Recommendations for the improvement of existing European norms for testing the resistance of windows and glazed façades to explosive effects

ERNCIP Thematic group
Resistance of structures
to explosion effects

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

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Resistance of structures to explosion effects

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Abstract:

It is important to protect critical buildings (shopping centres, government buildings and embassies), infrastructure and utilities, train and underground stations from 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 infrastructures against explosion incidents.
In order to protect the built infrastructure, testing methods are required which can answer the question whether certain building elements can withstand certain loading conditions created by an explosive event.

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, to 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.
The TG described in a fist report [JPC87202] the physical phenomena which have to be understood in order to ensure a proper testing of the elements and a correct interpretation of the results. In a second step, the differences between the existing standards for testing blast-resistant glazing and windows have been derived, and a basis for fundamental recommendations for the future development of the suite of European standards has been addressed [JRC94930].
Based on the prior findings, this report now formulates the proper enhancements of the existing standards in terms of actual recommendations for the improvement of the test standards.

Contents

1. Introduction

The standardisation of building products is an essential point of the building products. If the behaviour of materials and systems is known, their safe usage in buildings can be assured. Therefore, product standards define the required performance properties of components which have to be fulfilled. The related test standards describe methods and processes to analyse the behaviour of materials and systems for defined loadings in order to be conform to the regulations of the product standards.

Extreme dynamic loading scenarios are rarely considered in the building industry. Such loadings are characterized by high loading pressures which act in small loading times. Stress-wave and shock-wave loadings coming from detonation and impact events belong to such loading scenarios. There, the behaviour of the loaded materials differs from the behaviour under quasi-static loading, which can lead (in the case of dynamic loading) to an increase of strength and stiffness. However, the loading time is essential. Thus, for considering strengthening effects and to know the behaviour of materials and systems under such loadings, the loading process has to be standardised and ideally internationally harmonised. Therefore, the physical background is described in [JRC87202].

For safety glazing and safety windows, doors and shutters, international standards do exist, describing test procedures such as shock-tube test and arena test.

Based on the described test procedures, the standards propose a classification with respect to the blast properties and the damage status of the sample. Different classification levels are defined which show differences in comparison to each other [JRC94930].

Especially the European standard lacks are identified, which were investigated and analysed by the ERNCIP group in the past [JRC94930]. These lacks were considered in this report and recommendations for improvement of European standards for both, safety glazing and safety windows, doors and shutters will be formulated.

This report is structured as follows: Chapter 2 defines the boundary conditions for the report and documents the scope and the terminology. Furthermore, it gives an overview about internationally existing standards with respect to the considered topic. The Chapters 3, 4, 5 and 6 focus on special details to be addressed on in the tests standards. Of these, Chapter 3 describes the mounting of the test samples, Chapter 4 defines improvements with respect to the loading conditions, Chapter 5 focusses on the measurement technique which has to be applied in the tests for an exact and reliable evaluation of the tests, and Chapter 6 considers the interpretation of the results.

2. Scope of the report

The classification of security glazing panes, security window- and door systems with respect to their blast resistance is an important issue. Their loading can result from accidental or deliberated incidents. Today, the following main standards are available describing the testing process by using shock-tube facilities and arena tests applicable in the EU:

- *EN13541:2012-06 "Glass in Building – Security glazing – Testing and classification of resistance against explosion pressure"*
- *EN13123-1:2001 "Windows, doors, and shutters – Explosion resistance – Requirements and classification – Part 1: Shock-tube"*
- *EN13123-2:2004 "Windows, doors, and shutters – Explosion resistance – Requirements and classification – Part 2: Range test"*
- *EN13124-1:2001 "Windows, doors, and shutters – Explosion resistance, Test method – Part 1: Shock-tube"*
- *EN13124-2:2001 "Windows, doors, and shutters – Explosion resistance, Test method – Part 2: Range test"*
- *ISO16933:2007 "Glass in Building, Explosion-resistant security glazing – Test and classification for arena air-blast loading"*
- *ISO16934:2007 "Glass in Building, Explosion-resistant security glazing – Test and classification by shock-tube loading"*

The practical application of testing and classifying security glazing products reveals existing limitations. These limitations and identified gaps in the existing standardization have been collected and reported in [JRC94930] and are based on the gained experiences of the combined expert team. Each member of the expert team has a broad experience in the practical application of the testing standards. Thus, this knowledge and practical experience will again be incorporated.

In [JRC94930], a complex comparison of internationally available standards was prepared resulting in the identification of gaps in the European standards. The results of this former report are now addressed in this document, and improvements are formulated

The aim is to essentially improve the existing European standards for the testing and classification of security glazing products.

Hence, this report presents recommendations for the future development of one combined improved European standard in this area. By publishing this report and making it available for the responsible national standardization bodies, a stimulation of the discussion for the improvement of the European standards with respect to:

- *Applicability to glazing products*
- *Mounting of elements*
- *Loading conditions*
- *Measurement technique*
- *Interpretation of results*

is intended.

In general, the report will give recommendations for glazing and windows tested to explosion effects. The recommendations will address the following specific areas of the experimental test procedures:

- *Shock-tube tests*
- *Arena tests.*

2.3. Terminology on glazing

Since this document is a report which is based on the earlier reports [JRC87202, JRC94930], the same terminology is used for reasons of consistency.

In this report, **security glazing** is defined for both:

- *Security windows and security door systems and*
- *Security glazed façade systems.*

It is important to consider the window (or door) or the façade as a system, consisting of the security glass, the gasket or sealant, the frame, the fixing of the frame, and the support system.

The **blast pressure** is the loading pressure which acts as reflected pressure on the test sample. The loading is applied to the whole area of the window or façade with equal pressure-time history on each point of the test sample under permission of a certain scattering.
The behaviour of the glass is dependent on the pane size. The load 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 stresses in the glass and the fixings.

2.4. Available test standards

Introducing the theme of testing, classifying and certifying security glazing products, this section will give a short overview about existing standards, their availability and the contents addressed in them.
Generally spoken, in European standards, extreme loading on building components is limited to glazing products. Although the standard for loading conditions EC1 DIN EN1055 points out that the consideration of extreme loading events has to be taken into account [DIN EN1055-100], clear definitions of loadings are only available for security glazing and security glazing products.

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 panes (newest version: 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 façades. All these standards describe procedures for blast classification using shock tube or arena tests.

EN 13541:2012 only considers a single pane of laminated glass with a single fixed size in a rigid frame under exactly prescribed test- 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. In the scope of this report, only security window- door and façade systems are focused on. Standards describing testing procedures and classification levels of pure security glazing, like the EN 13541:2012, are not further taken into account.

EN 13123-1:2001 and EN 13123-2:2004 consider the whole opening system for windows, doors and shutters. The mentioned standards allow tests at the element's real size and with its real frame, producing realistic results. As well, no limitations are defined for the geometry of the samples. With respect to the fixation of the security glazing product on the substructure, it has to be realized as realistically as possible. This includes the kind of fixation, the number of fixation elements and the direction of the fixation elements in the substructure. 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 arena tests. The actual test loads are not included since they are classified.

The International Organisation for Standardisation (ISO) published the standard ISO 16933:2007 in 2007. It was largely based on the EN standards. It extended the test conditions to allow the use of large charges in arena 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 standard ASTM F 1642:2004 was developed in parallel with the ISO standards.

The available test standards describe procedures to investigate the blast resistance of security glazing systems. Guidelines are made with respect to:

- *Boundary conditions and mounting of elements*
- *Loading conditions*
- *Measurement technique*
- *Interpretation of results*

The comparison of the above mentioned standards identifies gaps and limitation of European standards. The result of the comparison was that the ISO 16934:2007 gives the best definitions and regularities and the clearest statements. Especially for the interpretation of the damage, the ISO standard defines hazard criteria.

In improving the practicability of the existing European standards for shock tube testing, the next chapters will refer to each of the above mentioned points and provide recommendation to increase the practicability.

It is worth to document one improvement here:
The European test standards for security glazing systems refer only to windows, doors and shutters. Since **glazing façade systems** with different mounting and boundary conditions with increasing trend are integrated into today's and future building structures, the **consideration** of such glazing systems as security glazing systems, which are already available on the market, is strongly recommended. Up to the present day, such elements are tested only referring to EN 13123-1:2001 and EN 13124-1:20 – however, without the permission of a certification. Table 2.1 summarizes the general items of the current standards.

