A Comparative Study of the Behaviour of Five Dense Glass Materials Under Shock Loading Conditions

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CP620, *Shock Compression of Condensed Matter – 2001*
edited by M. D. Furnish, N. N. Thadhani, and Y. Horie

THE DEVIATORIC RESPONSE OF THREE DENSE GLASSES UNDER SHOCK LOADING CONDITIONS

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Abstract. In-material longitudinal and lateral stress histories in three dense, silica-based glasses were directly measured by embedded manganin stress gauges during plate impact experiments. Lateral stress profiles in all of the materials show evidence of failure fronts that behave in a similar manner to those observed in open-structured glasses. The measured stress histories were used to calculate the deviatoric responses and results indicate that ahead of the failure front the shear stress increases linearly along the estimated elastic response. Behind the failure front, however, the shear stress appears to first decrease and then increase as the pressure increases, contrary to a previous interpretation [1].

INTRODUCTION

Previous work at the Cavendish Laboratory on silica-based glass materials under shock loading has demonstrated that the material response is highly dependent upon the composition of the glass [1, 2]. The shock responses of glasses with an open structure, such as borosilicate, exhibit a ramping behaviour in the longitudinal stress histories due to structural collapse. Glass materials with a *"filled"* microstructure, as in the case of Type-***D***, ***E***xtra ***D***ense ***F***lint (DEDF) do not exhibit a ramping behaviour and behave in a manner similar to polycrystalline ceramics [3]. Partially filled materials, such as soda-lime glass, show an intermediate response.

Although the shock response of the glasses previously tested varied considerably, one common feature was the existence of a damage front that propagated behind the initial shock at a lower velocity [4, 5]. Behind this damage front, denoted as the failure wave [6], or *failure front*, the shear strength undergoes significant reduction and the spall strength is essentially reduced to zero [7, 8]. Based on the deviatoric response in soda-lime, borosilicate and DEDF glasses, and two ceramics, it was suggested that the shear stress behind the failure front is independent of impact stress [9].

In the current investigation, results from plate impact experiments on three filled silica-based glasses are presented for a wider range of pressures than in previous studies. Contrary to the previous interpretation [1], there is now sufficient data to show that the shear stress behind the failure front initially decreases and then increases with increasing impact stress. A similar dependence of shear stress on pressure is assumed in the well-known model developed for brittle materials [10] and has recently been observed in cement paste subjected to shock loading [11].

MATERIAL

The glass materials used in this investigation consisted of two type-DEDF glasses and another filled glass designated as type-SF. The glasses are silica-based with different amounts of lead as the main filler material. One of the DEDF glasses was also tested in previous investigations [1-3, 5], and is denoted as DEDF-1 in this investigation. The new DEDF material is denoted as DEDF-2, and the type-SF material is denoted as SF-57. The wave speeds of materials were measured with quartz transducers in both the longitudinal and transverse orientations, using a Panametrics-5052PR pulse receiver operating at 5 MHz. The measured longitudinal (c_L) and shear wave (c_S) speeds, and the density at ambient conditions (ρ_0) were used to calculate the elastic properties, as shown in Table 1.

TABLE 1. Elastic Properties of Dense Glasses.

Glass Type	Density ($g\ cm^{-3}$)	C_L ($mm\ \mu s^{-1}$)	C_T ($mm\ \mu s^{-1}$)	C_0 ($mm\ \mu s^{-1}$)	Poissons ratio	Impedance ($10^3\ kg\ m^{-2} s^{-1}$)
DEDF-1	5.18±0.05	3.49±0.01	2.02±0.01	2.60±0.01	0.25±0.005	18.08
SF-57	5.53±0.02	3.42±0.01	1.98±0.01	2.53±0.02	0.25±0.005	18.91
DEDF-2	5.94±0.06	3.27±0.03	1.86±0.01	2.47±0.02	0.26±0.005	19.42

EXPERIMENTAL PROCEDURE

Plate impact experiments were performed on all three filled glasses in this investigation using the 50-mm, single stage gas gun at the University of Cambridge [12]. Longitudinal stress measurements were taken by embedding piezoresistive manganin gauges (Micromeasurements type LM-SS-210FD-050) between tiles of the target materials, or supported on the back of the target with a block of polymethylmethacrylate (PMMA). Lateral stress measurements were performed by embedding manganin gauges (Micromeasurements type J2M-SS-580SF-025) in the lateral orientation at various distances from the impact face. Figure 1 shows the specimen configurations used in the investigation. Gauge calibrations were performed for each experiment according to the work of Rosenberg [13], and the specimens were assembled using a low viscosity epoxy adhesive.

