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GLAZED FACADES UNDER BLAST LOADING: AN INVESTIGATION OF THE POST-FRACTURE RESPONSE OF LAMINATED GLASS UNDER HIGH STRAIN-RATES

S.C. ANGELIDES* and J.P. TALBOT

Department of Engineering, University of Cambridge, Cambridge, UK
Emails: sca36@cam.ac.uk
*Corresponding author

Abstract. *Laminated glass panels are often recommended for enhancing the blast resilience of commercial and residential buildings that are considered to be at risk as potential terrorist targets. Compared to monolithic glazing, these panels reduce glass-related injuries, as glass fragments remain attached to the polymer interlayer, and improve the residual post-fracture capacity due to the ductile response of the interlayer. The post-fracture blast response of these panels is still only partially understood, with an evident knowledge gap between the fundamental behaviour at material level and the response observed in full-scale blast tests. To help bridge this knowledge gap, this paper presents a small-scale experimental procedure that assesses the post-fracture response of laminated glass beams under the high strain-rates associated with blast loading and the in-plane restraint offered by blast resistant frames. The proposed research uncouples the inertia effects that are traditionally embedded in dynamic bending tests, to focus solely on the effects of high strain-rate and in-plane restraint. In these tests, high strain-rates are simulated with low temperatures by exploiting the time-temperature dependency of polymers and extending its application to poly vinyl butyral, the most common laminated glass interlayer used in building facades.*

Keywords: *Laminated glass; Blast; Post-fracture response; High strain-rates;*

1. INTRODUCTION

As the threat of terrorism continues to grow in scope and scale, counter-terrorist measures are now being implemented as standard in the design of buildings and infrastructure projects. As a result, it is often recommended that the glazed facades of commercial and residential buildings, which constitute the first barrier of defence in a blast event, include laminated glass panels. This composite material, consisting of multiple glass layers laminated with a ductile interlayer, enhances the blast resilience of buildings compared to monolithic glazing. This is due to the improved residual capacity offered by laminated glass, which provides resistance to the blast wave after the glass layers have fractured, as opposed to monolithic glazing which fails in a sudden, brittle manner. In addition, the broken pieces of glass remain attached to the interlayer of laminated glass panels, reducing the risk of injuries from fragmentation.

The most common laminated glass interlayer used in buildings facades is poly vinyl butyral (PVB). This thermoplastic polymer was first established by the automotive industry in the 1950s. Due to its ability to block UV radiation, its high strain to failure and its good adhesion properties, which enable it to retain glass fragments following the fracture of the glass layers, PVB was later also adopted by the construction industry in the 1970s. Lamination of the glass layers (typically, annealed, heat-strengthened or toughened glazing products) and the PVB is a

3-stage process, as shown in Figure 1. First, the laminated glass panels are assembled in a temperature-controlled room by placing multiple PVB sheets, of 0.38mm thickness each, between the glass layers and cutting the excess interlayer (Figure 1a). The assembled composite material is then passed through an oven (at approximately 70˚ C) and between rollers to form the initial bond (Figure 1b). Finally, it is placed in an autoclave (Figure 1c) under high temperature (approximately 140˚ C) and pressure (800 kPa) to form the final product (O'Regan, 2015).

Figure 1. Lamination process for PVB laminated glass panels: a) assembly of composite panel, b) passing through oven and rollers to form initial bond and c) placement in autoclave to form the final product (Courtesy of Romvos Glass S.A.).

Thermoplastic polyurethane (TPU) and ethyl vinyl acetate (EVA) are alternative polymer interlayers for laminated glass panels. The former is frequently used in trains and aircraft due to its high impact resistance, resulting from its ability to attach polycarbonate to the glass layers. More recently, ionoplast interlayer materials have also been developed, such as SentryGlas Plus, with the aim of improving the stiffness and tensile strength of PVB. Although, both the thermoplastic elastomers and the ionoplasts are stiffer and stronger compared to PVB, they are more expensive and therefore less frequently used in the construction industry (O'Regan, 2015). The focus of this paper is therefore laminated glass with PVB, as this is the most common interlayer used in buildings facades.

