A comparison of existing standards for testing blast resistant glazing and windows

ERNCIP Thematic Group
Resistance of structures to explosion effects

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DECEMBER 2014

The research leading to these results has received funding from the European Union as part of the European Reference Network for Critical Infrastructure Protection project.

Report EUR 27133 EN

European Commission
Joint Research Centre
Institute for the Protection and Security of the Citizen

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JRC94930

EUR 27133 EN

ISBN 978-92-79-46168-2

ISSN 1831-9424

doi:10.2788/361383

Luxembourg: Publications Office of the European Union, 2014

Printed in Italy

European Reference Network for Critical Infrastructure Protection (ERNCIP) thematic group

Work package 2

A comparison of existing standards for testing blast-resistant glazing and windows

Thematic group:

Resistance of structures to explosion effects

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Acknowledgements:

The research leading to these results received funding from the European Union within the European Reference Network for the Critical Infrastructure Protection project hosted at the Joint Research Centre (JRC) — European Commission — Via E. Fermi 2749 — Ispra, Varese (VA), Italy.

Abstract:

It is important to protect critical buildings (shopping centres, government buildings and embassies), infrastructure and utilities, train and underground stations against being damaged, destroyed or disrupted by deliberate acts of terrorism, criminal activity and malicious behaviour. Normal regulations and building guidelines do not generally take into account these threats. The introduction of appropriate regulations or guidelines, where deemed necessary, should enhance the resilience of buildings and infrastructure against explosion incidents.
In order to protect the built infrastructure, methods are required to quantify the resistance of structural components against explosive loading and to assess the hazards resulting from the failure of an element. The applicable state-of-the-art techniques may include either experimental or numerical methods, or a combination of both.
Therefore, the thematic group (TG) on the resistance of structures to explosion effects was formed in order to bring the required expertise together, make it commonly available and to find and define harmonised methods and solutions which can be provided to the decision-makers responsible for critical infrastructure protection.
This report discusses the differences between the existing standards for testing blast-resistant glazing and windows and it presents basic recommendations for the future development of the suite of European standards in this area.

Contents

1. Introduction

The purpose of blast-resistant glazing is to reduce the risk of injury to building occupants. The performance of the blast-resistant glazing has to be validated by testing based on the requirements. The first design step is to define the explosive loading. This is best specified as blast pressure and impulse, which can be derived from a charge weight ([1]) and standoff. This is often described as the threat.

In designing blast-resistant glazing, it is usually accepted that some degree of damage to the glass is almost inevitable. The second design step is to agree the acceptable risk within the building. This is normally specified as the acceptable hazard level.

2. Scope of the report

This report discusses the differences between the existing standards for testing blast-resistant glazing and windows and presents recommendations for the future development of the suite of European standards in this area. Detailed information on shock-tube testing and arena testing are given in the review report of testing methods — Deliverable D1 of the European Reference Network for Critical Infrastructure Protection (ERNCIP) thematic area 'Resistance of structures to explosion effects (JRC87202)'.

Current standards in the defined version are the basis of this report and are listed in the list of references (see Section 8).

2.1. Explosive loading

Explosive loading can be considered in four broad cases.

1. Small charges in contact with the window or facade. This type of charge will breach the glazing, causing localised damage. It is impractical to protect against this threat.
2. Small charges representing person-borne improvised explosive devices (PBIEDs). This may be delivered as a carried improvised explosive device (IED) such as a backpack or suitcase bomb, or by a suicide bomber. These IEDs are unlikely to exceed 20 kilograms (kg) of weight. Such charges at close distance generate very high pressures with short durations.
3. Large charges representing vehicle-borne improvised explosive devices (VBIEDs). These IEDs usually range from about 25 kg on a motorbike or in a car to several tonnes in a large truck. These charges at some standoff generate high pressures with long durations. At close range the effects may be so powerful that it is impractical to design a window or facade against the blast load.
4. Industrial explosions, typically resulting from a gas cloud or other petrochemical release. These will release much larger amounts of energy than high explosives, resulting in lower blast pressures of extremely long duration.

A shock wave is generated by the detonation of an explosive loading. The pressure-time history of the generated shock wave is characterised by blast parameters. Varying symbols and units are used

([1]) The output of an explosive can be compared to that of trinitrotoluene (TNT). This ratio is known as the TNT-equivalence. Charge masses in this document are TNT-equivalent masses.

for blast parameters in the different standards. Table 1 gives an overview of symbols and units used by the different standards.

Table 1: Symbols and units used for blast parameters.

Parameter	Symbol	Unit
Peak positive pressure; peak pressure; overpressure	P; P_{max}	Kilopascal (kPa); pounds ([2]) per square inch ([3]) (psi); bar.
Classification pressure	P_c	kPa; psi; bar.
Positive phase impulse	i; i_+;I_{pos}	kPa×ms; psi×ms; psi×msec ([4]); bar ms.
Classification impulse	i_{+c};I_c;	kPa·ms; psi·ms; psi·msec; bar ms.
Impulse calculated from the measured test values	I_t;	kPa·ms; psi·ms; psi·msec; bar ms.
Effective positive phase duration	t_+; t_{pos}	Millisecond (ms).

2.2. Test methods

There are two principal methods for conducting tests of glazing against explosions.

1. Shock tubes generate relatively low pressures with long durations. They are therefore suitable for testing the effects of large VBIEDs and industrial explosions.
2. Arena tests can be used to represent small close-in charges and VBIEDs. However, noise restrictions and range safety distances make it difficult to use charges larger than 500 kg.

2.3. Terminology on glazing

In the context of this work, glazing refers to both windows and glazed facade systems. It is important to consider the window or facade as a system. This includes the glass, the gasket or sealant, the frame, the fixing of the frame, and the support system.
The blast pressure is applied to the whole area of the window or facade and the behaviour of the glass is dependent on the pane size. The loads on the support system and its performance are also dependent on the size of the glass pane(s).
If glass is tested in a rigid frame, the stresses in the glass are maximised as are the loads in the frame's fixings. However, if the glass is mounted in a frame with gaskets or sealants, the system's flexibility tends to reduce the stresses in the glass and the fixings.

2.4. Test standards

The European Committee for Standardisation (CEN) published the first standards for testing blast-resistant glazing in 2001. These include a European standard (EN) for testing security glazing alone

([2]) 1 pound is 0.4536 kilograms (kg).
([3]) 1 inch is 2.54 centimetres (cm).
([4]) msec = ms = milliseconds.

(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 only considers a single pane of glass with a single fixed size in a rigid frame under prescribed tests and boundary conditions. Due to the importance of the pane size and the system's flexibility (as noted above) this standard has limited practical utility. The standard could be amended to permit any pane size to be tested. It should be noted that this standard produces conservative results, but may provide a usual limit case for the glass. This standard only makes provision for testing with a shock tube.
EN 13123-1:2001 and EN 13123-2:2004 consider the whole window system and permit it to be tested at its real size and with its real frame, producing realistic results. These standards make provision for testing with a shock tube and arena testing with small charges.
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 actual test loads are not included as they are classified.
The International Organisation for Standardisation (ISO) ISO 16933:2007 standard was published in 2007. It was largely based on the EN standards. It extended the test conditions to allow the use of large charges in range tests. It also included additional small charges to encompass the GSA test requirements. A parallel standard (ISO 16934:2007) covers shock-tube testing. The American Society for Testing and Materials (ASTM) standard (ASTM F 1642:2004) was developed in parallel with the ISO standards.

2.5. Hazard level

As mentioned above, in explosion testing, it is accepted that some degree of damage to the glass is almost inevitable. The purpose of blast-resistant glazing is to reduce the risk of injury to the building's occupants. Blast leakage, minor damage and glass fragments are allowed as long as they do not exceed specified criteria. As standards have been developed, these criteria have become better defined.
EN 13541:2012 does not allow any holes (breakthrough from the attack to the protective face) in the glass or between the glass and the frame. It permits an additional designation of splinters (S) or no splinters (NS) to be awarded. Splintering is defined as cracking of the rear (protective) face or small fragments (glass dust) being launched from the rear face.
EN 13124-1:2001 and EN 13124-2:2004 do not allow any opening that can be penetrated with a stiff rod of 10 millimetres (mm) in diameter. No part of the frame or gaskets can become detached. As in EN 13541:2012, splintering needs to be identified and registered as S or NS.
GSA-TS01:2003 adopted the United Kingdom (UK) hazard-rating levels with minor modifications. This rating system is based on the projection of the glazing debris into a 3 metre (m) deep cubicle.
In ISO 16933:2007 and ISO 16934:2007 more sophisticated hazard criteria were adopted. Finally, these standards allow a classification into hazard levels with regard to the observed damage. The UK hazard-rating levels were adapted to include better definitions of allowable fragments and permitted pull-out of the glass from the frame.