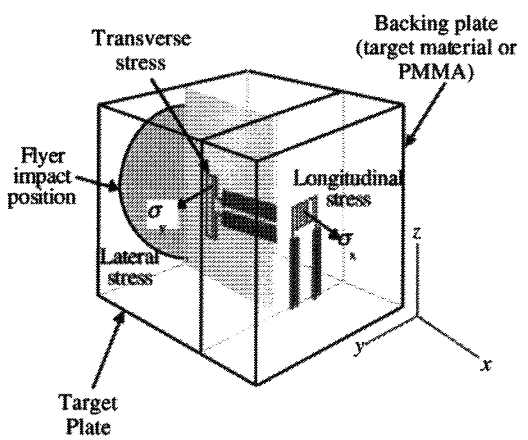

FIGURE 1. Specimen configuration.

Experiments were performed using 6, 10, and 19-mm-thick targets that had a minimum diameter of 50 mm. Copper and tungsten-alloy flyer plates (5 to 20 mm) were impacted onto the targets at velocities ranging from 0.19 to 0.84 km s^{-1}. Impact velocities were measured by the shorting of sequential pairs of pins to an accuracy of ± 0.5 %, and the specimen alignment was fixed to be less than 1 mrad by of an adjustable specimen mount.

RESULTS AND DISCUSSION

Longitudinal stress (σ_x) histories from tests performed in this investigation confirmed the HEL reported for the DEDF-1 material (4.3 GPa [3]) and extended the range of data. The HELs of the new glasses were determined to be *ca.* 4.4 GPa. The behaviour of the DEDF-2, however, is unique relative to the previously tested silica-based materials. In this material, there is a distinct two-wave structure that initiates at approximately the HEL. It appears that a structural densification or rearrangement of the SiO_2 tetrahedral is occurring that depends on material composition [14]. Work specifically related to the densification of glass materials is ongoing and will be addressed in future publications.

Results from the longitudinal stress histories were used in conjunction with the impedance matching technique to determine the principal Hugoniots, shown in Fig. 2. The Hugoniots of these filled glasses are consistent with the behaviour of other silicate glasses and follow the expected trend based on the impedance, as outlined in Table 1.

Lateral stress (σ_y) histories under the same impact conditions as the corresponding longitudinal measurements were measured to allow the deviatoric response of the materials to be characterised. Figure 3 shows the lateral response of the DEDF-2 material measured in three experiments using gauges located at 3 and 6 mm from the impact face. In these experiments longitudinal stresses of 3.3, 6.4, and 10.7 GPa, respectively, were produced. From the stress histories for the experiment in which

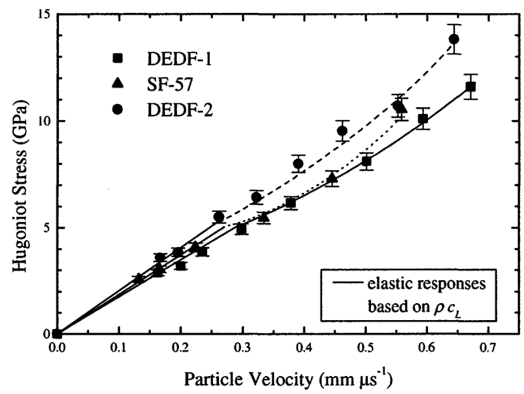

FIGURE 2. Principal Hugoniots of dense glasses in this study.

$\sigma_x = 6.4$ GPa, it is clear that a two-wave structure associated with the propagation of a failure front is present [1]. Similar results were observed in the other glasses tested and the existence of failure fronts was confirmed using high-speed photography. Comparing the lateral responses, it is seen that the delay time between the incident wave and failure front decreases as the longitudinal stress, or impact pressure, increases. This trend of decreasing delay times agrees with previous results on glasses and indicates that the failure front velocity increases with pressure [9]. It is also noted that there is a transition from the failure front lagging behind the incident shock, to the point where it is propagating with the incident shock, as the longitudinal stress is increased. In this case ($\sigma_x = 10.7$ GPa) there is

