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A high-speed photographic study of fracture wave propagation in glasses

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Abstract: Over the last ten years several observations have been made of compressive failure in glass by a so called fracture wave. A high-speed photographic study has been conducted in order to observe the propagation of fracture waves in glass. Streak and framing photography have been used to determine details of the wave speed and surface structure of fracture waves induced in glasses by planar impact. A 50 mm single stage gas gun was used to launch copper flyer plates at velocities of up to 1 km s⁻¹. A computer controlled high-speed camera was used capable of exposure and interframe times from 50 ns upwards. Simultaneous measurements of the longitudinal stresses were made using manganin pressure gauges embedded in the samples. Results will be presented showing separation between the shock and fracture fronts suggesting that the failure mechanism is by compression rather than resulting from relief waves propagating from the free surfaces.

1. INTRODUCTION

The dynamic response of glass to shock-wave loading has been the subject of many studies (see, for example, [1] - [4]) in which their Hugoniot curves, their elastic limits and spall strengths, were determined by plate impact techniques. The relatively high Hugoniot elastic limits (HEL = 6-8 GPa) and certain peculiarities concerning the shape of the shock fronts moving in the less dense glasses (like Pyrex) enhance the interest in these materials. The spall strength of glass was the subject of several workers who found contradicting evidence as to its magnitude especially when the specimen has been shocked to a stress above the HEL [4], [5]. These contradictions were settled by Kanel et al. [6] who suggested that an additional wave, which he termed the failure wave, moved behind the shock front at the relatively low speed of 1.5 - 2.5 km s⁻¹. The spall strength of some glasses behind these waves is zero as compared with strengths of the order of 5 GPa ahead of these fronts [7]. This large decrease in spall strength clearly indicates that the material has been fractured, an interpretation which has been supported by the measurement of shear strength of glass (using lateral piezoresistance gauges) on either side of the fracture front. The purpose of the work presented here was to clarify this issue by using high-speed photography to look at the various features behind the shock fronts in two types of glass; soda lime and Pyrex.
2. EXPERIMENTAL
The results presented were collected from instrumented plate-impact experiments carried out on the single-stage gas gun at the Cavendish laboratory (50 mm bore, 1 km s\(^{-1}\) maximum impact velocity). The gun has glass viewing ports to allow high-speed photography through the specimen during impact. Uniaxial strain compressive shock and release waves were recorded after travel through 25 mm thick tiles of float and Pyrex glasses backed with 12 mm thick PMMA blocks. The longitudinal stress normal to the planar wave fronts was recorded using piezoresistive stress gauges embedded at the glass/PMMA interface in the backing block. Separate experiments in 10 mm thick targets were carried out in order to determine representative longitudinal stress profiles for comparison with the photographic sequences.

The gauges used were Micro Measurements manganin gauges (LM-SS-125CH-048) and the calibration data of Rosenberg et al. [8] were used in reducing the voltage data collected. The signals were recorded using a fast (1 GS s\(^{-1}\)) digital storage oscilloscope and transferred onto a micro-computer for data reduction. Impact velocity was measured to an accuracy of 0.5% using a sequential pin-shorting method and tilt was adjusted to be less than 1 mrad by means of an adjustable specimen mount. Impactor plates were made from lapped copper discs of thickness 6 mm and were mounted onto a polycarbonate sabot with a relieved front surface in order that the rear of the flyer plate remained unconfined.

The glass targets were polished to allow observation of the waves travelling within. A coaxial copper pin was embedded in the target in order that a short could be detected to trigger a high-speed framing camera. The experimental set-up is described in figure 1. The high-speed camera used in these studies was the Ultranac FS501 programmable image converter camera. This camera is capable of framing at variable rates up to 50 million fps (frames per second) with arbitrary exposure times down to 20 ns. In this work the exposure time of each frame was set to be 50 ns, whilst the interfame time was varied in order to make measurements of wave speeds and of dynamic failure events. Only representative frames will be shown in the following section.

![Side View Before Impact](image1)

*Figure 1. Schematic of the experimental set-up adopted*

The sequence was lit with a QCA5 Xenon discharge tube. It delivered ca. 100 J of energy in 100 µs. The light was collimated using a parabolic reflector so that the sequences were taken using the shadowgraph technique. The field of view of the camera was set as shown in the figure so as to view the last 15 mm of the wave's travel in the glass so that any wave separations could be seen. Two velocity ranges were chosen for each glass, both within the elastic limit of the materials. Material properties are given below in table 1.

<table>
<thead>
<tr>
<th>TABLE 1. MATERIAL PROPERTIES</th>
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<tr>
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<tr>
<td><strong>Density (kg m(^{-3}))</strong></td>
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<tr>
<td>Borosilicate (Pyrex)</td>
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<tr>
<td>Soda Lime (float)</td>
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<tr>
<td><strong>Longitudinal Sound Speed (m s(^{-1}))</strong></td>
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<tr>
<td>Borosilicate (Pyrex)</td>
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<tr>
<td>Soda Lime (float)</td>
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<tr>
<td><strong>HEL (kbar)</strong></td>
</tr>
<tr>
<td>Borosilicate (Pyrex)</td>
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<tr>
<td>Soda Lime (float)</td>
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1.1 Analysis of High-Speed Photographs

In all the high-speed sequences taken in this study we observed a thick, black straight line moving at about 5.5 mm µs⁻¹ into the specimen ahead of all the other features (see figure 2). The thickness of this front corresponds to 1-2 mm in the specimen. Figure 2 c) and d) show stress gauge data for the two glasses. Soda-lime glass impacted at 530 m s⁻¹ (c) has a ramp of ca. 200 ns while Pyrex, impacted under the same conditions, shows a dual structure which has a ramp of ca. 300 ns at this velocity. In order to understand the dimensions of the dark wave front in the photographs it is necessary to consider the derivatives of the stress data since this quantity will be non-zero at positions at which the optical phase is changing. At other points, where the phase is constant, light passes without refraction to the camera. Thus the dark lines represent areas in which stress gradients exists and out of which light is refracted. The thickness of the front can be correlated with the peaks in the derivative plots by transforming the temporal data to distance using the shock velocity. An interesting consequence of this analysis is the appearance of a precursor wave in Pyrex which can be seen in figure 2 b), and which confirms that the ramping part of the rise contains structure.

