A set of essential requirements towards standardising the numerical simulation of blast-loaded windows and facades

ERNCIP thematic group
Resistance of structures to
explosion effects

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2015

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

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Thematic group:

Resistance of structures to explosion effects

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Abstract

The determination of the blast protection level of laminated glass windows and facades is of crucial importance, and it is normally done by using experimental investigations. In recent years numerical methods have become much more powerful also with respect to this kind of application. This report attempts to give a first idea of a possible standardisation concerning such numerical simulations. Attention is drawn to the representation of the blast loading and of the behaviour of the material of the mentioned products, to the geometrical meshing, as well as to the modelling of the connections of the glass components to the main structure. The need to validate the numerical models against reliable experimental data, some of which are indicated, is underlined.

Contents

1. Introduction

Numerical simulations are used for structural analysis and can be based on non-linear methods and material models representing the expected real behaviour under a given type of loading and environmental conditions. Numerical simulation techniques constitute another way of assessing structural performance and are an addition to the physical testing in a laboratory or on the site. Unlike in real testing, it could be claimed that simulation is not limited by structural size, load magnitude and testing facility. However, the possibilities provided by numerical simulations should not be overestimated and adequate checks in terms of validation should be performed to verify the results and conclusions. Several other technical limits are also known. For example, the development of the glass fragments has until now not been possible with numerical methods.

Clearly, the model formulation must be based on principles of mechanics, namely it must satisfy requirements of equilibrium of forces, compatibility of displacements and material constitutive laws. The inevitable errors due to numerical approximations should always be controlled by solution-error criteria. It is also known that the complexity of a model grows with each new feature added. Therefore, it is appropriate to include only those features which are significant for the given case, in order to keep the model as simple and efficient as possible.

The finite element method as well as similar methods like finite volumes or finite differences are typically used for the numerical solution of continuum mechanics problems. A finite element formulation should satisfy the requirement of convergence to the exact solution by reducing the element size (and increasing the number of degrees of freedom). It is understood that, independently of the material model, the approximations introduced by the finite element formulation can be a significant source of errors in numerical analysis. Similarly with other numerical methods, the errors due to these approximations should be adequately checked as shown for concrete in [1].

2. General considerations: What to expect from numerical simulations

European as well as American testing standards for laminated glass windows (e.g. [2]) define a hazard level that is measured by the fragments that are found after the experiment behind the glass pane. More details can be found in US General Services Administration [3] and ISO-standard [2] (Table 1), and also in the previous reports [4] and [5].

Scientific and technical literature has shown that numerical simulations can be used with confidence to determine the failure of the laminated glass and its interlayer and may be useful to approximate the launch conditions of the splinters. The bearing capacity and the glazing damage level of the window of full window systems and their components can also be determined by numerical simulations. However, the prediction of the formation and development of splinters or slivers of blast-loaded laminated glass has until now not been accurate enough and is a challenge for numerical simulations. Also the splinter velocity and dispersion behind the window cannot be determined numerically.

Table 1: Hazard-rating criteria for arena tests according to ISO 16933:2007 [2]

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

3. Selection of representative load scenarios

The loading scenario depends on the specific protection requirements and local conditions. Detailed instructions for defining loading scenarios are given in national regulations or must be discussed with the infrastructure operator/owner or the responsible authorities. Loads to be considered in designing a structure are usually expressed in terms of equivalent mass of TNT and stand-off distance, e.g. the distance between the structure to be designed and the postulated explosion source.

In general, numerical simulations are able to handle an almost arbitrary loading scenario for the structural element considered. Taking these capabilities concerning loading into account, it is important to ensure that the modelled scenarios can be compared to the experimental results. For this, it would be necessary to capture the actual loading of the structural component examined with the same logic as in the experiments. Therefore, it is recommended to record in each simulation the resulting loading pressure and impulse for the considered structural elements, especially in calculations that are combining fluid and structures.

