

Behaviour of a commercial wired glass under low energy ballistic impact

Shabbar Atiq

PCSIR Laboratories, Quetta (Pakistan)

Rees D. Rawlings and Aldo R. Boccaccini

Department of Materials, Imperial College London, London (UK)

A study of the ballistic impact resistance of a commercial wired glass has been undertaken using a gas gun capable of velocities up to 400 m s^{-1} . The projectile was a steel ball and impact energies up to 7.32 J were used. The extent of the impact damage was assessed by the mass of ejected material, the area of the Hertzian cone left by the impact and residual strength. Crack morphologies similar to those reported in monolithic glasses were observed, namely ring, cone and radial cracks. The impact energy dependencies of the mass of ejected material and cone area were similar showing a rapid increase at energies above about 4.35 J . In contrast, the residual strength remained at 20% or less of the as-received wired glass irrespective of impact energy. This was attributed to the wire mesh remaining intact for the ballistic impact conditions investigated.

1. Introduction

Glass has been an important material in a myriad of applications for centuries and in recent times it has evolved into an engineering material. Several modern day applications of glass require a range of properties including in some cases a reasonable load-bearing capacity [1]. These requirements have resulted in glasses being incorporated with a wide variety of fibres or particles to form composites, thereby improving properties such as fracture toughness, mechanical strength, thermal shock resistance, and impact resistance [2 to 5]. These composites are however highly opaque and therefore they cannot be used in applications requiring high light transmittance, i.e., transparency, or at least translucent properties.

In recent years, "optomechanical" composites have been developed based on translucent and transparent matrices incorporating fibres of matching refractive index or fibre meshes [6 to 10]. In fact, these novel transparent reinforced glasses can be considered enhanced or advanced systems derived from wired glass, which is the oldest transparent "reinforced" glass [11 and 12] and whose transparency arises from the large volumes of glass between the metal wires.

Wired glass, which consists of a metallic wire mesh incorporated into plate glass, is the oldest type of safety glass [11 to 13]. It was first produced in England over a hundred years ago [14] and is commonplace in domestic, educational

and industrial buildings. The original concept of incorporating metallic wires into the glass matrix was to enhance structural integrity and to make it safer in incidents involving impact. This well-established composite material is fabricated by placing the wire mesh on a ribbon of glass, and then rolling another ribbon of glass on top [14]. Typically the wire is in the form of a diamond or square welded mesh. Pioneering work on understanding the behaviour of wired glass under ballistic impact conditions was carried out as early as in 1938 using high-speed cameras to document crack propagation [13]. Nowadays, wired glass is primarily employed for its fire resistance. As a fire-rated material it has the ability to withstand a fire for a limited amount of time and also to remain intact if quenched by water from a hose [11 and 15]. Basically the wire acts as a reinforcing web that holds the cracked glass in place.

Although wired glass may be employed mainly for its fire resistance, its impact properties are also of concern because accidental impacts are likely to occur. Figure 1 shows a window made of wired glass after impact with a projectile (in this case a stone thrown manually by vandals), where the well known pattern of radial cracks emanating from the impact site can be seen. The fact that the glass window is still in one piece confirms the impact resistance of wired glass to foreign object impacts of relatively low energy. A brief account of the heat resistant characteristics of wired glass may be found in the article by Klein [16], but information on mechanical properties and especially on impact behaviour of wired glass is not readily available in the open literature. Furthermore, there are no recent quantitative

Received 25 August, revised manuscript 30 November 2003.



Figure 1. Typical damage to a wired glass window caused by a foreign body impact of low energy.

studies known to the authors devoted to an understanding of the behaviour of commercially available wired glass under ballistic impact, which could be used to compare with the early work of Schardin and Struth [13] mentioned above. The present investigation represents thus a first effort to assess the behaviour of wired glass under ballistic impacts at velocities up to 400 m s^{-1} corresponding to low impact energies in the range 0.63 to 7.32 J.

2. Experimental procedure

Samples of a wired glass product, known as 'Pyroshield Safety', measuring $(100 \times 100 \times 6.70) \text{ mm}^3$ were provided by Pilkington, St. Helens (UK). The glass was a normal float glass of soda-lime-silica composition and the continuous wires of mild steel (0.65 mm diameter) were laid in a 12 mm square mesh.

