Chapter 4
Performance of TGU Windows under Explosive Loading

Piotr W. Sielicki, Chiara Bedon, and Xihong Zhang

Abstract Glass windows and facades are very popular in buildings, both in the form of traditional partitions and novel adaptive skins. There, given a series of intrinsic material features, special care should be spent at the design stage, so as to ensure appropriate *fail-safe* requirements, especially in presence of extreme design loads such as impacts. Even more attention is required for complex glass assemblies such as Triple Glass Units (TGUs), where the interaction of multiple components (i.e. the glass layers and the bonding foils, with the framing members) as well as the presence of gas cavities can further affect the dynamic response of these systems. In this paper, major outcomes of a research project in progress for the performance assessment of TGU windows under explosive loading are reported.

Keywords Structural glass · Triple glass units (TGUs) · Vulnerability analysis · Soft targets · Explosions · Field blast experiments

4.1 Introduction

Glass windows and facades are popularly used in structures [1–3]. However, glass is typically fragile, as compared to other traditional building materials such as reinforced concrete and steel. Post-event investigations of terrorist bombing attacks and accidental explosions have cited the failure of glass windows being one of the major causes of personnel injuries and casualties. Many studies have therefore been

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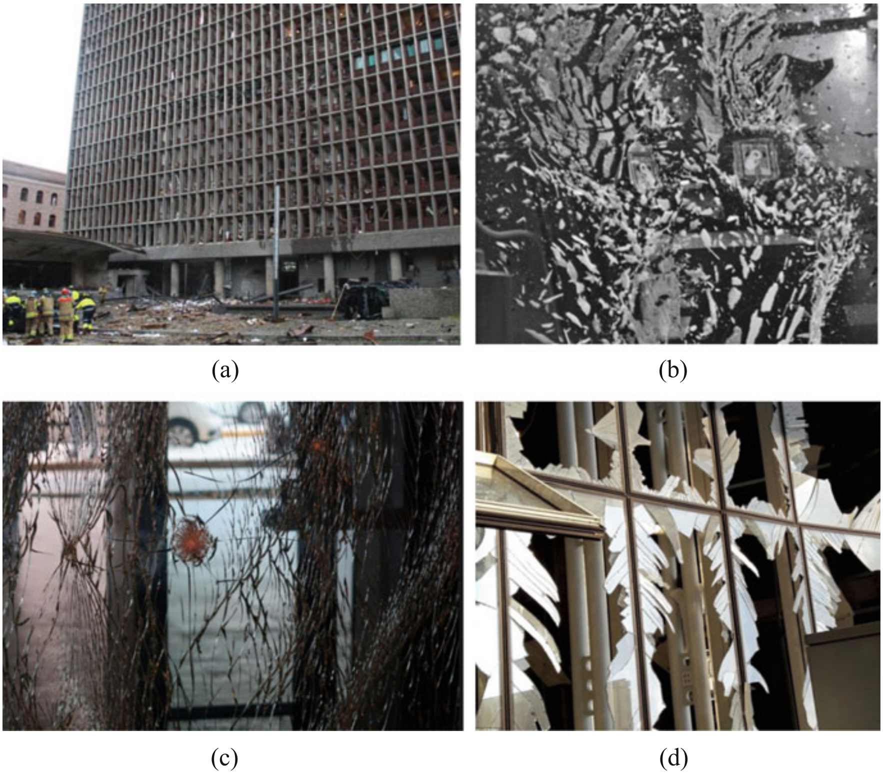


Fig. 4.1 Glass windows/facades under shock: (**a**) shattered glass windows in Norway attack, 2011 (Courtesy: Heidi Wideroe) and (**b**) flying glass fragments caused by controlled internal explosion [8]. Damage scenarios from the tragic attacks at (**c**) Instanbul and (**d**) Brussels Airports

carried out to investigate the behavior of glass windows/facades under blast loading for better protections of personnel and property safety [4–7].