4. Load characterisation

Blast waves are characterised by a compression phase (positive phase) with a very high peak over-pressure and a following under-pressure (negative phase). The compression phase starts with a strong increase in the pressure from the ambient pressure (p_0) to the peak pressure ($p_0 + p_{max}$) within a timescale of microseconds. Figure 1 shows a simplified form of the pressure-time history of a blast wave, and indicates the relevant parameters. Of importance for the loading of glass windows is also the negative phase since this could be strong enough to pull outwards fragments that were developed by the positive phase.
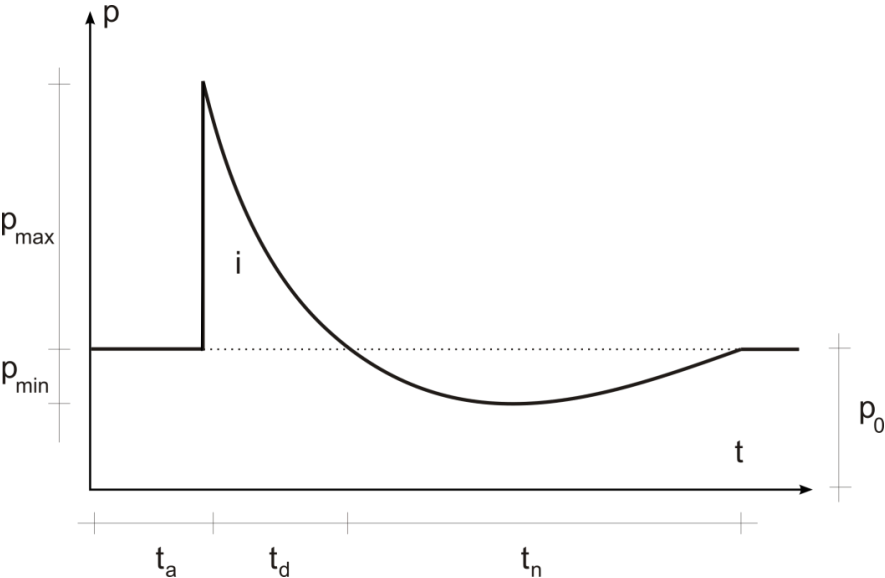

Figure 1: Pressure history for a free-field air-blast wave

For a blasted structure different loading conditions can be distinguished: impulsive, dynamic and quasi-static loading (Figure 2). Loads with very short duration (relative to the structure's natural period) are known as impulsive loading, and in laminated glass windows they often result in a shear

failure next to the border or at the boundary itself. Loads with longer duration (dynamic loading) tend to cause bending mode failures of glass panels. Only very slowly developed pressures (quasi-static loading) would be simulated by using a static load. For the structure under consideration these loading regimes can be schematically shown in the so-called PI (Pressure-Impulse) diagram, Figure 2.
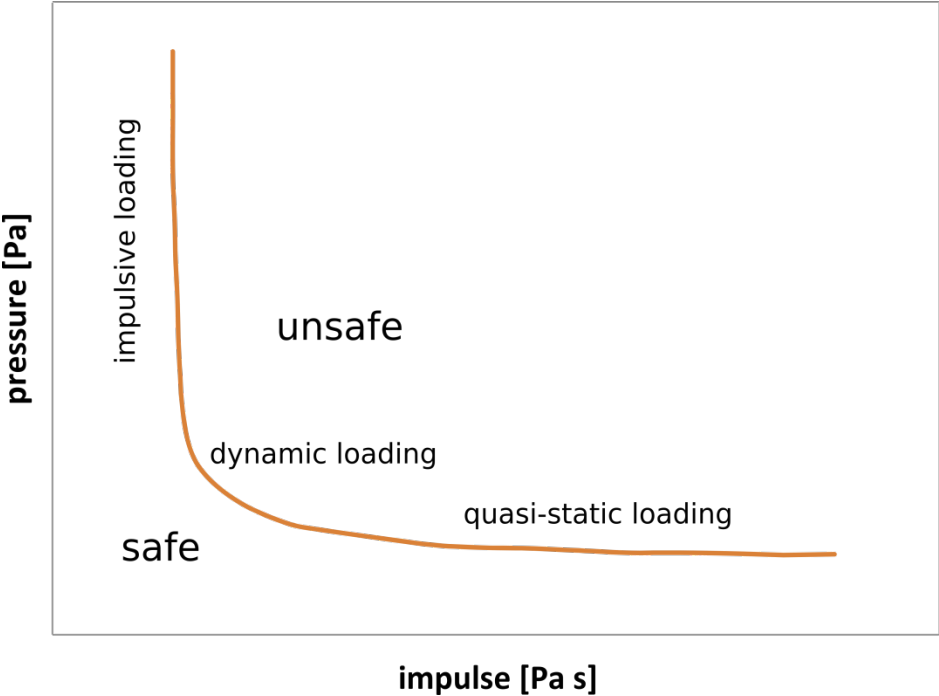
Figure 2: PI diagram: impulsive, dynamic and quasi-static loading

5. Model discretisation

Model discretisation is based on the transformation of real structural components in a numerical representation using finite elements. Elements are characterised by three main parameters:

- Element type (and degrees of freedom)
- Number of nodes/element order
- Integration

