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Impact and Penetration of a Borosilicate Glass

N.K. Bourne, L.C. Forde, J.C.F. Millett and J.E. Field

Shock Physics, PCS, Cavendish laboratory, Madingley Road, Cambridge, CB3 0HE, U.K.

Abstract: The impact and penetration of brittle solids has been the subject of study for many years. Recently, the development of gauge techniques to measure the deviatoric response of various materials has highlighted the role of the shear strength in determining the ballistic performance. Recent experiments on various glasses using plate impact and ballistic geometries have characterised materials and provided a detailed analysis of penetration behaviour using simultaneous X-ray, high-speed photography and gauges. We present a study of impact on a borosilicate glass using a combination of these techniques.

Résumé : La pénétration des solides fragiles fait l'objet de nombreuses études depuis plusieurs années. Récemment, l'utilisation de jauges de contrainte pour mesurer la réponse déviatoire des matériaux a mis la lumière sur le rôle de la résistance au cisaillement pour interpréter les performances balistiques. De récentes expériences sur divers verres ont été conduites tant en impact de plaque qu'en impact balistique. L'utilisation simultanée de la radiographie, de la cinématographie rapide et des jauges a permis d'apporter des éléments sur le comportement durant la pénétration. Nous présentons une étude sur l'impact d'un verre borosilicate utilisant cette approche.

1. INTRODUCTION

The response of brittle materials to impact has been the subject of much recent study. Of particular interest are transparent armour materials which may find use in various applications from security glazing in vehicles to blast proof windows in buildings. To this end we have conducted a program characterising the response of various glasses to impact loading [1-6]. These investigations have confirmed that open structure glasses such as borosilicate (pyrex) densify when loaded with a planar shock wave and show a compressive failure mode which runs behind the shock wave called a failure wave. The variations of properties across this front include complete loss of tensile strength, partial loss of shear strength, reduction in acoustic impedance, lowered sound speed and opacity to light [7-11]. The failure wave resembles a phase boundary in many respects. Whilst these observations are generally held to be true, there has been no universally agreed mechanism for the process or processes which gives rise to the failure. We present results in which high-speed imaging has been used to extend our findings to penetration and illustrate some features which may be applicable to processes in other brittle materials.

Recent work by Rasorenov *et al.* [9] suggested that a failure wave propagated behind the elastic wave in glass at velocities in the 1.5–2.5 km s⁻¹ range. Later work by Brar *et al.* [8] confirmed the existence of these waves by using more direct techniques of spall strength and shear strength measurements ahead of and behind the failure wave, using manganin stress gauges. It was found that the high spall strength diminishes to zero behind this front and a substantial decrease in shear strength, as evidenced by the lateral stress measurements, results when the failure front traverses the specimen. More recent work by Raiser *et al.* [11], using VISAR, showed that the failure wave phenomenon does not depend on surface roughness, and Bourne *et al.* [1, 2] successfully visualised these waves in soda-lime and borosilicate (pyrex) glasses using high-speed photography. In order to account for these waves, Clifton [12] proposed a model, in the context of non-linear wave theory, according to which the failure front is a propagating phase boundary which separates comminuted from intact material with a transformation shock. The purpose of the work presented here was to extend our previous measurements of the deviatoric stresses in borosilicate glass and to generate ballistic data of use as benchmark tests for models.

2. EXPERIMENTAL

Figure 1: Experimental arrangement for a). plate and b). rod impact.

The glass targets were impacted using a single stage 50 mm gun at the University of Cambridge [13]. The projectile velocity before impact was measured to 0.1% by the short circuit of four pairs of conducting pins. Longitudinal and lateral stresses were measured in plate impact experiments using manganin stress gauges of type J2M-SS-580SF-025 (resistance 25 Ω). The targets were cut and reassembled to introduce the gauges (figure 1 a). The data collected cannot be used directly to infer the lateral stress. Thus they were reduced using a new analysis requiring no knowledge of the longitudinal stress [14]. The lateral stress, σ_y was used along with measurements of the longitudinal stress, σ_x to calculate the shear strength τ of the material using the well known relation

$$\tau = \frac{1}{2} (\sigma_x - \sigma_y). \quad [1]$$

This quantity has been shown to be a good indicator of the ballistic performance of the material [15]. Our method of determining the shear strength has the advantage over previous calculations of being direct since no computation of the hydrostat is required.

