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Temperature effects on laminated glass at high rate

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ABSTRACT

The load bearing capacity of a laminated glass pane changes with temperature. In blast protection, laminated glass panes with a Polyvinyl Butyral (PVB) interlayer are usually employed. The post-crack response of the laminated pane is determined by the interlayer material response and its bond to the glass plies. An experimental study has been performed to determine the effects of temperature on the post cracked response of laminated glass at a test rate of 1 m/s for PVB thicknesses of 0.76 mm, 1.52 mm and 2.28 mm. Tensile tests were carried out on single cracked and randomly cracked samples in a temperature range of 0 °C–60 °C. Photoelasticity observation and high speed video recording were used to capture the delamination in the single cracked tests. Competing mechanisms of PVB compliance and the adhesion between the glass and PVB, were revealed. The adhesion showed an increase at lower temperatures, but the compliance of the PVB interlayer was reduced. Based on the interlayer thickness range tested, the post-crack response of laminated glass is shown to be thickness dependent.

1. Introduction

When an explosion occurs, a blast pulse propagates in the form of a pressure wave from the origin of the explosion. When this blast wave strikes a glass window, the glass can fail and the pressure wave then enters the building, causing damage. Furthermore, projection of glass fragments at high speeds can cause injuries. Laminated glass is often employed to avoid such effects. In protective design, three factors must be considered. Firstly, the laminated glass pane must be able to absorb the pressure pulse by its deformation. Secondly, the pane must stay in its frame and not detach from it. Finally the frame and its fixing must survive. All requirements are important. This paper addresses the first requirement.

As with most polymers, PVB's mechanical response is temperature dependant [1,2]. In some climates across the globe, air temperatures can reach up to 50 °C and surface temperatures can exceed this value. This has various effects on the material properties of the interlayer, hence affecting its blast performance. This study aims to shed light on this issue.

The through-cracked tensile test is a testing method which has been used by various authors to characterise the post-crack behaviour of laminated glass. In this test, originally called the 'tension adhesion test', the laminated glass is scored normal to the loading direction, creating a coincident single crack on both sides and tested in tension. This test had originally been carried out in 1996 by Sha et al. [3] to characterise the adhesion between the glass and the PVB interlayer. They developed this method as they believed it had advantages over the peel and pummel tests which are commonly used to assess adhesion levels.

Similarly, single cracked tensile tests were later used in 2000 by Seshadri et al. [4] to assess the mechanical behaviour of cracked laminated glass. They stated that if the material constitutive model is known, the interfacial fracture toughness and energy release rate can be calculated from the tensile tests on cracked laminates. The outcome of their work was the calculation of the energy dissipated in delamination of the interlayer.

Seshadri et al. [5] later extended their work by developing a finite element model which would allow analysis of more complex geometries other than the tensile specimens they tested; assuming a hyperelastic material model. This model predicts the behaviour of laminated glass as a function of geometry, interlayer properties and number of glass fragments. Delince et al. [6] continued the work of Seshadri, but they could not reproduce the results of Seshadri. They proposed that this was because their test specimens spent a very short time in the steady state.

In extension to the single crack tests, Hooper et al. [7] conducted tests with multiple parallel cracks normal to the loading direction at different spacings. They then used a rate dependent Johnson-Cook plasticity model to characterise the stress-strain post-crack response of laminated glass. Hooper [8] also conducted random cracked tests, in which the laminated samples were randomly cracked and tested

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in tension. Del Linz et al. [9] also looked at delamination of the PVB interlayer in single cracked tensile tests and compared experimental data with a finite element model.

In the literature, the work on temperature dependency of laminated glass is very limited. Bermbach et al. [10] have conducted shock tube experiments at 13 °C and 30 °C. They concluded that at 30 °C, greater strain and strain rate are observed than 13 °C. Hooper et al. [2] conducted DMA (dynamic mechanical analysis) tests on PVB alone and they reported that below 5–10 °C the material behaves glassy. Above this temperature, it goes into transition and finally it behaves rubbery above 40 °C.

From the literature, there is a clear gap in understanding the post-crack behaviour of laminated glass in the higher temperature range. The present study investigates this at a range of temperatures from 0 °C to 60 °C. Single cracked and random cracked tests were carried out for three different PVB interlayer thicknesses. These tests were carried out at a high rate of 1 m/s. As an example, in the delaminated PVB ligament at room temperature, this corresponds to an approximate strain rate of 21 s^{-1} for the 0.76 mm interlayer in the steady state region (it should be noted that the initial strain rate in the test is greater than this and it also varies during the test). This is a representative order of magnitude of the strain rate which the laminated glass experiences, under blast loading. Hooper conducted blast tests and reported that on the edges of the pane, where strain is highest, strain rates can reach up to 20–25 s^{-1} [8]. Bermbach et al. also conducted shock tube tests at which strain rates were reported to reach up to 19 s^{-1} on the laminated glass panel [10].