Some of the element types that are used in a stress analysis are presented in Figure 3. One of the main differences between those entire element types is their geometry. Elements may also be distinguished between solid elements, shell, beam and truss elements.
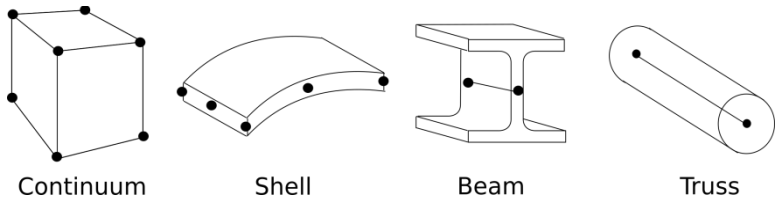
Figure 3: Some classical element types

Depending on the software used to assess the structural model, different element types are available and can be employed. The number of degrees of freedom is associated with the element type, and is the fundamental variable calculated during the analysis. For a stress/displacement simulation the degrees of freedom may be translational and, for shell, pipe, and beam elements, translational and rotational.

Specific element types and other features can also be available such as connector elements, infinite elements, multi-point constraint (MPC) links. As an example, those element types can be used to define the link between the window and the frame. Cohesive links can be used between two separated glass layers. This type of element can be very useful in order to evaluate the delamination process inside multi-layer glass panels.

Displacements and rotations are calculated at the nodes of the element. At any other point in the element, the values are obtained by interpolating them from the nodal ones. Usually the interpolation order is determined by the number of nodes used in the element.

- Elements that have nodes only at their corners, such as an 8-node brick use linear interpolation in each direction are called linear elements or first-order elements.
- Elements with mid-side nodes, such as a 20-node brick element use quadratic interpolation and are called quadratic elements or second-order elements.

As a rule, the increase of the element order improves the accuracy of the result for the same element size. However, the increase of the element order increases the CPU time (calculation time).

Numerical methods are used to integrate various quantities over the volume of each element. Using for example Gaussian quadrature for the simulation, the code evaluates the material response at each integration point in each element. Elements can often be used in full or reduced integration, a choice that can have a significant effect on the accuracy of the element for a given problem. Use of reduced integration can also decrease the needed CPU time. Reduced integration is mainly used in order to reduce the locking of the elements. This could result in hourglass modes that should be avoided.

Shell, pipe, and beam element properties can be defined as general section behaviours. Each cross-section of the element can be integrated numerically, so that non-linear response associated with non-linear material behaviour can be tracked accurately when needed. In addition, a composite layered section can be specified for shell elements.

In modelling a window panel or a facade, the following issues should be taken into consideration:

- The geometrical shape of the window panel
- The design of the structure (laminated, multi layered, etc.)
- The type of solver used to analyse the structure (explicit or implicit time integration)
- Type of damage studied (brittle failure, delamination, etc.)
- Type of links between the structural components considered
- Boundary conditions

An example of an insulated laminated glass panel and its frame is given in Figure 4. Additional information about simulations of isolated glass in facades is for example given by [6].
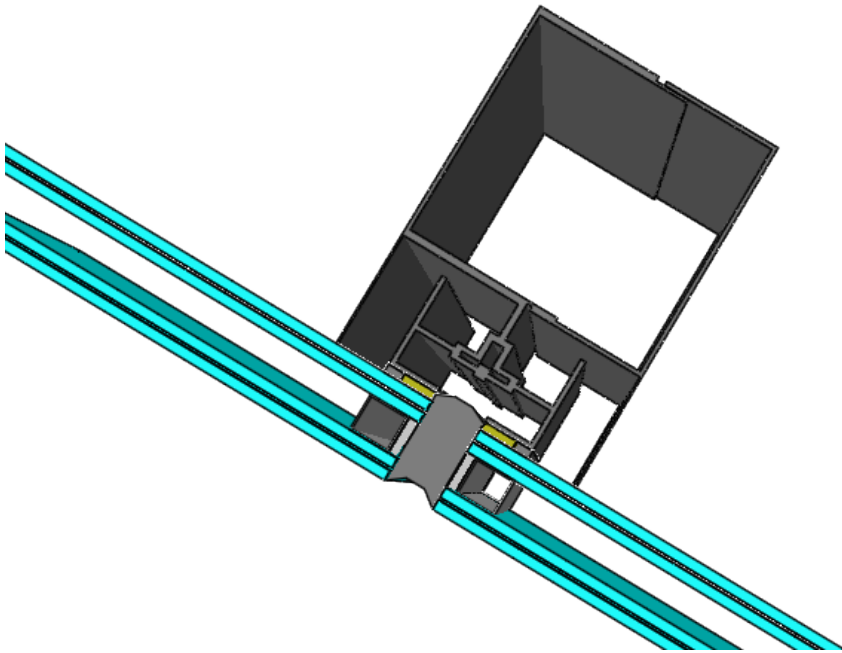

Figure 4: Detail of a façade system using laminated glass

6. Material models

The appropriate material models should be chosen to best represent the material behaviour under the examined loading conditions and in compatibility with the model discretisation described in Section 5. The mechanical calibration of all window components should be carried out, depending on the glazing system typology, by taking into account the specific damage constitutive behaviour and possible strain rate-dependent phenomena.

