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Recommendations for a New Generation of Standards for Testing Numerical Assessment of Blast-Loaded Glass Windows

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Abstract. The determination of the blast protection level of civil engineering buildings components against explosive effects represents a topic of crucial importance, in current practice. However, some key aspects of blast resistant structures design have been only marginally considered in the last decade, and currently still require appropriate regulations. This is especially true in the case of windows and facades, where the intrinsic material brittleness is the major influencing parameter for blast-resistant assemblies. While blast assessment of buildings and systems is usually achieved by means of experimental investigations, as well as numerical simulations, general regulations and guidelines are currently missing.

In this regard, the European Reference Network for Critical Infrastructure Protection (ERNCIP) Thematic Group "Resistance of Structures to Explosion Effects" attempts to develop guidelines and recommendations aimed to harmonise test procedures in experimental testing of glass windows under blast, as well as standardized approaches for their vulnerability assessment via numerical modelling. In this paper, major Thematic Group outcomes and next challenges are briefly summarized.

1. Introduction and ERNCIP Thematic Group Objectives

Glass material has become a major constituent in modern infrastructures. This material can be implemented under various architectural concepts, among them, glazed facades supported by a steel substructure (fig.1) or glass columns [1]. As a rather innovative construction material – compared to traditional components composed of timber, steel, concrete or masonry – glass is typically characterized by a very brittle behaviour and may result in numerous splinters that could seriously injure persons inside the building in case of explosions. An illustrative case of large scale explosion in a dense urban environment can be found in the explosion of the AZF factory in Toulouse, France, in 2001, where more than 3000 people were injured, mainly by splinters [2]. The mechanical behaviour of glass has been described by various experiments, in quasi static as well as dynamic approaches [3]. It results that glass is highly strain-rate and stress-orientation dependent.

In this context, it is clear that specific, experimentally supported, design procedures are required. This is true especially for novel structural glass applications – including specific loading/boundary conditions or different materials combined with glass – as well as load-bearing elements subjected to exceptional loads, such as accidental impacts, fire or explosive events, natural hazards, etc. [4].

Figure 1: European Commission's Charlemagne building in Brussels
(Wikipedia, Cancillería Ecuador).

The European Reference Network for Critical Infrastructure Protection (ERNCIP) Thematic Group "Resistance of Structures to Explosion Effects" [5], in this context, aims to provide a framework within experimental facilities and laboratories will share knowledge and expertise in order to harmonize test procedures throughout Europe, leading to better protection of critical infrastructures against all types of threats and hazards. The group also supports the use of numerical modelling of the behaviour of these structures loaded by blast waves. The use of numerical modelling, as known, represents in fact a very helpful tool for designing experiments, extrapolating experimental results, optimizing protections, reducing the number of tests and support classifying windows. On the other hand, guidelines for an appropriate use of these tools are currently missing.

The Thematic Group is composed of European experts and researchers. To achieve its goals, the Thematic Group proposes guidelines to help to harmonize test procedures for structural elements against explosion-induced loads. In what follows, only blast effects are considered (regardless fragment impact effects).

In this paper, aiming to give an overview of current tasks and next objectives of the current activities carried out by the Thematic Group, the second paragraph deals with the existing methodologies and standards for windows subjected to blast loading. The third paragraph summarizes some considerations about numerical modelling of blast loading including fluid-structure interaction. The Thematic Group has developed recommendations for the modification of standards for testing windows, doors and shutters under blast and fragments loading, that are presented in Section 4. Finally, it is planned to forward the developed recommendations to CEN/TC 33 and CEN/TC 129 to support the revision of the affected European Standards.

2. Summary of Existing Standards for Windows under Blast Loads

The European Committee for Standardization (CEN) published the first standards for testing blast-resistant glazing in 2001. These include a European standard (EN) for testing security glazing alone (EN 13541:2012) and a suite of standards for testing complete systems like windows, doors, and shutters (EN 13123-1:2001, EN 13123-2:2004, EN 13124-1:2001, and EN 13124-2:2004).
Currently, there are no standards for testing glazed facades. EN 13541:2012 considers only a single pane of glass, loaded by a plane shock front, with a single fixed size in a rigid frame under prescribed tests and boundary conditions. Also if this standard exists it should not been used to specify the protection of a building since the behaviour of window frame is imminent.

