BLAST RESILIENCE OF GLAZED FAÇADES: TOWARDS A NEW UNDERSTANDING OF POST-FRACTURE BEHAVIOUR OF LAMINATED GLASS

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ABSTRACT

The engineering of all future cities should aim for robust buildings to protect occupants from explosion threats. However, the design of glazed façades, which constitute the first barrier of defence in a blast event, remains a significant challenge in the achievement of blast-resilient buildings. Uncertainty remains over the post-fracture behaviour of laminated glass under blast, particularly concerning the significance of bending versus membrane action, and the applicability of plastic theory. Laminated glass panels, also known as security glazing, are often included as the cladding material in the façades of commercial and residential buildings, to improve on the post-fracture capacity of monolithic glazing and prevent glass-related injuries. The structural assessment of the post-fracture capacity of laminated glass panels under blast is a complex, multi-disciplinary topic, which often requires expensive, full-scale blast testing to be performed. This research project aims for a better understanding of the fundamental material behaviour of laminated glass under the high strain-rates associated with blast, through a cost-effective experimental programme. The objective is to develop new models that properly account for both the post-fracture bending and membrane action of laminated glass, and establish the extent to which plastic theory holds. Previous full-scale blast tests on laminated glass panels have resulted in a repeated failure pattern that resembles a yield-line mechanism formed from travelling plastic hinges arising from the combined effect of the attached glass fragments in compression and the interlayer in tension. A theoretical framework has therefore been developed for the post-fracture behaviour of laminated glass panels, with a view to improving on current analysis methods (finite-element analysis and equivalent single-degree-of-freedom models). The hope is that practicing engineers will benefit from a more efficient design method that utilises the full capacity of the material.

NOMENCLATURE

ANFO: Ammonium nitrate and fuel oil
B: Width of laminated glass
D_p: Diameter of projectile
I: Impulse of pulse
L: Length of laminated glass
L_p: Length of projectile
p: Pressure of pulse
p_c: Static collapse pressure
p_0: Pressure magnitude of pulse
PVB: Polyvinyl Butyral
RTV: Room temperature vulcanised
t: Time
t_d: Time duration of pulse
t_g: Thickness of glass layers
t_{PVB}: Thickness of interlayer
T_N: Natural period
V: Mid-span velocity of laminated glass
v_p: Velocity of projectile
$\varepsilon_{D,p}$: Densification strain of projectile
ρ_p: Density of projectile
$\sigma_{y,p}$: Yield strength of projectile

1. INTRODUCTION

Large pressures from blast waves and wind can cause damage to structures and harm humans. In petrochemical facilities, the structures are designed to resist blast loads, due to the presence of hydrocarbon products that can ignite and lead to vapour cloud explosions. The requirement for blast resilient structures has recently extended also to commercial and residential buildings due to the increased threat from terrorist attacks. In these events, high-explosives, which are manufactured from readily available chemicals, such as ammonium nitrate and fuel oil (ANFO), are detonated to produce shock waves and blast wind.

Building facades constitute the first barrier of defence against these blast loads. As a result, monolithic glazing, which is a brittle material and has no reserve capacity beyond fracture, is often replaced with laminated glass panels to enhance the blast resilience of buildings. These composite panels consist of two glass layers and an interlayer, as shown in Figure 1. The most common interlayer material used in building facades is Polyvinyl Butyral (PVB), a thermoplastic polymer that was first established by the automotive industry in the 1950s. The lamination process requires passing the laminate of glass layers and PVB through an oven and then rollers, to form the initial bond (Figure 2a), before curing in an autoclave to form the final product (Figure 2b). PVB is a ductile viscoelastic material that provides resistance to blast loads following the fracture of the glass layers. Additionally, it also tends to retain the glass fragments, thus reducing glass-related injuries from the fragmentation of glass shards [1].