3. Mounting of elements

This section describes the mounting of the test specimens into the installation of a test set-up. A distinction between shock-tube tests and arena tests is made. Table 2 and Table 3 document the findings regarding this considered point. Later in this section the boundary conditions of the standards will be compared and evaluated regarding practicability. Gaps will be identified and recommendations for improvements will be given.

3.1. Requirements defined by current standards

Table 2: Mounting of test specimens in shock-tube tests for the considered current standards.

Standard	Description
EN 13541:2012	— Stiff support, massive substructure, line support with support of the glazing in rubber and clamp-pressure of 14 ± 3 newtons (N) per square centimetre (cm) N/cm^2. — Dimensions of test specimens: 900×1 000 mm.
EN 13123-1:2001	— No requirements as the standard only concerns the definition of requirements and classification of windows, doors and shutters having explosion resistance.
EN 13124-1:2001	— A stiff frame or stiff sub-construction is required for fixing the specimen. Specific requirements are as follows. • High stiffness to avoid deformations of the substructure. • A realistic mounting of the sample without restraining stresses shall be possible. • The substructure must attach the specimen to the shock tube and prevent the explosion pressure escaping; no lateral gaps. • The mounting of pressure transducers shall be possible (if required). • Fittings, mechanisms, movable frames and door leaves must remain operable prior to the test.
GSA-TS01:2003	— Realistic mounting according to applications in the building structure, enclosed structure required to avoid blast loading on the protected face of the glass, test reaction structures non responding relative to the test specimens (6.4.1).
ASTM F 1642:2004	— Enclosed substructure to avoid blast loading on the protected face of the glass, simple sub-construction, special conditions possible at the request of the customer, windows: realistic (practical) mounting, maximum deflection sub-construction l/360 of span; witness area behind (see Section 8.4. and following in ASTM F16424:2004).
ISO 16934:2007	— Element support by rigid test frame securely attached to shock tube vertically, sufficiently stiff for repeated application of test loads without permanent distortion. — Reaction structure form: be integral with a rigid shield around edges of test specimen that meets the walls of the shock tube and prevents the escape of blast pressure other than through deformation or

	design intention of the test specimen. Support along full length of all four edges. — Specimen dimensions: (1 000 ± 5) × (800 ± 5) mm^2; bottom edge between 0.5 m and 1.0 m above the floor of witness area; edge capture of not less than 45 mm (all edges). — Specimens separated from frame and clamping plate by continuous rubber strips: dimensions: 4 ± 0.5 mm×50 ± 5 mm, hardness (50 ± 10) international rubber hardness degrees (IRHD) (ISO 48:1994); at bottom of rebate, seated on rubber strips, 4 mm (hardness (50 ± 10)), width equal to the full thickness of the test specimen. — All four edges clamped: clamping pressure of (14 ± 3) N/cm² (if supplied in own unique frame or fenestration assembly: attach to reaction structure as directed by manufacturer and in a manner that closely models the manner in which it will be mounted in the field). — Non-standard test specimens may be mounted at heights above the fragment-collection mat appropriate to the manner in which they will be mounted in the field. Attack surface aligned in a plane positioned in relation to attack surface of test frame/reaction structure. — Attack surface not more than 25 mm behind surface of test frame, reaction structure inside the shock tube to minimise entrapment, enhancement of blast effects; specimen placed normal to direction of explosive shock wave with accuracy of +2° in any orientation. — Witness panel (width > 2 m if contained within sides (see above), else width > 2.4 m (non-ductile, foam insulation board, material equivalent to extruded polystyrene, polyisocyanurate or urethane, density (30 ± 5) kg/m³), one or two layers of combined thickness of at least 35 mm), (3 000 ± 150) mm behind each test piece parallel to specimen surface, height of level of collecting mat to 200 mm over test specimen; removable face layer thickness > 12 mm, faced with contiguous sheets of aluminium foil (thickness < 0.025 mm) or cartridge paper (weight 100 g/m² to 150 g/m²).

Table 3: Mounting of test specimens in arena tests for the considered current standards.

Standard	Description
EN 13123-2:2004	Wall connection should have the same resistance level as the window/door.
EN 13124-2:2004	A stiff frame or stiff substructure is required for fixing the sample. Specific requirements are as follows. (a) High stiffness to prevent deformation of the substructure caused by blast loads or transmission of deformations from the substructure to the sample. (b) A realistic mounting of the sample without restraining stresses shall be possible. (c) Enclosed substructure that prevents air-blast pressure from wrapping behind the sample. No lateral gaps. (d) Mounting of pressure transducers shall be possible — if required. (e) Minimum dimensions 2.4 × 2.4 × 0.8 m (width × depth × height) with a minimum lateral overlap of 0.2 m and a minimum distance between the sample and the backside of the substructure of 0.8 m. (f) Samples shall be mounted 0.8 m above the ground (parapet height). Samples shall be mounted in a proper way so that the original functionality of the samples is ensured (usability of joints, etc.).
GSA-TS01:2003	Realistic mounting according to application in the building structure,

	enclosed structure required to avoid blast loading on the protected face of the glass, test reaction structures non responding relative to the test specimens (see Section 6.4.1).
ASTM F 1642:2004	Enclosed substructure avoids blast loading on the protected face of the glass, simple sub-construction, special conditions customer possible, windows: realistic (practical) mounting, maximum deflection sub-construction l/360 of span; witness area behind (see Section 8.4 and the following in ASTM F 1642:2004).
ISO 16933:2007	Distinction between test frame (testing glass) and reaction structure with the following requirements. (a) Test specimens (vision size × 800 mm) shall be mounted on a test frame along the full length of all four edges. The test frame and reaction structure shall be capable of resisting the air blast with deflections that do not exceed L/360, where L denotes the dimension of a test frame or reaction structure member measured between the lines of support. (b) The test frame shall be fixed securely in a vertical position to the reaction structure. The test frame shall be provided with clamping plates to hold each glazing in position and means for producing uniform clamping of the glazing. Bolt spacing of not more than 100 mm is recommended around the perimeter of each glazing. (c) The test specimens shall be mounted in a manner that meets the following requirements. — Mount standard-sized test specimens so that the bottom edge is between 0.5–1.0 m above the floor of the witness area. — Each test specimen shall have an edge capture of not less than 45 mm on all edges. — Each test specimen shall be separated from the test frame and the clamping plate by continuous rubber strips (4 ± 0.5 mm thick, 50 ± 5 mm wide, hardness 50 ± 10 IRHD in accordance with ISO 48:1994). — At the bottom of the rebate, each test specimen shall be seated on rubber strips (4 ± 0.5 mm thick, hardness 50 ± 10 IRHD in accordance with ISO 48:1994 and of width equal to the full thickness of the test piece). — All four edges of each test specimen shall be uniformly clamped with a clamping pressure of 140 ± 30 kN/m². For testing window assemblies. (d) If the glazing is supplied with its own unique frame or in a fenestration assembly, it shall be attached to the reaction structure as directed by the manufacturer and in a manner that closely models the manner in which it will be mounted in the field. Non-standard test specimens may be mounted at heights appropriate to the manner in which they will be mounted in the field. For both glass and window tests the following requirements on the substructure apply. (e) All test specimens and witness panels shall be completely enclosed in a structure designed to prevent air-blast pressure from wrapping behind the test specimens. (f) Unless otherwise specified, each test frame shall be placed so that the test specimens are oriented perpendicular to a line from the detonation point to the centre of the test frame in order that they experience reflected pressures. A vertically mounted test specimen is assumed. (g) If the reaction structure is oriented perpendicular to the line of the

	detonation point, the face of the reaction structure should not be less than 2.4 × 2.4 m. This is in order to avoid excessive reductions in reflected impulse that arise owing to the effects of blast clearing from the edges of small targets. (h) Any other orientation shall be agreed with the test sponsor in advance of testing and shall be recorded as it can affect failure modes and hazard ratings.