EN 13123-1:2001 and EN 13123-2:2004 consider the whole window system and allows to test windows at its real size and with its real frame, thus producing more realistic results. These standards define the procedures for testing windows by using a shock tube or arena testing with small charges. Table 1 gives the explosion resistance (ER) domains for shock tube experiments, completed by the peak overpressure in kPa of the upper limit of the domain.

The United States (US) government General Service Administration (GSA) published a test protocol for glazing in 2003 (GSA-TS01:2003), which permits testing by shock tube or range test.

The International Organisation for Standardization (ISO) published in 2007 the standard ISO 16933:2007. It extends the test conditions to allow the use of large charges in arena tests and it also includes small charges to encompass the GSA test requirements. A parallel standard (ISO 16934:2007) covers shock-tube testing. This standard defines explosion resistant domains (Table 2) in relation with the ones proposed by EN 13123-1 and -2. The classification of a window should be done by adding in brackets the hazard rating, given in Table 3, received during the test. A classification example would be: ER100 (C), that would apply to a test with a peak pressure of at least 100 kPa and positive phase impulse of at least 900 kPa-ms resulted in damage to the glazing resulting in hazard rating C.

Table 1: Shock tube test: extract from EN 13123-1:2012.

Windows/doors/shutters	**peak overpressure (P_r) [kPa]**	**Pos. spec. impulse** (i_+) (kPa-ms)	**Duration of positive phase (t+) [ms]**
EPR 1	$50<P_r<100$	$370<i_+<900$	>20
EPR 2	$100<P_r<150$	$900<i_+<1500$	>20
EPR 3	$150<P_r<200$	$1500<i_+2200$	>20
EPR 4	$200<P_r<250$	$2200<i_+<3200$	>20

Table 2: Shock tube test: extract from ISO 16934:2007.

Windows/doors/shutters	**peak overpressure (P_r) [kPa]**	**Pos. spec. impulse** (i_+) (kPa-ms)
ER30	0.30 bar	170
ER50	0.50 bar	370
ER70	0.70 bar	550
ER100	1.00 bar	900
ER150	1.50 bar	1500
ER200	2.00 bar	2200

Table 3: Hazard evaluation criteria for arena tests given by the ISO 16933:2007 standard [1].

Hazard rating	Hazard-rating description	Definition
A	No break	The glazing is observed not to fracture and there is no visible damage to the glazing system.
B	No hazard	The glazing is observed to fracture but the inner, rear face leaf is fully retained in the facility test frame or glazing system frame with no breach and no material is lost from the interior surface. Outer leaves from the attack face may be sacrificed and may fall or be projected out.
C	Minimal hazard	The glazing is observed to fracture. Outer leaves from the attack face may be sacrificed and may fall or be projected out. The inner, rear face leaf shall be substantially retained, with the total length of tears plus the total length of pull-out from the edge of the frame less than 50 % of the glazing sight perimeter. Also, there are no more than three rateable perforations or indents anywhere in the witness panel and any fragments on the floor between 1 m and 3 m from the interior face of the specimen have a sum total united dimension of 250 mm or less. Glazing dust and slivers are not accounted for in the hazard rating. If by design intent there is more than 50 % pull-out but the glazing remains firmly anchored by purpose-designed fittings, a rating of C (minimal hazard) may be awarded, provided that the other fragment limitations are met. The survival condition and anchoring provisions shall be described in the test report.
D	Very low hazard	The glazing is observed to fracture and significant parts are located no further than 1 m behind the original location of the rear face. Parts are projected any distance from the attack face towards the blast source. Also, there are no more than three rateable perforations or indents anywhere in the witness panel, and any fragments on the floor between 1 m and 3 m from the interior face of the specimen have a sum total united dimension of 250 mm or less. Glazing dust and slivers are not accounted for in the rating.
E	Low hazard	The glazing is observed to fracture, and glazing fragments or the whole of the glazing fall between 1 m and 3 m behind the interior face of the specimen and not more than 0.5 m above the floor at the vertical witness panel. Also, there are 10 or fewer rateable perforations in the area of the vertical witness panel higher than 0.5 m above the floor and none of the perforations penetrate more than 12 mm.
F	High hazard	Glazing is observed to fracture and there are more than 10 rateable perforations in the area of the vertical witness panel higher than 0.5 m above the floor, or there are one or more perforations in the same witness panel area with fragment penetration more than 12 mm.