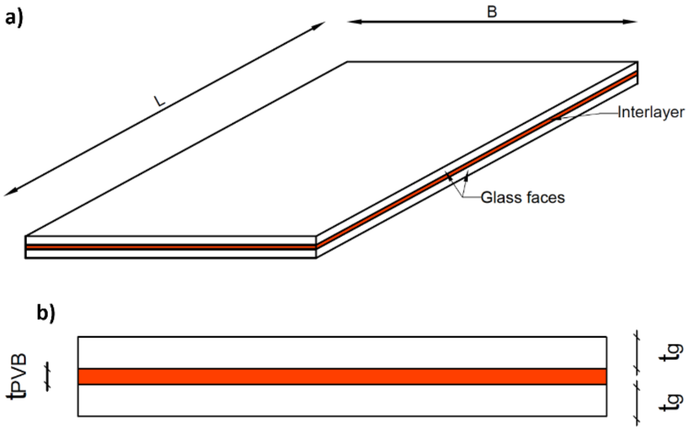
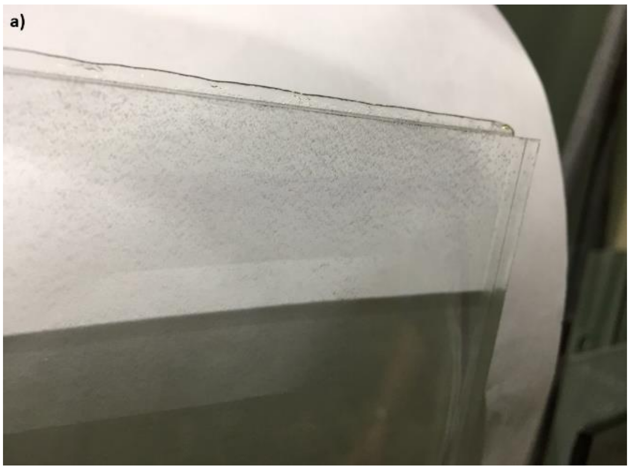


Figure 1: Sketch of laminated glass panels a) Geometry, b) Cross-section.

A literature review [2-12] has indicated that most structural analysis methods (equivalent single-degree-of-freedom methods, analytical solutions and finite-element analysis) ignore the bending response of fractured laminated glass panels and only consider a membrane behaviour of the interlayer in the post-fracture stage. However, quasi-static bending tests have demonstrated that fractured laminated glass panels possess a residual post-fracture bending capacity from the combined action of the attached glass fragments and the interlayer, which increases with stiffer interlayers [13-14]. A higher bending capacity is therefore anticipated under short duration blast loads, due to the strain-rate dependence of the viscoelastic PVB.

The hypothesis of combined bending and membrane response of fractured laminated glass panels is also reinforced by the failure pattern reported in multiple blast tests [2, 15, 16]. A sketch of the common failure pattern observed is provided in Figure 3. This failure pattern suggests the formation of yield lines caused by bending of the fractured laminated glass panels. The yield line mechanism is different to the observed response of ductile plates under static loading, such as reinforced concrete slabs. It is understood, that this different mechanism is due to inertia effects resulting from the high loading intensity under blast, which is more than three times the static collapse pressure ($p > 3p_c$). A temporary collapse mechanism is therefore formed during the application of the loading that transforms with travelling plastic hinges to the static collapse mechanism when the pulse has completely decayed [17].



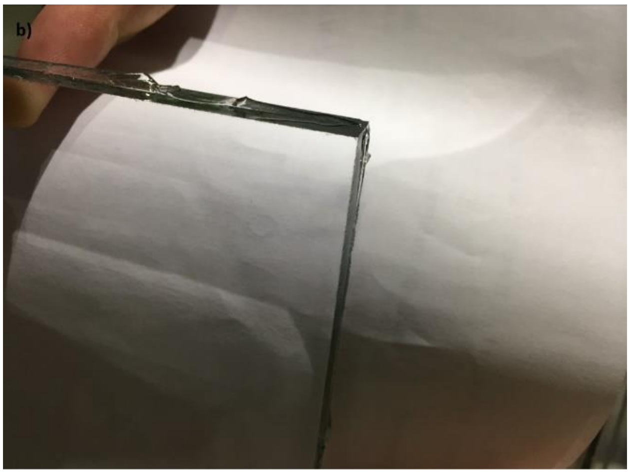


Figure 2: Lamination process for PVB laminated glass a) after passing through an oven and rollers, and b) after curing in an autoclave (Courtesy of Romvos Glass S.A.).