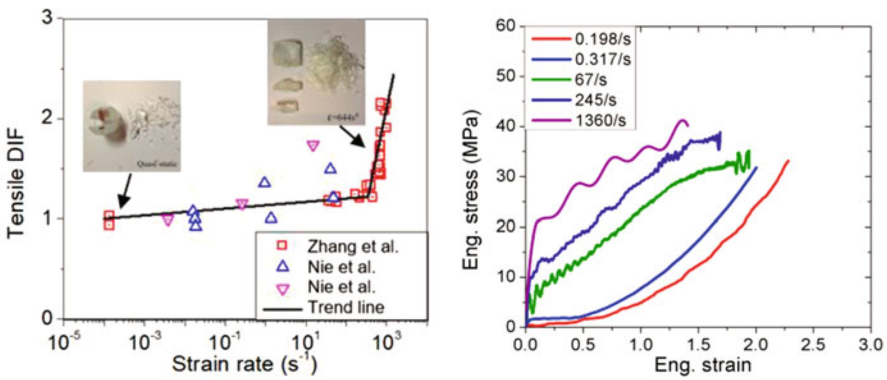
To improve the blast resistant capacity of windows/facades and reduce glass shard threats from breakage of glass panels, different techniques and new materials have been developed in the last decades, of which laminated glass (LG) is one of the most commonly used mitigation approach for the retrofitting of glass window applications. There, multiple glass layers are bonded via flexible plastic foils, aimed at enhancing the impact and post-cracked behaviour of glass panels, as well as to avoid the ejection of fragments. However, load bearing glass members still represent a critical component in buildings, hence requiring further efforts and investigations, see Fig. 4.1.

4.2 Glass and Interlayers under Shock

4.2.1 Glass Material Properties

For the design of glass structures under extreme loads and impact, major issues are related to the intrinsic mechanical and thermo-physical properties of such a rather innovative constructional material. With respect to the performance of glass structures under shock, literature studies on glass mechanical properties primarily concentrate on annealed glass (AN). Compared to Fully Tempered (FT) or Heat Strengthened (HS) glass, produced by heat treatment which introduces surface pre-compression effects, AN glass is suitable for material investigations since amorphous and homogeneous. AN glass panels for traditional windows and facades normally fails at around 100 MPa or lower stress values, because of the existence of surface flaws. The European standard prEN 13,474–3 [9] reports the measured glass fracture strengths from over 700 ring-on-ring tests, varying from 30 MPa to 120 MPa. The split tensile strength tested on 15 × 15 mm (diameter × length) AN cylinder was only about 20 MPa [10]. Such a marked variation is not only due to the different types of tensile strengths measured, i.e., bi-flexural, split-tensile, etc., but is mainly attributed to the surface conditions of the different tested glass panes.

In this context, it is commonly known that materials behave in different ways under dynamic loading, as compared to their static performance. Glass has no exceptions, and the dynamic properties of AN glass have been studied by different researchers. With respect to static conditions, the influence of surface flaw becomes less prominent under dynamic loading, because there is not sufficient time for existing flaws to fully develop. The British code [11], in this regard, suggests a tensile DIF of 1.78 for glass, when designing windows against blast loading. Analytical derivations from Brown's equation, however, showed that AN glass strength could increase up to three times the nominal value [12–14], see Fig. 4.2(a).



(a) (b)

Fig. 4.2 Dynamic material properties of (**a**) glass and (**b**) PVB

4.2.2 Interlayers

Within a typical LG assembly, the mechanical interaction of multiple glass layers is strictly related to the bonding contribution of interlayers. While several solutions are currently available on the market, PVB® (Polyvinyl Butyral) still represent - since decades - the commonly used interlayer material for bonding LG members. In terms of mechanical performance, PVB layers have a typical non-linear, time-dependent response, with large failure strain (see Fig. 4.2(b)). In the regime of small strains, the tensile behavior of PVB can be described with a viscoelastic model. A generalized Maxwell series and Williams-Landel-Ferry equation can be employed to account for the time-dependence and temperature-dependence of shear modulus (see for example [15–18]).