3. Summary of Existing Numerical Modelling Studies for Blast-Loaded Glazing Facades

3.1 State of the Art

In the last years, numerical investigations with various modelling assumptions and goals have been carried out on glass and laminated glass components and systems under blast. Müller and Wagner [6] have shown that a layered shell element can be sufficient to represent the failure behaviour of laminated glass, but on the other hand, the same modelling approach is not able to correctly consider the separate failure propagation in both the glass plies, as well as to account further key aspects on the structural performance of a blast-loaded glazing system, such as delaminations. Timmel et al. [7] and Sun et al. [8] proposed some further simplified models for laminated glass, but accounting for certain possible failure mechanisms.

Zhang and Hao [9], Bennison et al. [10], and Hidallana-Gamage et al. [11] presented full 3D models with solid elements, including detailed material laws for constitutive materials as well as for the interlayer. However, an accurate modelling requires a large number of parameters sets for constitutive and damage laws governing the behaviour of materials and their interfacing. Larcher et al. [12] compared several approaches for the simulation highlighting further their advantages and disadvantages. Müller and Wagner [6] and Burmeister [13] proposed some detailed examples and calculations with failure criteria of conventional glass. Other considerations have also been numerically investigated, like the boundary conditions, they have found to be of a major influence [9]. It points out the importance of the consideration of the connection between the glass and the rigid structure, to which the window or facade is fixed. Pelfrene et al. [14] modelled the possible delamination of the laminated glass using a combined shell-solid model. They underlined the fact that, depending on the polyvinyl butyral (PVB) interlayer, delamination could have an important role on the damage process.

Blast-loaded windows have been the object of experimental investigations, especially by considering some loadings defined as Pressure-Impulse domains like in [15], in which some formulas are deduced from parametric studies relying on finite element analysis. Nevertheless, infrastructure design often relies on security and safety standards that are not connected with the state of the art of such numerical approaches in engineering. As described below, these numerical models could replace expensive experimental works and could give better possibilities concerning parametric studies. Some essential requirements, for numerical approaches as well as for experimental studies, are given by [16, 17] and presented further on.

3.2 General Considerations about Numerical Tools

At least two main methods are emerging as engineering tools for civil engineers: discretized numerical methods and engineering toolboxes.

Numerical methods rely on discretization of the space domain in sub-domains for which material laws, element properties, boundary and initial conditions are attributed. Two approaches can be adopted for the material displacements: Lagrangian, for which the material is delimited by elements like in Finite Element Methods (FEM) – and Eulerian where elements define a grid through which fluid material is flowing. These two approaches can be coupled like in Arbitrary Lagrangian Eulerian (ALE) and Coupled Euler Lagrangian (CEL) approaches. When dealing with strong loading rates, it more convenient, for Central Processing Unit (CPU) time savings, to use an explicit scheme of resolution (solution computed for a given instant depends on the one computed at the previous instant). Mesh-free methods can also be implemented like Smooth Particle Hydrodynamics (SPH). Examples of the most popular commercially available software featured with FEM, CFD and CEL are: Abaqus CAE, AUTODYN, EUROPLEXUS, LS-DYNA, RADIOSS.

Engineering toolboxes rely on analytical formulae for describing the dynamic structural behaviour. A well-known method to obtain element strain under mechanical loading is the single degree of freedom approach (SDOF) [18], where also the loading conditions can be taken from.

3.3 Basic Modelling Considerations

Numerical simulations of blast-loaded glazing system generally requires a series of multi-level assumptions, including the definition of a set of geometrical and mechanical input parameters, as well as material and loading definitions. This is especially the case of assembled systems, in which glass elements interact with other structural components as a part of an entire structure.

A non-exhaustive list of basic modelling assumptions that should be considered including:

- A limited dependence of the results to the elements size and geometry, number of integration points, etc.,
- The relevance of material constitutive laws (including especially its strain-rate dynamic behaviour and the occurrence/propagation of damage mechanisms) and consistence with the chosen unit system,
- The relevance of the boundary conditions (symmetry planes, etc.),
- Neutrality of boundary conditions,
- Initial conditions,
- The relevance of the output variables and their recording frequencies regarding the time step and the duration of the phenomenon to be modelled,
- The use of scaling laws (Cranz-Hopkinson laws).