Table 2.1: General items of all current standards describing blast loads on security glazing products.

Standard / Item	Application	Test method	Sample
EN 13541:2012	Glass	Shock-tube	Fixed, vision size 1 100 mm × 900 mm
EN 13123-1:2001/ EN 13124-1:2001	Windows, doors, shutters	Shock-tube	User defined
EN 13123-2:2004/ EN 13124-2:2004	Windows, doors, shutters	Arena test	User defined
GSA-TS01:2003	Windows	Shock-tube or arena test	1650 mm × 1200 mm, specified other sizes are permitted
ASTM F 1642:2004	Glass, windows	Shock-tube or arena test	User defined
ISO 16933:2007	Glass, windows	Arena test	Fixed, vision size 1 100 mm × 900 mm
ISO 16934:2007	Glass, windows	Shock-tube	Fixed, vision size 1 100 mm × 900 mm

3. Mounting of elements

This chapter considers the boundary conditions with respect to the integration of the test samples into the shock-tube, here called mounting of elements.
Since building components should be tested with the goal to get a certificate indicating a certain resistance to a specific blast loading and the latter usage of such elements in building constructions, it has to be the aim to realize the fixation of the test samples on the substructure as realistically as possible.
Based on the existing test standards, this chapter will document the status quo shortly and will derive recommendations resulting from remarks of the expert team of the ERNCIP group. This section considers different test arrangements for the accomplishment of blast tests.

3.1 Requirements

The requirements of the current test standards regarding the mounting of test samples in test facilities (shock-tube tests and arena tests) are quite different. The deliverable D1 (JRC87202) documents the status quo of the existing test standards. Generally spoken, the more the specimen is purpose-built for a specific building, the harder it is to comply with common, complex regulations in standards for the testing institute. E.g. EN 13123-1:2001 and EN 13123-2:2004 or ISO 16933:2007 and ISO 16934:2007 force a realistic mounting of the test elements, which should be very close to the latter application of the building component. It is clearly stated to accomplish the test as realistically as possible to get realistic and comparable results with respect to the test sample behaviour under a certain loading. However, this requirement demands a high flexibility of the test site.
The specifications for testing laminated glazing panes (e.g. EN 13541:2012) are much more precise than the requirements for windows, doors or shutters [EN 13123-1:2001, EN 13123-2:2004, EN 13124-1:2001, EN 13124-2:2004], which is likely a result of the minor size of the specimen because the technical requirements are normally easier to achieve in that case. In addition to that, the later assembly conditions in the building are often not that clearly defined because the element to be tested is not designed for a specific building but as a standard product for many applications in the future. However, for a better comparability, certain specifications are necessary even if the loading variety is large. Table 3.1 documents a summary of all current standards considering blast loading on security glazing products with respect to mounting of the samples.

Table 3.1: Mounting of test samples of all current standards describing blast loads on security glazing products.

Standard / Item	Test of partially opened systems	Mounting of samples
EN 13541:2012	No	Well defined
EN 13123-1:2001/ EN 13124-1:2001	No	General description only
EN 13123-2:2004/ EN 13124-2:2004	No	General description only
GSA-TS01:2003	No	Outline description only
ASTM F 1642:2004	No	Outline description only
ISO 16933:2007	No	Well defined for glass; general description for windows
ISO 16934:2007	No	Well defined for glass; general description for windows

3.2. Remarks and comments

Based on the review report of testing methods — deliverable D2 (JRC94930) – indicating the requirements of the boundary conditions of blast tests needed today, the following remarks are given by the expert team, to be considered for mounting the specimens properly. Since the mounting of the test samples is a critical point in any test arrangement, the given remarks apply to both shock-tube tests and arena tests.

- **Stiffness of the substructure:** In most of test standards, a stiff substructure is demanded to resist the expected loading level without significant deformations, which can have an influence on the test sample response and thus an influence on the test result. This is not an appropriate approach in any case, for instance if the real substructure is actually a more flexible or weaker building façade.
- **Tightness of the test setup:** A closed substructure is required to prevent the explosion pressure from escaping, or, in the case of a test sample integrated into a closed stiff container/box, the air blast wrapping around the sample. The existing test standards demand that the blast pressure should only hit the attack face of the test sample. Air-flow effects, which can lead to a support of the test sample on its protective face, have to be avoided.

  A complete airtight sealing of the joint between the test specimen and the substructure or a completely airtight enclosed substructure can only be achieved with great mechanical efforts. Nevertheless, it has to be assured by the test institute that the resulting leaking pressure does not influence the loading conditions and the response of the specimen.

  Furthermore, in case of using an open test arrangement with a test sample integrated into a container, it has to be guaranteed that the pressure compensation between the inside of the container and the outside (pressure on attack face of the test sample) should not occur before the test object has reached its maximum deflection. This would result in an underload of the specimen and would influence the test sample behaviour positively. The next figure explains it graphically. It shows an exemplary pressure-time history with a comparison between the pressure inside (protective face) and the pressure outside (attack face) of a test specimen using an enclosed test box. The example visualizes that only the blast loading is significant for the target response only during the first 34 ms. After 34 ms, pressure compensation between interior and exterior of the test container occurs resulting in similar pressure-time histories.

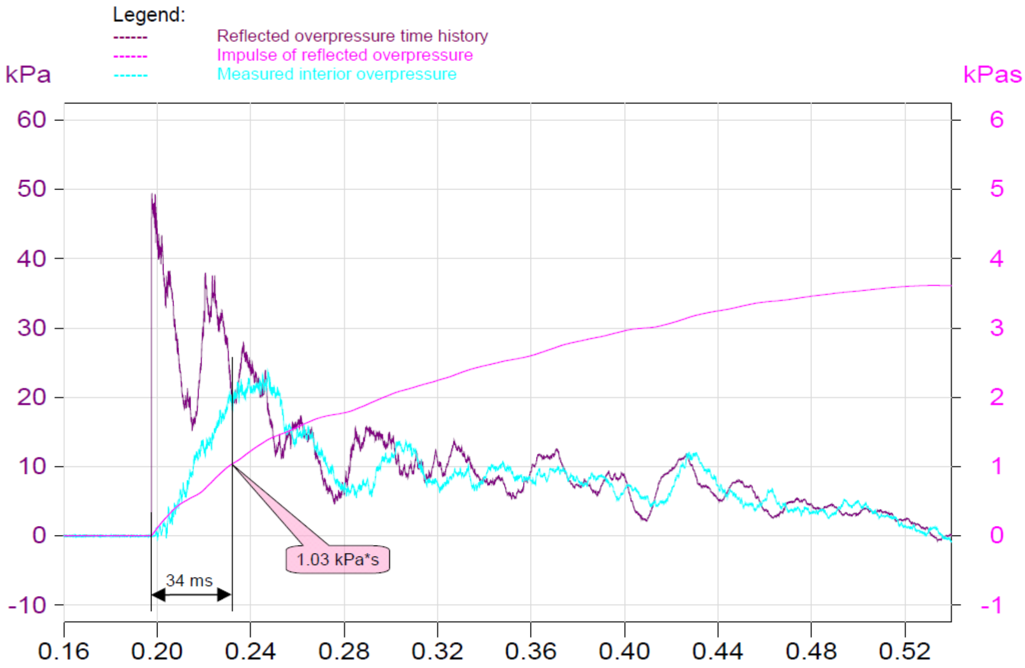

Figure 3.1: Comparison of exterior and interior overpressure

— **Connections:** According to EN13124-1 and EN13124-2, window-, door- and shutter-systems are tested, and these systems consist of the glazing, the frame and the fixation elements for an integration into the substructure. The standards demand that the substructure of the test facility should be able to provide a realistic integration of the test sample according to its later mounting situation. The connections between the test specimen and the supporting substructure, and here especially the interaction between fixation elements and substructure, are not within the focus of the test. However, they should be fabricated in such a way that they represent a realistic scenario and the expected failure mode.
In practice, the assembly of specimens depends on the connections to the test site substructure. Between the specimen and the walls or the bottom of the test site, a supporting substructure which either simulates a window- or door frame, a façade or another load-bearing structure of a building is erected. The following Figure 3.2 should indicate exemplary test setups with their connection lines or joints in principle.