The aim of this paper is to enhance our understanding of the blast response of laminated glass. Much of the theoretical research on this topic has concentrated on reproducing the experimentally recorded (centre of panel), peak-displacements of laminated glass panels from blast tests, whether this is by finite-element analysis (Hooper, 2011; Larcher et al., 2012; Hidallana-Gamage, 2015; Zhang and Hao, 2015; Pelfrene et al., 2016), analytical solutions (Yuan et al., 2017; Del Linz et al., 2018) or equivalent single-degree-of-freedom methods (Special Services Group, Explosion Protection, 1997; Applied Research Associates, Inc, 2010; Morison, 2007; Smith and Cormie, 2009).

An alternative, theoretical, first-principles approach was considered by Angelides et al. (2019) that breaks down the complex blast response of laminated glass to evaluate independently the effects of the high strain-rate associated with blast loading and the in-plane restraint offered by blast resistant frames. The effects of two-way spanning plate action and inertia loading are therefore uncoupled from the structural response. The objective of this paper is to present an experimental program that can validate this theoretical approach. Most high strain-rate bending tests are performed with a Split Hopkinson Pressure Bar (SHPB) that also results in inertia loading. An experimental technique is therefore proposed in this paper that simulates the effects of high strain-rate with low temperatures, due to the time-temperature dependency of PVB, and thereby avoids any inertia loading.

2. TIME-TEMPERATURE MAPPING FOR PVB

PVB is an amorphous thermoplastic polymer (Olabisi and Adewale, 2015). Its glass transition temperature is approximately 20˚C, resulting in a transitional, glassy-rubbery material behaviour at room temperature and low strain-rates (Hooper, 2011). This value varies depending on the manufacturer, with many different interlayer products currently available for laminated glass panels, including Butacite (from Du Pont), Saflex (from Eastman), Butvar (from Eastman) and Trofisol (from Kuraray). At lower temperatures or higher strain-rates, the PVB transitions to a glassy state, resulting in a stiffer structural response, while at higher temperatures and low strain-rates a softer response occurs due to its rubbery material state (Hooper, 2011).

The above viscoelastic response of PVB can be derived from a Dynamic Mechanical Analysis (DMA), which is performed by imposing a cycling stress on a sample and measuring the corresponding strain response (Menczel and Prime, 2009). Such analyses have been performed by Hooper (2011), Liu et al. (2014) and Pelayo et al. (2017). Alternatively, the mechanical properties of PVB can be recorded through tensile tests at various temperatures and strain-rates. Chen et al. (2018) have performed numerous tensile tests on Butacite PVB at strain-rates ranging from 0.1 s^{-1} to 300 s^{-1} at four different temperatures: -30˚C, -5˚C, 25˚C and 40˚C.

Figure 2 shows the recorded yield stress values from Chen et al. (2018), now plotted against the logarithm ($\log_{10}$) of strain-rate. It should be noted that the yield value refers to the change in stiffness observed in the stress-strain diagram and not to true plasticity (Angelides et al., 2019). A bilinear relationship that transitions to a steeper slope at high strain-rates is observed in Figure 2 at all temperatures. This conforms to the conclusions of Walley et al. (1989) for polymers in general.

