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Delamination properties of laminated glass windows subject to blast loading

Paolo Del Linz [a,b,*], Paul A. Hooper [b,*], Hari Arora [c,d], Yi Wang [b], David Smith [e], Bamber R.K. Blackman [b], John P. Dear [b,*]

[a] School of Civil and Environmental Engineering, Nanyang Technological University, Nanyang Avenue, 639798 Singapore
[b] Department of Mechanical Engineering, South Kensington Campus, Imperial College London, SW7 2AZ, UK
[c] The Royal British Legion funded Centre for Blast Injury Studies, Imperial College London, UK
[d] Department of Bioengineering, South Kensington Campus, Imperial College London, SW7 2AZ, UK
[e] Arup Resilience, Security and Risk, 13 Fitzroy Street, London W1T 4BQ, UK

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ABSTRACT

Delamination processes absorb significant amounts of energy in laminated glass windows when they are subjected to blast loads. Blast tests were performed previously and their results had been used to calculate the loads imposed on the support systems. In this research, the delamination process at realistic deformation rates was studied to understand the reaction force response obtained. Laboratory tensile tests were performed on pre-cracked laminated glass specimens to investigate their delamination behaviour. The experiments confirmed the presence of a plateau in the force-deflection graphs, suggesting that the delamination process absorbed significant energy. The experimental results were then employed to calibrate FEA models of the delamination process with the aim of estimating the delamination energy of the polyvinyl butyral (PVB) membrane and glass layers and its relationship with deformation speed. The delamination energies obtained through this research, if used with the appropriate PVB material model, are a valuable new tool new tool in the modelling and design of laminated glass façade structures.

1. Introduction

Blast threats represent an important design consideration for prominent building structures. Whilst all elements of buildings have to be designed considering their resilience to such threats, the façade, especially when composed of glass, requires special attention. A significant proportion of the injuries and economic losses are due to the failure of these components [1]. Façade failure can cause injuries to bystanders inside and outside the building both directly through fragments and indirectly through allowing blast pressures to penetrate the building envelope. Glass is a brittle material with relatively low fracture toughness and hence is not well suited to absorbing large quantities of energy. In a blast situation, it will fracture early, producing significant quantities of fragments [2]. Instead, laminated glass can absorb significantly a higher amount of energy by combining the strength of the glass layers with the ductility of an internal polyvinyl butyral (PVB) membrane bonded to the glass surfaces. When the shock wave reaches the laminated glass pane, the glass plies will tend to bend and the tensile stresses will cause them to fracture. However, the PVB layer can subsequently deform, absorbing energy whilst stopping the blast pressure from entering the building space and containing the glass fragments on its surface.

Whilst laminated glazing can offer much higher levels of protection than monolithic glass, the behaviour of all its components, including supports and connections, needs to be considered to assure the resilience of the structure. To estimate the design requirements for the components, it is important to understand the behaviour of the cracked laminated glass, as this will determine the loads imposed on other parts of the structure.

To improve this understanding, blast tests have been performed by several researchers, for example, Stephens [3], Zhang et al. [4,5], Kranzer et al. [6] and Larcher et al. [7]. Hooper et al. [8] performed tests using Digital Image Correlation (DIC) to collect full field deflection and strain data in 3 dimensions. The glass panes were composed of two 3 mm thick plies of annealed glass with a 1.52 mm PVB interlayer. The charges used were 12.8 kg and 25.6 kg C4 (15 kg and 30 kg TNT equivalent) and the stand-offs were between 10 and 16 m. These experimental data allowed the observation of the entire

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* Corresponding authors. School of Civil and Environmental Engineering, Nanyang Technological University, Nanyang Avenue, 639798 Singapore. Tel.: 44 (0)20 7594 7086; Fax: +44 (0)20 7594 7017.

E-mail addresses: paolo@ntu.edu.sg (P. Del Linz); paul.hooper@imperial.ac.uk (P.A. Hooper); j.dear@imperial.ac.uk (J.P. Dear).