These considerations must be the object of sub-studies. In addition, numerical results have to be compared with available analytical theories or experimental results (taken from the open literature, some examples are given in [12]), if necessary, transposed in a simpler configuration, to check software ability to face with the physics to be modelled.

3.4 Additional Considerations about the Mechanical Loading

The mechanical loading definition is a leading parameter in the overall numerical approach. When dealling about blast loading, several approaches can be followed:

1) The modelling of the high explosive charge itself (**equation of state**). It will lead to a large number of elements and very small time steps, thus very long computational time.
2) Loading by a **pressure-time function**, *P(t)*, that has to be judiciously chosen. This is a critical step because it requires the assumption of a TNT-equivalent of the explosive charge
   TNT-equivalent: The behaviour of TNT is not well standardised since it depends on the chosen TNT and the parameter of reference (Pressure, impulse, detonation energy, …) [20]. It must be kept in mind that the performance of high explosives strongly depends on their micro-structure and their density. Regarding this last consideration, there is no information about the TNT density that is mentioned in UFC 3-340-2 [19]. Dobratz [21] gives some parameters for TNT (Table 4).

Table 4: TNT characteristics according to [21].

	ρ_0 (g/m^3)	**P_{CJ} (GPa)**	**D_{CJ} (m/s)**
TNT (Trinitrotoluene)	1.63	21	6930

Among the existing methods for the determination of the TNT equivalent, two of them are proposed here, for their simplicity:

- The Berthelot (dating from 1892) method states that the TNT equivalent, in %, can be expressed as (1):

$$TNT\ Equivalent\ (\%) = 840\ \Delta n\ (-\Delta_d H(explosive))\ /\ M_{EXP}^2 \quad (1)$$

Where:
Δn is the number of moles of generated gases by the detonation of one mole of explosive.
$-\Delta_d H$(explosive) is the heat of detonation in kJ/mol.
M_{EXP} is the Molecular weight of the Explosive (g/mol)

- Cooper [21] proposed a practical formula giving the equivalent TNT of a high explosive from its detonation velocity (2):

$$W_{eqTNT}=D^2_{explo}/D^2_{TNT} \tag{2}$$

With D the detonation velocity.

Once the TNT equivalent is determined, the reduced distance Z (or scaled distance) of the target to the explosive charge of weight W can be deduced by (3):

$$Z=R(m)/W^{1/3}(Kg) \tag{3}$$

Knowing the reduced distance, it is possible to deduce the pressure profile using tables given by Kingery [23], Kinney & Graham [24] or UFC [19] and the modified Friedlander equation (4):

$$P(t) = P_{atm} + \Delta P_0(Z)\left(1 - \frac{t - t_a(Z)}{t_d(Z)}\right)e^{-\frac{\alpha(Z)(t - t_a(Z))}{t_d(Z)}} H(t - t_a(Z)) \tag{4}$$

With H the Heaviside function that is 1 if $t > t_a$ and 0 otherwise. α is the decay parameter given in [23], [24].

In the case that the pressure profile is directly applied on the structure, one must keep in mind that the pressure loading is not the incident pressure, but the reflected pressure on the structure.

4. Open Challenges and Objectives of the ERNCIP Thematic Group

To the ERNCIP Thematic Group "Resistance of Structures to Explosion Effects" knowledge, there are no standardized procedures to define numerical approaches that could support the design of laminated glass or window components. Despite the fact that numerical simulations of blast-loaded windows or facades could present many difficulties, numerical simulations are currently employed in order to design such kind of structures. Thus, in order to reduce possible faults and misinterpretations, a standardized procedure for numerical simulations would be helpful. Some propositions are given in order to draw a standardized procedure in the future.