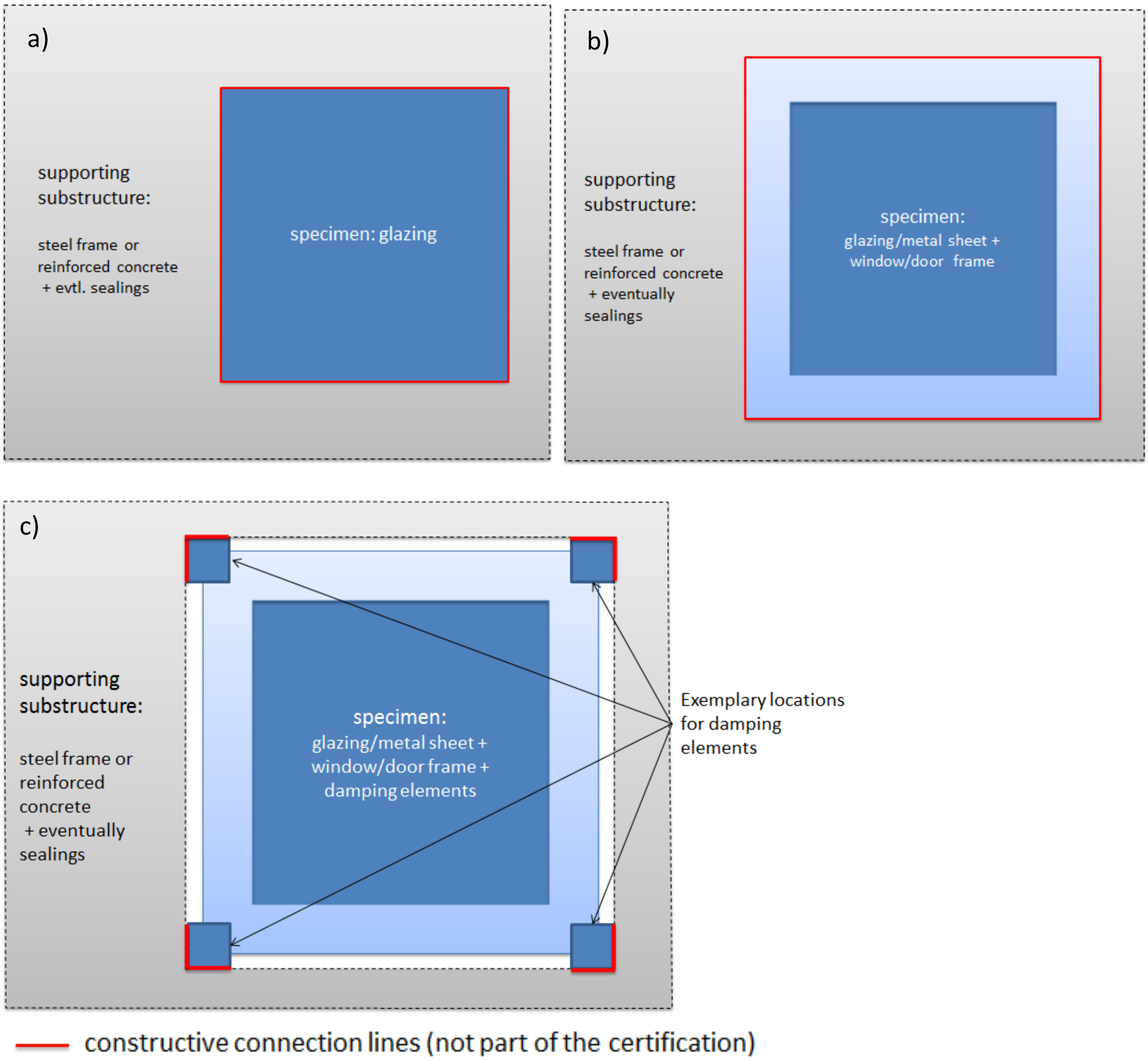

Figure 3.2: Exemplary test setups and their connection lines in principle; a) test of a glazing, b) test of a window/door, c) test of a façade element with damping elements

The constructive design of the supporting substructure and the connections to the specimen (red lines) are critical for the success of the test. The supporting structure and their connections are not to be tested. If glazing elements are to be tested, the connections are mostly made by screwed joints. If whole windows or doors are to be tested, the joint is often welded, even to ensure a sealed connection. If the specimen includes damper elements, it is also possible that the connections have to simulate a cable façade instead of a reinforced concrete wall. In that case, the design acts in accordance with the actual principle of the mounting, which is intended for the building. The tightness of the connection for movable parts is hard to consider in general.

— **Clamping pressure for glass:** For testing glazing panes only, the clamping pressure of the line-support surrounding the whole test sample can have a significant effect on the test results and should be specified according to ISO 16933:2007, ISO 16934:2007 and EN 13541:2012.
— **Area of the substructure:** As mentioned in deliverable 1 'Review of testing methods' in Figure 24, the measured reflected peak pressures depend on the surface area of the surrounding substructure. The test institute has to guarantee a plane shock-front. The substructure should be large enough so that the impulse acting on the test specimen is uniformly distributed. This uniformity has to be proven by calibration measures.

3.3. Recommendations for improvement

Based on the above documented remarks and comments, the following recommendations for the improvement of the existing European standards are proposed by the expert team.

1. **Stiffness of the substructure:**

The actual assembly conditions should be considered as realistic as possible during the certification process. That means it is recommended to adapt the integration of the test samples into the substructure of the test facility to achieve a realistic mounting of the sample which is comparable to the expected mounting situation in the later usage of the tested building component. In any case, it is recommended to document the mounting of the test sample in the test report.
Nevertheless, since the knowledge about the real mounting of the structural elements into the building is often inadequate or the efforts to achieve these conditions through constructive measures would result in too high expenses, simplifications should be possible whereby the specimen is erected in a stiffer substructure than in reality. This is in agreement with the current test standards. Only the window-, door- and shutter-system is tested and not the system including the substructure. This would avoid a positive influence of the substructure on the behaviour of the tested system. The result from this procedure is a little higher loading of the test sample. For example, a setup with a whole cable façade is normally not affordable. The solution would be to simplify the cable with a steel bar to test a single element.

Furthermore, future standards should determine that the deflection of the substructure should be measured during the test. The result of the measurement will quantify the stiffness of the sub-structure and will be part of the test report and the test certificate as a description of the boundary conditions of the test arrangement. This is especially recommended if the test specimen is tested as a product for unknown infrastructure projects in the future.

2. **Tightness of the test setup:**

A closed substructure is required to prevent the explosion pressure from escaping (shock-tube) or, in the case of a closed container/box, the air blast from wrapping around the sample. To ensure that the leaking pressure behind the test specimen does not influence the behaviour of the test sample and even the test result, the improved test standards should specify:

- *Which degree of tightness of the test arrangements (substructure) is required?*
- *Which methods could be used for closing the substructure?*

Furthermore, there is a need for additional measurements of the pressure on the protective face to ensure that no relevant air blast intrudes the test chamber or wraps around the test specimen. Some specimen designs allow openings during the loading. In this case, especially when long positive phase durations are requested, regulations should require pressure transducers on the back side or protection side of the test object.

3. **Connections:**

For future regulations, it is recommended to consider a requirement for the connections. The connections should not be more ductile or weaker and even not unnecessarily stiffer or stronger than in the real application, if the real conditions are known or achievable. However, if they are, conscious ductile connections should be tested as part of the specimen.

4. **Clamping pressure for glass:**

The specifications of the kind of clamping realising the line support and its clamping pressure in ISO 16933:2007, ISO 16934:2007 and EN 13541:2012 should be included in all relevant test standards for testing glazing panes only.

5. **Area of the substructure:**

For the improvement of current standards, the expert team recommends to indicate a minimal nominal value for the area surrounding the specimen. The test institute has to guarantee a plane shock-front acting on the test specimen. The pressure and the positive specific impulse should be uniformly distributed on the test sample. This has to be proven by providing calibration measurements. In the case that this uniformity is not given, the institute has to take measures reaching this requirement.