Material models for the simulation of laminated glass windows and facades are usually based on the following theories:

- Linear behaviour with brittle failure limit (cracking)
- Theory of plasticity with plastic flow rule
- Damage theory
- Visco-elastic and visco-plastic theory

The choice of an appropriate theory depends on the specific application.

Glass

Glass is a very brittle material. A linear-elastic representation with a failure or erosion criterion works well in most cases. Sometimes a plastic part is added in order to fade out the stress in a slower way and to also reduce numerical instability problems if such a material model is not physical. The strain rate behaviour of glass is still not sufficiently investigated. First results show that the failure strength increases at very high strain rates [7]. Typical material parameter values for annealed as well as for tempered glass are given in Table 2.

Interlayers

The material model for the PVB interlayer strongly depends on the damage level considered. Its behaviour until the first glass cracking can be assumed to be elastic since the strain is still very small. A more accurate description of the behaviour of the interlayer becomes important when the glass is cracked. Also a plastic material law could, for example, represent the loading behaviour under higher strain rates quite well when the unloading behaviour of PVB becomes more viscoelastic. Some values for the interlayer material are given in [8] and Table 2.

Adhesives and structural sealants joints

Adhesive joints and structural sealants are usually introduced between the glass panels and the metal frames. Literature references are available for their mechanical characterisation, e.g. from the producers. In general, adhesives and sealants of common use in structural glass applications are typically characterised by low modulus of elasticity, limited tensile/shear resistance and large ultimate strain. The simplest numerical modelling approach for the mechanical description of structural sealants in tension takes the form of equivalent linear elastic materials with brittle behaviour [9].

Steel and aluminium components

The strain rate effect of aluminium is generally small while that of steel could be high. Depending on the structural configuration, the strain rates in the bearing construction could be smaller. Nevertheless, a Johnson–Cook material law could represent the strain rate behaviour of many metallic materials. Examples are given in the previous report [4].

Table 2: Typical material properties for glass, PVB and sealant

Property	Annealed glass	Tempered glass	PVB	Sealant
Initial Young's modulus [Pa]	7.0e10	7.0e10	2.2e8	1.8 e5-6.2e5
Poisson ratio [-]	0.23	0.23	0.45	0.49
Elastic stress limit [Pa]	-	-	11e6	-
Density [kg/m³]	2 500	2 500	1 100	1 000
Failure strain [-]	0.0012	0.00228	2.0	4-4.6
Failure stress [Pa]	84e6	196e6	28e6	9.4 e5-12e5

7. Boundary conditions

For the analysis of the blast response of a glass window or facade, FE numerical models should be properly validated and assessed not only in terms of mechanical characterisation of materials, but by properly taking into account all the main influencing parameters.

Specifically, careful attention should be given to the numerical modelling of each window component (e.g. glass panel, metal framework and possible adhesive joints between them) and the connection to the building structure.

Both geometrically simplified models and computationally expensive detailed models can be used, if properly validated for the specific case.

An example of simplified models can be the description of a window in the form of 3D shell elements (glass panels), beam elements (metal frame) and mechanical point connectors (properly calibrated so that they could adequately reproduce the physical interaction between the glass panel and the frame). The same modelling approach can be extended to glazing systems in general, namely consisting of curtain wall modular units, cable-net systems and metal point connectors for the glass panels (Figure 5).

The appropriate numerical description of each window component should be suitably checked and validated against simple analytical models or experiments derived from small specimens/single facade components.