Further experimental examination to investigate the post-fracture bending capacity of laminated glass will subsequently improve the currently available structural analysis methods that consider a pure membrane analysis. In this paper, therefore, an experimental programme is proposed that uses foam projectiles launched from a gas gun to simulate blast loading and assess the post-fracture bending capacity of laminated glass panels.

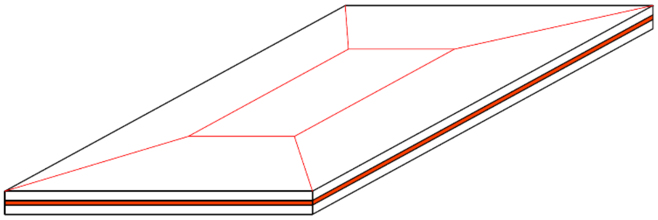


Figure 3: Failure pattern observed in blast tests of laminated glass panels

2. FOAM PROJECTILES LAUNCHED FROM A GAS GUN TO SIMULATE BLAST LOADING

The pure bending capacity of fractured laminated glass panels has only been experimentally examined under pseudo-static loading [18-20]. Under dynamic loading, the nature of the structural response (e.g. travelling plastic hinges) and the material behaviour (e.g. stiffer PVB response under high-strain rates) is fundamentally different. Previous blast experiments have measured the mid-span deflection time-history of laminated glass panels under combined bending and membrane response, without uncoupling the individual contributions.

2.1 MOTIVATION

Pseudo-static bending tests, which are performed at low strain-rates, are not considered appropriate to assess the bending capacity of laminated glass under blast events. On the other hand, full-scale blast tests performed with high-explosive detonations are expensive and therefore unsuitable for assessing multiple glass specimens. An alternative experimental method has been developed in Cambridge University Engineering Department that simulates blast loading using a soft impact generated by launching metal foam projectiles from a gas gun. This experimental method has been used for the blast assessment of sandwich structures [21-29]. The use of the gas gun results in high strain-rates, characteristic of blast events, that should ensure the viscoelastic response of the PVB interlayer is accurately captured. The method is significantly cheaper than full-scale high-explosive detonation tests, and therefore more suitable for examining in detail the material behaviour of laminated glass, via a systematic and controlled series of tests.

Shock tube testing is also considered a suitable experimental method for the post-fracture bending capacity assessment of laminated glass panels under blast loading. However, this is considered better suited to the later stages of larger scale testing.

2.2 MECHANICS OF SOFT IMPACT TESTS

The response of a solid projectile during impact with a target can be categorised into five different physical regimes depending on the impact velocity: a) elastic, b) plastic, c) hydrodynamic, d) sonic and e) explosive [30]. In the plastic regime, metallic foam projectiles, such as aluminium foam, impacting on a rigid target generate an approximately rectangular pressure pulse (time-history) on the target, as shown in Figure 4. The peak pressure (p_0), time duration (t_d) and impulse (I) of the rectangular pulse depend on the projectile yield strength ($\sigma_{y,p}$), density (ρ_p), densification strain ($\varepsilon_{D,p}$), velocity (v_p) and length (L_p), as shown in Table 1 [31]. The geometry of a cylindrical metallic foam projectile is provided in Figure 5. The use of a polymer foam is also considered a suitable material for projectiles impacting targets with a low strength, and provides a cheaper alternative to metallic foams. However, this remains to be confirmed in practice.

