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Critical assessment of the post-breakage performance of blast loaded laminated glazing: Experiments and simulations

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A B S T R A C T

Glass windows are the most vulnerable building components when impacted by an air blast wave. For safety requirements, the customary choice for the window glazing is laminated glass, where two or more glass plies are bonded with a polymer interlayer to retain glass fragments upon breakage. With proper choice of interlayer material, the window can keep functioning as a shield to the blast wave even when fractured. Numerical simulation of the post-breakage response of a laminated glass panel can be a valuable tool for optimisation of the interlayer material and the glass panel configuration.

This article presents the results of a blast testing campaign for laminated glazing, according to a standardised procedure, and subsequent numerical simulation thereof. The experiments show that laminated glass using a soft polyvinyl-butyral (PVB) interlayer with low adhesion properties achieves the best safety performance at higher loads with no interlayer tearing, while still efficiently retaining glass fragments. The numerical simulation of these experiments attempts to capture the fracture and post-breakage behaviour of laminated glass under the blast load. In the finite element model, glass elements are deleted upon reaching a fracture criterion. The model can globally reproduce crack formation and post-fracture deformation, but lacks prediction of ultimate failure, mainly because of a strong dependency on the element size for both glass and interlayer parts.

1. Introduction

Blast waves present an extreme load case for any structure, and need to be considered during the design stage for constructions with higher risk of being subjected to an explosion. Because of catastrophes such as accidental gas explosions and terrorist attacks, safety against blast loading has become a qualification demand in the construction and in the automotive industry. The supporting structure of the building or vehicle needs to be able to withstand such events. When glass is used in these structures, the brittleness of the material presents a high risk for injury [1]. Especially in the building industry, the trend to light and filigree structures is challenging for the current standards in blast-safe window design. Laminated glass is the customary choice when safety towards glass fracture is required. It consists of two or more glass plies bonded together with a polymer interlayer to retain broken glass fragments.

In the fractured state, the mechanical behaviour of the remaining laminate depends mainly on the interlayer properties: deformation up to high strain levels and delamination, both at high strain rates. Investigations of PVB interlayers under high strain rates are published in Refs. [2–4]. This paper uses the data from earlier investigations at TU Darmstadt [5,6] because the same type of PVB was used for the test specimen in the shock tube experiments.

In all experiments it is observed that the mechanical behaviour of PVB strongly depends on the applied strain rate. At room temperature and under quasi-static loading, PVB behaves rubbery as its glass transition temperature is typically around 20 °C.

In accordance with the time–temperature superposition principle, PVB deformation at high strain rates is comparable to the glassy state observed for quasi-static testing at low temperatures. When the load is suddenly removed in a test at a high strain rate and room temperature, the material immediately returns close to its original shape in its rubbery state except for a small part which needs a longer period of time to relax [5].

Only few results of blast tests on laminated glass are found in literature since they are mostly assembled in confidential documents. Kranzer et al. [7] tested laminates of two 3 mm annealed glass plies and a 1.52 mm PVB interlayer according to EN 13541 [8]. Three small scale arena air-blast tests and one shock tube test were executed. Beside the incident and reflected pressures, the displacement at the centre of the panel was measured and high speed videos were recorded. Hooper et al. [9] conducted four arena air-blast tests

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with larger laminate panels (1.5 m × 1.2 m) of the same thickness. The glazing was glued by silicone into a rigid frame and the reaction forces in the frame were evaluated. Further, the displacement of the whole glazing was measured with digital image correlation and compared to numerical calculations. Morison et al. [2] showed displacement vs. time curves of two arena air-blast tests with equal glass assembly and dimensions 1.25 m × 1.55 m and used the results for calibration of a single degree of freedom (SDOF) model. Larcher et al. [10] compared his numerical calculations with the results from the mentioned literature and conducted additional shock tube tests according to EN 13541 [8] with two 6 mm heat-strengthened glass plies and 2.28 mm PVB interlayer. Kuntsche and Schneider [11] performed experimental tests according to EN 13541 [8] of thick multiple glass laminates, mainly without fracture, and compared this to finite element calculation without consideration of the post-breakage state. The experiments presented in this paper aim to identify the influence of interlayer properties in the blast response of laminated glass panels.

A number of publications present possibilities to conceive a finite element model of impact or blast loaded laminated glass into the fractured state. Timmel et al. [12] introduced a straightforward smeared modelling technique where the elastic properties of a shell element are adjusted to represent only the polymer interlayer upon glass fracture. Larcher et al. [10] compared this method to the element deletion technique as used by Sun et al. [13] and concluded that the latter enables more physically correct material representation and is favoured for detailed analysis. This approach is followed by Wu et al. [14] and Zhang et al. [15] who also endeavour to take delamination into account. The numerical investigations in this paper explore the possibility of modelling the post-breakage behaviour of laminated glass in a detailed way, using recent experimental data to characterise the dynamic behaviour of PVB interlayer and delamination. The simulation results are then discussed to identify the merits, limitations and current reliability issues of the used method.

