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Design and analysis of blast loaded windows

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Abstract

The increasing number of terrorist attacks brings the need to research on the blast resistance of buildings and transportation systems. Most of these attacks are lastly concentrated on the so called “soft targets” as railways stations, airports, bus stations, shopping centers, etc. In them, high vulnerability is frequently given by fenestrations or novel glass façade systems in general. In this regard, the paper is focused on the analysis of the dynamic behavior of blast loaded glazing windows. Given a reference specimen geometry and wood or plastic frame representative of traditional or new fenestrations respectively, the blast performance of such system is assessed via analytical SDOF calculations. Refined Finite Element (FE) numerical simulations are then presented and discussed, as a preliminary outcome of further exploratory investigations. Following the actual research study, experimental tests will be in fact carried out on the same fenestration systems.

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1. Introduction

The crucial role of blast resistance in design of buildings and constructed facilities rapidly increased in last years, with the increment of terrorist attacks involving explosives. Most of those attacks are concentrated on the so called “soft targets” as railways stations, airports, bus stations, shopping centers etc. During any blast-related event, buildings can be damaged or collapse, hence defense of occupants and avoidance of possible injured people is of

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crucial importance. Various loading configurations are possible, including direct exposure to blast loading, impact of fragments and debris, impact with surroundings when either a structural element or a person is impelled by the blast waves, or structural collapse. In any case, the most vulnerable part of the building is represented by fenestrations (i.e. windows, doors, skylights) and glass façade systems, due to the fact that they are usually not designed as blast-resistant.

In this research study, the blast resistance of old wooden or new PVC windows for office buildings is assessed. Setup features and major results here discussed are aimed to provide support for further open air experimental tests, planned on the same fenestration systems.

2. Blast load description

The real detonation of a spherical charge runs in such a way that the detonation wave extends from the centre of the charge in all directions. Its front strikes against the surrounding environment at the charge brim. From this point the blast wave extends and after the gas explosions the reflected one is distributed. For design purposes, the blast wave due to an explosive event is usually described in the form of a time-pressure profile with two distinct phases – i.e. the positive and negative one. Its actual decaying form is approximated by a regular shape having a positive peak (being dependent on the charge weight, distance, height) and dropping below the ambient pressure in the range of few milliseconds.

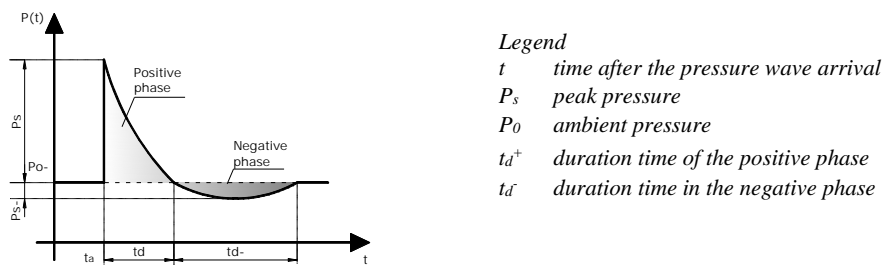


Fig. 1: Time-pressure profile of a typical blast wave

3. Standards for design and testing of blast loaded windows

3.1. Recapitulation of existing EU design regulations

Design of blast loaded glazing windows currently represents an issue of crucial importance. However, no comprehensive standard actually existing in Europe for design and verification of blast loaded windows and façades.

In the EU, the generally accepted, reference standard for design is represented by EN 1991-1-7 “Actions on structures - Part 1-7: General actions - Accidental actions”. Within the general actions for design, blast load should be considered as accidental. The standard itself, however, highlights that loads from “external explosion, war and terrorist activity” are not covered by the design provisions. The same EN 1991-1-7 deals with the topic only in Section 5 “Internal explosion”. Explosions shall be in fact taken into account in the design of all the components of a building or a civil engineering facility where gas is burned or regulated, or where explosive material such as explosive gases, or liquids forming explosive vapor or gas, are stored or transported (e.g. chemical facilities, vessels, bunkers, sewage constructions, dwellings with gas installations, energy ducts, road and rail tunnels). Annex D of EN 1991-1-7 hence provides guidelines for specific types of explosions, including dust or gas explosions, as well as explosions in tunnels, rail or road constructions. Finally, the standard defines the reference parameters for the powder of different materials such as brown coal, cellulose, coffee, corn, grain, milk powder, mineral coal etc. An updated version including Annex A1 to EN 1991-1-7 is available from April 2015, which makes corrections in formulas of original Sections D.1 - D.3. A novel Section D.4 “Explosion of dust, gas/vapors in pipelines” is also included in it.