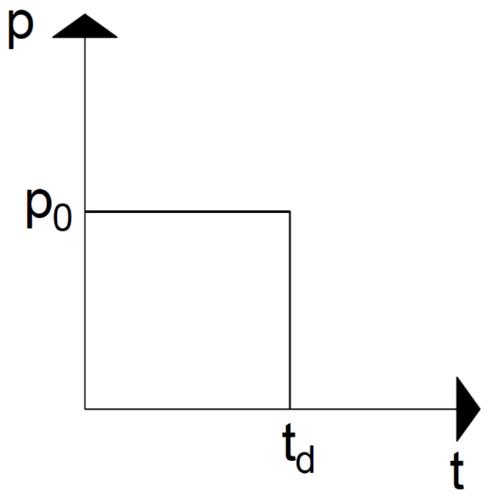


Figure 4: Pressure time-history of rectangular pulse

Table 1: Properties of pulse generated from foam projectiles

Pulse property	Equation
Pressure of pulse	$p(t) = \begin{cases} p_0, & t < t_d \\ 0, & t \geq t_d \end{cases}$
Peak-pressure of pulse	$p_0 = \sigma_{y,p} + \frac{\rho_p (v_p)^2}{\varepsilon_{D,p}}$
Time duration of pulse	$t_d = \frac{L_p \varepsilon_{D,p}}{v_p}$
Impulse of pulse	$I = \rho_p L_p v_p$

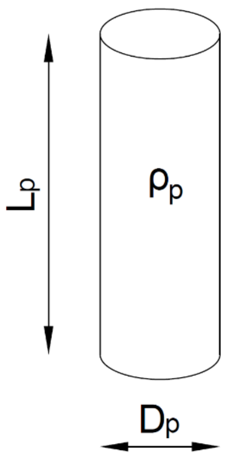


Figure 5: Sketch of foam projectile geometry

3. PROPOSED EXPERIMENTAL WORK

Foam projectiles launched from a gas gun are proposed in this paper to assess the post-fracture blast response of laminated glass, as shown in the sketch of Figure 6. The rectangular pulse generated from the soft impact of the foam on the laminated glass can be considered an approximation of the positive phase of a shock wave resulting from the detonation of high-explosives, which has an approximately triangular pulse shape. The negative phase of blast loading is therefore neglected in these experiments. Also, during any plastic response of the panel, the rectangular pulse is expected to result in plastic hinges travelling when the loading has completely decayed, in contrast to the triangular pulse, where the travelling of the hinges occurs immediately [32]. Nevertheless, the understanding of the simpler post-fracture response of laminated glass to a short-duration rectangular pulse is fundamental and can yield important conclusions for the more complex response to triangular pulses. Additionally, the properties of the rectangular pulse provided in Table 1 were derived for impact on a rigid target, however, good agreement was demonstrated in experimental work performed on sandwich beams [21-29]. Gas gun experiments on laminated glass targets have been previously performed, however, room temperature vulcanised (RTV) rubber projectiles within a hydrodynamic impact regime were considered to simulate bird impact on aircraft [33-35].

