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An oblique impact anomaly in high-velocity liquid impact on glass

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The residual strength of glass discs after impact by high-velocity water jets has been found as a function of impact angle. An unexpected result is that under certain conditions the damage suffered is a maximum for non-normal impact. This effect is shown to be caused by radial cracks forming during the oblique impact. These cracks are not observed for normal impact and their formation is dependent upon specimen geometry. The result is of practical significance to the rain erosion situation where aircraft and missile components may suffer damage by encounters with rain drops.

1. Introduction

The flight of high-speed aircraft and missiles through rain poses an interesting practical problem: components, particularly brittle electromagnetic window materials, may suffer severe or catastrophic damage by impact with water drops. We present here the results of an investigation of the residual strength of soda-lime glass discs (25 mm radius, 6 mm thickness) after impact by high-speed water jets at various speeds and impact angles. In general, previous work on erosion and on the basic mechanics of liquid impact has shown that damage is reduced as the angle of impact deviates from the normal. Layered materials with weak interfaces, such as composites and coated materials, can be exceptions to this rule [1]. The work presented here shows the unexpected result that glass specimens of suitable geometry may suffer more damage for oblique impact than for normal impact. Clearly, this result is of great practical significance.

2. Experimental details

The glass discs were impacted centrally by 3 mm diameter water jets from the apparatus described by Bowden and Brunton [2]. These jets have been shown to be a good model for the more realistic case of impact with spherical drops [3].

The pressure history from a jet or drop impact consists of a very short pressure peak generated when the liquid is behaving compressibly, followed by a longer duration of a lower pressure when a stable flow has been established. Velocities in the range 100 to 1000 m sec^{-1} can be obtained with the jet technique. For a 3 mm jet impacting glass at 600 m sec^{-1}, the only significant part of the pressure history is the initial pulse of 1.2 GPa lasting for $\sim 1\,\mu$sec. A successful and realistic method for quantifying impact damage in brittle materials subjected to this type of loading is to measure the residual strength of the damaged specimen. A test described by Gorham and Rickerby [4] in which the glass discs are simply supported near their perimeter and uniformly loaded on one side by a hydraulic system until they burst was used in this investigation. From the bursting pressure the fracture strength of the specimen may be calculated.

3. Results

Fig. 1 shows the post-impact fracture strength as a function of impact angle, α, for four impact velocities, each point being an average for ten specimens. α is defined as the angle between the impacting jet and a normal to the target surface. For the lower two velocities the strength rises monotonically towards the unimpacted strength in the expected manner. For the higher velocities, however, the strength passes through a minimum at some non-zero α before rising rapidly towards the unimpacted strength.

Fig. 2 shows some specimens from these

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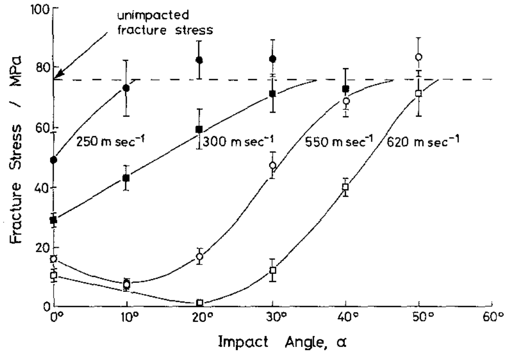

Figure 1 The residual strength of glass discs after impact by 3 mm diameter water jets as a function of impact angle, α, for four impact velocities.

anomalous $620\,\mathrm{m\,sec^{-1}}$ results. The normal impact site (0°) shows a circularly symmetric pattern of short circumferential cracks. Most of this damage is nucleated by the Rayleigh wave from the impact interacting with surface flows [5]. As the impact becomes slightly oblique, the damage becomes concentrated in the "downstream" direction and long radial cracks extend rearwards from the contact area. These cracks cause the anomalously low post-impact strengths of these specimens; indeed at 20° the radial cracks extend completely across the disc in 80% of cases, leaving the specimen with effectively zero residual strength. In the absence of radial cracks, as in the case of the lower two impact velocities, the total amount of damage decreases monotonically and the strength rises in the expected manner. It is interesting to note that these cracks are concentrated in the downstream direction which suggests that the stress wave is very much more intense in this direction. This idea is supported by the observation that damage to the specimen edges becomes localized in the downstream direction as the obliquity is increased (features marked D in Fig. 2).

4. Discussion

The circumferential cracks caused by the impact are analogous to the Hertzian cone crack formed when a sphere is loaded on a flat [5]. Taking this comparison further, oblique impact will be analogous to the case of oblique indentation analysed by Hamilton and Goodman [6]. These authors predicted an enhanced radial stress at the "upstream" edge of the contact, and we have observed abnormally large circumferential fractures in this position (features marked F in Fig. 2). These fractures are the origin of the radial cracks, seen most clearly for the 25° impact site. The radial cracks are too long to be formed on a microsecond time scale and are therefore a result of stress waves (reflected from the specimen boundaries) interacting with the large circumferential crack. The formation of the radial cracks is then a result of the present geometry; for example, they do not form in 50 mm x 150 mm glass plates in which the usual monotonic strength increase with oblique impact is found. For velocities $\gtrsim 700\,\mathrm{m\,sec^{-1}}$ radial cracks also occur for normal impact; however, they are caused by bending of the disc and they nucleate from the rear surface. The radial cracks formed here under oblique impact are