3.2. Regulations for testing

CEN published the first standards for testing of blast-resistant glazing in 2001. The full set of regulations include an EU standard for testing the blast resistance and security of single glass plates only (EN 13541:2012) and a suite of standards for testing full assemblies and systems like windows, doors, shutters (see for example EN 13123-1:2001, EN 13123-2:2004, EN 13124-1:2001, EN 13124-2:2004). However, no specific standards are available currently, for testing glazed facades. The EN 13541:2012, for example, considers a single glass pane only, with a fixed overall size, assuming a supporting rigid frame and prescribed test conditions. EN 13123-1:2001 and EN 13123-2:2004, on the other hand, consider the whole window system and allow it to be tested at its real size and with its real frame, thus providing more realistic results. Provision are given for testing either with shock tube or in arena, with small charges. The International Organization for Standardization published in 2007 the ISO 16933:2007 standard. This latter one is largely derived from EN regulations, including the use of large charges in range tests, as well as additional small charges. A parallel standard (ISO 16934:2007), finally, covers shock-tube testing.

3.3. General design criteria for blast loaded glazing windows

The basic criteria for an optimal design of blast-resistant fenestration is that the glass panels should remain intact and in the frame, broken but not blown out. The frame itself should stay attached to the background building (i.e. the supporting wall). As such, the wall/structural background should finally remain intact to hold the frame in position. The protective glazing measures would also be appropriate for buildings that are located near the high-risk targets, even though the buildings themselves are not considered as a target [1]. From a practical point of view, the design of a blast-resistant glazing window and its main components should be hence carried out by considering the following aspects:

- Detection of scenarios and risk assessment. This phase, valid for all blast loaded structures, requires joint decision of the owner or stakeholder and the designer
- Calculation of the design load. Various simplified formulations exist, mainly intended for TNT (or equivalent mass) explosives. The resulting pressure can vary largely, depending on the used formulation.
- Design of the fenestration and its components as a whole assembly, according to available standards and guidelines. To this aim, a key role is given to testing, as well as to advanced FE numerical simulations validated and assessed towards experiments.

4. Assessment of the blast performance of glazing windows: a case study

4.1. Geometrical and mechanical properties

In this research study, two window systems representative of an old wooden and a new PVC fenestration system, respectively, are considered. Both window systems have identical nominal dimensions, see Fig. 2. The size of specimens as a whole is 1.21×1.38 m, consisting of a supporting frame and a monolithic glass plate, 3 mm in thickness, with nominal width of 1.05 m by 1.12 m of height. The mechanical interaction between the glass plate and the supporting frame (supposed to be rigidly connected to the structural background) is given by a continuous sealant joint, acting (together with the frame geometry) as a partially rigid continuous clamp along the plate edges.

The difference between the wooden and PVC specimens is hence given by the frame only. In the first case, with ≈30×80 mm the framing cross-section, the age of the wooden members is 51 years. The so assembled system is representative of an old typology of windows in use in Czechoslovakia over 1960s. In the second case, a plastic frame currently available on the market is taken into account.

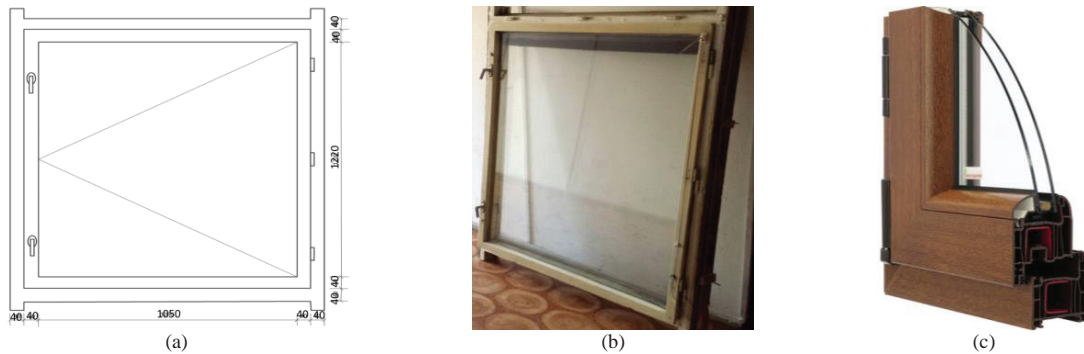


Fig. 2: Fenestration system. (a) Front view of the window (dimensions in mm); (b) wooden window; (c) detail (example) of PVC frame [6]

4.2. Analytical and FE numerical analysis of the monolithic glass plate under blast

An analysis of the dynamic response of blast-loaded structures is typically very complex. To this aim, simplified calculations can be carried out on the glass plate alone, preliminary assuming ideal boundary conditions and simplifications on the expected dynamic behavior. More refined investigations, able to take into account the interaction of all the fenestration components, should in fact be carried out via advanced FE numerical models. As a major influencing parameter for design of fenestrations, in any case, monolithic glass represents the crucial component, due to its brittle tensile behaviour, abrupt cracking and null post-failure residual resistance. Glass resistance is also strictly related to time loading. At this stage of the research study, calculations and simulations are carried out by taking into account the mechanical properties considered in [2], see Table 1.