4. Loading conditions for blast testing

The loading of the element is the most important boundary condition in a classification test, which is addressed in this chapter. The definition of the blast load and its generation is a basis for a classification of glazing products used in building constructions. In this scope, the chapter first describes compactly the status quo of existing standards (EN 13123-1:2001, EN 13123-2:2004, EN 13124-1:2001 and EN 13124-2:2004) (Section 4.1).
In Section 4.2, the status quo will be analysed and evaluated. Comments will be given with respect to identified gaps. Finally, in Section 4.3, recommendations for the improvement of the existing standards will be formulated.
The source of an explosion, for example, can be a chemical reaction (or detonation of high explosives). This reaction results in a rapid rise of temperature and pressure in a very short time. In particular, the very high pressures can cause considerable damage to building structures. Furthermore, the type of explosions can differ, starting from deflagration to fast deflagration up to detonations. The actual type of the regarded explosion determines also the significant loading parameters pressure amplitude, shape and increase of pressure profile and the loading duration. Phenomena which could cause the different type of explosives are detonation of high explosives, gas and dust explosions caused by accidents, sabotage or terrorism.

An explosion is a physical process in which suddenly, large amounts of energy are released that previously was concentrated in a small space. This leads to a sudden volume expansion of gases, which finally creates blast waves travelling through the surrounding medium air emanating from an idealised point source

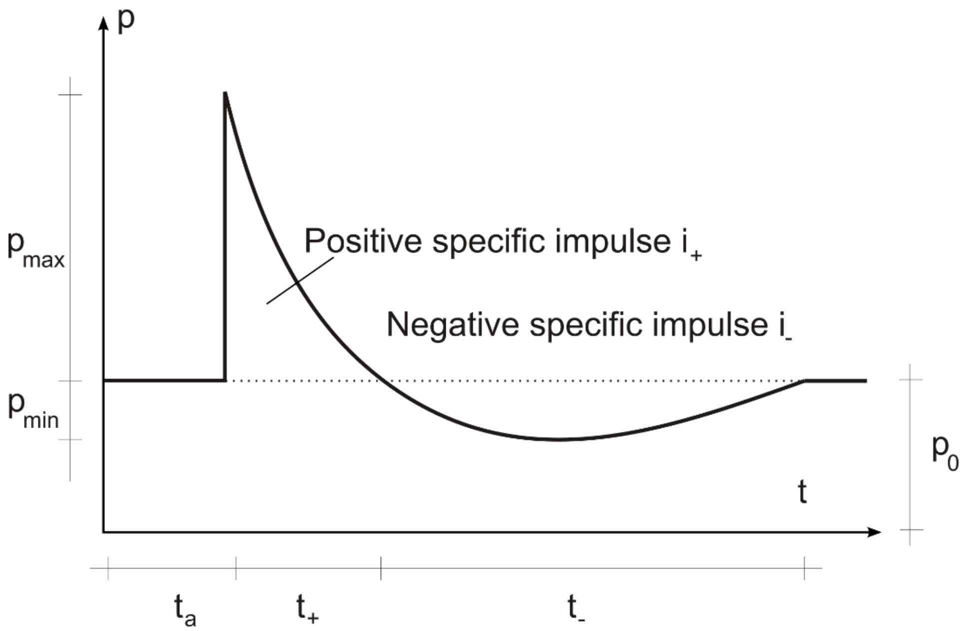

Figure 4.1: Characterisation of a blast wave described by the three properties: peak overpressure (loading pressure), positive duration and positive specific impulse.

Blast waves propagate in the medium air spherically with strongly decreasing peak pressures by increasing the distance to the detonation source. If a blast wave hits a structure, it is loaded by a specific pressure-time-history, ideally shown in Figure 4.1. In general, a blast wave is characterized by a shock front, characterized by a sudden strong increase of the loading pressure up to the ultimate loading pressure (p_{max}), a decay of the pressure over the time with a positive phase (period of overpressure) and a following negative phase (undertow phase). The loading pressure on the structure is the reflected pressure (p_{max}). The decay phase is controlled by the positive duration (t_+) – the time of an existing overpressure. The third describing property is the positive specific impulse (i_+), mathematically described by the area under the pressure-time history of the positive phase. The negative specific impulse due to the undertow phase (i_-) is mostly not considered.

Depending on the scenario (explosive type, explosive substance, mass, stand-off), the pressure-time-history can differ significantly. Thus, pressure, positive duration and positive specific impulse are in direct correlation with charge mass and distance as well as the explosion type.

4.1. Requirements

This section provides a comprehensive overview about current European and ISO standards for blast testing on security glazing products. Here, the loading conditions for both methods of blast resistance analysis – arena tests and shock-tube tests are summarised. Table 4.1 summarises the rough loading conditions of all current standards used for a certification of glazing products against blast loading.

Table 4.1: Summary of general description of the loading conditions of all current standards describing blast loads on security glazing products.

Standard / Item	Standard loading	User defined loading	Petrochemical loading and gas explosion
EN 13541:2012	Large charge VBIED	No	No
EN 13123-1:2001/ EN 13124-1:2001	Large charge VBIED	No	No
EN 13123-2:2004/ EN 13124-2:2004	Small charge PBIED	No	No
GSA-TS01:2003	Large charge VBIED	Yes	No
ASTM F 1642:2004	Small PBIED and large charge VBIED	Yes	No
ISO 16933:2007	Small PBIED and large charge VBIED	No	No
ISO 16934:2007	Large charge VBIED	Yes, without certification	No

In the current standards applicable for shock-tube tests (EN13541, EN13123-1, EN13124-1 and ISO16934), see Table 4.2 and Table 4.3, four to six loading levels used for a product certification are defined. These levels are described by the three above mentioned blast properties: reflected pressure (p_{max}), positive duration (t_+) and positive specific impulse (i_+). In addition, the positive duration is proposed to be greater than 20 ms. Furthermore, the current standards describe the generation of the blast load [EN 13124-1:2001, EN 13124-2:2004, EN 13541:2012, ISO 16933:2007, ISO 16934:2007].

Table 4.2: Definition of loading levels in existing European standards (EN 13541:2012-06 and EN13123-1, 2001-10) applicable for shock-tube tests.

EN 13541:2012-06, applicable for laminated glazing			EN13123-1, 2001-10; applicable for windows, doors		
Level	p_{max} [kPa]	i_+ [kPa ms]	Level	p_{max} [kPa]	i_+ [kPa ms]
ER1	$50 < p_{max} < 100$	$370 < i_+ < 900$	EPR1	$50 < p_{max} < 100$	$370 < i_+ < 900$
ER2	$100 < p_{max} < 150$	$900 < i_+ < 1500$	EPR2	$100 < p_{max} < 150$	$900 < i_+ < 1500$
ER3	$150 < p_{max} < 200$	$1500 < i_+ < 2200$	EPR3	$150 < p_{max} < 200$	$1500 < i_+ < 2200$
ER4	$200 < p_{max} < 250$	$2200 < i_+ < 3200$	EPR4	$200 < p_{max} < 250$	$2200 < i_+ < 3200$

Table 4.3: Definition of the loading levels according to ISO19634:2007-07 applicable for shock-tube tests.

ISO 16934:2007-07, applicable for laminated glazing panes, windows, doors				
Level	p_{max} [kPa]	i_+ [kPa ms]	Mass [kg]	Stand-off [m]
ER30	30	170	30	33
ER50	50	370	100	34
ER70	70	550	160	33
ER100	100	900	500	39
ER150	150	1500	1000	41
ER 200	200	2200	2000	46

For completeness, Table 4.4 and Table 4.5 summarise the loading conditions applicable for arena tests, described by charge mass and stand-off. In Table 4.5 (ISO16933), the resulting blast parameters p_{max} and i_+ are given as well.

Table 4.4: Definition of loading levels according to EN13123-2:2004-05 for application in arena tests.

EN13123-2: 2004-05; applicable for windows, doors and shutters		
Level	Mass [kg]	Stand-off [m]
EXR1	3	5.0
EXR2	3	3.0
EXR3	12	5.5
EXR4	12	4.0
EXR5	20	4.0

Table 4.5: Definition of loading levels according to ISO16933:2007-07 for application in arena tests.

ISO 16933:2007-07, applicable for laminated glazing panes, windows, doors				
Level	p_{max} [kPa]	i_+ [kPa ms]	Mass [kg]	Stand-off [m]
EXV45	30	180	100	45
EXV33	50	250	100	33
EXV25	80	380	100	25
EXV19	140	600	100	19
EXV15	250	850	100	15
EXV12	450	1200	100	12
EXV10	800	1600	100	10

All values given for the loading levels are defined as minimal values. However, this leads to the assumption that the tests have to be carried out by using these minimal values.