2. Laminated glass under blast loading

When blast protection is demanded in a structural design, it can dominate over the conventional structural requirements. The typically demanded protection scenario in the building industry is a detonation caused by explosive agents.

A blast pressure wave propagates in the surrounding air with supersonic velocity and a shock wave is formed with an abrupt rise of the air pressure followed by exponential decay. When the wave reaches a structure, this structure is loaded by the reflected pressure, which is two to eight times higher than the free incident pressure [16]. The pressure–time curve for the loading on a structure at a certain distance from the origin of detonation is shown in Fig. 1. The form of such a curve can be described by the Friedlander equation (1).

$$P(t)=P_R\left(1-\frac{t}{t_+}\right)e^{-A\frac{t}{t_+}}+P_0 \quad (1)$$

The testing procedure and classification of glass laminates subjected to blast loads are described in EN 13541 [8], ASTM F 1642-04 [17], ISO 16933 [18] and ISO 16934 [19]. The prescribed testing procedure can either be an arena air-blast test or a plane shock wave in a shock tube. An introductory overview of evaluation procedures for blast loading on civil constructions is presented in Ref. [20].

Laminated glass is composed of at least two glass plies bonded together with a polymer interlayer. The most common interlayer material used in the automotive and the building industry is polyvinyl butyral (PVB).

Until breakage, the glass panes behave linear elastic and the interlayer transfers shear forces (Fig. 2a). Still, a common approach

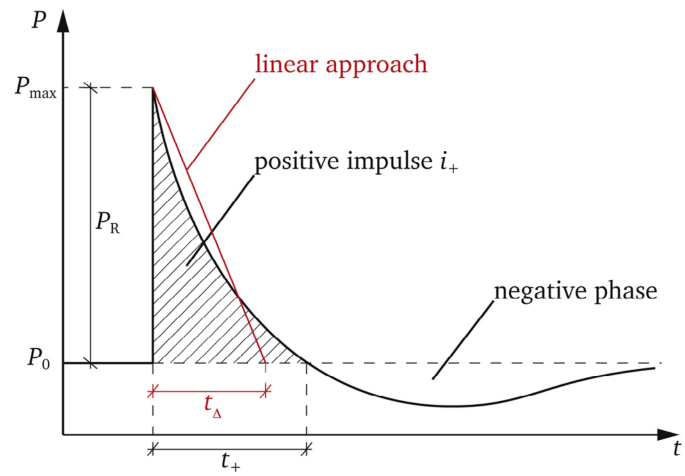

Fig. 1. Pressure–time history of a detonation wave.

for design under short-term loads is to model the laminate as a monolithic glass pane. This is justified in many situations because the polymer interlayers behave relatively stiff when loaded shortly, and a shear modulus of about G = 10 MPa already results in glass bending stresses that do not differ significantly from those of a monolithic pane for typical glass sizes, thicknesses and boundary conditions [11,21,22].

A much more complex behaviour is observed when the glass breaks (Fig. 2b–d): the cracks in the glass are narrow, such that the glass panes can still be able to transfer compressive forces but no tensile forces. Perpendicular to the crack, the interlayer needs to transfer all tensile forces. Consequently, delamination must occur over an area along the crack length, which allows the interlayer material at the crack to stretch over a greater length. If no delamination could form, the crack would remain infinitesimally small and the interlayer strain would be locally infinite, leading to instant tearing of the interlayer. This consideration already illustrates that a low adhesion of interlayer to glass could yield a safer post-breakage behaviour, provided that the bond is still strong enough to avoid the propelling of glass fragments. However, a high adhesion grade is often current practice because of processing and durability considerations.

The behaviour at higher strains now also needs to be considered for the interlayer material, along with its dependency on temperature and strain rate. Fig. 3 shows results of uniaxial tensile test at different strain rates [5]. Additionally, the result of a quasi-static uniaxial tensile test with a stiffer PVB is shown.

In contrast to bullet or burglary resistant glazing, where a high thickness of the laminate is needed to meet classifications, for explosion resistant glazing often the approach of balanced design is chosen [23]. This means a consideration of the complete load path from the facade to the foundation and a design of the structural members accordingly. If the glazing remains intact, the sub-construction needs to be designed for the full blast load. A breakage of laminated glass is therefore not only acceptable but desirable because the short-term acting pressure wave gets partially absorbed through various mechanisms: surface generation due to glass breakage as well as delamination by the breaking of hydrogen bonds between glass and interlayer, friction between glass fragments and viscoelastic deformation of the interlayer. Thus, the sub-construction can be designed in a more economical way without the risk of a total collapse of the building, but two main problems arise. Firstly, the fracture strength of glass shows a very high scatter with coefficients of variation of up to 30%. This must be taken into account in the design in order to guarantee glass breakage under blast loading