4.2.3 Protection of Glass Soft Targets

Based on some recent literature efforts, the protection of 'soft target' is one of the key goals of *fail-safe* design procedures. However, no official definition exist for 'soft targets' [19, 20]. In terms of protection of citizens, for example, the 'soft target' definition is conventionally used to denote places with high concentration of people and low degree of security against possible attacks. These places can typically include sports venues, shopping venues, schools, transportation systems, religious facilities, open spaces, etc. The major distinction is made between 'soft' and 'hard targets' - being representative of well-secured premises (i.e., government buildings, military premises, law enforcement offices, guarded non-governmental or commercial facilities, etc.). Given such a general definition of soft targets, existing glass structures - due to their intrinsic vulnerability - can represent an additional source of risk for the citizens, requiring appropriate studies and possible structural health monitoring activities, so as to timely plan possible retrofit/mitigation interventions.

Based on past observations from some tragic terroristic attacks, it is in fact commonly recognised that glass shards and fragments are the major issue due to extreme design loads. In the past, they have been responsible of more than 60% of the casualties, see Fig. 4.1. Structurally speaking, the so-called blast-resistant glass windows and facades still represent an open topic for researchers and designers, since appropriate static/dynamic performances of these systems under service loads should be achieved, while preserving their integrity under shock. The achievement of a such an optimal performance directly reflects on added protection for the citizens, but requires, on the other hand, specific knowledge of their static and dynamic performances of glass structures, including global and local phenomena. Further knowledge is required for the blast performance assessment and enhancement of glass windows composed by multiple, i.e. by assembling multiple LG components in the so-called Double (DGUs) or Triple Glass Units (TGUs), so as to account for gas cavities and load sharing phenomena [21, 22], etc.

4.3 Field Blast Experiments

4.3.1 Literature Background

In this paper, the dynamic performance of Triple Glass Units (TGUs) under blast is analysed, via on-site field experiments. Especially in the last years, the assessment of the dynamic response of traditional glass windows under explosions attracted the attention of several research studies. Major feedback, in this regard, can be expected from shock tube or field experiments [22–24]. In the past, efforts were made by Morison and others, see [25–28], etc. While the blast wave source consisted in both solid explosive or shock tube loading (TNT, C4 or PETN the charge), the common aspect of these investigations was represented by the type of windows, i.e. with dimension in the order of 1.1 × 1 m (up to 1.25 × 1.55 m), and consisting in a single LG plate. Their LG section was in fact obtained by bonding two 3 mm thick AN layers via a middle PVB foil (1.52 mm). Recently, Makki et al. [29] also experimentally investigated the blast response of a LG window. In their study, special care was spent for the effects of combined blast loads and temperature variations, so as to assess the potential of cladding safety films.

4.3.2 Geometrical and Mechanical Features of the TGU Samples

The typical glass window for the research project herein summarised consisted of a TGU, given by three glass panels (0.88 × 0.88 m the net dimensions) and a polycarbonate frame. The final result (1 × 1 m window) is shown in Fig. 4.3, with an actual bending span of glass equal to 0.85 m. Compared to past efforts, the presence of two gas cavities at the interface of glass panes represented the key aspect of the experiments. More in detail, the three glass layers were made LG sections, in which two AN foils were bonded via a soft PVB film.

4.3.3 Experimental Methods

The field experiments were carried out in September 2018 at Poznan University of Technology, Poland. At the time of the tests, seven repetitions were carried out on a set of four TGU samples with identical geometrical/mechanical properties. To this aim, each TGU window was rigidly connected to a concrete reaction wall, via metal screws and an expansion buff foam (Fig. 4.4). The TGU samples were hence subjected to 10Kg of TNT. Within the set of experiments, variations were made in terms of location of the charge with respect to the TGU samples (see Table 4.1 and Fig. 4.4), and location of the measurement instrumentation.