4.2. Remarks and comments

The review report (Deliverable D2 [JRC94930]) and the comprehensive overview of Section 4.1 summarise the resulting definition of loading conditions by application of the current test standards. The following conclusions are drawn:

— A strict distinction is made in European and ISO standards with respect to the simulated loading scenario – close-in detonations and far-field detonations. Shock-tube experiments are capable to represent far-field detonations, and arena tests are applicable for close-in and far-field detonations.
— The European standards consider loading scenarios for vehicle borne improvised explosive devices (VBIEDs) in arena tests, unlike the ISO standard.
— The test standards which are applicable for shock-tube testing show a strong similarity in terms of loading levels. That means that all standards define loading levels expressed by reflected overpressure and positive specific impulse with a defined range of scattering, which are equal between EN and ISO. Only ISO defines two more loading levels.
— The current European standard EN13123-1 defines four loading levels (EPR1 – EPR4). For these levels, values for pressure and impulse are defined, which the products have to withstand within the test. However, these values represent only minimal values for both parameters. In this scope, the standards prescribe that pressure and impulse should not be lower than these values and should not exceed the values of the next higher level. Taking this into account, a range for pressure and impulse is defined and it is encouraged to test the products at the class range minimum. As well, EN13541 defines for reflected pressure and positive specific impulse ranges with the requirement of fulfilling at least the minimal values. From our point of view, this procedure is not sufficient. The product has to be tested against the highest values for pressure and impulse to represent all combinations of a certain loading level.
— The test standards applicable for arena tests are very similar in terms of loading levels.
— The defined real test scenarios, which are the basis for the definition of the loading levels according to reflected overpressure and positive specific impulse, cover only detonations from

high-explosive events and do not define loading levels for gas explosions coming from accidental events.

4.3. Recommendations for improvement

Taking the remarks of section 4.2 into account the following recommendations are derived.

- The expert team recommends at first a harmonisation of the EN and ISO standards with respect to the number and the definition of loading levels. Here, the classification levels of the ISO standards offer a wider, more specialized classification of building products with loading levels below EPR1 and between EPR1 and EPR3.
- Furthermore, it is proposed that the European standards will be extended to include arena tests to represent VBIEDs. This would lead to a higher flexibility in the application of the test method. However, the test institute has to guarantee and to prove that the conditions of a far-field detonation, resulting from a VBIED in a large distance, are fulfilled with respect to: planar wave, only loading on the attack face and no supporting by streaming effects. There, the following questions have to be discussed and the definitions have to be made, respectively:
    - How should VBIED scenarios be characterised with respect to charge weight, explosive type and distance?
    - Taking into account the different substances that can cause explosive events, the question is how equivalent factors for the description of reflected overpressure and positive specific impulses can be defined for all tests? Especially for shock-tube testing, it has to be guaranteed that the scenario specific blast parameters represent the decisive loading scenarios.
- The expert team suggests the implementation of an option for user-defined loading scenarios. Blast tests should be accomplished with respect to pressure-impulse combinations below, between or above the defined loading levels. Since certificates can be issued for tests outside the defined loading levels, a higher practicability will be reached with this option. With this procedure, the tendency of more individualised demands on building structures and their components will be addressed. For building components like glazing façades, which are constructed and manufactured for a special single application, a certification with respect to specific loading scenarios should be possible.
- With respect to the definition of loading levels and the related blast properties, an improvement is strongly recommended. New loading levels have to be defined with a new identification (see Figure 4.2). However, it is still recommended to integrate the old loading levels. In order to represent the upper limits of reflected pressure and positive specific impulse, a new identification of the loading levels is suggested. The new fixed loading levels are defined as documented in Table 4.6. There, the required parameters to be reached in the test are printed in bold.

Table 4.6: Recommendation for the definition of loading levels with respect to reflected pressure and positive specific impulse according to the current standard [EN 13123-1:2001].

Level	p_{max} [kPa]	i_+ [kPa ms]
EPR1	$0 < p_{max} <$ **50**	$0 < i_+ <$ **370**
EPR2	$51 < p_{max} <$ **100**	$370 < i_+ <$ **900**
EPR3	$101 < p_{max} <$ **150**	$9001 < i_+ <$ **1500**
EPR4	$151 < p_{max} <$ **200**	$1501 < i_+ <$ **2200**
EPR5	$201 < p_{max} <$ **250**	$2201 < i_+ <$ **3200**

— Additionally, in the scope of the implementation for user-defined loading scenarios, the range of loading scenarios should be extended to gas explosions as well. For this purpose, scenarios should be specified with respect to the transient loading profile consisting of maximum and minimum pressure, and positive and negative impulse. Furthermore, the shape of pressure rise and decrease has to be defined with respect to applicability in the test facility.

— For arena tests, the type and shape of the charge should not 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 often not 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 accepted as alternatives in order to consider realistic loading scenarios resulting from a VBIED or PBIED.

Suggestions for the realization of the improvements

Below, the recommendations are specified and described in greater detail. Here, a distinction for the recommendations is made. The following points will be addressed:

- *Shock-tube testing*
- *Arena testing*

Shock-tube testing

With respect to the loading levels, European test standards for glazing and security windows, doors and shutters show that equal blast properties have to be reached within the tests. Harmonization with the ISO standards is strongly recommended. This standard defines 6 loading levels instead of 4 fixed levels. Taking a higher flexibility and the requirement of loading levels of customers' demand into account, a new distinction into loading levels is proposed in this document. Starting from a pressure-impulse diagram, several loading levels can be identified. There, lower and upper limits for reflected overpressure and positive specific impulse are defined:

- p_{low}: *0 kPa*
- p_{up}: *400 kPa*
- i_{low}: *0 kPa ms*
- i_{up}: *5200 kPa ms*

With this new classification, beside far-field detonations due to high explosives, gas explosions are also addressed. With the distinction into loading levels, a similarity to the current standards is enabled allowing a comparison of products tested before ensuring a very high flexibility. Thus, a certification of glazing products with respect to the expected blast loading for the specific building component can be reached resulting in a customer defined product certification. For the test institutes, the new classification offers the possibility to offer a wide and full range of tests within the performance capabilities of their test facility.

Furthermore, for the application of new fixed loading levels, the expert team strongly recommends to define the highest values for a specific loading level for both blast parameters reflected pressure and positive specific impulse as standard. Hereby it can be guaranteed that the worst case of the loading level is tested and not its minimal representation. If the product withstands this loading, it is assumed to also withstand all loading with p-i combinations with lower reflected pressure and positive specific impulse.

Additionally, a new, more specific identification of the loading level is needed. The expert team proposed an identification label (ID) consisting of the maximal values of the reflected overpressure and the positive specific impulse. Figure 4.2 shows the proposed new loading levels definition in a general overview. The pressure-impulse diagram could be integrated into the standard. An application of this description in arena tests with the same advantages is also possible.