3.2. Remarks and comments

Based on review report of testing methods — deliverable D1 (JRC87202) and the recommendations of the reviewed standards — the following remarks should be considered for mounting the specimens properly.

- A stiff substructure is required to resist the expected loading level without significant deformations that influence the response of the test specimen.
- A closed substructure is required to prevent the explosion pressure escaping (shock tube) or, in the case of a closed container/box, the air blast wrapping round the sample.
- Connections between the test specimen and the supporting substructure are not within the focus of this test. But they should be made in such a way that they represent a realistic scenario and the expected failure mode.
- For testing glass, the clamping pressure can have a significant effect on the test results and should be specified as ISO 16933:2007, ISO 16934:2007 and EN 13541:2012.

3.3. Recommendations for improvements

Based on the remarks and comments given in Section 1, the following recommendations can be derived.

Shock tube

The test frame is integrated in a wall connection. Normally this connection is built of reinforced concrete or with quite a strong steel beam construction: e.g. a HEB 260 steel beam with a length of 3 m does not have measurable deformations for most blast scenarios. As a consequence no deformations are transferred to the test frame or to the specimen.
The manufacturer or the testing institute should supply a sufficiently rigid test frame. The test frame with the specimen is mounted in/on the shock tube.
A complete airtight sealing of the joint between the test specimen and the substructure or a completely airtight enclosed substructure (container, box, etc.) can only be achieved with great efforts. Nevertheless, it has to be assured that the resulting leaking pressure does not influence the loading conditions and the response of the specimen.
For facade systems, the influence of the supporting substructures (e.g. cables, bolts, spiders, shock absorbers, etc.) has to be considered in the design and realisation of the test set-up.
Since facade systems become more relevant, blast tests on complete systems should be applicable, thus flexible boundary conditions (fixation of the glazing elements to the supporting substructure) should be realisable [EN 13123-1:2001 and EN 13124-1:2001].

Arena test

Recommendations on the substructure regarding stiffness, airtight sealing, etc. as mentioned before for shock-tube testing apply also for arena tests. Besides this, the area surrounding the test specimen should be sufficient to avoid the effects of clearing. The test institute should be able to show that the pressure acting on the test specimen meets the specified loading and is not affected by clearing.

4. Loading conditions

This section focuses on the boundary conditions of the generation of the blast load for a classification. Important loading parameters are described to be fulfilled in the test configurations.

4.1. Requirements defined in current standards

Loadings in shock-tube tests are an idealised one dimensional part of a spherical blast wave generated through either a sudden release of gas into the shock tube or the detonation of a small explosive charge. The loading in an arena test is provided by the detonation of a charge of a certain mass and a certain distance to the structure. In both cases the blast parameters are specified to represent the required loading scenario. Table 4 and Table 7 document the relevant findings.

Table 4: Loading conditions of test specimens in shock-tube tests for the considered current standards.

Standard	Description
EN 13541:2012	— No detailed description, reference to EN 13123-1:2001 Annex A and there reference to EN 13124-1:2001. — Required reflected pressure and impulse (see Table 6) and duration of positive phase according to required level of explosion resistance. — Mounting of test specimen, definition of loading properties to be reached, generation of loading wave, measurement of pressure over time of reflected wave, evaluation of reached wave properties, repeat test on two other test specimens.
EN 13123-1:2001	— No requirements as the standard only concerns the definition of requirements and classification of windows, doors and shutters having explosion resistance.
EN 13124-1:2001	— Shock waves are to be generated by a shock tube or similar device which is able to simulate a pressure wave. — At least the prescribed values for peak pressure, possible phase duration and impulse are to be achieved. — Reflected pressure values are to be measured. — For classification in an EPR class -5 % is permitted for the peak pressure. — Decay coefficient has to be between 0 and 4. — The measured values have to be lower than those of the next higher class. — There are upper limits for EPR4: P_{max} = 2.5 bar, i_+ = 32 bar ms. — In shock tubes a negative phase does not need to be present.
GSA-TS01:2003	— A high-explosive source shall be used to generate the desired peak pressure and the positive phase impulse on the test specimen. — Alternative explosives can be used as long as the desired waveform characteristics are produced and the corresponding peak overpressure and positive phase impulse are obtained. — The charge shall be hemispherical and detonated at ground level. — Other charge configurations can be used, but must be

	accounted for and documented. — A blast mat, concrete pad or sand pit may be used to reduce the potential for ejecta debris from the crater.
ASTM F 1642:2004	— A high-explosive charge shall be used to generate the desired peak overpressure and the positive phase impulse. — The charge shall be hemispherical and detonated at ground level or at an elevated position (between 60 and 120 cm above the ground where the charge will be detonated) — Other charge configurations and explosives can be used, but must be accounted for and documented for information to be used in calculating pressures, impulses, and durations.
ISO 16934:2007	— Required reflected pressure and impulse (table) according to required level of explosion resistance; mount test specimen in frame and position in shock tube. — Recording inspection results: ambient pressure, relative humidity, ambient shade temperature, protected/rear face surface temperature (test specimen); within 30 minutes of the test and verification regarding criteria for a test leading to classification. — Provide shock tube and specimen with appropriate shading if necessary to avoid heat build-up or loss from sun or wind chill until the test takes place. — Sweep protected fragment collecting area of any debris and fragments. — Set witness panel in place, carry out appropriate safety procedures and prepare for test. — When classification is required, repeat the test and evaluation on another two specimens in order to determine an overall rating and classification.

A classification of the blast resistance regarding reflected pressure (peak pressure) and impulse is given in ISO 16934:2007 and EN 13541:2012 as shown below.

Table 5: Loading conditions of test specimens in shock-tube tests described in ISO 16934:2007.

Classification Code ([a])	Minimum values ([b])	
	Peak pressure Pc [kPa]	Impulse Ic [kPa-ms]
ER30 (X)	30	170
ER50 (X)	50	370
ER70 (X)	70	550
ER100 (X)	100	900
ER150 (X)	150	1 500
ER200 (X)	200	2 200
([a]) In the classification code the letters, i.e. 'ER', refer to the classification code, the number designates the peak pressure, expressed in kilopascals and the (X) denotes the hazard rating received during the test; for example classification ER100 (C) would apply to a test in which a standard blast having peak blast pressure of 100 kPa and positive phase impulse of 900 kPa-ms resulted in damage to the glazing resulting in hazard rating C.		

([b]) For the following conditions: the positive phase duration should be not less than 20 ms except for ER30 (X) (30 kPa), for which a duration of about 15 ms can be expected. The recorded pressure-time trace shall conform to an idealised curve having a modified Friedlander decay coefficient (waveform parameter) assessed as lying between 0 and 4. Refer to Annex A for definitions.

Table 6: Loading conditions of test specimens in shock-tube tests described in EN 13541:2012.

Classification Code from EN 13541:2012	Characteristics of the plane shock wave (plane blast front)		
	Positive maximum overpressure of the reflected blast p_r [kPa]	Positive specific impulse I_+ [kPa-ms]	Duration of positive phase t_+ [ms]
ER1	$50 \leq p_r < 100$	$370 \leq i_+ < 900$	≥ 20
ER2	$100 \leq p_r < 150$	$900 \leq i_+ < 1500$	≥ 20
ER3	$150 \leq p_r < 200$	$1\,500 \leq i_+ < 2\,200$	≥ 20
ER4	$200 \leq p_r < 250$	$2\,200 \leq i_+ < 3\,200$	≥ 20

Table 7: Loading conditions of test specimens in arena tests for the considered current standards.