On the one hand, the blast scenarios have evolved – like the threat from terrorist attacks in urban environment, kamikaze, Improvised Explosive Device (IED) or *Vehicle*-Borne Improvised Explosive Device (VBIED), industrial massive explosions. On the other hand, glazed façades are more and more used in modern infrastructures and the available standards do not represent this use. There is no harmonization between existing standards (ISO and CEN standards). These two considerations point out a need of standard evolution that could be:

1) The need of free specification of specimen size.
2) The need of detailed definition of window supports conditions.
3) The need of taking into account glazed façades in standards.
4) A harmonization of hazard classes and hazard levels.
5) The derivation of different EPR classifications (CEN, Fig. 2) for additional threats like explosions occurring from industrial sites.
6) The need of standardizing numerical simulations for protective glass modelling in civil engineering. In this topic, it is suggested to specify modelling requirements (numerical

method, element size, domain size, materials properties) but also loading conditions (fluid-structure interaction or pressure-time history). The standard should also set the expected outputs like loading necessary for first cracks appearance, panel damage, shear failure or frame resistance. In any case, it is crucial to clarify the validation process of the numerical simulation. At last, numerical results have to be interpreted and related to the corresponding classification that refers to test standards in term of hazard evaluation.

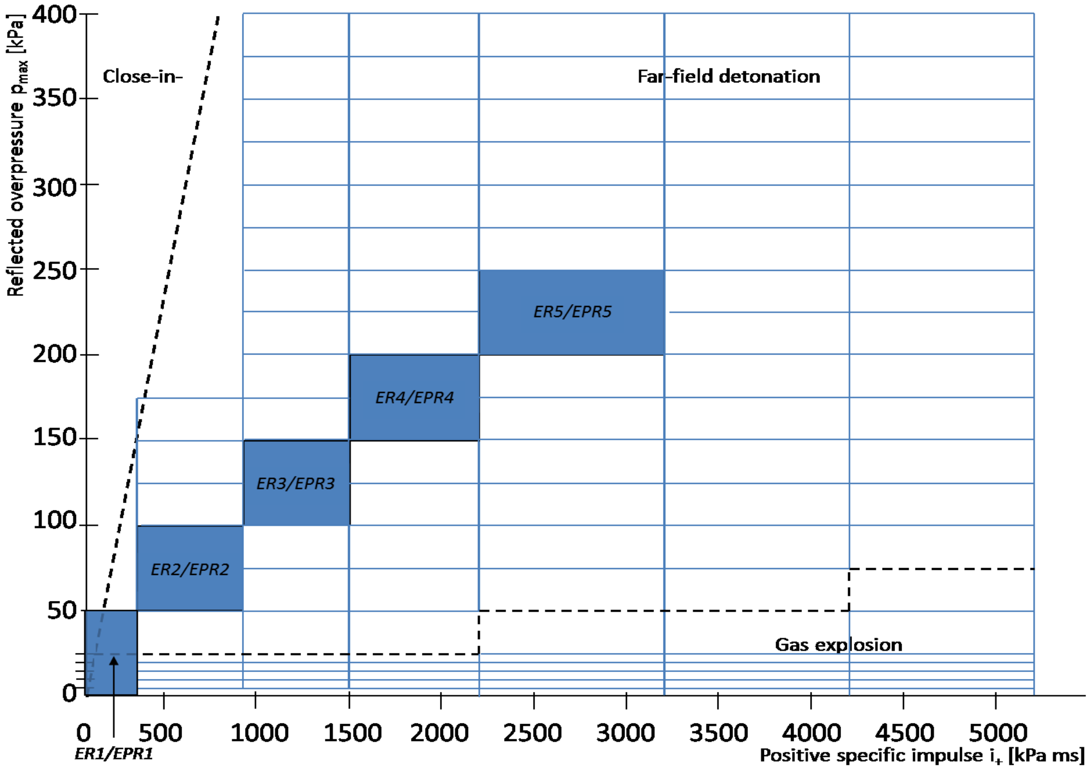

Figure 2: Proposed definition of loading levels by using a pressure-impulse (P-I) diagram for application in shock-tube tests.

5. Current Status of ERNCIP Activity

In summary of the ERNCIP Thematic Group work, existing test standards have been reviewed and differences between existing standards have been identified. The review points out for example the need of harmonization and the need to extend test standards to cover glazed façades. One of the major needs is also the development of a new standard for numerical modelling for the performance of windows and glass façades under blast loading.

At the end of the year 2016, discussions have been initiated with the CEN (European Committee for Standardization), CEN/TC 33/ Working Group n° 1 “Windows and Doors” about ERNCIP Thematic Group proposals. The related work group will further be supported from ERNCIP.

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