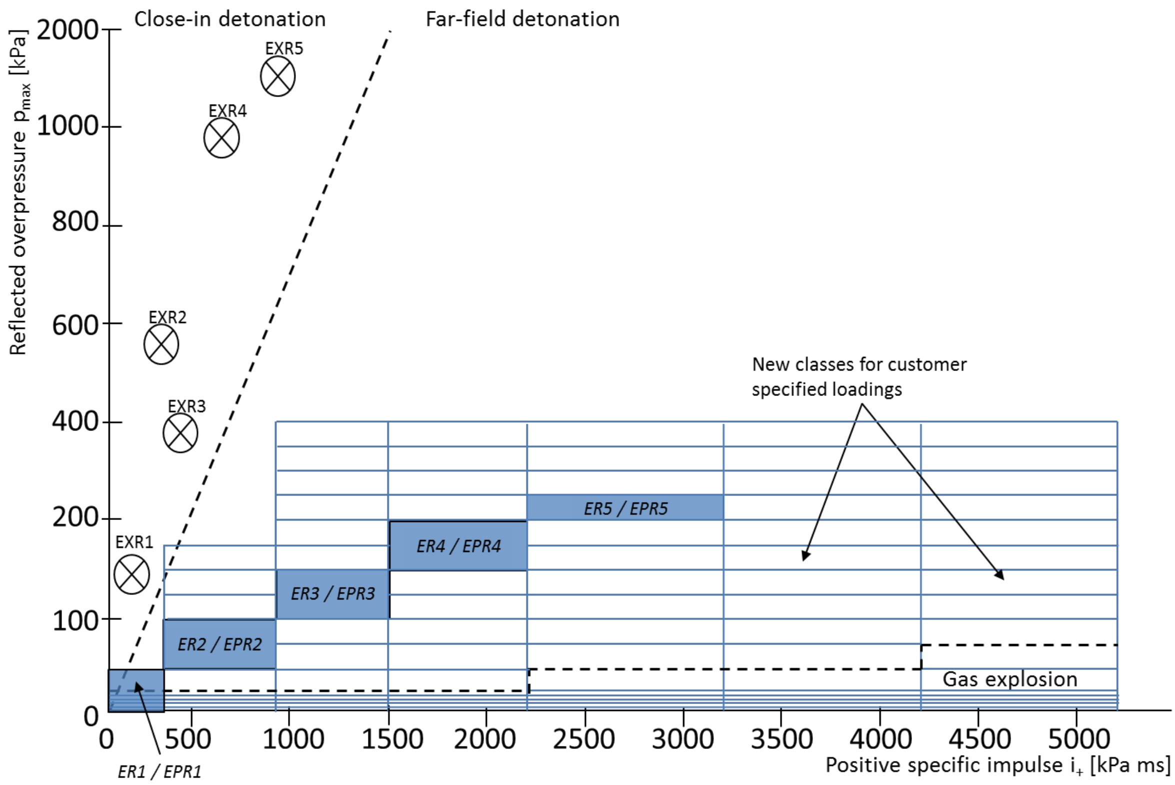

Figure 4.2: Proposed definition of loading levels by using a pressure-impulse diagram.

The graphic shows beside the loading levels of the current European standards a distinction into a certain number of loading levels within the proposed bounds for reflected pressure and positive specific impulse defining the new additional loading levels. The choice of the range for both blast parameters is taken with respect to the loading levels of the current standards. Only for the low pressures, an increment of 5 kPa is chosen. Figure 4.3 visualizes the p-I diagram applicable for shock-tube tests. The p-I diagram proposes values for detonation with TNT as well as chemical substances. If in the underlying scenario the blast loading is caused by other substances than TNT, the blast properties required for testing have to be calculated by using the TNT equivalent factors or numerical simulations.

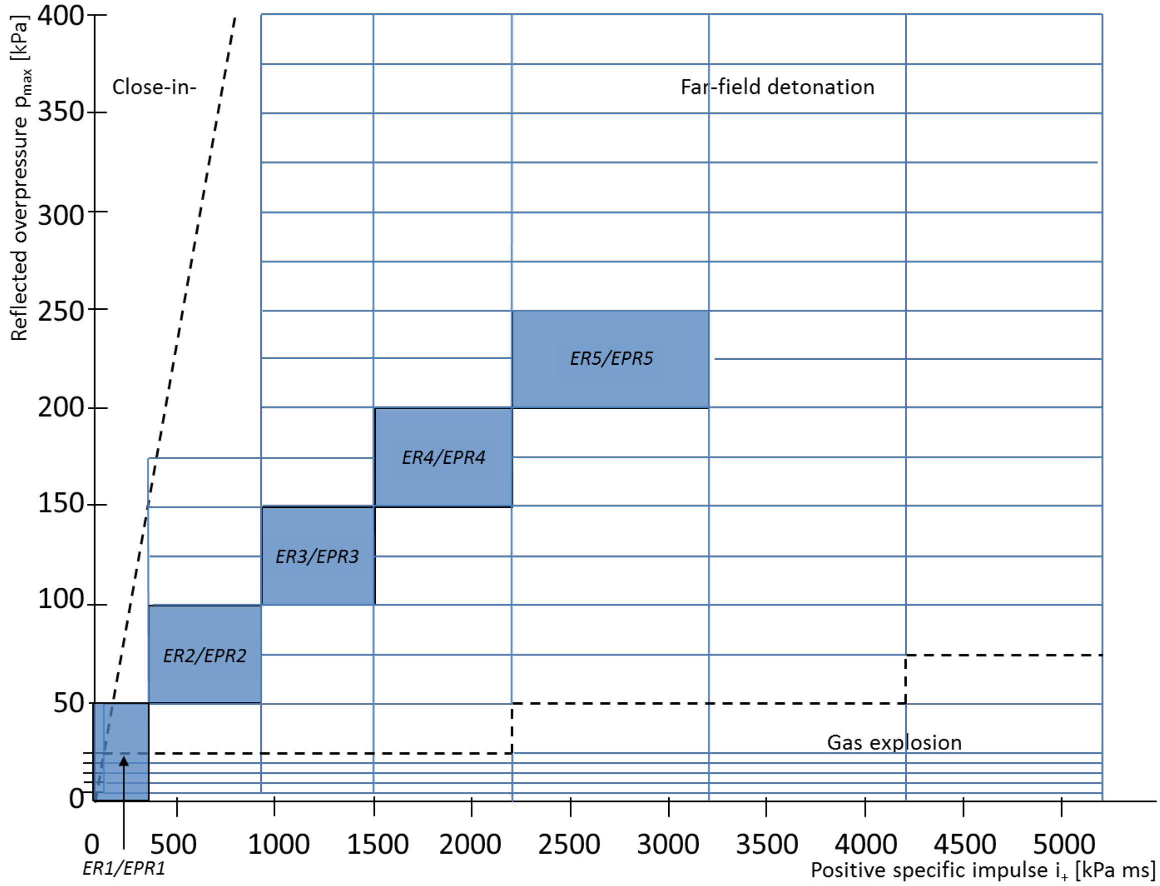

Figure 4.3: Proposed definition of loading levels by using a pressure-impulse diagram for application in shock-tube tests.

However, tests with specific customer requirement for a p-i combination, which lies within a specific level, should be possible as well. In this case the combination of reflected pressure and impulse of the test represents the upper bond for both blast properties. If the product withstands this loading, it is assumed that it withstands loadings of lower p-i combinations as well. However, a clear documentation in the test certificate and the test report is required.

If more than 1 sample is tested, the loading combination with the lowest reflected pressure is the decisive one. A graphical explanation in a p-i diagram indicating the experimental results and visualizing the covered loading levels is recommended.

Arena tests

A harmonisation of the European standard with the ISO standard with respect to the definition of loading levels is recommended by the expert team. Furthermore, the same procedure as for shock-tube testing is applicable for close-in detonation scenarios. For arena tests, the same procedure with respect to the classification is suggested.

Considering the requests for a higher flexibility in the definition of loading levels with respect to the customers' demand, a certification for levels not specified in the standards should be possible. According to shock-tube tests, the expert team proposes to integrate an equivalent flexibility in the loading conditions for arena tests used for a product certification as well. In this scope, extreme loading scenarios characterised by detonations of high explosive substances can differ strongly in their loading parameters (reflected pressure, positive and negative specific impulse, positive and negative duration, increase and decay of the shock-front), controlled by:

- *Charge substance*
- *Charge mass*
- *Stand-off*
- *Charge shape*

Especially the substance has a strong influence on the loading properties reflected overpressure and impulse. Being as close as possible to a realistic scenario, a limitation to TNT as the only applied high explosive material seems to be too strict. Here, the improved standard should allow the use of other substances than TNT or similar high explosives, as long as they could ensure reliable and reproducible results. The realization is not critical in arena tests, since the loading can be achieved by using the required chemical substance.

5. Measurement technique

This chapter considers the required measurement technique to be used in the blast test setups. Besides the required sensor-solutions measuring loading properties and response of the structural elements, their properties and characteristics are summarised as well. For example, the sensitivity and the sampling rate are important measures to be fulfilled in such fast running tests.

5.1 Requirements

The certification of building products requires a standardised test setup with a specific measurement technique to analyse the load. In high pressure experiments carried out by both shock-tube and arena tests, the characterisation of the blast wave is, beside the evaluation of the damage, the most essential criterion. Thus, for the accomplishment of the tests pressure, transducers are required for the evaluation of the loading. The damage analysis is done optically. Adding deflection and strain measurement systems will give additional information about the element behaviour. However, such systems are not essential for the qualification of glazing products for a certification against blast loadings and thus not part of the requirements.