Standard	Description
EN 13123-2:2004	— No requirements as the standard only concerns the definition of requirements and classification of windows, doors and shutters having explosion resistance.
EN 13124-2:2004	— Spherical charge of Trinitrotoluene (TNT) of varying mass and melting point between 80.4–80.9 degrees Celsius (°C). — Further requirements on the charge regarding the following. • Final density ≥ 15180 kg/m³. • The spherical charge shall be composed of two hemispheres with a radius tolerance of ± 4 %. • The mould for producing the hemispheres shall be filled equally in layers of 50 mm thickness with TNT of about 90 ± 2 °C. — Further requirements are prescribed in EN 13124-2:2004 regarding charge preparation. — Near-surface shrinkage cracks shall not exceed 0.5 mm in width and 10 mm in depth. — The ignition charge shall be placed in the centre of the sphere. — The centre of the charge shall be placed in front of the test specimen at corresponding standoff distance with a tolerance of ± 25 mm and at corresponding height. — A non-fragmenting support shall be used for placing the charge (e.g. polystyrene). — The test arena around the charge shall be paved with concrete or comparable material. — An additional steel plate with maximum thickness of

	100 mm can be placed under the charge. — The charge shall be detonated from its centre in a way that an instantaneous and complete detonation of the charge is ensured.
GSA-TS01:2003	— A high-explosive source shall be used to generate the desired peak pressure and the positive phase impulse on the test specimen. — Alternative explosives can be used as long as the desired waveform characteristics are produced and the corresponding peak overpressure and positive phase impulse are obtained. — The charge shall be hemispherical and detonated at ground level. — Other charge configurations can be used, but must be accounted for and documented. — A blast mat, concrete pad or sand pit may be used to reduce the potential for ejecta debris from the crater.
ASTM F 1642:2004	— A high-explosive charge shall be used to generate the desired peak overpressure and the positive phase impulse. — The charge shall be hemispherical and detonated at ground level or at an elevated position (between 60 and 120 cm above the ground where the charge will be detonated). — Other charge configurations and explosives can be used, but must be accounted for and documented for information to be used in calculating pressures, impulses, and durations.
ISO 16933:2007	— Distinction between 'vehicle bombs' and 'hand-carried satchel bombs' based on the intended classification class. Classification criteria and corresponding nominal charge sizes and standoff distances are given in Table 9 and Table 10 for vehicle bombs and in Table 11and Table 12 for hand-carried satchel bombs.

Table 8: Classification class and corresponding charge mass and standoff distance (EN 13123-2:2004).

Class	Charge mass [kg]	Standoff distance [m]	Charge height [mm]
EXR1	3	5	500 ± 50
EXR2	3	3	500 ± 50
EXR3	12	5.5	800 ± 50
EXR4	12	4	800 ± 50
EXR5	20	4	800 ± 50

Table 9: Classification criteria for vehicle bombs (ISO 16933:2007).

Classification code ([a])	Mean peak air-blast pressure [kPa]	Mean positive phase impulse [kPa-ms]
EXV45(X)	30	180
EXV33(X)	50	250
EXV25(X)	80	380
EXV19(X)	140	600

EXV15(X)	250	850
EXV12(X)	450	1 200
EXV10(X)	800	1 600
([a]) In the classification code, the letters, i.e. 'EXV' refer to the type, i.e. a vehicle bomb; numbers denote a nominal standoff distance, expressed in meters, when a charge of 100 kg TNT equivalent is placed at a point perpendicular to the surface of the test specimen when mounted in a reaction structure (test cubicle) of face size about 3 × 3 m and (X) denotes the hazard rating received during the test. For example, classification code EXV25(C) applies to a test in which a standard blast having peak air-blast pressure of 80 kPa and positive phase impulse of 380 kPa-ms, resulting in damage to the glazing resulting in hazard rating C.		

Table 10: Nominal charge sizes and standoff distances for typical test frames compared to those normal to a large facade calculated to equate to the blast values for the vehicle-bomb classifications (ISO 16933:2007).

Classification code	**Classification criteria blast values ([a])**		**Nominal standoffs ([b]) of approx. 100 kg TNT for a small test frame**	**Calculated nominal equivalents ([c]) to a large facade**	
	Pressure [kPa]	**Impulse [kPa-ms]**		**TNT equivalent size [kg]**	**Standoff distance[m]**
EXV45(X)	30	180	45	30	32
EXV33(X)	50	250	33	30	23
EXV25(X)	80	380	25	40	19
EXV19(X)	140	600	19	64	17
EXV15(X)	250	850	15	80	14.4
EXV12(X)	450	1 200	12	100	12.4
EXV10(X)	800	1 600	10	125	11
([a]) See Table 9. ([b]) Derived from test measurements of reflected blast values on the face of vertical 3.15 × 3.15 m test frames positioned at standoffs from 100 kg TNT equivalent charges placed 1.2 m above a hard surface to exceed the classification criteria. ([c]) Calculated assuming hemispherical surface bursts on the ground at standoffs normal to the vertical face of large facades.					

Table 11: Classification criteria for hand-carried satchel bombs (ISO 16933:2007).

Classification code([a])	**Mean peak air-blast pressure [kPa]**	**Mean positive phase impulse [kPa-ms]**
SB1(X)	70	150
SB2(X)	110	200
SB3(X)	250	300
SB4(X)	800	500
SB5(X)	700	700
SB6(X)	1 600	1 000
SB7(X)	2 800	1 500
([a]) In the classification code the letters, i.e. 'SB', refer to the type, i.e. a hand-carried satchel bomb, the number designates the standard blast and (X) denotes the hazard rating received during the test. For example, classification SB4(C) applies to a test in which a standard blast having		

peak air-blast pressure of 800 kPa and positive phase impulse of 500 kPa-ms resulted in damage to the glazing resulting in hazard rating C.

Table 12: Nominal charge sizes and standoff distances for typical test frames compared to those normal to a large facade calculated to equate to the blast values for the satchel bomb classifications (ISO 16933:2007).

Classification code	Classification criteria blast values ([a])		Nominal charge mass and standoffs ([b]) for a small test frame		Calculated nominal equivalent ([c]) to a large facade	
	Pressure [kPa]	Impulse [kPa-ms]	TNT equivalent charge size [kg]	Standoff distance [m]	TNT equivalent charge size [kg]	Standoff distance [m]
SB1(X)	70	150	3	9	3.25	9.00
SB2(X)	110	200	3	7	3.50	7.26
SB3(X)	250	300	3	5	3.50	5.07
SB4(X)	800	500	3	3	3.70	3.40
SB5(X)	700	700	12	5.5	12.00	5.26
SB6(X)	1 600	1 000	12	4	12.60	4.06
SB7(X)	2 800	1 500	20	4	21.00	4.00

([a]) See Table 11.
([b]) Derived from test measurements of reflected blast values on the face of vertical 2.4 × 2.4 m test frames positioned at the standoffs listed from charges of TNT equivalent mass listed to exceed the classification criteria. The charges were positioned at the distances above the hard surfaces as defined above.
([c]) Calculated assuming hemispherical surface bursts on the ground at standoffs normal to the vertical face of large facades.

4.2. Remarks and comments

Based on the review report of testing methods: Deliverable D1 (JRC87202) and the overview above, the following remarks and comments can be made.

- Test standards are very similar in terms of loading levels.
- The European standards do not consider loading scenarios for VBIED in the arena test, unlike the ISO standard.
- Test scenarios cover only high-explosive events and do not represent petrochemical explosions.

4.3. Recommendations for improvements

Based on the remarks and comments given in Section 1, the following recommendations are given.

- The European standards should be extended to include arena tests to represent VBIEDs.
- An option for user-defined loading scenarios should be included to represent either high-explosive or petrochemical events.

- The loading scenario should be defined using blast parameters according to Table 1 and allowed tolerance such as that defined in ISO 16933:2007 and ISO 16934:2007. A definition purely based on charge mass and standoff distance is not sufficient.
- The type and shape of the charge should not to be specified as long as the correct blast parameters are applied to the test specimen. The use of spherical or hemispherical charges represents an ideal, but not a realistic scenario. Furthermore, the use of spherical charges made of TNT is cost-intensive. Therefore, alternative explosives, such as ammonium nitrate/fuel oil (ANFO), should be used in order to consider realistic loading scenarios resulting from a VBIED or PBIED.

5. Measurement technique

This section documents the required measurement technique to be used in the tests set-ups. Besides the required sensor-solutions, measuring loading properties and response of the structural elements, their properties and characteristic are summarised as well. For example the sensitivity and the sampling rate is an important measure to be fulfilled in such fast running tests.

5.1. Requirements defined by current standards

Table 13 and Table 14 document the relevant findings of the test standards for shock-tube and arena tests, respectively.

Table 13: Measurement technique provided for in current standards for shock-tube tests measuring the relevant loading parameters.

