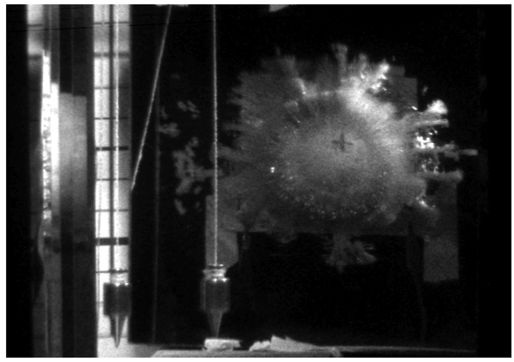

Figure 4. Side and rear views at 26 μs.

INTERPRETATION

The post-test damage features seen around impact sites have their origin in early transient events. Failure waves apparently give rise to bundled radial cracks that branch into fan cracks. These early features propagate faster than single crack speeds. This suggests they are *pulled* by hoop stresses, as opposed to *pushed* by crack opening displacements.

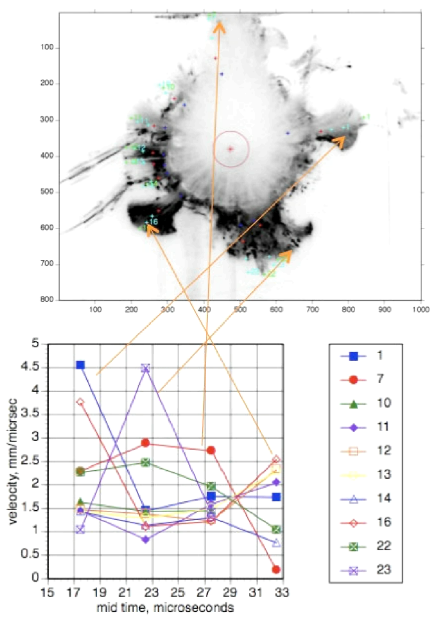

Figure 5. Damage pattern at 30 μs and feature speed.

ACKNOWLEDGMENT

The research reported in this document was performed in connection with Award Number N00014-06-1-475 from the Office of Naval Research. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Office of Naval Research.

REFERENCES

1. Patel, P. J., Gilde, G. A., Dehmer, P. G., and McCauley, J. W., "Transparent ceramics for armor and EM window applications," Proc SPIE 2000 4102.
2. Holmquist, T. J., Johnson, G. R., Grady, D. E., Lopatin, C. M., and Hertel E. S. Jr., "High strain rate properties and constitutive modeling of glass," 15th Int'l Symp Ballistics, Jerusalem, Israel, 21–24 May 1995.
3. Chocran, S., Anderson, C.E. Jr., Nicholls, A. E., and Rickmann, R., "Constitutive model for borosilicate glass and application to long-rod penetration," 23rd Int'l Symp Ballistics, Tarragona, Spain, 18–20 April 2007.
4. Kanel, G. I. and Bless, S. J., "Compressive fracture of brittle solids under shock-wave loading," In Ceramic armor materials by design, *Ceramic Trans* 2002, 134:197–216.
5. Anderson, C. E. Jr., Chocran, S., and Walker, J.D., "Analysis of time-resolved penetration of long rods into glass targets," 29th Int'l Conf and Exposition on Advanced Ceramics and Composites, Cocoa Beach, FL, 23 January 2005.
6. Hornemann, U. and Kaltoff, J., "Experimental Investigation of Wave and Fracture Propagation in Glass Slabs Loaded by Steel Cylinders at High Velocities," *Int. Phys. Conf.* Series No. 70, Oxford, UK, 1984.
7. Brajer, X., Forquin, P., Gy, R., and Hild, F., *J. Non Cryst. Solids*, 316:42–53, 2003.
8. Bless, S. J. and Chen, T., "Impact Damage in Layered Glass," *Int. J. Fracture*, in press.
9. Bless, S., Failure Waves and Their Possible Roles in Determining Penetration Resistance of Glass, *J. Appl. Cer Tech*., in press.