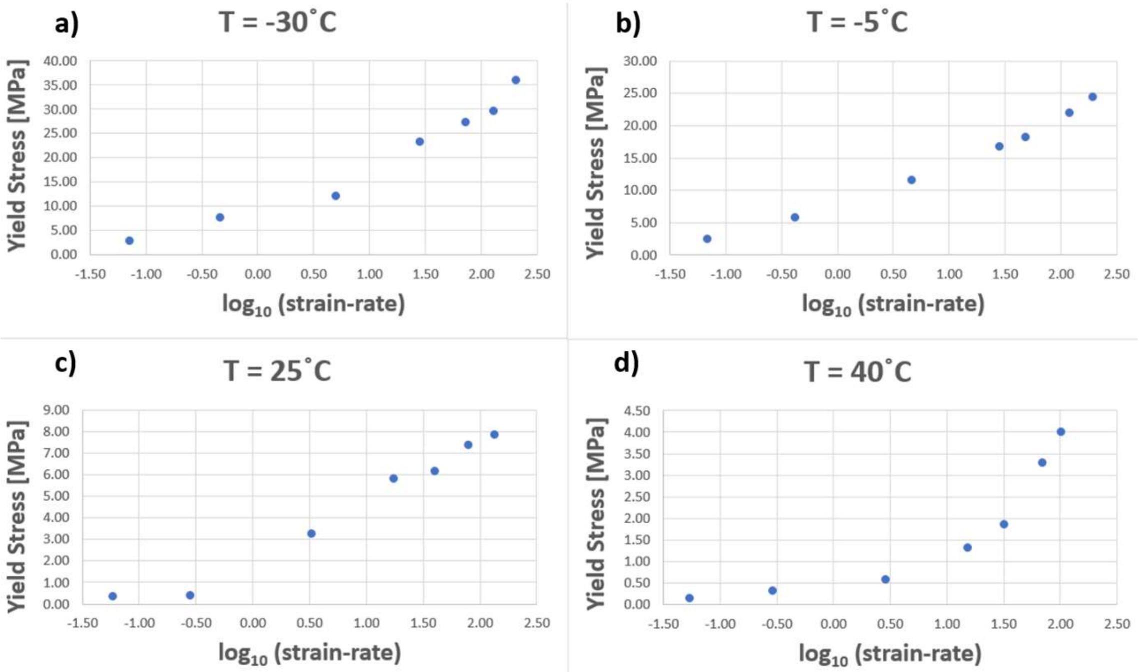

Figure 2. Plots of yield stress against strain-rate for PVB, as recorded by Chen et al. (2018) at different temperatures: a) T = -30˚C, b) T = -5˚C, c) T = 25˚C and d) T = 40˚C.

To quantify the time-temperature dependency evident in Figure 2, the yield stress values recorded at 25˚C may be compared with yield values recorded at -30˚C, -5˚C and 40˚C but now 'mapped' to 25˚C. This mapping is similar to that performed by Siviour et al. (2005) on polycarbonate and polyvinylidene difluoride:

$$\mathrm{T}' = \mathrm{T} + \lambda(\log_{10}(\dot{\varepsilon}) - \log_{10}(\dot{\varepsilon}')) \tag{1}$$

where T and $\dot{\varepsilon}$ are the temperature and strain-rate respectively, corresponding to a measured yield stress data point, while T' is the mapped temperature of the same yield stress value corresponding to a strain-rate value of $\dot{\varepsilon}'$. The constant in the mapping equation, λ, is defined by considering two measured data points with the same yield stress ($\sigma_{y,A} = \sigma_{y,B}$) at different temperatures ($\mathrm{T_A}, \mathrm{T_B}$) and strain-rates ($\dot{\varepsilon}_A, \dot{\varepsilon}_B$):

$$\sigma_{y,A}(\mathrm{T_A},\ \dot{\varepsilon}_A) = \sigma_{y,B}(\mathrm{T_B},\ \dot{\varepsilon}_B) \ \Rightarrow \ \lambda = \frac{\mathrm{T_A} - \mathrm{T_B}}{\log(\dot{\varepsilon}_B) - \log(\dot{\varepsilon}_A)} \tag{2}$$

The comparison of the measured and mapped yield values, using a mapping constant value of $\lambda = -18$, is presented in Figure 3. A good agreement is observed between measured and mapped values, with some small discrepancies noted at higher strain-rates. These could be attributed to the reliability of the yield stress values at high strain-rates: Chen et al. (2018) repeated each measurement three times, for each actuator speed (strain rate) considered, and it is evident that higher speeds result in greater experimental variability. Nevertheless, a bilinear relationship that transitions to a steeper slope at high strain-rates, similar to Figure 2, is also observed for the combined mapped and measured points plotted in Figure 3. It is therefore concluded that time-temperature mapping offers a promising means of simulating the effects of high strain-rate.