Standard	Description
EN 13541:2012	– Pressure measurement equipment required (without documentation of position and number of sensors) measuring the reflected pressure on the attack face of the test specimen, (with a accuracy of ± 5 %); reference to EN 13123-1:2001 (Annex A): A.6: shock wave properties to be recorded with electronic recording systems, 2 pressure sensors, in EN 13123-1:2001reference to EN 13124-1:2001. Measurement technique has to consist of the following. (a) Temperature sensors for ambient temperature and surface temperature (protective face): measurements within 30 minutes prior to the test (accuracy ± 1 °C). (b) Pressure sensor measuring ambient pressure (accuracy ± 2 mbar). (c) Pressure sensors and systems for recording loading wave, recording of pressure differences of less than 0.1 ms (sample rate: 10 kHz) accuracy ± 5 % of the peak overpressure.
GSA-TS01:2003	– Photographic equipment shall be available to document the test (high-speed photography (500–1 000 frames per second (fps)); normal speed video, and photography. – A minimum of two air-blast pressure transducers shall be used on each test reaction structure to measure the pressure-time waveform acting on the exterior surface of tested specimens.

	— A minimum of one interior pressure transducer is required in each test structure. — The air-blast pressure transducers shall be capable of capture the anticipated air-blast pressure-time history within the linear range of the transducer. — The transducers shall have a rise/response time and resolution sufficient to capture the complete event. — The data-acquisition system (DAS) shall consist of either an analogue or digital recording system with a sufficient number of channels to accommodate the pressure transducers and any other electronic measuring devices.
ASTM F 1642:2004	— A minimum of three reflected pressure transducers shall be used in the test frame. — The air-blast pressure transducers shall be capable of capturing the anticipated air-blast pressure-time history within the linear range of the transducer. — The transducers shall have a rise/response time and resolution sufficient to capture the complete event. — Limited low-frequency response transducers shall have a discharge-time constant equal to approx. 30–50 times the initial positive phase duration of the anticipated reflected air-blast pressure history. — The DAS shall consist of either an analogue or digital recording system with a sufficient number of channels to accommodate the pressure transducers and any other electronic measuring devices. — The DAS must operate at a sufficient high frequency to record reliably the peak positive pressure. — The DAS shall also incorporate filters to preclude alias frequency effect from the data. — Photographic equipment shall be available to document the test. — Temperature measuring device shall be used to accurately measure the glazing-surface temperature. — A witness panel shall be mounted parallel to the interior face of the specimens. — The witness panel shall cover the entire back wall of the witness area and shall consist of two layers of material. Rear layer: extruded Styrofoam; Front layer: rigid foam plastic thermal insulation board of polyisocyanurate foam.
ISO 16934:2007	— Pressure measuring equipment (2 reflected pressure transducers) shall permit determination of magnitude, above ambient pressures, time development of reflected shock wave impinging on the test specimen; calibration records be maintained (demonstrate that the equipment can measure pressure with an accuracy of ± 5 %, with rise-time sensitivity response to peak pressure 10 µs). — Record-intervals of pressure < 0.01 ms (>100 kHz), trigger offset: > 10×t+ before the shock wave reaches the test specimen. — Pressure gauges be positioned enable accurate determination of reflected pressure-time signal (at the centre of the test specimen). — Gauges be calibrated against gauges set in centre of rigid blanking plates fixed in test specimen support (special pre-tests).

	— Calibration records demonstrate that either readings are identical in the two locations or provide means of adjusting the test-location gauge readings to values that accurately represent the reflected pressure-time values at the centre of the test specimen. — Examine protected/rear face of test specimen for breakage/cracking of any surface or laminate layer and for any openings between back and front. Results should be recorded in descriptions of all cracks, tears, openings, and pull-outs. — Images of test specimen, fragment collecting area and witness panel before test.

Table 14: Measurement technique provided for in current standards for arena tests measuring the relevant loading parameters.

Standard	Description
EN 13124-2:2004	— The following data have to be measured: (a) ambient temperature (b) ambient air-pressure (c) surface temperature of the specimen (d) relative humidity (e) pressure–time history (if required). — Furthermore, the specimen shall be documented by photography prior to and post test. If required, the test can be recorded by high-speed cameras. — Additional requirements on the measuring technique (sensors, data acquisition, etc.) in terms of measuring range, accuracy and calibration are not given. This comprises also the placement of pressure transducers, which arrangement influences the recorded data.
GSA-TS01:2003	— Photographic equipment shall be available to document the test (high-speed photography (500–1 000 fps); normal speed video, and photography. — A minimum of two air-blast pressure transducers shall be used on each test reaction structure to measure the pressure-time waveform acting on the exterior surface of tested specimens. — A minimum of one interior pressure transducer is required in each test structure. — The air-blast pressure transducers shall be capable of capturing the anticipated air-blast pressure-time history within the linear range of the transducer. — The transducers shall have a rise/response time and resolution sufficient to capture the complete event.

	— The DAS shall consist of either an analogue or digital recording system with a sufficient number of channels to accommodate the pressure transducers and any other electronic measuring devices.
ASTM F 1642:2004	— A minimum of three reflected and one free-field air-blast transducers shall be used in each test frame or in a separate transducer panel for arena tests. — The air-blast pressure transducers shall be capable of defining the anticipated air-blast pressure-time history within the linear range of the transducer. — The transducers shall have a rise/response time and resolution sufficient to capture the complete event. — Limited low-frequency response transducers shall have a discharge-time constant equal to approx. 30–50 times the initial positive phase duration of the anticipated reflected air-blast pressure history. — The DAS shall consist of either an analogue or digital recording system with a sufficient number of channels to accommodate the pressure transducers and any other electronic measuring devices. — The DAS must operate at a sufficient high frequency to record reliably the peak positive pressure. — The DAS shall also incorporate filters to preclude alias frequency effect from the data. — Photographic equipment shall be available to document the test. — Temperature measuring device shall be used to accurately measure the glazing-surface temperature. — A witness panel shall be mounted parallel to the interior face of the specimens. — The witness panel shall cover the entire back wall of the witness area and shall consist of two layers of material. Rear layer: extruded Styrofoam; Front layer: rigid foam plastic thermal insulation board of polyisocyanurate foam.
ISO 16933:2007	— Pressure transducers (a) A minimum of three air-blast pressure transducers shall be mounted on the exterior of each reaction structure. The air-blast pressure transducers shall be flush with the surface of the reaction structure on the air-blast side. The transducers shall be located such that the pressure and impulse in the centre of each test specimen can be computed. As an alternative, the pressure transducers may be installed on a transducer panel of the same size as the test frame and located and oriented in the same manner with respect to the charge as the test frame. (b) All pressure transducers shall be capable of defining the anticipated air-blast pressure history within the linear range of the transducer. Each transducer shall have a rise/response time and resolution sufficient to capture the complete event. Limited low-frequency response transducers shall have a discharge-time constant equal to approximately 30–50 times the initial positive phase duration of the anticipated air-blast pressure history. Calibration records shall be maintained that demonstrate the equipment can measure pressure within

	an accuracy of ± 5 %. (c) At least one free-field pressure transducer shall be used in each test. The free-field pressure transducer shall be located at least 5 m or the width of the reaction structure, whichever is greater, from any reaction structure and at the same horizontal distance from the high-explosive charge as the centre of the glazing. (d) Optionally, appropriate pressure transducers may also be located within the enclosure behind the glazing to measure the pressure within the protected area during the blast. All pressure transducers shall be attached to the DAS and tested prior to the blast to verify proper operation. — The DAS (a) The DAS shall consist of either an analogue or a digital recording system with a sufficient number of channels to accommodate all pressure transducers and any other electronic measuring devices. (b) The DAS shall operate at a minimum sampling rate of 100 000 samples per second with a rise-time sensitivity response to peak pressure of 10 ms. A higher sampling rate is recommended for the satchel tests. (c) The system shall be capable of recording reliably the peak positive air-blast pressure and the complete pressure-time trace through the negative phase loading as well. The DAS shall also incorporate filters to exclude alias frequency effects from the data. — Further equipment (a) Adequate photographic equipment shall be available to document the test. (b) A temperature measuring device shall be used to accurately measure glazing-surface temperature and air temperature no more than 30 minutes prior to the blast. (c) A witness panel of deformable material should be positioned behind the test specimen in order to register the incidence of material forcibly detached from the test specimen during test. A detailed description of the witness panel is given in Section 6.6 of ISO 16933:2007.