(a)   (b)
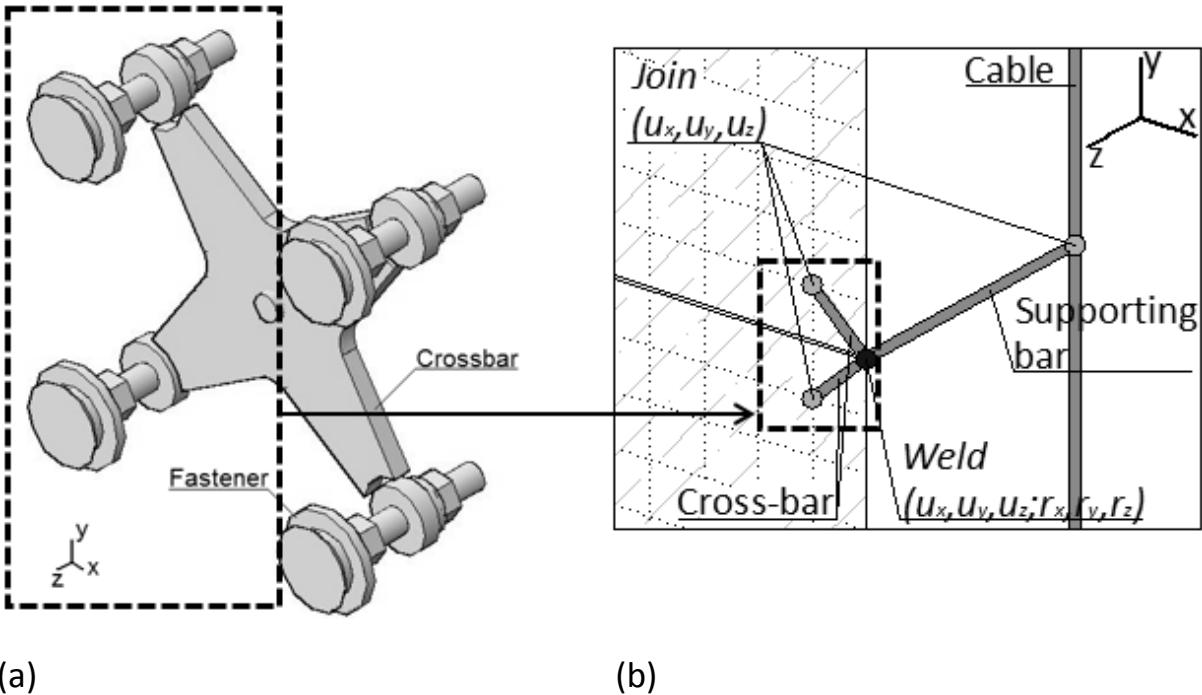
Figure 5: Example of point-supported glass panel. (a) Typical 'spider' connector and (b) corresponding geometrically simplified FE model [10].

Before performing dynamic analyses on full 3D solid FE models, careful consideration should be given to the assessment of the correct description of adhesive joints and/or mechanical connectors. Regarding the boundary conditions of the FE models, the presence of special devices/connection systems or brackets between the glazing window and the structural system (e.g. the concrete slab of a building) should be properly taken into account, so that the accuracy of the predicted effects due to the design blast load on glass as well as the maximum reaction forces transmitted to the substructure can be ensured.

8. Application of loading

The numerical approaches can be divided into two main groups: coupled and uncoupled calculation approaches. A coupled approach may be needed in a case where the structure-fluid interaction is

substantial, e.g. in the case of a very flexible structure, isolated glass, fragment trajectories, openings in the glass. In general, the loading definition is based on the TNT-equivalent method.

Uncoupled approach

Pressure, loading perpendicularly a plane wall, caused by blast waves can be calculated according to the theory of normal and oblique shock wave reflection, where the parameters of the spherical blast wave are estimated from empirical equations or diagrams (e.g. Kinney and Graham [11], Kingery and Bulmash [12]). These load functions can be applied if there are no alterations of the propagating blast wave between the detonation point and the studied structure (due to terrain anomalies, other obstructions, etc.). Clearly this method considers exclusively the dynamic behaviour of the structure (and not the surrounding air), and its advantage is the much lower computational cost.

Coupled approach

More comprehensive explosion simulations use a coupled Eulerian-Lagrangian (CEL) simulation scheme. In CEL the explosive and surrounding air are modelled using an Eulerian approach, typical in fluid mechanics. The behaviour of both gaseous materials is modelled using Equation-of-State (EOS) models that relate the pressure to the density of the material. For air this is typically the ideal gas law and for explosives, such as TNT, a Jones–Wilkins–Lee (JWL) model can be used [5]. The structure subjected to the blast loads is modelled using the traditional Lagrangian approach. The coupling between the Eulerian and Lagrangian elements is included so that the solid Lagrangian structure occupies Eulerian space and pressures on the interface act as loads on the solid structure.

9. Sensitivity study for essential calculation parameters

The topic of sensitivity study is broad and can cover a lot of aspects. This chapter focuses on some important parameters to be analysed such as

- Mesh size definition
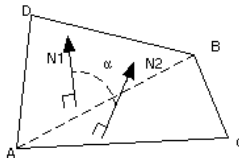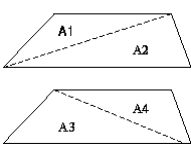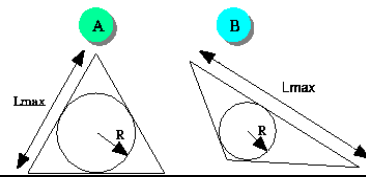- Elements shape
- Material parameters

Mesh size definition and element shape

Some recommendations have been written in [4] and [5]. Table 3 presents typical parameters to be checked before and during the simulation. Most numerical codes provide their own quality checks that might help engineers to design the numerical model.