The pins were used to trigger and synchronise the oscilloscopes, camera and flash via a three-channel delay generator. An Ultramac FS501 image converter camera, capable of 2×10^7 frames per second framing rate and a maximum of 24 frames per sequence, was used to acquire a high-speed sequence of events during impact. Each exposure and interframe delay was set independently. The framing rate was adjusted through the sequence to capture events occurring on different timescales and for this reason each frame is separately labelled with the time after frame 1 that it was taken. The impacts were backlit uniformly using a Xenon discharge tube and a schlieren system. The manganin gauges were monitored using a 2 GS s^{-1} storage oscilloscope. The X ray images were taken using a short duration 100 kV pulse.

Mild steel EN3B rods were used for penetration experiments. The steel has been characterised at high strain-rate using a compression split Hopkinson pressure bar (SHPB) and plate impact. The steel had density 7818 $kg\ m^{-3}$, longitudinal sound speed 5.9 $mm\ \mu s^{-1}$ and yield strength 440 MPa quasistatically and 940 MPa at a strain rate of 3500 s^{-1} . The glass had density 2230 $kg\ m^{-3}$, longitudinal sound speed of 6.05 $mm\ \mu s^{-1}$ and a shear wavespeed of 3.69 $mm\ \mu s^{-1}$. The impact and opposite faces were finished to an optical quality by polishing with jeweller's rouge. The experimental arrangement for the rod impact experiments is shown in figure 1 b). The rod was mounted within the sabot and the glass held stationary. The velocity pins were used to trigger the localised Xe flash source and a 25 μm brass foil impact sensor on the surface of the target was used to trigger the Ultramac and the flash X-ray tube. The X-ray was operated in single shot mode building up a sequence over several experiments by successively delaying the firing of the tube. The sample was 75x75 mm square and 25 mm thick for the high-speed photography and 60x30x20 mm^3 for the flash X-ray. A small marker screw was inserted 40 mm from the nose of the rod to monitor rod erosion. In experiments where the rear surface of the glass plate was observed, the surface was carefully cleaned and treated with a proprietary matt white paint. A grid of pitch 1 mm was then ruled onto the surface using a stylus mounted into a milling machine. The resulting rear-surface grid was then lit through an arrangement consisting of two mirrors in order to visualise the surface through side windows in the gun.

3. RESULTS

3.1 Plate impact experiments

The left of figure 2 shows typical lateral gauge traces obtained for plate impacts carried out with thick copper flyers at two velocities which result in longitudinal stresses of 5.2 (dotted) and 5.7 (solid) GPa respectively. The traces are in pairs, the first is for a gauge at 3 mm from the impact face, the second is for a gauge at 6 mm. Both gauges are simultaneously introduced into the target and shot in the same experiment. The two shots shown were conducted within the elastic range of this glass since the Hugoniot elastic limit was determined to be 8.0 ± 0.2 GPa. The traces clearly show the features of the failure wave observed previously in soda-lime glass. A plateau is seen initially which rises to a second higher stress after a delay of around 500 ns at the 3 mm gauge and 1-1.5 μ s at the 6 mm. This indicates that the shear strength drops across a boundary travelling behind the shock. Thus two values of the shear strength can be measured for each longitudinal stress according to whether the plateau ahead or behind the failure front is used. Values ahead of the failure front correspond to elastic strengths calculated according to

$$\sigma_y = \frac{v}{1-v} \sigma_x \text{ and thus } 2\tau = \frac{1-2v}{1-v} \sigma_x. \quad [2]$$

Figure 2: Left: Lateral stress histories recorded by gauges 3 and 6 mm from the impact face of borosilicate targets. Flyers lapped copper velocities 650 and 727 m s⁻¹. Right: Deviatoric behaviour of borosilicate, soda-lime and a lead glass. The strength initially follows the elastic prediction and then fails (after a delay) to the lower flat curve.

Values behind the failure front fall to about half of the elastic figure. The right of figure 2 shows a summary of the data collected in this way for three glass types. Data for soda-lime and a lead glass (described elsewhere [5, 6]) is presented along with the present borosilicate. A universal behaviour is observed for all glasses with the initial values lying on an elastic curve with slope 2/3 (since the Poisson's ratio for glass is around 0.25) and the failed strength lying on a lower curve. The common deviatoric behaviour observed for all three glasses is remarkable given the great variations in density (2.2, 2.5 and 5.2 g cm⁻³) and microstructure. These results are discussed elsewhere [16].