Table 1. Mechanical properties of glass, in accordance with [2]

Flexural strength under dynamic load	55 MPa	Glass weight	2700 kg/m ³
Mean (long-term) static strength	13 MPa	Limit rotation	6°
MOE	6.0×10 ⁴ MPa	Ductility factor	1
Poisson's ratio	0.26		

The structure was idealized as (SDOF) system and preliminary analytical calculations were carried out, aiming to predict the ultimate resistance under blast loads. The window was described both in the form of (i) a 1D simply supported beam, as well as (ii) a 2D plate simply supported along the four edges. See also [4] for additional details on the SDOF modelling assumptions for such a structural system. The 1D and 2D SDOF window systems were considered for the analysis of the ultimate flexural deformation of the fenestration, according to [5]. Due to the brittle elastic behavior of glass, only elastic analyses were carried out. The worse of the two limit configurations (representative of resistance or deformation limits) was considered to detect collapse, following [2]. Tensile cracking of the glass panel in bending was hence taken into account. At the same time, the window structural performance was assessed on the base of dynamic displacements and rotations around the mid-span axis of beam/plate system. The ultimate dynamic rotation φ was calculated as:

$$\varphi = \arctg(y_m/0.5l) \leq 6^\circ \quad (1)$$

where y_m denotes the maximum dynamic displacement due to blast load and l is the span of glass.

All the SDOF analyses were carried out by taking into account a velocity of 0.001s for the blast wave, with mechanical properties of glass given in Table 1. As a first comparative assessment, a simplified FE model, consisting of a single monolithic glass plate, was also analysed in ABAQUS/Explicit (Fig. 3a [7]). Such a model consisted of 2D shell elements, simply supported along the edges as a plate. Finally, as a further reference value for preliminary estimating the ultimate blast resistance of the examined windows, Fig. 3b and [2] were also considered, being these plots based on experimental measurements and calibrated to assess the limit bearing capacity of single glass plates under blast waves.

Table 2. Ultimate blast resistance of the examined glazing window systems

Type of model	Type of analysis	Peak pressure (in kPa) at collapse detection	
		Ultimate tensile strength	Ultimate rotation
SDOF	1D Beam model	33.02	10.55
	2D Plate model	38.05	17.80
ABAQUS	2D shell FE model – plate	39.10	23.00
Graphical/experimental	Figure 3	15.00	

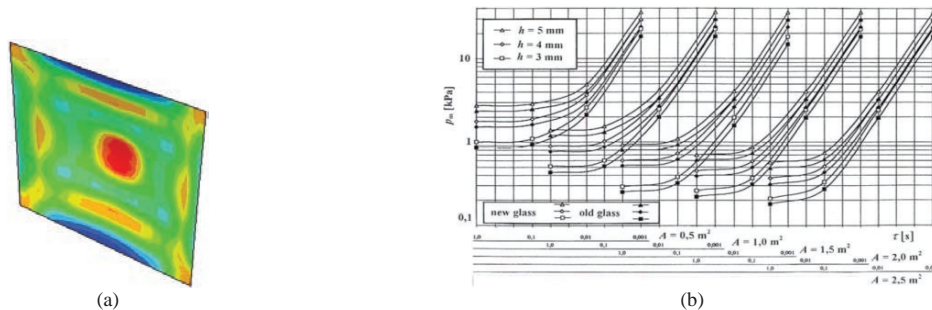


Fig. 3: Blast analysis of a single glass plate. (a) FE numerical model (ABAQUS), with distribution of maximum stresses close to collapse, and (b) limit bearing capacity [2]

Following the SDOF as well as FE calculations, the critical failure configuration for the reference window system proved to be associated by exceedance of the limit rotation for glass, see Table 2. Those findings are also in line with FE dynamic simulations on the single glass plate, as well as with graphical estimations of ultimate residual resistance for the examined plate. On the other hand, ideal restraints are only taken into account and possible mechanical interaction (including failure of supports) with the other system components is fully disregarded.