5.2. Remarks and comments

The best location to measure the pressure history on the attacked side would be in the middle of the test specimen, because the highest reflected impulse usually appears there. In most instances, this is not feasible, because of three reasons: first, the eigenfrequency of the glazing can have a significant effect on the measurement. Second, pressure transducers are a considerable cost factor and could be destroyed during the test. Third, the pressure transducer on the glazing would influence the response of the glazing.

For that reason it is recommended to measure the signal at the edges of the test object or on a more rigid part of it. Nevertheless, statements about the pressure conditions in the middle of the pane are possible, if the test is conducted in a well-known, calibrated test bench or if, e.g. in case of arena tests, a rigid cubicle having transducers in the middle and the same dimensions and standoff distance

as the test cubicle is erected. Additionally, the pressure history in the middle can also be calculated by numerical methods based on a validated numerical model and the pressure records at the edges.

5.3. Recommendations for improvements

A sufficient number of pressure transducers should be used to record the reflected pressure in both shock-tube and arena tests. What is sufficient depends on the test set-up.
Furthermore, the incident pressure should be recorded by side-on pressure measurements to ensure full detonation of the charge in arena tests. An additional pressure transducer inside the test cubicle is recommended to document leak pressure wrapping round the samples.
A calibration of the experimental set-up should allow for a validation of the pressure–time history.
It is also recommended to adopt measurements of the circumstances, such as temperature, humidity and ambient pressure. Likewise pictures of the specimen prior to and post test.

6. Interpretation of results

This section is focused on the interpretation of the results. Beside the loading properties the behaviour of the test specimens regarding cracking and fragmentation is considered. It also describes the contents of a test report according to the current standards and documents the experimental findings. A comparison is made regarding the evaluation of the damage in current standards and the definition of classification levels.

6.1. Requirements defined by current standards

Table 15 and Table 16 summarise the relevant findings and the contents of a test report for shock-tube tests and arena tests, respectively.

Table 15: Interpretation of the experimental results and contents of a test report according to current standards for shock-tube tests.

Standard	Description
EN 13541:2012	— No detailed description documented in test standard, only the requirement of issuing of a test report after the test with all test parameters. — Ambient climate conditions, properties of the loading wave, comparison of the test result (material status) with the requirements according test standard (ER level, S/NS). — Contents of the test report: • name and address of test laboratory, • test report identification (ID), • date of test, • reference to standard, • name of glazing product, • name and address of producer and submitter of specimens, • description of construction (material, number, thickness, sequence of layers) attack face, • temperature of storage before test, • climate conditions during tests, • characteristics of shock wave, • class and resistance against explosive blast including suffix S/NS.
EN 13123-1:2001	— The test specimen has to be exposed to a shock wave according to requirements defined in Table 1 of EN 13123-1:2001. — After testing the sample, the degree of damage may not exceed the specified criteria of EN 13124-1:2001.
EN 13124-1:2001	— After testing the specimen for its explosion resistance, the following criteria have to be fulfilled. (a) The test specimen shows no opening that can be penetrated with a stiff rod of 10 mm in diameter. (b) No opening between the test specimen and the substructure that can be penetrated with a stiff rod of 10 mm in diameter.

	(c) The test specimen shows no opening that arises from the separation of material or system parts. (d) No parts of the frame or the window hardware can become detached from the rear face of the test specimen. (e) Relevant safety parts such as hinges, locks, etc. that are not accessible from the front side prior to testing may not be accessible after testing. (f) S/NS of the rear face have to be documented. (g) Further criteria such as air permeability, water tightness, resistance to wind loads, etc. as defined by other EN standards are not relevant for the classification.
GSA-TS01:2003	— Protection and related hazard levels are categorised as a performance condition as indicated in Table 17 and Figure 2.
ASTM F 1642:2004	— The hazard rating of the glazing or glazing system shall be according to the rating criteria. — The hazard rating that glazing or glazing systems receive is based upon the severity of fragments generated during an air-blast test. The fragment severity is determined based upon the number, size and location of fragments observed during post-test data gathering (see Figure 1). — Fragments to be considered in rating the glazing or glazing system include those genera ted by the glazing, and any other parts of the glazing system not considered to be part of the test facility. — Criteria for the hazard rating are as follows. • No break — The glazing is observed not to fracture and there is no visible damage to the glazing system. • No hazard — The glazing is observed to fracture but is fully retained in the facility test frame or glazing system frame and the rear surface (the side opposite the air-blast loaded side of the specimen) is unbroken. • Minimal hazard — The glazing is observed to fracture and the total length of tears in the glazing plus the total length of pull-out from the edge of the frame is less than 20 % of the glazing sight perimeter. Also, there are three or fewer perforations caused by glazing slivers and no fragment indents anywhere in a vertical witness panel located 3 m (120 inches (in.)) from the interior face of the specimen and there are fragments with a sum total united dimension of 25 cm (10 in.) or less on the floor between 1 m (40 in.) and 3 m (120 in.) from the interior face of the specimen. Glazing dust and slivers are not accounted for in the rating. • Discussion — Fragments are defined as any particle with a united dimension of 2.5 cm

	(1 in.) or greater. The united dimension of a glass particle is determined by adding its width, length, and thickness. Glazing dust and slivers are all other smaller particles. • Very low hazard — The glazing is observed to fracture and is located within 1 m (40 in.) of the original location. Also, there are three or fewer perforations caused by glazing slivers and no fragment indents anywhere in a vertical witness panel located 3 m (120 in.) from the interior face of the specimen and there are fragments with a sum total united dimension of 25 cm (10 in.) or less on the floor between 1 m (40 in) and 3 m (120 in.) from the interior face of the specimen. Glazing dust and slivers are not accounted for in the rating. • Low hazard — The glazing is observed to fracture, but glazing fragments generally fall between 1 m (40 in.) of the interior face of the specimen and 50 cm (20 in.) or less above the floor of a vertical witness panel located 3 m (120 in) from the interior face of the specimen. Also, there are ten or fewer perforations in the area of a vertical witness panel located 3 m (120 in.) from the interior face of the specimen and higher than 50 cm (20 in.) above the floor and none of the perforations penetrate through the full thickness of the foil-backed insulation board layer of the witness panel. • High hazard — Glazing is observed to fracture and there are more than ten perforations in the area of a vertical witness panel located 3 m (120 in.) from the interior face of the specimen and higher than 50 cm (20 in.) above the floor or there are one or more perforations in the same witness panel area with fragment penetration through the first layer and into the second layer of the witness panel.
ISO 16934:2007	— After test • Record the presence, location, description of fragments in the protected area. • Inspect witness panel: describe and record dimensions and locations of all perforations or indentations within the required area. • Carefully remove the test specimen from the reaction structure and examine the attack face. • Record descriptions and measurements with details as required to determine the rating; location, description of all parts of specimen. • Record whether retained in frame of fallen inside or outside the shock tube, with identification of rear- and attack-face leaves of glass where appropriate. • Glazing-face located away from blast to be examined. Determine/note noted whether any breakage or rupture of this protected side

	surface has occurred. • Pressure data should obey the Friedlander equation; calculate Impulse I_t (numerical integration of recorded positive phase, before smoothing); match measured and recorded pressure-time trace *P(t)* for positive phase to best fit, smoothed curve through the measured points to derive the values of P_{max}, t_{tr} and A. • Establish P_{max} (recording pressure from intersection point of mean pressure-time trace and time of arrival axis). • If no clear point recorded p-t trace crosses zero overpressure, or trace continues positive for long period: the time where smoothed curve (extrapolated if necessary) reaches zero overpressure is used to determine positive phase duration for calculation of impulse. • Compare shape of mean trace with Friedlander curve: (same values: peak overpressure, duration, impulse). • Determine decay coefficient A sufficiently precisely to verify that: $0 \leq A \leq 4$. • Determine validity of the test: derived peak pressure is above the minimum specified, calculated impulse load above the minimum specified, positive phase duration is more than the minimum specified, positive phase wave-decay shape lies within the waveform parameter (Table 5, footnote b), shield and reaction structure remain in position with no openings between walls of shock tube and test frame, recorded blast values are within a range of ± 12.5 % from test to test. • Describe, evaluate results, record hazard rating and preliminary classification. — Test report structure: • testing agency information (name, address, calibration statement), • test specimen information (manufacturer's name, address, product name, date of manufacture, description of set-up, dimensions and materials, description of condition as received), • test set-up information (number specimens tested, class of explosion, date and time test, description with drawings, clamping, apparatus witness panel, orientation of specimens attack face, number and locations of pressure transducers, air temperature prior to the test, temperature of exterior surface prior to the test, relative humidity), • test results (peak positive pressure, impulse, duration of each sensor and derived mean peak, air-blast history over positive and negative phase, conditions of location of all parts [openings, dispositions, fragments, rating

	criteria], damage to witness panel, hazard-rating classification code of glazing), photographic recording (of test apparatus set-up, detailed photos of each specimen following the test). Manufacturer — 1 This deviation is derived from the combination of the 0 % to + 15 % accuracy of the pressure-generating device required in ISO 16934:2007 Section 6.1 and the + 5 % accuracy of the pressure-measuring equipment required in ISO 16934:2007 Section 6.6. This leads to a potential variation from – 5 % to + 20 %; a range of 25 % with latitude from a mean point of ± 12.5 %.