3.2 Penetration and failure of borosilicate glass monoliths under impact

In previous work [1, 2] we have shown high speed sequences of plate impact experiment where copper flyers impact 25 mm thick tiles of borosilicate which were 75x75 mm square. Schlieren imaging and high-speed framing photography were used to obtain sequences showing the response of the material to a planar shock. The important feature of such a loading is that the material is subjected to a long pulse whose length is controlled by the thickness of the flyer plate. Thus all the features observed in the sequence are occurring in regions experiencing compression loading. The shock wave was visualised and the morphology of the failure was seen very different from that observed in other work where float glass was used and the failures were large and bifurcated. The front in borosilicate appears behind the shock and is very regular having the appearance of many small failures travelling together. The shock wave travels at ca. 6 mm μ s⁻¹ whilst the failure front travels at ca. 3.4 mm μ s⁻¹. It will be noticed that the front is travelling at approximately the shear wave speed however at higher impact velocities the failure front propagates at ever higher velocities, eventually merging with the shock front itself [6]. We extend the planar loading experiments to impact of a hemispherical nosed rod as described above.

Figure 3 shows 8 frames from a high-speed framing sequence on the left. The impact is between a mild steel rod with a hemispherical end fired at a borosilicate block at 536 m s^{-1} . The shock enters from above and is of hemispherical form and can be seen at the first scale marker, which is 5 mm from the impact face, in the first frame.

Figure 3: Mild steel round-ended rod fired at a 25 mm borosilicate block at a velocity of 536 m s^{-1} . Left hand side: 8 frames from a sequence showing development of damage within the glass. Right hand side: reconstructed streak picture showing the evolution of the failure behind the shock. Shock wave shown as black dotted line, failure front as white dotted line.

Since the wave is divergent and loses amplitude quickly, the schlieren system does not have the sensitivity to pick up its presence in subsequent frames. However, the region behind it can clearly be seen. A black front of initially hemispherical form may be seen travelling downwards in each frame. Ahead of this front, in the first four pictures, a circular darkened region may be observed into which the black front runs. This zone is believed to contain damaged glass in which the structure is partially failed. The initial pressure induced upon impact in the glass is of the order 4.5 GPa for these impact conditions, although the stress is quickly relieved by lateral releases. Plate-impact experiments indicate that the glass may take up to $2 \mu s$ to fail 6 mm from the impact face. There is also densification at the impact point due to open structure of the glass leading to a negative pressure dependence of the moduli. The black, following front is believed to be the locus of failure. The front travels more slowly than in the planar loading case but then the stress system here is three dimensional and the wave is divergent. The initial hemispherical failed region of the first frame appears to flatten as it travels through the darkened zone until by frame 6 the wavefront shows a flattened form which runs outward in a self-similar manner through the sequence.

To the right of figure 3 is a 'pseudostreak' picture constructed from slices of image taken down the central axis of subsequent frames (close to the vertical line) and stacked one upon the other. Each slice corresponds to a time interval of $0.5 \mu s$ which defines the time axis of the plot. The evolution of the fracture front and the initial formation of the darkened zone can be seen at the beginning of the sequence. Dotted lines have been added to show the positions of the shock wave (black line) and failure front (white line). The fracture front is travelling at a velocity of $1.8 \text{ mm } \mu s^{-1}$. This value is *ca.* 0.5 times the shear wave speed which is close to the Rayleigh wave speed for borosilicate. As can be seen from the figure, the velocity of the fracture front is constant for the duration of the sequence. Assuming this behaviour were to persist, the block would be completely fragmented through the thickness of the block, *ca.* $14 \mu s$ after impact. Clearly this front velocity is very much slower than observed in the planar impact case. However, the failure there was in conditions of compression where the stress was maintained by using a thick plate to drive the failure. In order to further study the impact event it became necessary to use flash X-ray since the opacity evident in the previous figures hidden details of the penetration.

The results of these experiments are presented in figure 4. Since the power of the system was limited, it was decided to use tiles of size $30 \times 60 \text{ mm}^2$ and 20 mm thick. This presents some problems in comparing the results since the lateral inertial constraint has been reduced compared with the previous experiments. However, the observations are nevertheless valuable for deducing mechanisms in the early stages where edge effects are unimportant. The sequence was built up from four shots in which different delays after impact were introduced. The black blocks at the top and the bottom of the each frame to which the glass is fixed are mounting brackets for the target. There is a wire visible in each frame connected to the impact sensor which is used to trigger the X-ray tube. The rod is 9.5 mm in diameter and has 20 mm of borosilicate tile to penetrate through. In the first frame the rod can be seen $2.8 \mu s$ after impact, sitting on the surface of the pyrex. There is little evidence of penetration at this stage, however,