Beside the measurement characterising the loading, the climate properties and the storage properties housing the test sample prior to the tests have to be recorded. There, beside the temperature and the relative humidity, the ambient pressure is prescribed for documentation in the test protocols as well.

Table 5.1: Measurement systems prescribed in all current standards for the accomplishment of blast tests.

Standard / Item	Number of pressure transducers	Required parameters of climate condition	Storage conditions
EN 13541:2012	2	Ambient temperature, air-pressure; surface temperature	Not specified
EN 13123-1:2001/ EN 13124-1:2001	Not specified; at least 1	Ambient temperature, air-pressure; relative humidity; surface temperature	Not specified
EN 13123-2:2004/ EN 13124-2:2004	Not specified	Ambient temperature, air-pressure; relative humidity; surface temperature	Not specified
GSA-TS01:2003	≥ 2 outside; 1 inside	Not specified	Not specified
ASTM F 1642:2004	Shock-tube: 3 Arena test: 4	Surface temperature	Not specified
ISO 16933:2007	≥ 3	Surface temperature	Not specified
ISO 16934:2007	≥ 1; not specified	Ambient temperature, air-pressure; relative humidity; shade temperature	Not specified

5.2. Remarks and comments

Current standards [JRC94930] prescribe the use of pressure transducers to measure pressure-time histories. There, the best location on the attack face 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 eigen frequency 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 required and 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 stand-off distance as the test cubicle is erected.
Especially in the mentioned arena tests, calibration protocols or pressure time histories from additional rigid test cubicles should be a mandatory part of the test report and results. Additionally, the pressure history in the middle of the test sample can also be calculated by numerical methods based on a validated numerical model and the pressure records at the edges.

Current standards prescribe shock-tube and arena tests for the analysis of single elements, like one pane, one security window or one security door, applicable to the integration in one story of the building structure. However, tests on single- and multi-story façade systems of larger dimensions are not foreseen in the current standards. Especially in these cases, a clear statement about the number and the places of pressure transducers seems to be required, taking into account the large dimensions of security glazing systems with respect to the shock-wave loading.

5.3. Recommendations for improvement

For both shock-tube tests and arena tests, the instrumentation of experimental setup and the supporting structure is necessary for an appropriate evaluation of the test results in terms of correct loading and damage analysis.
The measuring systems should allow for the complete documentation of all relevant data from the resulting shock-wave and shock-wave propagation, but also of climate data.
For the characterisation of the load, the side-on pressure and the peak overpressure on — or, if not possible, close to — the sample, are strongly required. Furthermore, the interior air blast pressure behind the test sample (in the protective area) has to be recorded by additional transducers. When using cubicles in both test arrangements, this measurement becomes relevant in analysing possible supporting pressures on the protective face of the test sample (Chapter 3).

In the next sub-sections, the measurement systems are documented and recommendations are provided with respect to their position and their number within the test setup.

Air-Blast Pressure Transducers

Air-blast pressure transducers should be used to record the magnitude, above ambient pressures, and time development of the reflected shock wave impinging on the test specimen. The air-blast pressure transducers used should be capable of recording the anticipated air-blast pressure-time history within the linear range of the transducer and should be calibrated properly prior to the blast test. Each transducer shall have a rise/response time and resolution sufficient to capture the complete event. Calibration records should be provided so as to demonstrate that the equipment is able to measure air-pressure in the expected range with a tolerance of ± 5 %.

Positioning of Air-Blast Pressure Transducers in Shock-Tube Tests

The expert team recommends the use of at least 2 pressure transducers in one test setup. They should be mounted adjacent to the test specimen to record the history of the reflected overpressure. The number and the position of transducers depend on possibly occurring clearing effects. This has to be taken into account in the planning stage of the test series. The positions of all pressure transducers have to be documented in both the test protocol and in the test report. There, the positions and the distances to the test sample should clearly be addressed.
The pressure transducers mounted adjacent to the test specimen should be calibrated during special pre-tests against pressure transducers set in the centre of rigid blanking plates fixed in the test specimen support. The calibration records should either demonstrate that the readings are identical in the two locations or provide means of adjusting the readings of the pressure transducers mounted adjacent to the test specimen to values that accurately represent the reflected pressure-time values at the centre of the test specimen. The test institute should document a relevant pressure-time history indicating a planar shock-wave loading acting on the specimen, in terms of a calibration experiment. There, it is recommended to show the pressure-time histories of adjacent pressure transducers and of one transducer located in the middle of the sample position.

Positioning of Air-Blast Pressure Transducers in Arena Tests

For the accomplishment of arena tests, the expert team recommends three air-blast pressure transducers to be placed adjacent to the test specimens or on separate concrete blocks at the same stand-off distance in order to avoid transducers on the test specimen itself, as in that case they would influence the response of the specimen. Furthermore, 2 pressure transducers should be placed in the free field at the same distance as the test specimen to prove whether a complete detonation of the charge has been achieved. The installation of an additional pressure transducer inside the enclosed supporting structure is required to record the pressure-time history inside the enclosed supporting structure. However, in case of an expected internal supporting pressure, an additional pressure gauge has to be installed inside the substructure as close as possible to the test sample.

If the pressure transducers are placed adjacent to the test specimen, the actual blast load acting in the centre of the test specimen can be calculated via appropriate numerical simulations based on the recorded data of the pressure transducers located at defined points around the test specimen. Using this approach, the clearing effect can also be considered. The numerical model is adjusted to the experimental data that are determined by the pressure transducers mounted on the exterior wall of the supporting structure as well as the transducers used in free field.

Data-Acquisition System

The data-acquisition system should record the sensor data collected by the pressure transducers and the additional measurement systems and has to be used in both: shock-tube tests and arena tests. It consists of either an analogue or a digital recording system with a sufficient number of channels to accommodate all pressure transducers and any other facultative chosen electronic measuring devices (e.g. strain gauges, etc.).
Furthermore, the highly dynamic characteristics of detonations and the resulting shock wave require a high sampling rate (at least > 100 kHz) and rise time sensitivity response to a peak pressure of 10 µs. A higher sampling rate is recommended by the expert team and should reach about ideally 1

MHz. Filters to exclude alias frequency effects from the data should be incorporated [ISO 16934:2007, GSA-TS01:2003].
The system used for arena tests shall be capable of recording the pressure-time trace of the high peak pressure (positive phase) and the following undertow phase (negative phase) reliably. The test institute has to guarantee that the chosen recording time of the data acquisition system is long enough to enable an evaluation of the load with respect to the test sample behaviour. Therefore, the recording of the pressure-time history of a shock-tube and an arena test should start before the shock wave reaches the test specimen and should last for a time span of at least 10 times the duration of the positive phase from the time of arrival at the test specimen.

Climate Data

The climate conditions should be recorded within 30 min prior to the test, as they are necessary for a proper analysis of arena and shock-tube tests.
Depending on the test configuration, the following requirements are recommended for shock-tube tests and arena tests:

- *Shock-tube test: ambient air temperature, relative humidity, ambient atmospheric pressure, surface temperature of the sample*
- *Arena test: ambient air temperature, relative humidity, ambient atmospheric pressure, wind speed and direction, surface temperature of the sample*

The ambient temperature should be measured on a shadow area close to the test sample in an appropriate way. The surface temperature should be captured in the centre of the test specimen. If the test sample consists of different materials (e.g. glass and steel), the temperature of each component should be measured. The results of the measurements have to be documented in the experimental protocol and should be stated in the test report.

The climate conditions of the storage of the test samples should be recorded with respect to temperature and relative humidity. The average values of a time of 24 hours prior to the test should be documented in the test report.

Additional Measurements

The test report should give a comprehensive but complete overview about the test and its conditions. Photographic images and high-speed recordings can support the analysis of the element behaviour and its evaluation. Photographs are strongly recommended and thus required for:

- *Test setup*
- *Test conditions prior and after the test*
- *Status of the test sample after the test on relevant positions (middle of test specimen, edges, connections of the frame and the glazing with the frame, space surrounding the test setup with respect to splinters and fragments.*

The use of a high-speed camera for the analysis of the damage process is not prescribed, but the use of such systems is useful supporting the damage analysis if it can give information about the damage stages with respect to the loading. For tests with a hazard classification, a witness panel working as debris catcher is required and strongly recommended.
Furthermore, the behaviour of the test specimen during the blast load can be observed using laser-optical deflection measurement systems and strain measurement. With that, the damage process

and the element behaviour with respect to the applied load is realized supporting the evaluation of the blast test. Such facultative systems can be arranged on points of interest.