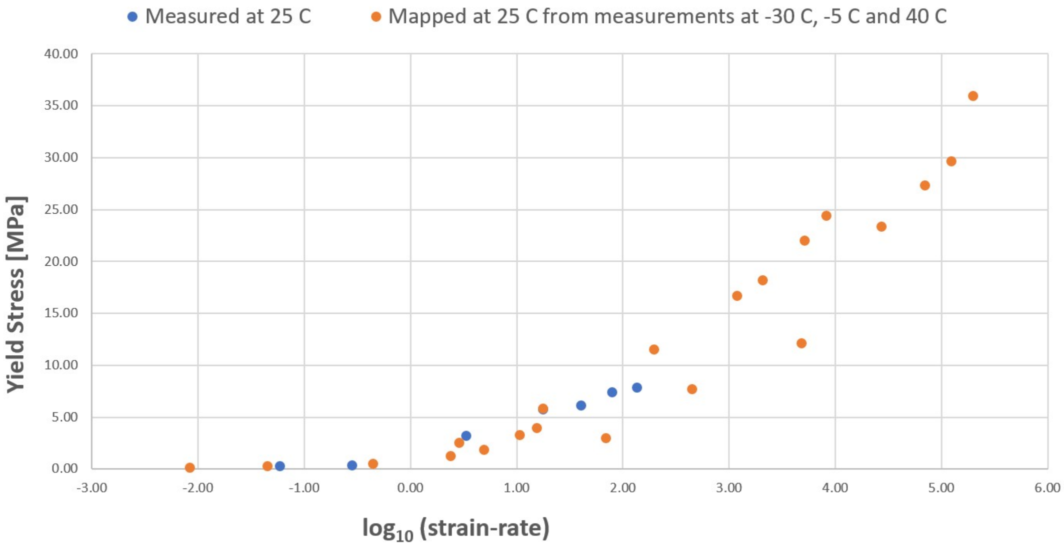

Figure 3. Comparison of the variation of yield stress with strain-rate, as recorded experimentally by Chen et al. (2018) at 25˚ C, and the variation of yield stress with temperature mapped onto strain-rate.

3. BENDING TESTS OF FRACTURED LAMINATED GLASS WITH SIMULATED HIGH STRAIN-RATES

The post-fracture response of laminated glass at room temperature and low strain-rates has been experimentally investigated by Kott and Vogel (2003, 2004 and 2007) with four-point bending tests, as shown in Figure 4. These tests concluded that the residual, post-fracture capacity is negligible. This is not believed to be the case for high strain-rates, due to the enhanced shear modulus of PVB, as demonstrated theoretically by Angelides et al. (2019). There is a need, however, for this theoretical work to be validated experimentally.

This section presents an experimental procedure that simulates the high strain-rates associated with blast loading with low temperatures, based on the time-temperature dependency of PVB discussed in Section 2.

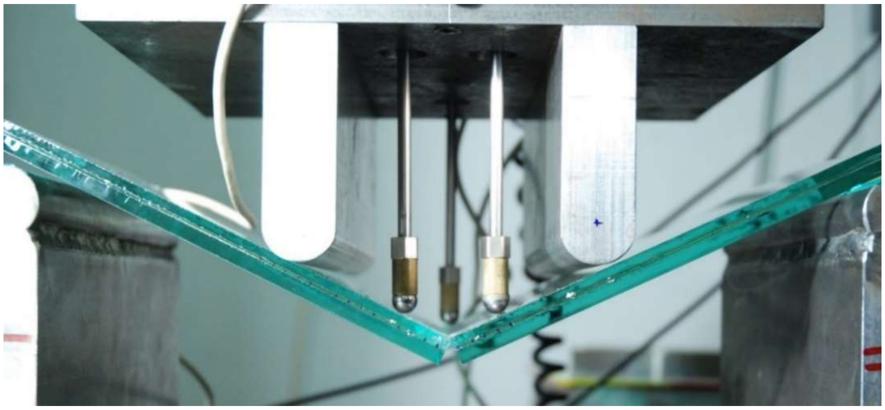

Figure 4. Four-point bending test of a simply-supported laminated glass beam under low strain-rates at room temperature (Gordon-Smith, 2009).