Ballistic impact tests were carried out by subjecting the as-received wired glass samples to impacts by projectiles of varying velocities. The samples were mechanically clamped in a sample holder without a backing plate and steel balls measuring 4.74 mm diameter (mass: 0.435 g) were fired using a laboratory gas gun. The gun employed was a single stage gas gun capable of firing spherical projectiles with diameters up to 13 mm at velocities up to 400 m s^{-1} . The gun used compressed nitrogen gas to fire the projectile and was operated by a bursting-diaphragm firing mechanism. The compressed gas was transferred from the cylinder to the gas reservoir (at one end of the barrel), which was joined to a breech adaptor. A suitable diaphragm was placed between the barrel and the breech adaptor. The pressure in the reservoir caused the diaphragm to rupture, shooting the projectile down the barrel. The velocity of the projectile was controlled by the pressure, which was required to burst the diaphragm. A more detailed description of the gas gun used is given by McQuillan [17]. After each impact, the chamber

was carefully cleaned and all fragments from the impacted samples were collected and weighed using an electronic balance with a precision of 0.001 g.

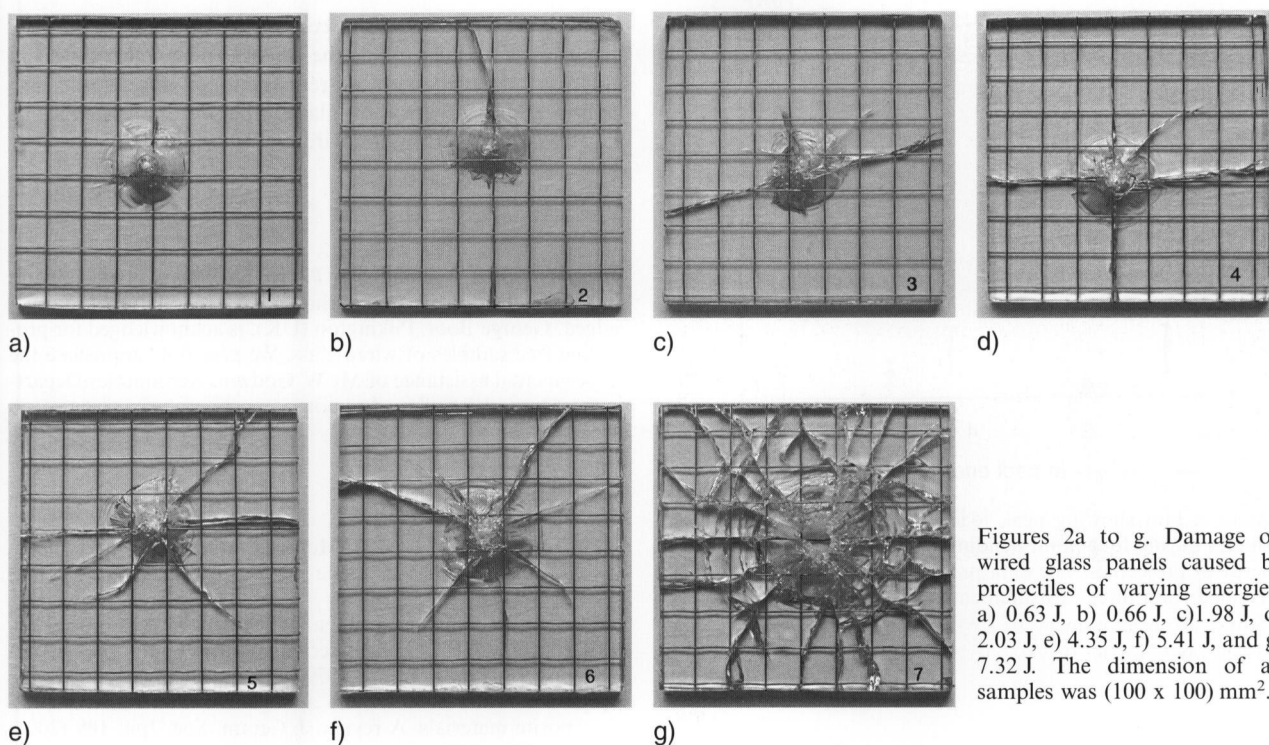
Damage of the samples after impact was recorded by a digital camera (Olympus D-510, Olympus Optical Co., Tokyo (Japan)). Moreover, the area of Hertzian cone impression was measured by tracing the rim of the cone and employing cut and weigh method. At least three samples per each condition were considered and the relative error in the determination of the cone area was 10 %.