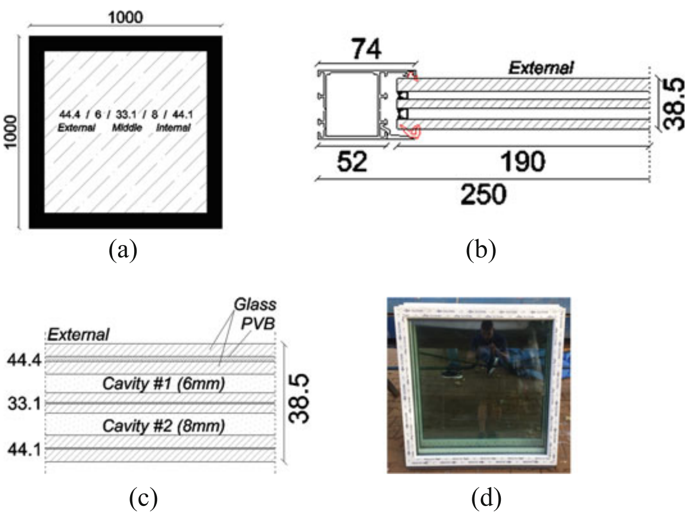


Fig. 4.3 Nominal geometry of the tested TGU samples (dimensions in mm): (**a**) front view, (**b**) cross-section (detail, with schematic section of the frame); (**c**) LG sandwich detail and (**d**) view of an assembled window

In particular, the stand-off distance for the explosive charge was changed in the range from 8 to 15 m, see Table 4.1. Accordingly, the accelerometers were positioned in the centre of the glass windows, or in the framing members. An high-speed camera was also used (Fig. 4.4), to capture the TGU windows response under shock (rear side).

The measurement instruments consisted in gauges and accelerometers that were placed within the test setup so as to properly capture the incident blast pressure on the front (i.e. exposed) and rear (unexposed) sides of the TGU windows, see Fig. 4.4, as well as the response of each sample. More in detail, conventional piezoelectric accelerometers (PCB®352A60 type, with a nominal mass of 0.006 kg) were used record the accelerations and then the displacements at a control point in the centre of each glass window. Given the nominal cross-section of TGU samples, no experimental measurements were made for the dynamic response of the middle LG panel, while the gauges – see Table 4.1 – were placed both on the frontal (i.e. exposed) and on the rear (i.e. unexposed) surface of each glass sample, see Fig. 4.4.

4.4 Summary of Results (Sample #W1)

For the sake of clarity, the experimental sample #W1 is primarily discussed in this paper. The TGU sample, see Fig. 4.5, was characterised by a stand-off distance of 15.10 m (0.99 m the height of detonation from the ground), and sustained a maximum overpressure in the order of 30 kPa. The full recorded time history can

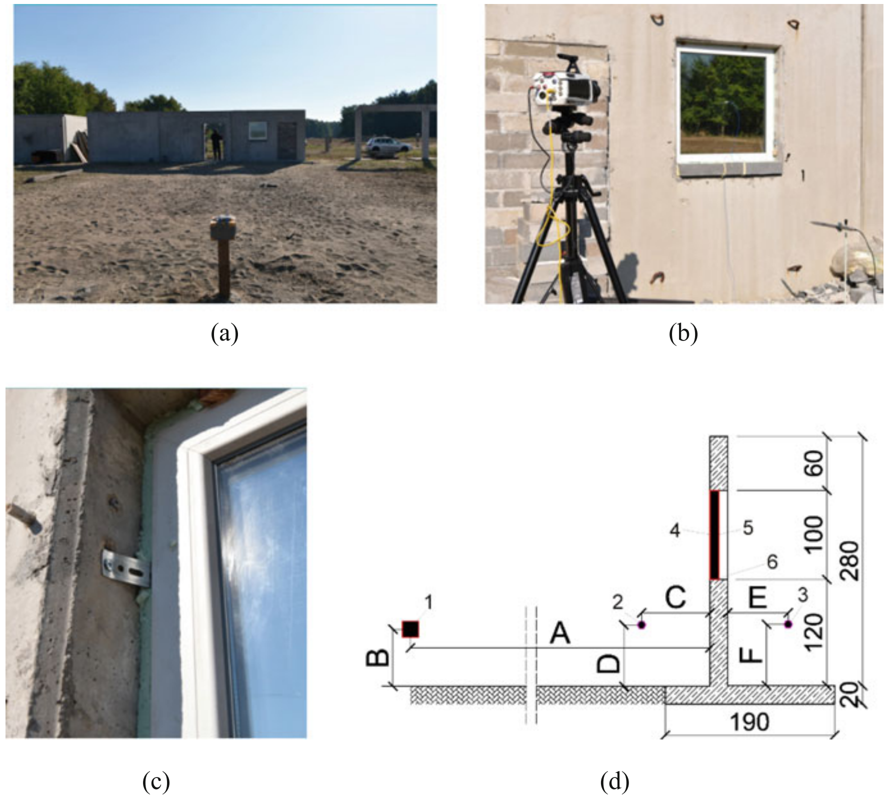


Fig. 4.4 Experimental setup: (**a**) frontal view, (**b**) rear side; (**c**) frame connection detail and (**d**) schematic setup (lateral view, dimensions in cm)