The proposed experiments will be performed in Cambridge University Engineering Department using the Schenck Hydropuls PSA testing facility, together with an environmental chamber, as shown in Figure 5a. This testing machine is traditionally used for axial fatigue testing with a maximum loading rate of $1\,{}^{\mathrm{m}}/_{\mathrm{s}}$ but bending tests can also be performed by inserting a four (or three)-point bending test rig inside the environmental chamber, as shown in Figure 5b. An alternative rig, with axial restraints, will also be used to evaluate combined bending and membrane action. The maximum load capacity is 10kN and the displacement can be measured from the movement of the piston at the bottom. The width of the environmental chamber, W = 240mm, dictates the maximum allowed length for the tested specimen. Cold temperatures up to -196 ˚C can be applied in the environmental chamber using liquid nitrogen.

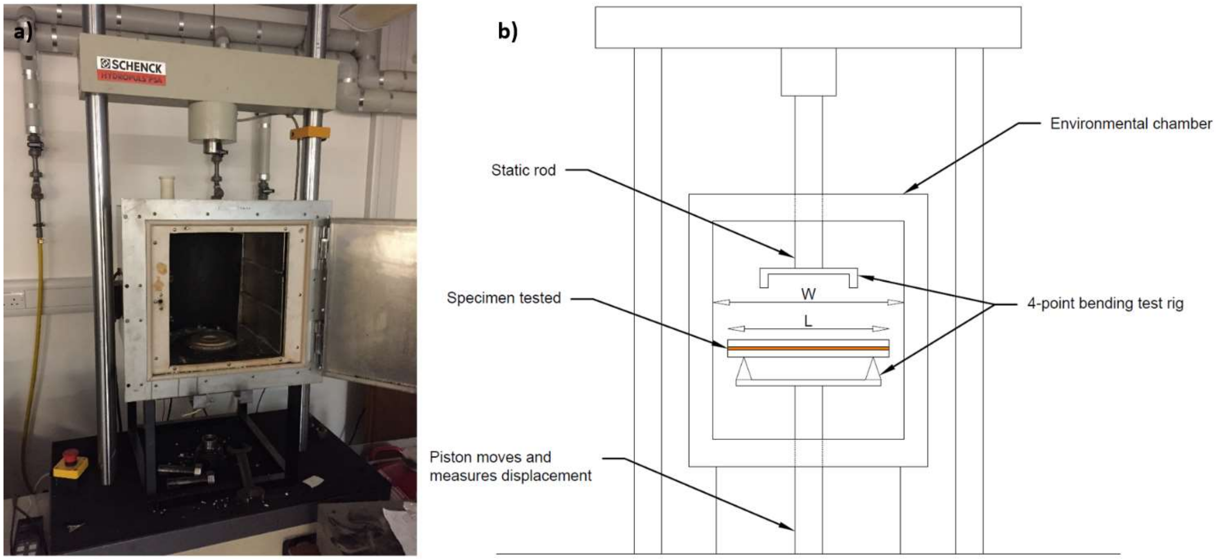

Figure 5. a) The Schenck Hydropuls PSA testing facility, b) sketch of proposed four-point bending tests at low temperatures.

The experimental investigation will test pre-fractured laminated glass specimens with length L = 200mm and width B = 50mm. The specimens will be composed of two annealed glass layers of thickness t_g = 6 mm, each and a single PVB interlayer with thickness t_{pvb}= 1.52 mm. Three different fracture patterns will be considered. First, specimens with a single fracture at the midspan of both glass layers, as shown in Figure 6a, will be tested for simplicity, representing a theoretical case. The second and third fracture patterns include multiple glass fragments, uniform (L_f = 10mm glass fragments size) and random, simulating the failure pattern observed from blast tests (Figure 6b). The specimens with single and uniform cracks will be pre-fractured by first scoring the glass layers, while the random fracture pattern will be achieved by impacting the specimens with a ball hammer. Similar methods for pre-fracturing laminated glass specimens have been described by Nhamoinesu & Overend (2010), Hooper (2011) and Samieian et al. (2018).