the hemispherical nose has deformed to form a flat profile. There may be a darkened region in the body of the target which is *ca.* 1 mm deep which may be penetration of the steel or densification of the glass. By the second radiograph, which is taken 30 μs after impact, the rod has started to mushroom on the surface and expels glass from the impact crater in jets visible on either side of the rod. There is a noticeable bulging of the rear surface of the tile and lighter lines are visible within the block indicating that it is breaking up into blocks of material. The previous figure has shown that the tile is fragmented on axis by 16 μs so that it is perhaps not surprising that the lowered strength of the comminuted material allows the rod to move material forward. It appears that the blocks move as units even though the material within them has failed. This is even further accentuated by the 40 μs radiograph. The white lines are now clearly seen. Particularly interesting are the cracks seen parallel to the impact face running out from the nose region. It may be that this feature is connected with the lateral motion of the mushroom within the impact crater forcing surface material to flow laterally. The other interior cracks have also opened up and the rear surface bulge has accentuated. In both figures the four light coloured cracks are at similar angles to the impact axis corresponding to a cone of half angle 50° and a plane parallel to and 5 mm from the impact surface. The rod is plastically deforming at a high rate and is much greater in diameter behind the mushroom than further back. The ejecta jets are still present as before.

Figure 4: Flash X-ray sequence of the penetration of a steel rod travelling at *ca.* 540 m s^{-1} through a 20 mm borosilicate block. Frames taken at 2.8, 30, 40 and 80 μs after impact.

The final radiograph shows the moment at which the penetrator is about to exit the block and was taken 80 μs after impact. The profile of the rod has assumed a shape very similar to that when undeformed. The two pieces of steel to either side of the rod and about 10 mm from the impact face show that the original mushroom on the nose has had its extremities sheared away giving the effect of sharpening it. Thus, the channel through which the rod penetrates in the second half of the block is *ca.* half the diameter of that penetrated at the impact face. The rear surface of the block is very clearly bowed and the material ahead of the rod nose can be seen ejecting in a hemispherical cloud. The whole outer surface of the block (including the free edges) has been pushed outwards by the flow of material from the rod channel. The large cracks commented upon earlier are further opened up. The cone cracks are now at 60° to the impact axis but this is explained by a rigid rotation of the entire backward section since the rear face is now 15° from the vertical. The fiducial screw can be clearly seen in the X-ray having reached the position of the original impact. This allows a measurement of the erosion of the rod to be made during its passage through the tile. Such a measurement shows a reduction of 10 mm. Some of this may be attributed to and some to plastic deformation in the rod which has increased in diameter by *ca.* 20%.

Figure 5 shows the sequence of failure events observed on the rear-surface of a 9.5 mm thick borosilicate block impacted by a mild steel rod at 523 m s^{-1} . A sensor is used to trigger the sequence so that frame 1 is correlated (to within 100 ns) to the impact. The surface has been painted matt white and a dark, 1 mm grid has been ruled onto it. The black dots at the top left hand corner of each frame are alignment markers. The lighting is oblique and from the left as is evident from the sequence. Frame 1 shows no deformation but rear surface motion is seen in the next three frames after the longitudinal elastic wave has reached the rear surface and interacted with it. By 4 μs after impact, a clear disc shaped region can be seen coming out of the surface of the same diameter as the rod. By 5 or 6 μs a larger region of diameter 30 mm can be seen moving. The appearance of this feature at a later stage correlates with the arrival of the shear wave from the impact face. By the last frame, this bulk deformation is clearly evident.

It will be noticed that the grid in the central region across the rod diameter remains intact and largely undeformed throughout the sequence. Clearly, the glass is comminuted by this stage (as can be seen from figure 4) but the fragments move together en masse. There are times at which one area gets ahead of another as can be seen from the frame taken 10.5 μs after impact where a diagonal fracture runs from the top left to bottom right of the plug region. The periphery of the plug region shows a jagged form which is evident throughout the sequence.

Figure 5: The rear surface deformation recorded on a 9.5 mm thick borosilicate tile impacted with a 9.5 mm diameter, hemispherically nosed steel rod of L/D 10 travelling at 523 m s⁻¹.

4. CONCLUSIONS

This paper has presented results showing the measurement of the deviatoric behaviour of borosilicate glass and the measurements of response of targets to hemispherical-nosed rod impact. It has been shown that the material exhibits delayed failure due to the propagation of a failure wave. This has the effect of giving increased time for rod erosion in the initial stages of impact. Failure in rod impact occurs in a dark front travelling at the Rayleigh wave speed. It is assumed that the glass is comminuted behind such fronts. Deformation in the glass occurs in larger block structures indicated by brighter slip bands in the X-ray sequence. It appears that the comminuted material retains significant strength. Work is in progress employing similar techniques to investigate these phenomena further.

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