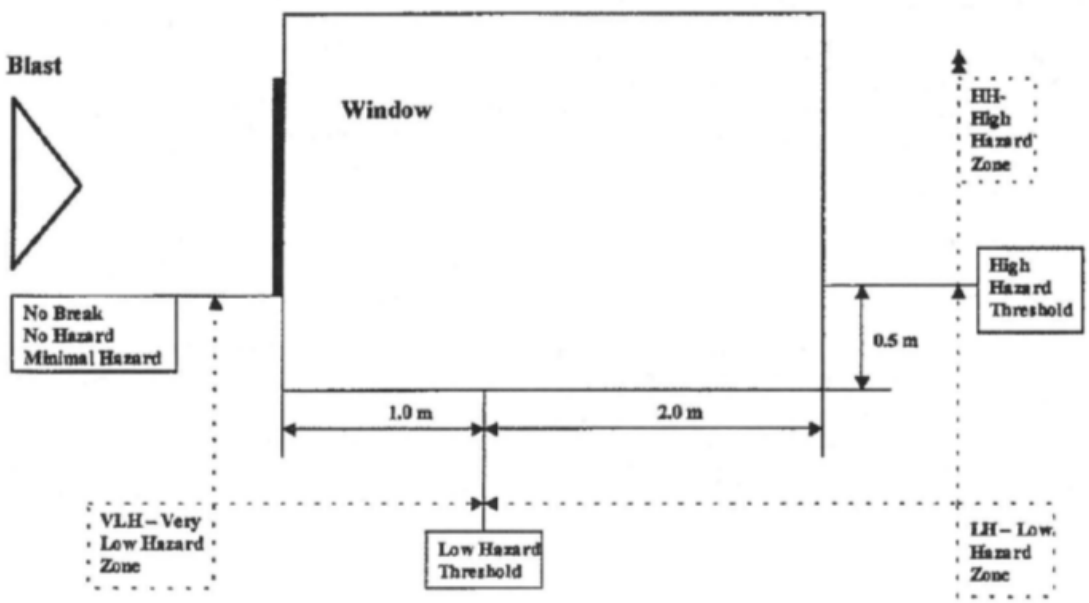


Figure 1: Cross section through witness area (ASTM F 1642:2004)

Table 16: Interpretation of the experimental results and contents of a test report, according to current standards for high-explosive tests.

Standard	Description
EN 13123-2:2004	— The test specimen has to be exposed to a shock wave according to requirements given in EN 13124-2:2004. — After testing the sample, the degree of damage may not exceed the specified criteria of EN 13124-2:2004
EN 13124-2:2004	— After testing the specimen for its explosion resistance, the following criteria have to be fulfilled. (a) The test specimen shows no opening that can be penetrated with a stiff rod of 10 mm in diameter. (b) No opening between the test specimen and the substructure that can be penetrated with a stiff rod of 10 mm in diameter. (c) The test specimen shows no opening that arises from the separation of material or system parts. (d) No parts of the frame or the window hardware can

	become detached from the rear face of the test specimen. (e) Relevant safety parts such as hinges, locks, etc. that are not accessible from the front side prior to testing may not be accessible after testing. (f) S/NS of the rear face have to be documented. (g) Further criteria such as air permeability, water tightness, resistance to wind loads, etc. as defined by other EN standards are not relevant for the classification.
GSA-TS01:2003	— Protection and related hazard levels are categorised as a performance condition as indicated in Table 17 and Figure 2.
ASTM F 1642:2004	— See Table 14
ISO 16933:2007	— A hazard rating is applied to glazing based on its performance under the blast conditions chosen for the test (see Table 18 and Figure 3). — The hazard rating that glazing or glazing systems receive is based upon the severity of fragments generated during an air-blast test. — The fragment severity is determined based upon the number, size, effects and location of fragments that lie at, or behind, the original location observed during post-test data gathering. — Glazing dust and slivers, fragments smaller than the particles with a unified dimension of 25 mm and their effects are not taken into account for the ratings. — For rating purposes only, the minimum area of the witness panel shall be considered and no account shall be taken of perforations and indents of size less than 3 mm in any direction (width, length and depth) or caused by particles classed as smaller than fragments (unified dimension less than 25 mm). — Fragments that shall be considered in rating the glazing or glazing system include those generated by the glazing and any other parts of the glazing system not considered to be part of the test facility. — For hazard ratings B and C, parts of the outer leaves may be projected any distance outwards from the attack face towards the blast source. — For hazard ratings D, E and F, any parts of the glazing or frame may be projected any distance outwards from the attack face towards the blast source.

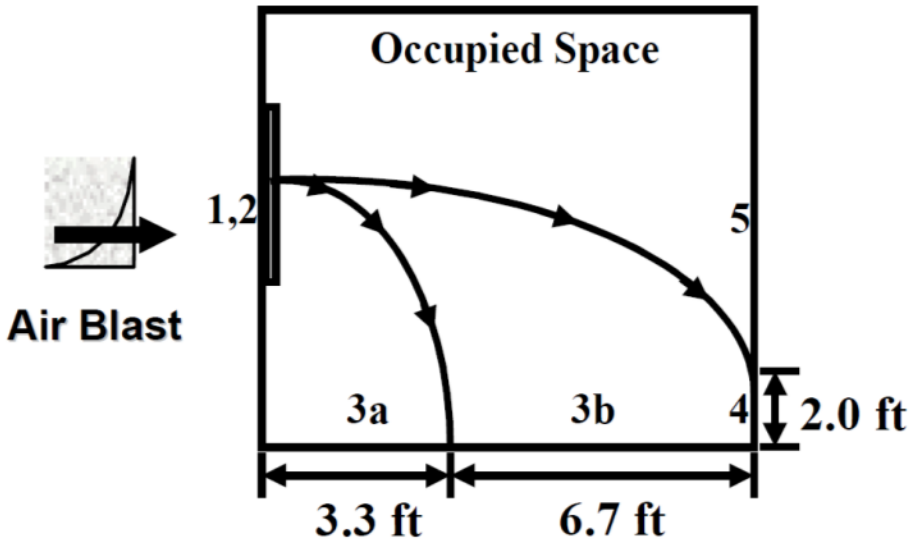
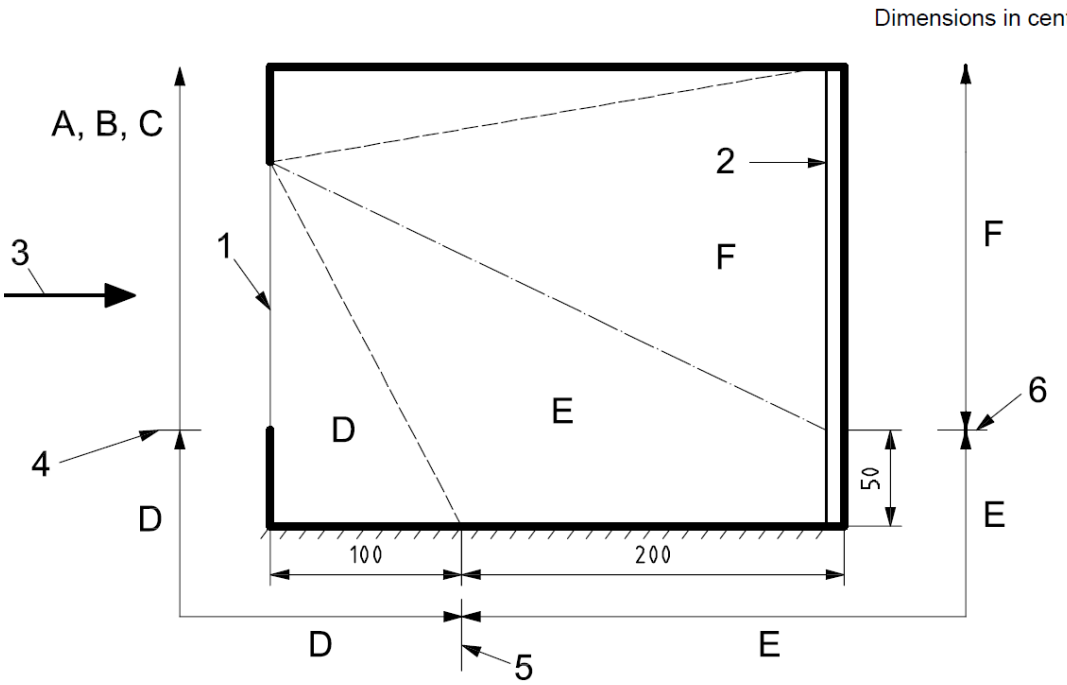