The outline of this paper is as follows. The specimen geometry and test matrix are given, and the experimental setup is described. This is followed by the presentation of the results for the single and random cracked tensile tests on laminated glass. Finally a discussion is made on the behaviour of the laminate at different temperatures and interlayer thicknesses depending of stiffness and adhesion.

2. Materials and methods

2.1. Test specimens

The experiments were carried out on laminated glass samples comprising of three different PVB interlayer thicknesses, namely, 0.76 mm, 1.52 mm and 2.28 mm. These interlayers were laminated with 3 mm annealed glass on each side. The sample length was 150 mm and the width was 60 mm. The specimens were prepared using a standard lamination procedure by a commercial company (Kite Glass). The PVB used in the laminate was sourced from Everlam.

To enable the gripping of the sample by the machine, aluminium tabs were bonded to the laminated glass using an adhesive (Araldite 2021). Prior to bonding, the aluminium tabs and the gripping ends of the glass were grit blasted; followed by cleaning of the surface with acetone.

The single cracks were prepared using a tool designed at Imperial College. The laminated glass samples were scored on each side, followed by a gentle tap over the crack with a light ball hammer. This propagated the crack on the opposite side of the hammer tap. This procedure was repeated on the opposite side of the glass, thus, enabling a coincident crack to form on either side of the glass. Figs. 1 and 2 display a schematic of the single crack and random crack samples.

The random cracked specimens are closer to what the laminated pane experiences under blast loading. They were prepared using a ball hammer by forming random cracks on the laminated glass sample. The location of the hammer impact and number of hits were kept almost the same between subsequent samples, such that the size of the fragments produced were approximately 5–10 mm.

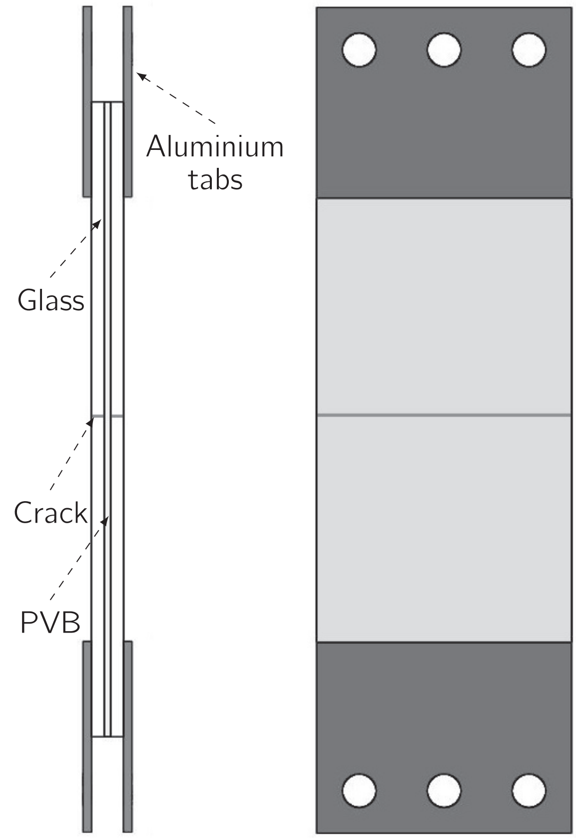

Fig. 1. Single cracked test specimen.

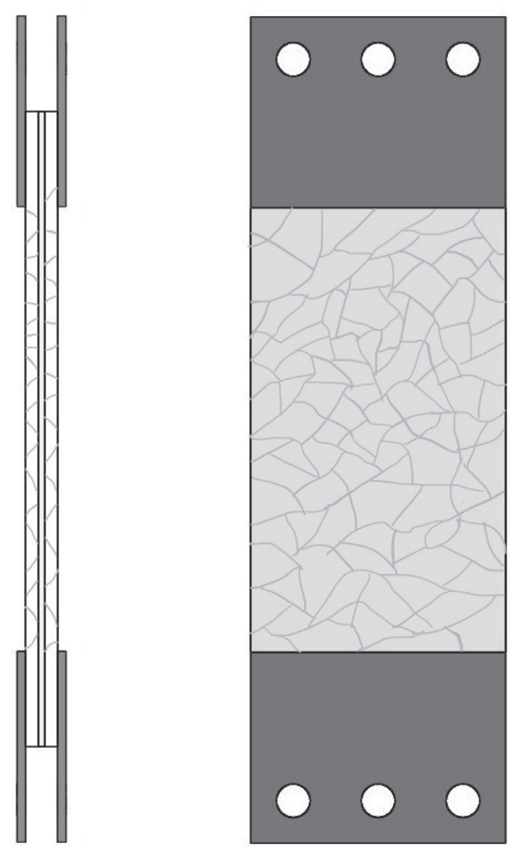

Fig. 2. Random cracked test specimen.