Table 4.1 Experimental setup for the field experiments (dimensions in m)

SAMPLE #	TEST #	TNT charge		Instruments		
				Gauge (overpressure)		Accelerometer
		A	B	C	D	
W1	1	15.10	0.99	1.20	0.87	Middle / front
	2	15.08	0.99	1.18	0.87	Middle / front
W2	3	10.10	0.74	1.20	0.87	*Failure*
	4	8.08	0.69	1.20	0.87	Middle / rear
W3	5	14.39	0.80	1.23	0.86	Middle / rear
	6	10.69	0.80	*Failure*	*Failure*	Middle / rear
W4	7	10.69	1.00	0.80	0.91	Middle (frame) / rear

be shown in Fig. 4.5(a). According to Fig. 4.5(b), the backward deflection of the front (exposed) glass panel was measured after 0.03 s in the order of 2.5 mm, hence corresponding to 1/400 the window dimensions. Failure of the front glass panel occurred after 0.05 s.

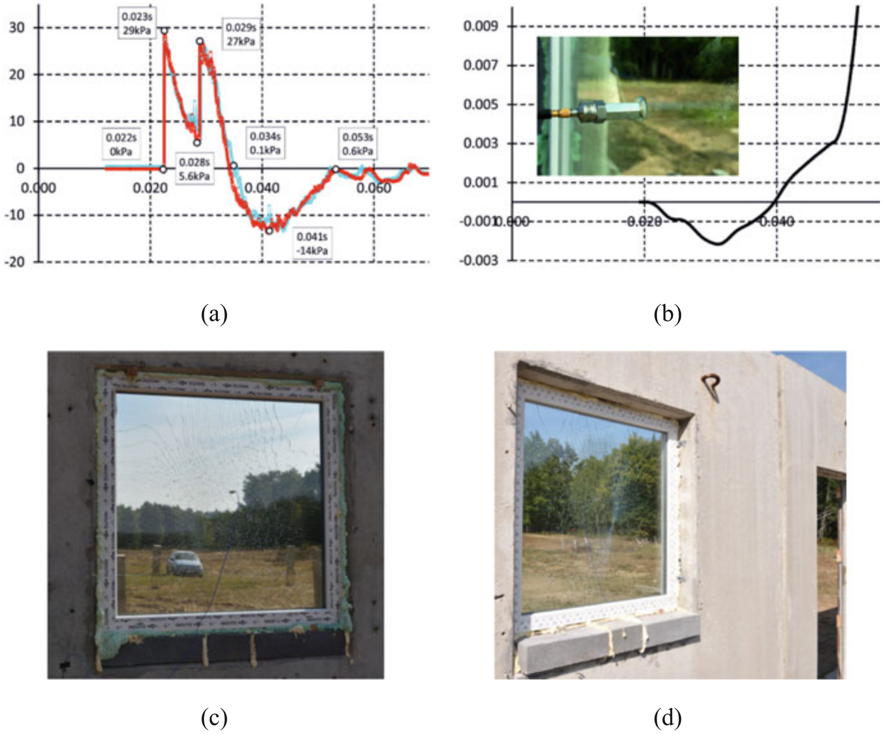


Fig. 4.5 Experimental results for the sample #W1: measured (**a**) overpressure (in kPa) and (**b**) displacement (in m) histories, as a function of time (in s). (**c**) and (**d**): Selected views of the Damaged #W1 sample after the experiment

To further assess the experimental observations and measurements, a preliminary Finite Element (FE) numerical study of the glass window was also carried out in ABAQUS [30]. Dynamic/Explicit analyses were performed.