After ballistic impacts, damaged samples were subjected to four-point bending test which was carried out on a universal testing machine using a four-point flexure fixture with 40 mm inner span and 70 mm outer span. Specimens were fixed in the fixture such that the impact side was under tension and the point of impact was located in the centre of inner spans following a procedure described by Choi et al. [18]. Tests were conducted using a 100 kN load cell and at a crosshead speed of 1 mm min^{-1} . At least three samples for each impact velocity were tested and the results averaged. The data obtained from the four-point bending tests were used to assess the structural damage in terms of peak load sustained by damage samples before failure.

3. Results and discussion

The structural damage to brittle materials that takes place under ballistic impact loading depends on parameters such as toughness, hardness, flaw density and other microstructural characteristics of both the target and the projectile. Damage to wired glass caused by ballistic impacts demonstrated a pattern similar to those for monolithic glass and glass-ceramics [19 to 21] and ceramic plasma-coated glasses [22], in terms of nature and pattern of crack formation. Figure 2a shows the post-impact damage due to a projectile having 0.63 J of energy. Examination of the rear face of the specimen showed formation of a cone due to localized disintegration of the glass. Also signs of formation of initial ring cracks could be seen on the edges of the cone. Increase in impact energy resulted in initiation of radial cracks, as seen in figure 2b, emanating from the impact site. Further increase in projectile energies resulted in greater number of radial cracks emanating from the point of impact as documented by figures 2c to g.

The pattern of crack propagation in wired glass is of particular interest as the wires seem to have very little or no effect on crack propagation. Careful post-impact examination of damaged samples revealed that when a propagating crack encountered a wire there was no noticeable deflection of the direction of propagation. This indicates that the interface bonding between the wires and the glass matrix was strong and no significant local thermal stresses due to the wires existed in the glass matrix. The wires, therefore, do not act as barriers to crack propagation, instead they add to the integrity of the glass structure by holding the fractured pieces of glass together. In this context, the wired glass does not behave like a typical brittle matrix composite, where relatively weak fibre/matrix interfaces must be present to induce crack deflection and fibre pull-out mechanisms [2 to 5].



Figures 2a to g. Damage on wired glass panels caused by projectiles of varying energies; a) 0.63 J, b) 0.66 J, c) 1.98 J, d) 2.03 J, e) 4.35 J, f) 5.41 J, and g) 7.32 J. The dimension of all samples was (100 x 100) mm².

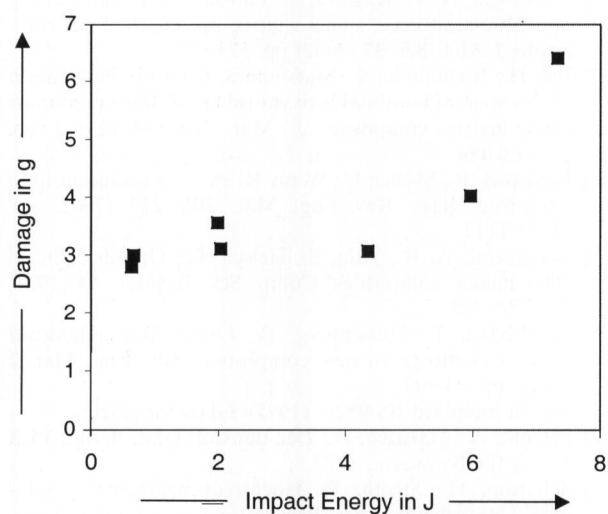


Figure 3. Damage of wired glass samples as measured by the mass of ejected material (i.e., the mass of the fragments collected from the sample after impact) plotted as a function of impact energy of the projectile. The maximum relative error in the determination of the mass was 10%.

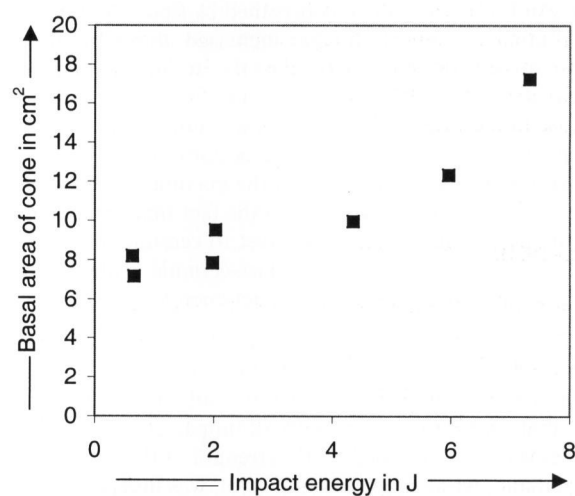


Figure 4. Damage of wired glass samples as measured by the basal cone area of the damaged zone of impacted samples as a function of impact energy. The maximum relative error in the measurement of the area was 10%.