4.3. Finite Element numerical analysis of the blast loaded fenestration system

For a detailed dynamic analysis of the fenestration systems under blast, further refined FE numerical models were implemented in ABAQUS/Explicit (Fig. 4). Compared to section 4.2, all the fenestration components and their interactions were properly taken into account (although with preliminary assumptions), aiming to reproduce the experimental setup for near future open air tests.

To this aim, the windows were supposed to be rigidly fixed on a frame composed of the HEB profile (i.e. as in the case of the actual test setup, see Figs. 2 and 4). The typical FE model, representative of the nominal geometry and inertial features of each fenestration component, consisted of 1D beam elements for the HEB profiles, as well as for wood/plastic frame, while 2D monolithic shell elements were used for the glass plate. The HEB mullions were rigidly supported at the ends. The mullions sustain the HEB transoms, which are rigidly bolted on them, acting as a rigid restraint for the wood/plastic framing of the fenestration (transoms only). As such (due to test setup only), the stiffness and resistance of wood/plastic mullions have a key role on the overall behaviour of the fenestrations. The mechanical interaction between the glass plate and the wood/plastic frame members took the form of distributed point connectors representative of the sealant joints at their interface. At a preliminary stage, such mechanical connectors were calibrated to account for: (a) fully rigid rotational stiffness, (b) fully rigid translational stiffness in the direction perpendicular to the glass surface and (c) null translational stiffness in the in-plane direction (i.e. weak adhesive joints). In terms of material properties, glass was described in the form of a tensile brittle material, with input mechanical properties derived from Table 2, including the *brittle cracking* option for damage (see [8, 9] for calibration). An isotropic, elasto-plastic constitutive law was used for steel profiles, with 210 GPa the MOE, $\sigma_y = 313$ MPa and $\sigma_u = 441$ MPa the yielding and ultimate stress respectively. For the wooden or PVC framing system, finally, mechanical properties were preliminary estimated, given the actual lack of experimental material tests. A tensile brittle stress-strain relationship was taken into account for wood, with 12000 MPa the average MOE, 30 MPa a reference value for bending resistance. In the case of PVC, MOE of 30000 MPa and bending/tensile resistance of 55 MPa were used.

Dynamic impact analyses were carried out on the so assembled models. The blast wave pressure (with 39.10 kPa the peak pressure (Table 2) and 0.001s the time loading) was first applied, on the glass surface only. In Fig. 4, an overview of the FE model is shown, with evidence of principal stresses near collapse (Fig. 4a) and out-of-plane deformations (Fig. 4b). An interesting correlation was observed with results of Table 2. As expected, however, the full FE model also highlighted a marked sensitivity of predicted responses to all the fenestration components, including the wooden/plastic frame. For the FE model in Fig. 4 and the reference test setup, in particular, the wooden frame, acted as a partially rigid support only for the four edges of the glass plate, hence assuming a deformed shape comprised between the limit conditions of the 1D beam and the 2D plate of Table 2. Further detailed calibration and investigation at a component as well as at the assembly level, is hence required for the examined fenestration systems.

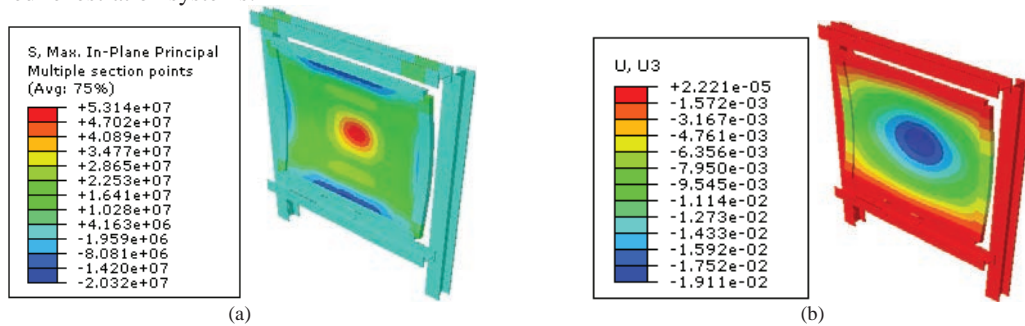


Fig. 4: Dynamic performance of the wooden fenestration system under blast loads (ABAQUS/Explicit), with evidence of (a) maximum stresses (values in Pa) and (b) out-of-plane deformations (values in m).

5. Conclusions

In this paper, the blast performance of old wooden or new plastic fenestration systems has been explored. Analytical SDOF calculations as well as refined FE numerical analyses, have been proposed for both the window systems, giving evidence of the expected performance and of the key role of boundary restraints and interaction between all the system components. As a part of an ongoing research activity, current outcomes will be further extended with open air blast tests aimed to assess the overall performance of such systems.

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