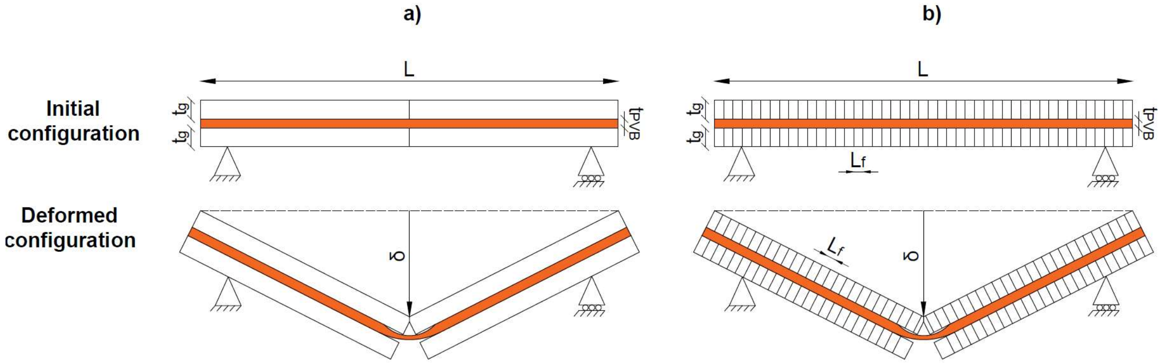

Figure 6. Anticipated response of simply-supported laminated glass beams from four-point bending tests under simulated high strain-rates with low temperatures: a) single crack, b) multiple glass fragments.

Morison (2007) presented full-scale blast tests performed at 20˚C and reported mean strain-rates ranging from 7.6 s^{-1} to 17.5 s^{-1} in fractured, laminated glass panels. To simulate these high strain-rates, the pre-fractured laminated glass specimens will be tested at low temperatures ranging from -50˚C to -60˚C and a strain rate of $0.001s^{-1}$, according to the time-temperature mapping derived in Section 2. It should be noted, however, that the enhanced crushing strength of the glass fragments resulting from high strain-rates under blast loading will not be captured in these simulated experiments. This should result in a lower residual post-fracture moment capacity compared to the theoretical models developed by Angelides et al. (2019).

Another drawback of the proposed experimental work is the stronger adhesive bond between the glass layers and the PVB at low temperatures, as reported by Samieian et al. (2018), who performed high strain-rate tensile tests on pre-fractured laminated glass panels at various temperatures. This prevents the delamination of the attached glass fragments and causes brittle failure of the PVB. This, however, is not expected to affect the proposed experimental work to assess the post-fracture bending moment capacity, as instantaneous failure is likely to occur for the simply-supported specimens tested only when the first plastic hinge forms. The true failure load that causes interlayer tearing under combined bending and membrane strains for axially restrained beams will indeed be affected by the brittle post-yield behaviour of fractured laminated glass at low temperatures. Nevertheless, the yield condition developed by Angelides et al. (2019) to assess the relative contribution of bending and membrane action may still be validated with these simulated experiments.

5. CONCLUSIONS

This paper has presented an experimental procedure to validate the post-fracture response of laminated glass beams with PVB, subjected to the high strain-rates associated with blast loading and the in-plane restraint from blast resistant frames. In contrast to Hopkinson Bar tests, traditionally performed to assess the bending response of materials under high strain-rates, an experimental procedure has been presented that uncouples the strain and inertia effects by simulating high strain-rates with low temperatures. These simulations can be performed due to the time-temperature dependency of polymers, which has been demonstrated here for PVB using existing tensile test data recorded at various temperatures. Limitations of the proposed procedure include a stronger, adhesive bond and a lower, glass crushing strength compared to the properties of laminated glass at room temperature. Nevertheless, the procedure is expected to provide valuable insight into the links between the fundamental, material behaviour of laminated glass panels and their response under full-scale blast loading.

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