After the element quality check, a mesh sensitivity study should be performed by using models with different mesh refinement and comparing the main results, such as failure location and size, maximum deflection of the structure, maximum strain (plastic strain) value. At least two different mesh refinements should give similar results in order to minimise mesh sensitivity. Some examples of mesh refinement studies of classical simulations can be found in [2].

Another way to guide the mesh generation is to evaluate where the highest stress values occur and then to verify that the mesh size is able to model the gradient of the stresses. If the gradient is too steep, it can generate a wrong estimation of stress maximum value. A general example of mesh convergence is given in [14].

Table 3: Mesh conformity recommendations for shell and solid elements (see also [13])

Mesh	Description
Mesh uniformity	It is admitted mesh is as homogenous as possible. In case of mesh size modification, size of two adjacent elements shouldn't differ more than 1.5 times (ratio of element size)
Minimum number of integration points through the thickness of a shell element	In case of linear material model, three integration points may be sufficient. In case of non-linear deformation, number of integration points should be seven or more. In case of layered structure, the number of integration points should follow previous rule per layer.
Skewness: Measures the deviation of an element's angles α_i from 90° for quadrilateral elements and 60° for triangular elements	Quadrilateral: $Skew = \sum_{i=1}^{4}(90 - \alpha_i)$ Triangular: $Skew = \sum_{i=1}^{3}(60 - \alpha_i)$
Warp: Measures the deviation in an element face from a maximum allowable planar warp	
Taper: $A_a = 0.25 \times (A_1 + A_2 + A_3 + A_4)$ $\left\vert \dfrac{A_i - A_a}{A_a} \right\vert > 0.5$	
Aspect ratio: Should be chosen as it is defined for the element type	The ratio of the maximum element edge length to the minimum length (it might also be the thickness).
Stretch: (example for triangular element) stretch=(R/Lmax) $_{actual}$ * (Lmax/R) $_{target}$ A: Target, B: Actual	

An example of local discretisation is given below, representing a blast-loaded laminated glass plate similar to the experiment of Kranzer [16]. The simulation is done in the same way as proposed by Larcher [8] using layered elements (linear) through the thickness. The glass plate is clamped between two steel frames as defined by ISO 16933. The element sizes, the number of elements and the calculation time is given in Table 4. The results (Figure 6 and Figure 7) show that the coarsest mesh results in a different displacement history. This may result from the wider boundary conditions. Only the finest mesh can represent the failure behaviour of the laminated glass as indicated by the experiment. The displacement history is therefore also quite different for the finest mesh size, especially in the rebound phase.

Table 4: Mesh sensitivity analysis for a blast-loaded laminated glass)

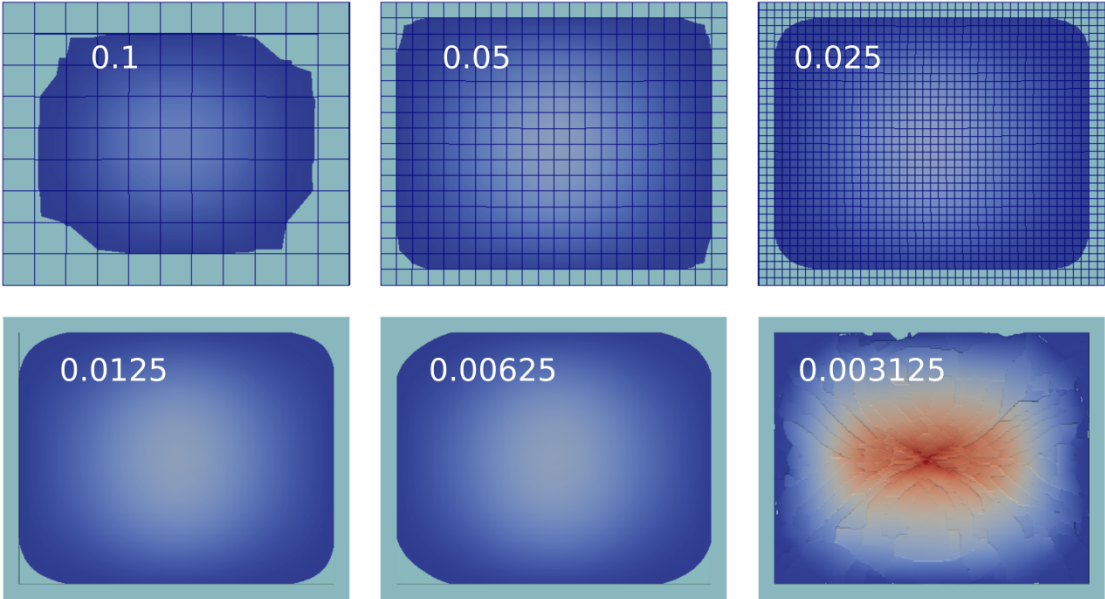| element size [m]	elements	calculation time [s]
0.1	63	8
0.05	396	33
0.025	1280	233
0.0125	5120	1923
0.00625	20480	13821
0.003125	81920	95635