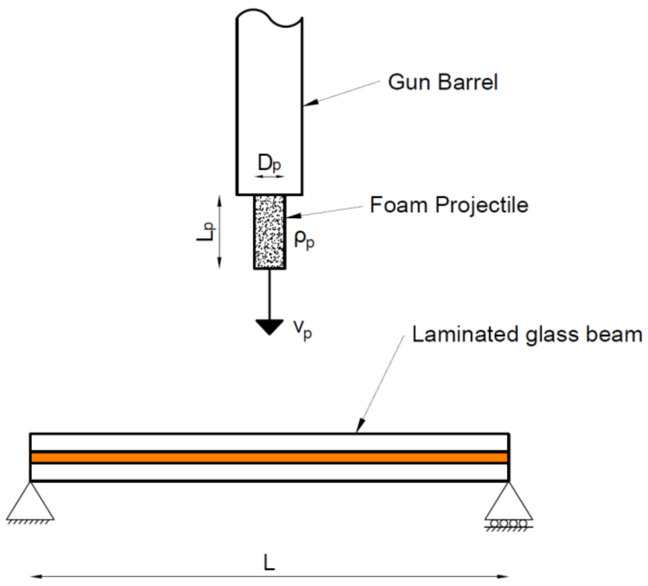
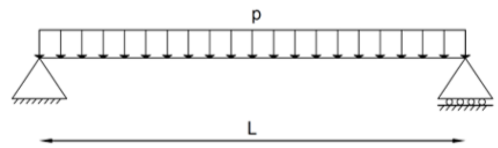
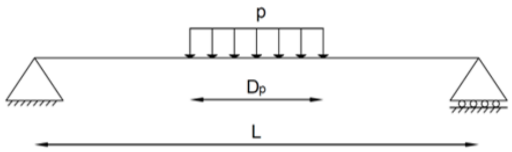
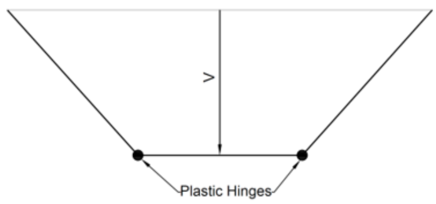
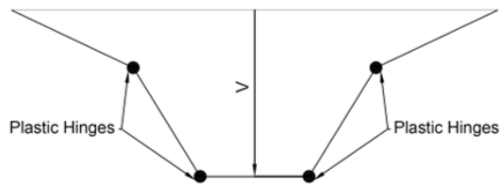
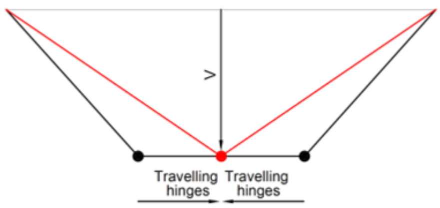
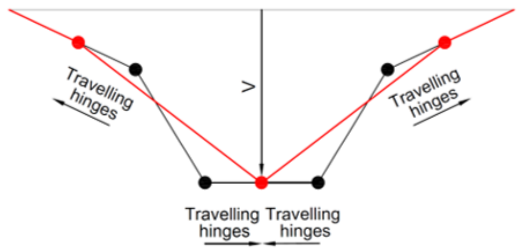


Figure 6: Sketch of foam projectile launched from the gas gun and impacting laminated glass specimen

3.1 TESTING OBJECTIVES

The objective of the experiments proposed is to investigate the bending capacity of fractured laminated glass beams. Pre-fractured laminated glass specimens will be tested to validate the dynamic rigid-plastic solutions for simply-supported beams presented in [17]. It should be noted, however, that these rigid-plastic solutions were developed for beams with uniform distributed loading. This will result in a slightly different collapse mechanism compared to the patch loading produced from the launched foam projectiles, as shown in Table 2, which is dictated by the diameter of the foam projectile (D_p). This is due to the different initial velocity distribution resulting from the patch loading, which requires an alternative velocity profile in order to satisfy the yield condition at all points along the length of the beam, as discussed in [36-3

Table 2: Velocity profiles for simply-supported rigid-plastic beams under uniformly distributed and patch loading

		Uniformly Distributed Load	**Patch Load**
Free-body diagrams			
Velocity profiles	$t \leq t_d$		
	$t > t_d$		

In addition to validating the dynamic rigid-plastic solutions developed in [17], these experiments will also be used to assess the effects of inertia loading and in-plane restraint, and the contribution of the pre-fracture stage. To assess the inertia effects, these experiments will be compared with quasi-static bending tests performed at low temperatures that simulate the effects of high-strain-rates uncoupled from inertia loading [38]. Additional tests using on axially restrained boundary conditions will also be performed, to assess the combined bending and membrane action under large-deflections and validate the yield condition derived in [39]. To restrain the edges, a metallic clamp will be used on both sides, similar to the experiments reported in [33]. To avoid contact with the glass specimen, and therefore potential damage, rubber gaskets of thickness 4mm will be used on both sides. In addition, a metallic spacer of 14mm will be used, resulting in a small pressure applied to the gaskets from the tightening of bolts, thus simulating pinned boundary conditions. Finally, the contribution of the pre-fracture stage can be evaluated by performing additional tests on intact samples and comparing the response with the pre-fractured samples.