6. Interpretation of results

This chapter is focused on the interpretation of the results. Beside the evaluation of the loading properties, the behaviour of the test specimens regarding cracking and fragmentation is considered to result in a qualification into loading levels and hazard classes. 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

The interpretation of the results is focused on the analysis of the behaviour of the test sample with respect to the applied loading. Current standards cover loading levels described by the blast properties reflected overpressure and positive specific impulse (see Chapter 4) with respect to the observed damage after the specific experiment.
The damage is described in terms of the destruction of the glass by splintering or fragmentation, or of the complete system by the destruction of the glass and the destruction or damage of the frame construction in case of security windows and doors [EN 13124-1:2001].
Furthermore, the interpretation of the results contains the documentation of the results in a test certificate and in a test report. Thus, the essential points of both documents like the written result of the test leading to a defined structure with all required information are addressed in this chapter.

Table 6.1: Requirements on the interpretation of results in comparison to all current standards describing blast loads on security glazing products.

Standard/Item	Number of test samples	Damage assessment criteria
EN 13541:2012	3	No opening permitted
EN 13123-1:2001/ EN 13124-1:2001	1	No opening permitted > 10 mm + splinter criteria
EN 13123-2:2004/ EN 13124-2:2004	1	No opening permitted > 10 mm + splinter criteria
GSA-TS01:2003	1	Hazard criteria
ASTM F 1642:2004	Minimum 3	Hazard criteria + fragment definition
ISO 16933:2007	Minimum 3	Hazard criteria + fragment definition
ISO 16934:2007	Minimum 3	Hazard criteria + fragment definition

6.2. Remarks and comments

EN standards define pass/fail criteria based on damage to the glass (S/NS) and the anchoring. The application of the damage class NS/S with respect to the observed glass damage is qualitatively described. Furthermore, the largest acceptable damage of the glazing and/or security glazing products is defined quantitatively.

In comparison to EN standards, ISO and ASTM standards define a certain number of hazard levels based on the distribution and size of fragments behind the test sample. There, a more detailed qualified evaluation of the damage can be achieved.

With respect to the derivation of blast parameters from a blast experiment, only ISO 16933:2007 and ISO 16934:2007 (Annex A) describe a clear method for how to derive them 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.

All test standards provide a structure and essential points required for a test certificate and the test report.

6.3. Recommendations for improvement

Based on the given requirements and the comments resulting from the review of current European standards, the following recommendations are given by the expert team. The current ISO 16934:2007(E) "Glass in building – Explosion-resistant security glazing – Test and Classification by shock-tube loading" has been considered as basis and the recommended changes and amendments are summarised below.

General:

In general it has been noted that the style and content of ISO 16934:2007(E) and ISO 16933:2007(E) are noticeably different and any future review of the latter document should ensure consistent phrasing and terminology.

Loading Levels:

Additional loading requirements include VBIED scenarios for 100 kg to 1000 kg at ranges of 15 m to 30 m as well as PBIED scenarios of 3 kg to 20 kg at ranges of 3 m to 10 m. These may not all be achievable in shock-tubes.

For petro-chemical and gas explosion scenarios, other requirements may need to be considered.

Loading Conditions:

Load conditions should generally be quoted as a combination of reflected pressure (peak overpressure) and impulse (positive specific impulse) with a representative equivalent charge mass and range.

User defined load conditions should be allowed for testing and certification with input parameters beyond the listed existing range.

Test and Classification:

The test method should be aimed at classifying "security windows and doors" but should also have the facility to cover both glass and façades where possible so that the general principles of the test method can be applied to glass or façades.

Testing of framed window systems should be allowed with "representative and realistic fixings". This is covered in paragraph 5.2 (ISO 16934:2007) Fenestration Assemblies; but the sample can only be assessed and cannot be classified.

Testing of a minimum of three identical samples (as per ISO 16933:2007) is recommended in order to estimate the statistical significance. Each test has to lead to the same categorization. The limitations of testing a single sample are clearly explained in Paragraph 5.3 (ISO 16934:2007), but a requirement to test multiple samples would be beneficial.

The explosion resistance of the test specimens should continue to be rated according to the defined hazard levels and the corresponding analysis of the fragmentation of the sample. For this, the damage on the protective face of the test sample (with respect to splintering, fragmentation, cracking and openings) has to be considered. By testing multiple elements, the sample showing the highest damage is the essential one which defines the hazard criterion for the product.
Classification of fragmentation for glass and for windows is considered satisfactory under the existing A-F system defined in Paragraph 8.2 (ISO 16934:2007).

NOTE For façades it may be possible to use the same system with a limit of acceptable performance; such as A-C only for tall façades.

Annex A "Blast parameters and derivation" a standardised method of deriving the blast parameters from the raw data is described in both ISO 16934:2007(paragraph A.4) and ISO 16933:2007 (Paragraph A.4). These methods should be reviewed to ensure that they are consistent with each other.

NOTE: The process for dealing with raw data should be more or less identical for both shock-tube and air-blast loading.

The use of multiple pressure transducers (minimum: two sensors) in a shock-tube would provide greater confidence in the data recorded. The method for assessing tolerances of recorded pressure and impulse values from ISO 16933:2007 (paragraph B.3) should be included in ISO 16934:2007 to cover use of multiple pressure transducers. The average maximum pressure and standard deviation should be calculated and compared with the loading scenario (maximum deviation should not exceed 10 %). Only pressure transducers working correctly and thus showing reasonable results should be considered in the calculation of the blast properties.

NOTE EN 13123-1:2001 gives a "latitude of -5 % on the pressure value to allow for gauge reading tolerance".

Table 6.2 gives an overall summary of the recommended requirements of a revised test and classification by shock-tube loading standard in terms of interpretation of results.

Table 6.2: Summary of overall requirements.

No.	Item	Recommended requirement
1	Application	Aim to cover glass, windows and façades. Façades may be subject to a separate test method proposed at a later date, but test houses should be able to apply the general principles of a revised test method.
2	Test method	Shock-tube Test (ISO 16934) Arena Test (ISO 16933) to follow
3	Standard loading	Large (VBIED) and small (PBIED)
4	User defined loading	Yes (possibly without certification)
5	Petrochemical loading	Yes (possibly without certification)
6	Sample dimension	User defined
7	Number of samples	Minimum 3
8	Test of partially opened windows/doors	No
9	Test of glazing façades	Yes (initially through application of general principles)
10	Mounting of samples	Well defined for glass, windows and façades (fixings must be representative of operational use)
11	Number of pressure transducers	Minimum 2
12	Damage assessment criteria	Hazard criteria and fragment definition

These requirements will also apply to the future revision of the test and classification by arena air-blast loading standard.

Identification of the test sample by classification code:

The identification of the loading level is recommended to integrate both fixed loading levels according to the current standards, but with a new label of the levels EPR1 to EPR5 and flexible classes. A certification should be possible for both. With respect to a higher flexibility, it is recommended for the additional (not fixed loading levels) to use a new identification code for the distinction of the classification level of security windows and doors. There, the identification code should contain:

- *Average reflected overpressure*
- *Average positive specific impulse*
- *Hazard class reached*
- *Example: security window tested at 50 kPa 400 kPa ms, no damage:*
  EPR 50/400 A

7. List of references

7.1. Standards

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

EN 13123-1:2001-10. Windows, doors and shutters — Explosion resistance; Requirements and classification — Part 1: Shock tube. CEN European Committee for Standardisation, 2001.

EN 13123-2:2004-05. Windows, doors and shutters — Explosion resistance; Requirements and classification — Part 2: Range test. CEN European Committee for Standardisation, 2004.

EN 13124-1:2001-10. Windows, doors and shutters — Explosion resistance; Test method — Part 1: Shock tube. CEN European Committee for Standardisation, 2001.

EN 13124-2:2004-05. Windows, doors and shutters — Explosion resistance — Test method — Part 2: Range test. CEN European Committee for Standardisation, 2004.

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8. List of tables

9. List of figures

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