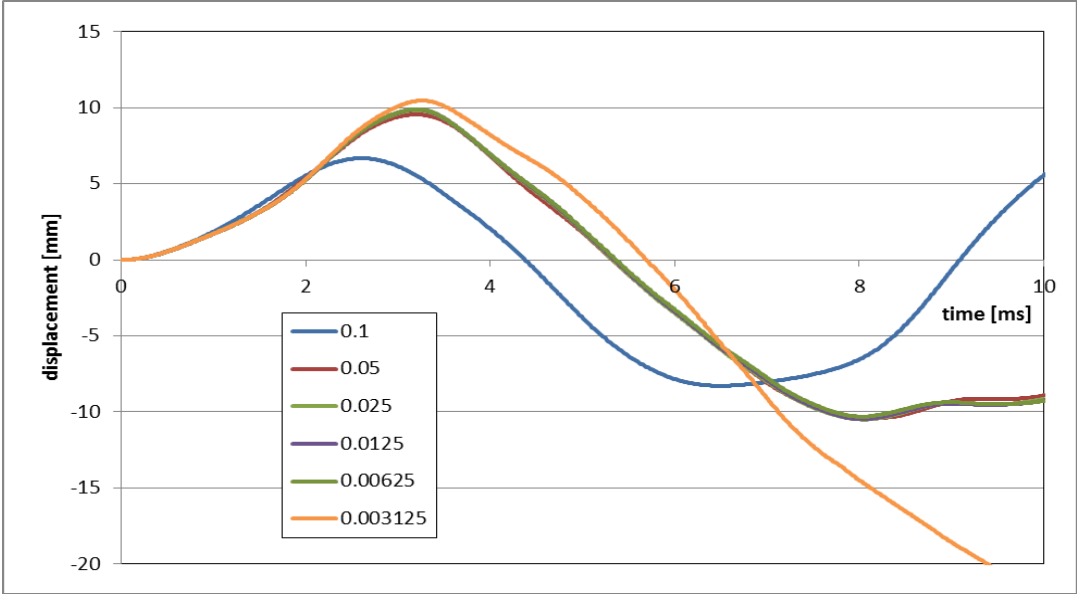Figure 6: Displacement at 10 ms for different element sizes

Figure 7: Displacement history for different mesh sizes for a blast-loaded laminated glass

Parameters for material modelling

The choice of a material model defines the number of input parameters. For example, for a purely elastic material (such as glass) with a stress limit, the material parameters needed for the analysis are:

- Young's modulus
- Poisson's ratio
- Density (due to dynamic structure response)
- Stress elastic limit

In many cases, the number of material parameters is much bigger. For example, the number of parameters for the Johnson–Cook model (strain rate and temperature-dependent model) is generally six. Typically, the more 'advanced' the material model is, the more input parameters are needed.

In order to evaluate the influence of each material parameter, it is useful to determine the degree of uncertainty of the value. Then, an option is to generate a sensitivity analysis on each material parameter in order to check its influence on the results.

Different mathematical approaches can be used in order to solve this type of problem. Based on an iterative process, several simulation codes provide a numerical approach to conduct this type of analysis (optimisation problem, for example LS-OPT, tool based on LS-DYNA software).

10. Validation and assessment of performance

Validation of numerical models

The numerical method and the material model should be validated by experimental data. This validation should include:

- Basic material tests: namely intended for the proper mechanical characterisation of glass and the other window components (e.g. interlayers in presence of laminated glass and frames, adhesive joints, mechanical connectors, etc.). Basic material testing would be appropriate even if this is in most cases neither possible nor cost efficient. Data from literature or the manufactures of the products could replace the material tests.
- Structural tests: the individual glazing window components (glass pane, frame, connectors), as well as their reciprocal structural interaction, should be sufficiently validated.
- A mesh sensitivity study: it must be performed, as outlined above, in order to validate the model.

The objective of a non-linear analysis is to simulate the structural behaviour and to determine the structural resistance. Such a task can also be formulated as a prediction of the most probable resistance, which would then be the mean value of ultimate resistance. Therefore, the mean resistance is chosen as a reference for safety assessment by non-linear analysis. The uncertainty due to random variation of material properties (and possibly of other parameters of resistance) can be described by the random variation of resistance. In addition a model uncertainty must be included separately.