3.2 SAMPLE PROPERTIES

To allow direct comparison and assess the inertia effects, the tested specimens will have the same dimensions as the low temperature quasi-static bending tests described in [38]. The properties of the tested laminated glass beams are provided in

Table 3. The laminated glass beams will be pre-fractured by first scoring the glass layers, similarly to the work described in [2, 40, 41], to form a uniform pattern with 10mm glass fragments. This simulates the fracture pattern in laminated glass panels observed from blast tests [2].

Table 3: Properties of laminated glass beams

Property	Value
Annealed glass layers thickness (t_g)	6mm
PVB thickness (t_{pvb})	1.52mm
Length (L)	200mm
Width (B)	50mm

3.3 PROJECTILE PROPERTIES

The proposed properties of the foam projectiles are provided in Table 4, based on the size of the glass specimens. The material properties ($\sigma_{y,p}$, $\varepsilon_{D,p}$, ρ_p) depend on the manufacturer; the values shown in Table 4 are for a particular Alporas Al alloy foam that was used in previous experimental work on sandwich beams [21-29]. The projectile velocity (v_p) is varied to achieve the required impulse (I), pressure (p_0) and time duration (t_d) of the rectangular pulse. The time duration of the pulse should be low compared to the natural period of the laminated glass (T_N) to ensure the structural response is in the impulsive regime. This will ensure the accuracy of the rigid-plastic solutions presented in [17].

Table 4: Properties of foam projectiles

Property	Value
Diameter (D_p)	28.5mm
Length (L_p)	30mm
Yield strength ($\sigma_{y,p}$)	$3\frac{N}{m^2}$
Densification strain ($\varepsilon_{D,p}$)	0.7
Density (ρ_p)	$300\frac{kg}{m^3}$

3.3 MEASUREMENTS

The displacement time-history will be measured using high-speed photography (Hadland Imacon-790 image-converter camera). The collapse mechanisms and the travelling hinges can be observed from the failure patterns of the laminated glass beams. The projectile velocity can be measured in two different ways, using the four laser diode velocity gates located at the end of the barrel and the high-speed camera.

4. CONCLUSIONS

Most structural analysis methods for the blast response of laminated glass panels consider a pure membrane response for the post-fracture stage. This, however, contrasts with the common failure pattern observed from blast tests, which suggests the formation of yield lines under bending. This is also reinforced from the small-scale quasi-static tests on laminated glass beams that have demonstrated the presence of a residual post-fracture bending capacity from the combined action of the attached glass fragments and the interlayer, which increases with stiffer interlayers. Considering that Polyvinyl Butyral, the most common interlayer in building facades, is a viscoelastic polymer that becomes stiffer under high strain-rates, an experimental programme is presented in this paper to assess the post-fracture bending capacity.

Simulated blast experiments with metal foam projectiles launched from a gas gun have been proposed to investigate the post-fracture capacity of laminated glass beams. These small-scale tests that have been previously used to assess the blast response of sandwich beams, are a more cost-effective alternative to full-scale high-explosive detonations. The mechanics of these soft impact tests, which produce a rectangular short-duration pulse, have been described in this paper and compared with the shock waves resulting from high-explosive detonations. Furthermore, the difference in the collapse mechanism of simply-supported beams resulting from a uniformly distributed load, anticipated under blast loading, and a patch loading, occurring from the foam projectile, has also been discussed. These tests are, therefore, considered suitable to assess the post-fracture response of laminated glass beams and validate available rigid-plastic solutions. Additionally, the individual contribution of inertia loading can be estimated through comparison with existing quasi-static low-temperature tests, while the effects of in-plane restraint can be evaluated with additional gas gun testing.

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