Figure 2 a) and b) Typical frames are presented for soda-lime and Pyrex glasses with schematics to the right. Representative longitudinal stress gauge records (dotted line) for 10 mm thick specimens, c) soda lime and d) Pyrex. The derivative of each stress record is also shown (heavy line).

3. Results and Discussion

Figure 3 shows the gauge records for the shots on the two glasses for both low (ca. 250 m s⁻¹) and high (ca. 530 m s⁻¹) velocity impacts. As one can see the gauges in Pyrex show a distinct ramping at the wave
from zero to about 30 kbars and a steep rise up to the final shock. This behaviour has been noted by many workers before. However, the soda lime glass records show a feature which, to our best knowledge, has been overlooked. It appears that this glass also results in a ramping elastic wave and that this ramp, although smaller than that of Pyrex, is persistent through the whole elastic range of this glass which is up to about 65 kbars. The slope of this ramping elastic wave, as determined by the rise time in our gauge records is ca. 350 kbars $\mu$s$^{-1}$.

![Figure 3](image)

Figure 3  Longitudinal stress gauge records for a). soda-lime and b). Pyrex targets at 250 and 530 m s$^{-1}$.

Figure 4 a). shows several frames from the high-speed photographs of the soda lime glass impacted at a low velocity. We can clearly see the shock wave front, S, which moves at about 5 mm $\mu$s$^{-1}$. Behind this wave we see several features which may belong to the lateral release waves coming from the edges of the impactor. We see a dark irregular front, F, propagating from the impact face of the specimen. This moves behind the shock at a lower velocity ca. 2 mm $\mu$s$^{-1}$. This velocity is in good agreement with that found in [7] for the fracture front.

![Figure 4 a) and b)](image)

Figure 4 a) and b). Impacts on a) soda lime and b) Pyrex glasses at 250 m s$^{-1}$. The elastic waves S and R and the failure waves $F$, $F_1$, and $F_2$ can be seen. In b) the rear interface with a PMMA backing plate is visible. The scale lines are 5 mm apart.
However, one has to remember that this dark region appears from the impact surface very late, actually if we construct an x-t diagram, we find that their initiation time corresponds to the arrival of the first release from the back of the impactor to the impact interface. A similar set of dark features is initiated by the reflection of the shock wave from the free surface of the glass, F₂. This front moves back behind the release wave until it coalesces with the forward moving front F₁.

Figure 4 b). shows a series of frames corresponding to a low velocity shock on Pyrex. The same basic features also appear here although with much less prominence. The fracture front is more regular and this time the lateral release waves are much more visible (as white arcs). The crack sizes are clearly of a much smaller scale than in soda-lime glass. One should note that the stress in this shot is near 20 kbars (below the end of the ramping range for Pyrex), so that the thickness of the elastic front seen in the frames is constant and corresponds to the rise time of the ramping elastic wave.

Higher velocity impact on soda lime glass (ca. 530 m s⁻¹) resulted in somewhat different features (figure 5 a). This time the area behind the shock front is blackened by a front which moves very close behind it. In the region between the shock and fracture front a speckled region is visible in which nucleation processes appear to occur. The fact that this fracture wave is so fast is in certain contradiction with earlier findings concerning the velocity of these fracture waves [6], [7]. The reason for this discrepancy is not clear to us at the moment. It could be due to the fact that the front we observe in the high speed photographs are the nucleation fronts of the fracture while the gauges record the final state of the fractured material.

Figure 5 a) and b). Impacts on a) soda lime and b) Pyrex glasses at 530 m s⁻¹. The elastic waves S and R and the failure waves F₁, F₂, and F₃ can be seen. In b) the rear interface with a PMMA backing plate is visible in b). The scale lines are 5 mm apart.

A high-speed sequence of the high velocity impact of Pyrex is shown in figure 5 b). One can clearly see a lot of planar features which were not seen at the low speed impact. However, the fracture front is qualitatively similar to the lower velocity shot. It seems that the fracture front is very slow in this material and that the nucleation sites are much smaller than those in soda lime glass. The cracking front behind the longitudinal release from the rear surface of the specimen, F₂, is better developed in this sequence than the lower velocity shot.

4. CONCLUSIONS
We have demonstrated the usefulness of using high speed photography in shock wave experiments on transparent materials like glass. We were able to follow the various waves which form in different glasses and demonstrate the existence of fracture waves in soda lime glass. The nature of these waves can be
understood more clearly in terms of crack nucleation and growth, if one is focusing on the fracture fronts, both at the loading and unloading points of the signal. The fact that no fracture waves have been seen in Pyrex is very interesting by itself and is in good agreement with previous findings using stress gauges. The planar features which Pyrex shows bear further investigation.

REFERENCES