At a first stage of the investigation, a simplified FE numerical model representative of the exposed LG panel (44.4) was only described, according to Fig.4.3, via 2D *shell composite* elements accounting for the nominal cross-section. Glass and PVB materials were characterised, respectively, via a tensile brittle constitutive law (*brittle cracking* damage model, see also [22]) and an equivalent, elasto-plastic stress-strain response [22, 31, 32]. Ideal rigid supports were defined along the edges of glass, hence disregarding the flexibility of glass-to-frame restraints, as well as the structural contribution of the middle and rear LG plates. The net bending span of the glass panel (0.85 × 0.85 m) was in fact accounted, with linear clamps for the four edges. A sweep mesh pattern was used for the shell elements, with an edge size spanning from a minimum of 5 mm (i.e. in the central region of the glass panel), up to 15 mm along the clamped edges (9000 elements, 55,000 DOFs, see Fig. 4.6(a)).

The input blast load was then described in the form of a uniform pressure, according to the experimentally measured pressure-time history. As shown in

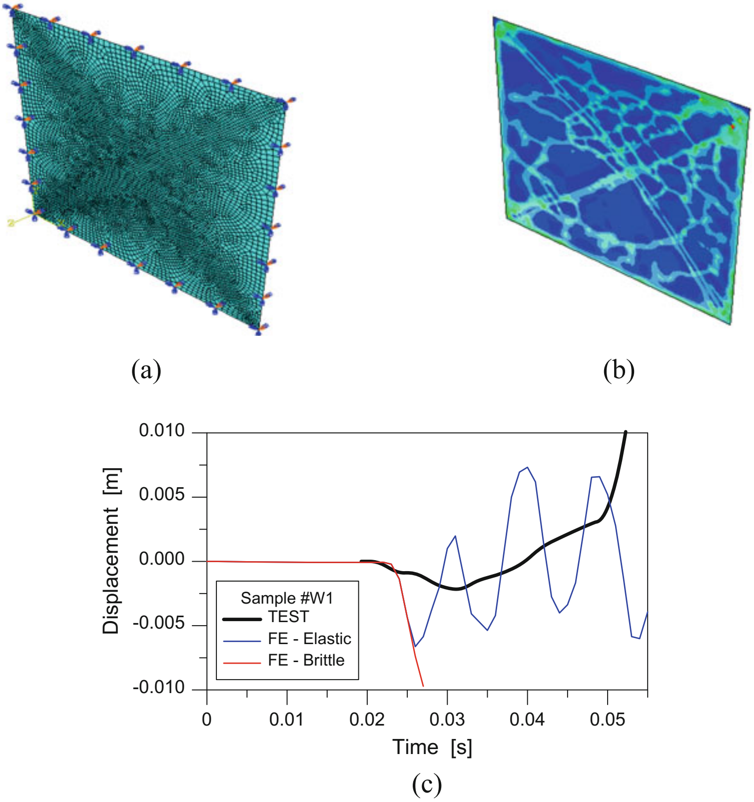


Fig. 4.6 (**a**) Simplified numerical model for the #W1 TGU sample (mesh pattern in evidence), with (**b**) cracks in glass (t = 0.025 s) and (**c**) time-displacement comparisons (ABAQUS)

Fig. 4.6, even such a simple FE model can qualitatively capture the crack pattern of glass (Fig. 4.6(b)). Otherwise, the global response and displacement evolution in time of the TGU window is strictly related to a combination of mechanical and geometrical parameters, including the tensile resistance of glass (45 MPa the nominal value for the FE model), the actual boundary conditions (see also [22]), the effective blast pressure-time history, the effect of gas cavities on the dynamic response of the full TGU assembly.

4.5 Conclusions

In this paper, the blast response of Triple Glass Unit (TGU) windows under blast has been preliminary investigated, based on field experiments and simple Finite Element numerical models. As known, glass windows represent one of the critical and most vulnerable components in buildings, hence requiring special care and design considerations under shock and extreme loading conditions. Further attention should be spent when these windows are obtained by a combination of assembled elements, i.e. like in the case of TGUs, where three laminated glass panels can mechanically interact via the interposed gas cavities, as well as are restrained to a supporting frame.

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