In order to quantify the amount of damage to the glass as a function of impact energy, several parameters were investigated. One of these indicators of damage is the amount and extent of fragmentation caused by the projectiles, which has been used in the ballistic resistance assessments of other brittle materials [17 and 21]. Figure 3 shows a plot of the fragmentation mass as a function of impact energy. The curve in figure 3 shows that energies as low as 0.63 J caused

considerable fragmentation of the sample and that the amount of debris formed was relatively constant up to 4.5 J. At higher energies the mass of debris increases and this is associated with significant penetration of the sample as clearly seen in figure 2g. It is interesting to note that small penetration holes were observed at energies as low as 2 J and that even at the highest energy of 7.32 J the wires of the mesh were not broken.

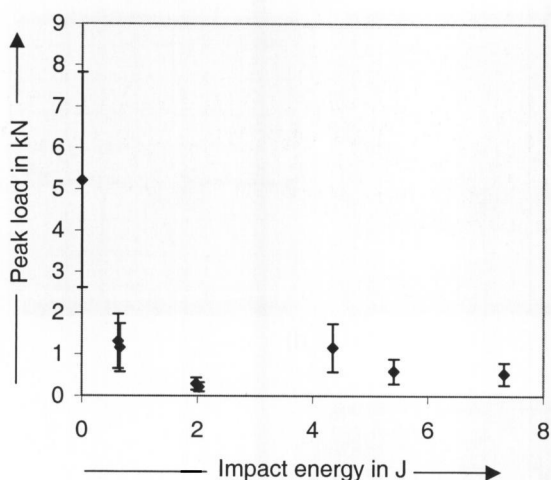


Figure 5. Plot showing peak loads sustained by the damaged samples during four-point bending test as a function of impact energy of projectiles. The data presented are average values determined from three measurements.

A similar trend was also seen when the basal area of the truncated cone left by the impact on the rear face of samples was plotted as a function of energy, as shown in figure 4. In fibre reinforced polymer and glass-ceramic matrix composites full penetration is accompanied by fibre fracture and as the impact energy is further increased above the minimum required for full penetration, the amount of damage decreases and the residual strength increases [3 and 23]. A decrease in damage at high energies was not observed in the present investigation. This may be because higher energies are required to see this effect than the maximum used in the present investigation and/or due to the fact that the metallic wire mesh remains intact, in contrast to ceramic fibres (e.g. carbon or SiC fibres) used in glass-ceramic matrix composites which break at similar impact energies [3].

The results of the four-point bending tests are presented in figure 5. Taking the peak load sustained by a specimen during a test as an indicator of the residual strength, it is clear that the residual strength of impacted wired glass samples was 20 % or less than the strength of the as-received material and, within experimental error, was independent of impact energy. This is consistent with the wire mesh remaining intact after impact, i.e. the residual strength has a negligible contribution from the fragmented glass matrix and is largely a measure of the load required to deform the mesh.

4. Conclusion

This study showed that low energy impacts result in the formation of ring, radial and Hertzian cone cracks in wired glass similar to that reported in other brittle materials. An increasing number of radial cracks is observed as the impact energy increases. The mass of ejected material and the area of the cone crack remain approximately constant up to 4.35 J and then increase at higher energies.

The presence of the steel wires in wired glass does not affect the crack propagation by crack deflection mecha-

nisms typical of fibre reinforced brittle composites. The steel wires are not fractured at the impact energies employed in this work, i.e. the wire mesh remains intact and its role is to enhance the integrity of glass. The residual strength is largely determined by the wire mesh.

*

Financial support provided by Pakistan Ministry of Science and Technology to one of the authors (S.A) is gratefully acknowledged. George Boot, Pilkington (UK), is acknowledged for providing free samples of wired glass. We gratefully appreciate the experimental assistance of Mr W. Godwin, Aeronautics Departments, Imperial College London.