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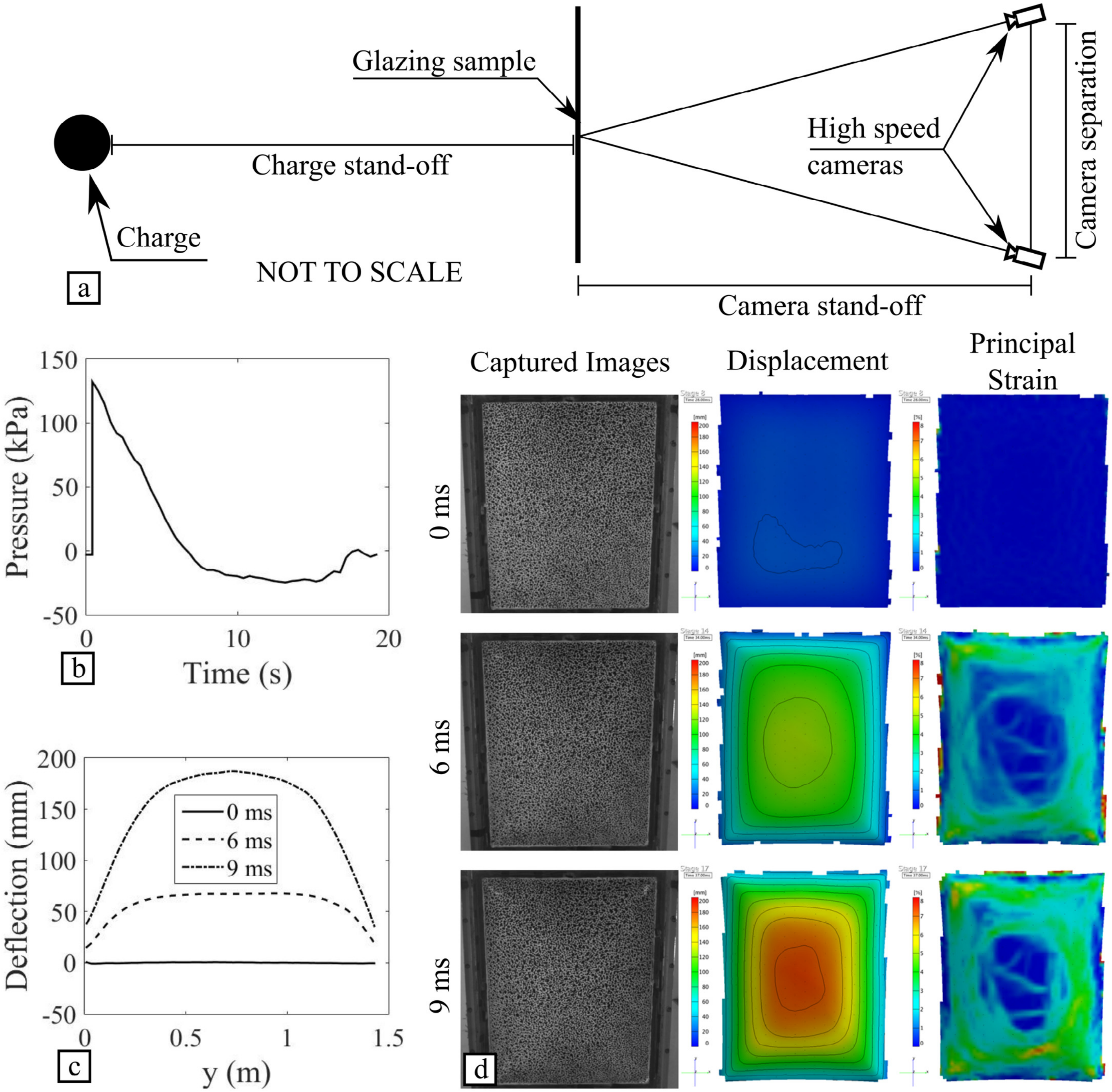

Fig. 1. Typical blast and DIC set up and results from a blast test (30 kg TNT equivalent at 16 m). The DIC set up is shown (not to scale) (a), together with the pressure time trace (b) and the deflected profile of the glazing sample (c). The raw high speed images and DIC results are also shown at the same three time points as the deflected profiles (d) (adapted from Reference 8).

loading process, starting from blast wave arrival, glass fracture and post-crack deformations. Typical graphical results are shown in Fig. 1 together with a diagram of the experimental set-up.

Additionally, Hooper et al. [8] placed several strain gauges around the window frame to estimate the reactions at discrete points around the frame. The results, whilst they included some noise, showed that the reactions at these discrete points did not increase significantly after an initial time.

These experimental data were employed by Del Linz et al. [9] to calculate the reaction forces along the entire perimeter. A typical result is shown in Fig. 2. It was noticed that the results strongly supported the presence of a plateau in the reaction forces at large deflections, as was first noticed in the early discrete reaction results.

The plateau in reaction force versus central displacement suggests that an energy absorption mechanism contributes in the absorption of the blast energy. Whilst the behaviour of the PVB membrane could account for this, a further possibility for such mechanism is progressive delamination of the glass fragments from the PVB membrane.

The performance of the glazing could be therefore dependent on the bond between the internal PVB membrane and the glass plies. These glazing panels are generally bonded in an autoclave, where

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