Figure 2: GSA/ISC performance conditions for window system response (GSA-TS01:2003) ([5]).

Table 17: GSA/ISC performance conditions for window system response (GSA-TS01:2003).

Performance condition	Protection level	Hazard level	Description of window glazing response
1	Safe	None	Glazing does not break. No visible damage to glazing or frame.
2	Very high	None	Glazing cracks but is retained by the frame. Dusting or very small fragments near sill or on floor acceptable.
3a	High	Very low	Glazing cracks. Fragments enter space and land on floor no further than 3.3 ft (1 m) from the window.
3b	High	Low	Glazing cracks. Fragments enter space and land on floor no further than 10 ft (3 m) from the window.
4	Medium	Medium	Glazing cracks. Fragments enter space and land on floor and impact a vertical witness panel at a distance of no more than 10 ft (3 m) from the window at a height no greater than 2 ft (0.61 m) above the floor.
5	Low	High	Glazing cracks and window system fails catastrophically. Fragments enter space impacting a vertical witness panel at a distance of no more than 10 ft (3 m) from the window at a height greater than 2 ft (0.61 m) above the floor.

([5]) 1 foot (plural: feet) (ft) is equal to 30.48 cm.



Key		A to F	Hazard ratings
1.	Window	A.	No break
2.	Witness panel	B.	No hazard
3.	Blast	C.	Minimum hazard
4.	Very low-hazard threshold	D.	Very low hazard
5.	Low-hazard threshold	E.	Low hazard
6.	High-hazard threshold	F.	High hazard

Figure 3: Cross section through witness area for arena test according to ISO 16933:2007

Table 18: Hazard-rating criteria for arena tests according to ISO 16933:2007.

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 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.

6.2. Remarks and comments

EN standards define pass/fail criteria based on damage to the glass (S/NS) and the anchoring. ISO and ASTM standards define hazard levels based on the distribution and size of fragments behind the test sample.
Only ISO 16933:2007 and ISO 16934:2007 (Annex A) describe a clear method deriving the blast parameters from a pressure–time history. If more than one pressure transducer is used, only the ISO standards describe a procedure for how to calculate the relevant values and how to consider deviations from mean values.

6.3. Recommendations for improvements

The blast parameters should be determined from the recorded raw signals according to the procedure described by ISO 16933:2007 and ISO 16934:2007. If more than one pressure transducer is used to record the reflected pressure, the average maximum pressure and standard deviation should be calculated and compared with the loading scenario (maximum deviation should not exceed 10 %).
The explosion resistance of the test specimen should be rated according to defined hazard levels and the corresponding analysis of the fragmentation of the sample. Testing at least three identical samples is recommended in order to estimate the statistical significance (see ISO 16933:2007).

7. Gaps in current test standards

This section summarises the findings of the relevant sections before in terms of a detailed overview of the different reviewed standards in Table 19. The comprehensive overview enables the identification of existing gaps within the standards.

Table 19: Comparison of standards for testing blast resistance of glazing.

Item	EN 13541:2012	EN 13123-1:2001/ EN 13124-1:2001	EN 13123-2:2004/ EN 13124-2:2004	GSA-TS01:2003	ASTM F 1642:2004	ISO 16933:2007	ISO 16934:2007
Application	Glass	Windows, doors, shutters	Windows, doors, shutters	Windows	Glass, windows	Glass, windows	Glass, windows
Test method	Shock tube	Shock tube	Arena test	Shock-tube or arena test	Shock-tube or arena test	Arena test	Shock tube
Standard loading	Large charge VBIED	Large charge VBIED	Small charge PBIED	Large charge VBIED	Small PBIED and large charge VBIED	Small PBIED and large charge VBIED	Large charge VBIED
User defined loading	No	No	No	Yes	Yes	No	Yes without certification
Petrochemical loading	No	No	No	No	No	No	No
Sample dimension	Fixed, vision size 1 000 × 800 mm	User defined	User defined	1650 × 1200 mm specified other size are permitted	User defined	Fixed, vision size 1 000 × 800 mm	Fixed, vision size 1 000 × 800 mm
Number of samples	3	1	1	1	Minimum 3	Minimum 3	Minimum 3
Tests of partially opened windows or doors	No	No	No	No	No	No	No
Testing glazed facades	No	No	No	No	No	No	No
Mounting of samples	Well defined	General description only	General description only	Outline description only	Outline description only	Well defined for glass; general description for windows	Well defined for glass; general description for windows
Number of pres. transducers	2	Not specified; at least 1	Not specified	≥ 2 outside; 1 inside	Shock tube: 3 Arena test: 4	≥ 3	≥ 1; not specified
Damage assessment criteria	No opening permitted	No opening permitted > 10 mm + splinter criteria	No opening permitted > 10 mm + splinter criteria	Hazard criteria	Hazard criteria + fragment definition	Hazard criteria + fragment definition	Hazard criteria + fragment definition

8 List of references

8.1 Standards

ASTM F 1642:2004. Standard test method for glazing and glazing systems subject to air blast loadings. ASTM International, 2004.

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EN 13124-1:2001. Windows, Doors and Shutters — Explosion Resistance; Test Method — Part 1: Shock Tube. CEN European Committee for Standardization, 2001.

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GSA-TS01:2003. Standard test method for glazing and window systems subject to dynamic overpressure loadings. US General Services Administration, 2003.

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8.2 Literature

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9. List of tables

10. List of figures

European Commission

EUR 27133 EN – Joint Research Centre – Institute for the Protection and Security of the Citizen

Title: A comparison of existing standards for testing blast resistant glazing and windows

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2014 – 42 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424

ISBN 978-92-79-46168-2

doi:10.2788/361383

Abstract

It is important to protect critical buildings (shopping centres, government buildings and embassies), infrastructure and utilities, train and underground stations against being damaged, destroyed or disrupted by deliberate acts of terrorism, criminal activity and malicious behaviour. Normal regulations and building guidelines do not generally take into account these threats. The introduction of appropriate regulations or guidelines, where deemed necessary, should, enhance the resilience of buildings and infrastructure against explosion incidents. In order to protect the built infrastructure, methods are required to quantify the resistance of structural components against explosive loading and to assess the hazards resulting from the failure of an element. The applicable state-of-the-art techniques may include either experimental or numerical methods, or a combination of both. Therefore, the thematic group (TG) on the resistance of structures to explosion effects was formed in order to bring the required expertise together, make it commonly available and to find and define harmonised methods and solutions which can be provided to the decision-makers responsible for critical infrastructure protection. This report discusses the differences between the existing standards for testing blast resistant glazing and windows and presents basic recommendations for the future development of the suite of European standards in this area.

LB-NA-27133-EN-N

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doi:10.2788/361383

ISBN 978-92-79-46168-2

Publications Office