Examples for validation experiments from literature

In order to validate numerical models experimental data are needed. Appropriate experiments are not often available in advance. Table 5 includes some sets of experiments, published in the open literature, which could be used for the model development and validation in this field.

Table 5: Blast-loaded laminated glass experiments published in the open literature

	Glass type/plies	Panel size [m]	Blast wave source	Charge (equivalent)	Distance [m]	Failure
Morison [15]	Float glass 3 mm	1.25 × 1.55	Solid explosive	60 kg TNT	12	Interlayer
Kranzer [16]	Float glass 3 mm	1.1 × 0.9	Solid explosive/shock tube	0.5/0.25/0.1 25 kg PETN	5.75/3.7/2.0	Glass
Hooper [17]	Float glass 3 mm	1.5 × 1.2	Solid explosive	15 kg C4	10/13	Interlayer
Morison [15]	Float glass 3 mm	1.25 × 1.25	Shock tube	(100/500 kg TNT)	31/65	Interlayer
Larcher [8]	Tempered glass 6 mm	1.1 × 0.9	Shock tube	(820-4 500 kg)	45-83	Glass/interlayer
Zhang [9]	Float glass 3 mm, 6 mm	1.5 × 1.2	Solid explosive	10/20	7.2-12.3	Glass/interlayer /boundary

Assessment of performance

The interpretation of the results can be done in several ways. A damage parameter or failure limit together with an erosion criterion can identify cracks in the glass, in the interlayer or in the other structural components. A simulation resulting in a completely undamaged state can be identified as a full protection, without any glass splinters in the interior. Assuming a model that can represent the failure of the interlayer is available, for simulation resulting in an undamaged interlayer it can be stated that the interior of the room is protected from major glass splinters. Also the window failure can be distinguished between shear failure near the window borders and bending failure in the middle of the pane. Finally, point connectors may have a different local failure mechanism. The interacting force between anchors/links and the surrounding structures should also be checked in order to avoid their failure.

11. Numerical simulation domains of application regarding actual standards

Table 1 shows the hazard levels that are normally determined experimentally. They represent in a way the formation and projection of splinters or fragments behind a laminated glass window. The fragmentation of laminated glass cannot yet be represented very well by numerical simulations. Therefore, with regard to hazard levels, numerical simulations can only be seen as a supplement to the experimental investigations.

Concerning specifically the hazard levels in ISO 16933:2007 [2], some correspondences of numerical results to the hazard levels A, B and C can be drawn, as indicated in Table 6. Eventual developments of calculation methods and models should enable reliable results on higher hazard levels, too.

Table 6: Hazard-rating criteria for arena tests according to ISO 16933:2007 [2]

Hazard rating	Hazard-rating description	Definition	Example of interpretation of numerical results
A	No break	The glazing is observed not to fracture and there is no visible damage to the glazing system.	No failure in the glass, i.e. there is elastic behaviour of the glass. Some very small failed zones near the boundary conditions may occur.
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.	Both glass plies could fail to reach their stress limit. Small strains in the interlayer, no large plastic (permanent) deformation of the window at the end of the simulation (this way the delamination should be small).
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. | Both plies fail. Failure of the interlayer. Distinction between class C and the higher ones could perhaps be possible using the velocity of the fragments and their trajectories. |
| D | Very low hazard | The glazing is observed to fracture and significant parts are located no further than 1 m behind the original location of the rear | |

		face. Parts are projected any distance from the attack face towards the blast source. Also, there are no more than three rateable perforations or indents anywhere in the witness panel, and any fragments on the floor between 1 m and 3 m from the interior face of the specimen have a sum total united dimension of 250 mm or less. Glazing dust and slivers are not accounted for in the rating.	
E	Low hazard	The glazing is observed to fracture, and glazing fragments or the whole of the glazing fall between 1 m and 3 m behind the interior face of the specimen and not more than 0.5 m above the floor at the vertical witness panel. Also, there are 10 or fewer rateable perforations in the area of the vertical witness panel higher than 0.5 m above the floor and none of the perforations penetrate more than 12 mm.	
F	High hazard	Glazing is observed to fracture and there are more than 10 rateable perforations in the area of the vertical witness panel higher than 0.5 m above the floor, or there are one or more perforations in the same witness panel area with fragment penetration more than 12 mm.	

12.   Conclusions

A review has been made of the capabilities of numerical simulations to assess blast-loaded laminated glass windows and facades, and to be used under certain circumstances to determine related hazard levels. As emphasised, special attention must be given to the validation of the numerical models since the choice of loading conditions, material parameters and boundary conditions could have a strong influence on the results. This report shows the first steps towards European standardisation in that field. The next step would be to further elaborate these findings and contact the responsible technical committee at CEN.

13.   References

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