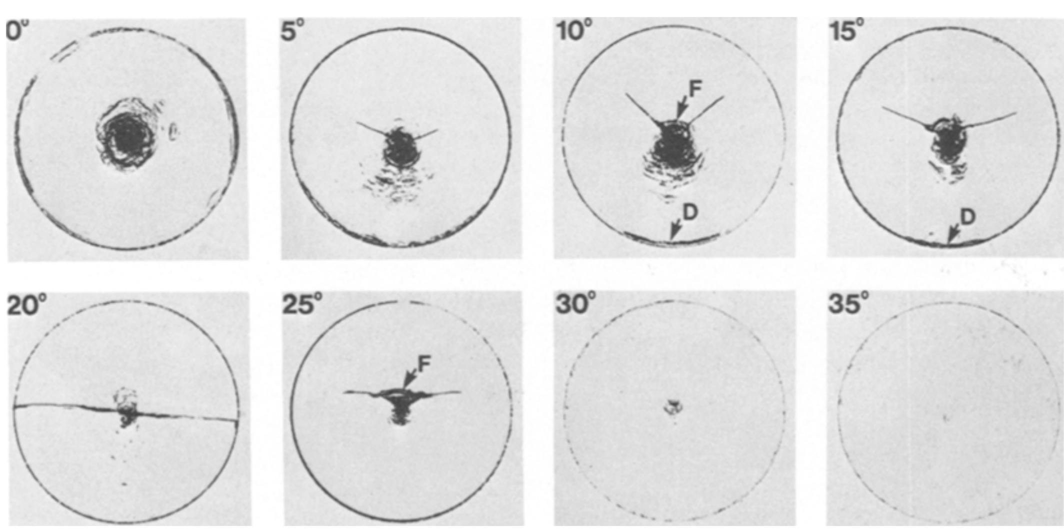

Figure 2 Typical damage produced by $620\,\mathrm{m\,sec^{-1}}$ impacts at various angles (marked). The impact is from top ("upstream" direction) to bottom ("downstream" direction).

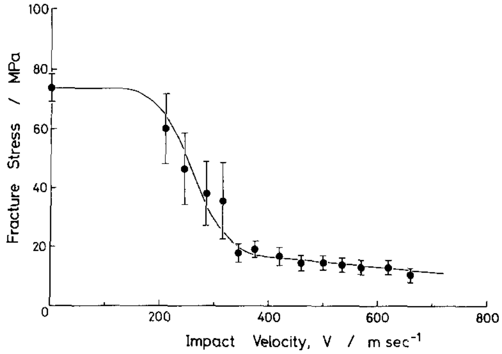

Figure 3 The residual strength of glass discs as a function of impact velocity for normal impact. Taken from Field *et al.* [3].

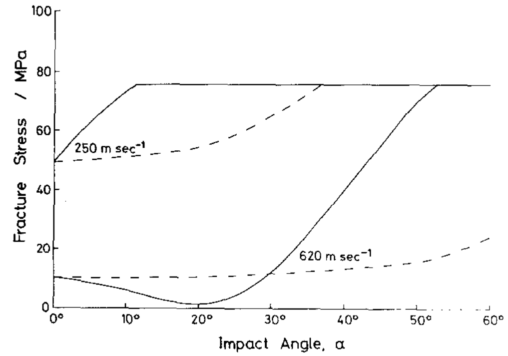

Figure 4 Comparison of observed behaviour (solid lines) with predicted behaviour (dashed lines) of the residual strength with impact angle. The prediction assumes damage depends on $V \cos \alpha$.

quite different in nature as they nucleate at and propagate along the front surface.

A simple model for oblique impact might be to suppose that the damage produced by an impact with velocity V at an angle α is the same as that caused by a normal impact with velocity $V \cos \alpha$. Normal impact residual strength data from [3] are presented in Fig. 3. The graph consists of an initial plateau, corresponding to low-velocity impacts which do not reduce the specimen strength, a transition region where there is an increasing probability of strength degradation due to impact, and a final roughly constant part in which all specimens are damaged. Fig. 4 shows the sketched lines (solid) of Fig. 1 for 250 and 620 m sec^{-1} impacts, together with the behaviour calculated from the data of Fig. 3 with the $V \cos \alpha$ assumption (dashed lines). Once any anomalously low strength behaviour is passed the strength rises far more rapidly towards the unimpacted strength than the assumption predicts and the form $V \cos^n \alpha$ seems to be more appropriate. The exponent, n, is difficult to determine accurately but is in excess of 5.

5. Conclusions

Small glass components may suffer more damage for oblique impact than for normal impact and this has obvious practical implications. The effect is due to the formation of radial fractures which do not occur for normal impact. These fractures are a result of stress wave interactions with the specimen geometry and therefore may be controlled by redesigning components or by impedance matching the boundaries to reduce the amplitude of reflected stress waves. In the absence of radial cracks, damage falls extremely rapidly as the obliqueness of the impact increases, but not according to any simple rule.

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