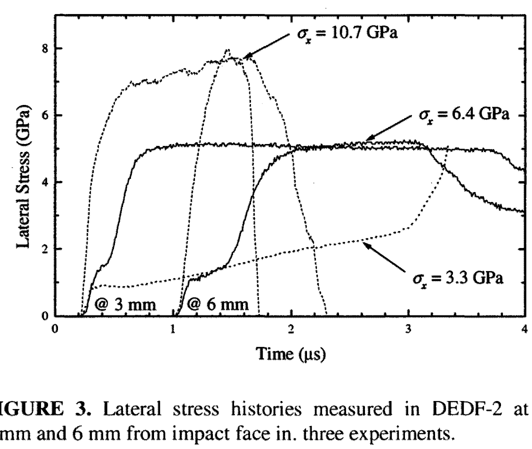

FIGURE 3. Lateral stress histories measured in DEDF-2 at 3 mm and 6 mm from impact face in. three experiments.

no initial step in the lateral response, but an increase directly to the higher value of stress behind the failure front.

Using the lateral stress measurements ahead of, and behind the failure front, the shear stress (τ) defined by,

$$2\tau = \sigma_x - \sigma_y \tag{1}$$

was calculated. The resulting deviatoric responses for the three glasses tested, as a function of longitudinal stress, are presented in Fig. 4. The results are based on measurements at 6 and 10 mm in the DEDF-1, and 3 and 6 mm in the SF 57 and DEDF-2. From Fig. 4, it is seen that the same basic trend occurs for all the filled glasses. That is, ahead of the failure front the shear stress increases linearly along the estimated elastic response, based on Poisson's ratio, to *ca.* 6 GPa. Behind the front, however, the shear stress appears to first decrease and then increases as the impact stress increases.

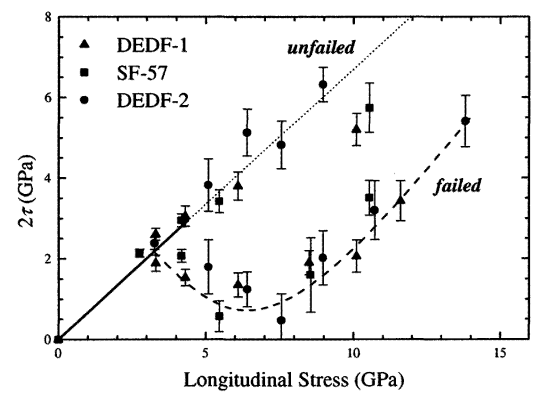

FIGURE 4. Deviatoric responses of dense glasses tested up to *ca.* 14 GPa longitudinal stress.

This observation modifies the previous interpretation based on longitudinal stress data to *ca.* 8.5 GPa, which suggested that the shear stress behind the failure front remains constant [1]. In that investigation, results from three silica-based glasses and two polycrystalline ceramics were shown to follow the same non-failed and failed curves, with the shear stress behind the failure front remaining constant within experimental error. However, study

of the earlier data (Fig.4 of [1]) does suggest the trend now established in the present study. A plausible explanation is that the comminuted material behind the failure front consists of fragments that will impart force/resistance as they attempt to move past one another under a shear force. As the pressure is increased, more force is required to move the fragments, due simply to mechanical constraint. This explanation is consistent with the well-known model for brittle materials, due to Johnson and Holmquist [10]. Similar behaviour has recently been observed in cement paste [11], which also behaves in a brittle manner.

CONCLUSIONS

Results from plate impact experiments on three dense glass materials have been presented. Longitudinal stress histories were used to determine the principal Hugoniot. Lateral stress histories show the existence of failure fronts in all three materials. Based on corresponding longitudinal and lateral stress measurements, the deviatoric response was characterised. The calculated shear strengths ahead of the failure fronts were similar to previously tested silica-based glasses. Behind the failed material, however, the shear stress shows a dependency on impact stress.

ACKNOWLEDGEMENTS

We acknowledge financial support from DERA, under contract SMC/4U1348, and are grateful to T. Andrews, P.D. Church, B. Goldthorpe, and I.G. Cullis for encouragement. We also thank J.C.F Millett and N.K. Bourne for performing some of the early experiments on the DEDF-1 material. Finally, we acknowledge D.L.A. Cross and R.P. Flaxman for valuable technical support.

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