5. References

- [1] Donald, I. W.: Review. Methods for improving the mechanical properties of oxide glasses. *J. Mat. Sci.* **24** (1989) pp. 4177–4208.
- [2] Beier, W.: Hart im nehmen. *Schott Inf.* **73** (1995) pp. 3–6.
- [3] Rawlings, R. D.: Glass-ceramic matrix composites. *Compos.* **25** (1994) pp. 372–379.
- [4] Boccaccini, A. R.: Glass and glass-ceramic matrix composite materials. A review. *J. Ceram. Soc. Jpn.* **109** (2001) pp. S99–S109.
- [5] Prewo, K. M.; Brennan, J. J.; Layden, G. K.: Fibre reinforced glass and glass-ceramics for high performance applications. *Ceram. Bull.* **65** (1986) pp. 305–322.
- [6] Dericoglu, A. F.; Kagawa, Y.: Fail-safe light transmitting SiC fibre-reinforced spinel matrix optomechanical composite. *J. Mat. Sci.* **37** (2002) pp. 523–530.
- [7] Iba, H.; Naganuma, T.; Matsumura, K. et al.: Fabrication of transparent continuous oxynitride glass fibre-reinforced glass matrix composite. *J. Mat. Sci.* **34** (1999) pp. 5701–5705.
- [8] Fankänel, B.; Müller, E.; Weise, K. et al.: Translucent fibre reinforced glass. *Key Eng. Mat.* **206–213** (2002) pp. 1109–1112.
- [9] Boccaccini, A. R.; Atiq, S.; Hensch, G.: Optomechanical glass matrix composites. *Comp. Sci. Technol.* **63** (2003) pp. 779–783.
- [10] Leutbecher, T.; Hülsenberg, D.: Oxide fibre reinforced glass: a challenge to new composites. *Adv. Eng. Mat.* **2** (2000) pp. 93–99.
- [11] British Standard BS 952-1 (1995): Glass for glazing.
- [12] Petzold, A.; Marusch, H.: *Der Baustoff Glas*. Berlin: VEB Verlag für Bauwesen, 1973.
- [13] Schardin, H.; Struth, W. Hochfrequenzkinematographische Untersuchung der Bruchvorgänge im Glas. *Glastechn. Ber.* **16** (1938) pp. 219–227.
- [14] Spauszus, S.; Schnapp, J. D.: *Glas allgemeinverständlich*. Leipzig: VEB Fachbuchverlag, 1977.
- [15] Amstock, J. S.: *Handbook of glass in construction*. New York: McGraw-Hill, 1997.
- [16] Klein, W.: Glazing against fire. *Glastechn. Ber.* **66** (1993) no. 6/7, pp. 185–190.
- [17] McQuillan, F.: The response of Silceram glass-ceramics to projectile impact. University of London, Ph D thesis 1992.
- [18] Choi, S. R.; Pereira, J. M.; Janosik L. A. et al.: Foreign object damage of two gas-turbine grade silicon nitride at ambient temperature. *Ceram. Eng. Sci. Proc.* **23** (2002) no. 3, pp. 193–202.
- [19] McQuillan, F. C.; Rawlings, R. D.; Rogers, P. S.: The ballistic resistance of Silceram glass-ceramics. In: *Proc. European Ceramic Society Conference, Augsburg 1991*. Pp. 2551–2555.
- [20] Kim, H.-G.; Choi, N.-S.; Cho, N.: Evaluation of the impactive-surface-fracture behaviour of glass plates using a

- back-surface strain measurement. *J. Mater. Res.* **16** (2001) pp. 3042–3045.
- [21] Bouzid, S.; Nyoungue, A.; Azari, Z.: Fracture criterion for glass under impact loading. *Int. J. Impact Eng.* **25** (2001) pp. 831–845.
- [22] Suh, C.-M.; Lee, M.-H.; Hwang, B.-W. et al.: Damage behaviour in ceramic plasma-coated and uncoated glass with steel-ball impact. *J. Am. Ceram. Soc.* **86** (2003) pp. 1220–1222.
- [23] Matthews, F. L.; Rawlings, R. D.: *Composite materials: engineering and science*. Cambridge, UK: Woodhead, 1999. Pp 342–354.

■ E104P005

Contact:

Dr. Aldo R. Boccaccini
Department of Materials
Imperial College London
South Kensington Campus
London SW7 2AZ
UK

E-mail: a.boccaccini@imperial.ac.uk