European Commission

# Numerical simulations for classification of blast loaded laminated glass: possibilities, limitations and recommendations

ERNCIP Thematic Group
Resistance of structures to explosion effects


Editor:
Alexander Stolz, Fraunhofer Institute

Kevin C.
Ans van Doormaal, TNO
Christof Haberacker, WTD 52
Götz Hüsken, BAM
Martin Larcher, European Commission
Arja Saarenheimo, VTT
George Solomos, European Commission
Alexander Stolz, Fraunhofer Institute
Laurent Thamie, CEA
Chiara Bedon, University of Trieste


DECEMBER 2014


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

Report EUR 27137 EN

Joint Research Centre

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

Contact information
Georgios Giannopoulos
Address: Joint Research Centre, Via Enrico Fermi 2749, TP 721, 21027 Ispra (VA), Italy
E-mail: erncip-office@jrc.ec.europa.eu
Tel.: +39 0332 78 6211
Fax: +39 0332 78 5469

https://ec.europa.eu/jrc/en



JRC94928

EUR 27137 EN

ISBN 978-92-79-46172-9

ISSN 1831-9424

doi:10.2788/083832

Luxembourg: Publications Office of the European Union, 2014



Printed in Italy

**European Reference Network for Critical Infrastructure Protection (Erncip) thematic group**

# Numerical simulations for classification of blast-loaded laminated glass: possibilities, limitations and recommendations

## Thematic group:

## Resistance of structures to explosion effects

**Coordinator: Dr Alexander Stolz, Fraunhofer Institute for High-Speed Dynamics, Ernst Mach Institute (EMI)**

**Editor:**
**Alexander Stolz**

**Authors (in alphabetical order):**
**Kevin C.**
**Ans van Doormaal**
**Christof Haberacker**
**Götz Hüsken**
**Martin Larcher**
**Arja Saarenheimo**
**George Solomos**
**Alexander Stolz**
**Laurent Thamie**
**Chiara Bedon**

**Acknowledgements:**

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

**Abstract**

It is important to protect critical buildings (shopping centres, government buildings and embassies), infrastructure and utilities, train and underground stations against being damaged, destroyed or disrupted by deliberate acts of terrorism, criminal activity and malicious behaviour. Normal regulations and building guidelines do not generally take into account these threats. The introduction of appropriate regulations or guidelines, where deemed necessary, should, enhance the resilience of buildings and infrastructure against explosion incidents.

In order to protect the built infrastructure, methods are required to quantify the resistance of structural components against explosive loading and to assess the hazards resulting from the failure of an element. The applicable state-of-the-art techniques may include either experimental or numerical methods, or a combination of both.

Therefore, the thematic group (TG) on the resistance of structures to explosion effects was formed in order to bring the required expertise together, make it commonly available and to find and define harmonised methods and solutions which can be provided to the decision-makers responsible for critical infrastructure protection.

The current report summarises existing best practices for the numerical finite element modelling of blast loading, including the important topics of domain discretisation, implicit/explicit formulation, Lagrangian/Eulerian solvers, the mathematical description of the material behaviour etc. Furthermore recommendations for the modelling of laminated glass elements are formulated and knowledge gaps in this application area are pointed out.

Hence the report builds the basis for an actual evaluation of the different numerical methods, their suitability to certain problems, and their capability to support/complement the experimental testing of glass components. It thus provides helpful information to design architects and engineers, and more generally to critical infrastructure stakeholders, responsible for the structural integrity and security of the infrastructure in the event of an explosion.

# Content

1. Terminology on glazing ..... 7

2. Introduction ..... 7

3. Objectives of numerical simulations ..... 7

4. Finite element modelling (FEM) best practices ..... 9

4.1. Implicit and explicit FEM ..... 9

4.1.1. Numerical schemes ..... 9

4.1.2. Solvers ..... 10

4.1.3. Synthesis ..... 11

4.2. Simulation of the air-blast loading ..... 12

4.2.1. Coupled and decoupled approach ..... 12

4.2.2. Decoupled approach ..... 12

4.2.3. Coupled approach ..... 13

4.2.4. Modelling detonation and shock waves ..... 13

4.3. Material modelling ..... 14

4.3.1. Glass ..... 15

4.3.2. Annealed glass ..... 16

4.3.3. Fully tempered or toughened glass ..... 16

4.3.4. Heat-strengthened glass ..... 16

4.3.5. Laminated glass ..... 16

4.3.6. Metallic materials ..... 19

4.3.7. Rubber-like materials ..... 19

5. Recommendations for the simulation of blast-loaded laminated glass ..... 20

5.1. Components modelled ..... 20

5.2. Material models ..... 20

5.3. Model verification ..... 21

5.3.1. Shell and solid elements ..... 21

5.3.2. Main mesh verification ..... 21

5.3.3. Model check ..... 22

5.4. Model validation ..... 23

5.4.1. Structure response ..... 23

6. Open gaps in research ..... 23

6.1. Simulation of tempered glass ..... 24

6.2. High strain rate behaviour of glass and inter-layer ..... 24

6.3. Simulation of the cracks in the glass ..... 25

6.4. Damage definition ..... 25

6.5. Support conditions ..... 26

6.6. Insulated glass ..... 26

6.7. Experiments for validation ..... 26

7. Conclusions ..... 28

# 1. Terminology on glazing

In the context of this report, glazing refers to both windows and glazed facade systems. It is important to consider the window or facade as a system. This includes the glass, the gasket or sealant, the frame, the fixing of the frame, and the support system.

The blast pressure is applied to the whole area of the window or facade and the behaviour of the glass is dependent on the pane size. The loads on the support system and its performance are also dependent on the size of the glass pane(s).

If glass is tested in a rigid frame, the stresses in the glass are maximised as are the loads in the frame's fixings. However, if the glass is mounted in a frame with gaskets or sealants, the system's flexibility tends to reduce the stresses in the glass and the fixings.

# 2. Introduction

This report extends the previous one [1] with more details about possibilities of numerical simulations and scientific knowledge gaps in that field.

The objective of this report is to show all parties involved in the chain of security building constructions for protection purposes (such as producers, designers and end-users of laminated glass, windows and facades), an introduction of the capabilities of numerical simulations. Numerical simulations refer to finite element simulations or similar approaches. Until now numerical simulations cannot replace experimental investigations since too many influences are to be considered. This report presents a best practice for numerical simulations that should (not only) be used for blast-loaded laminated windows. The report will only consider near-field explosions for smaller charges or person-borne improvised explosive devices (PBIEDs) and far-field explosions for bigger charges or vehicle-borne improvised explosive devices (VBIEDs) and is focused on glass components. Therefore, simulations methods for contact and big near-field detonations are out of scope.

Numerical simulations for blast-loaded laminated glass are still not fully investigated and established. Several detailed questions should be solved and further numerical models should be developed to use numerical simulations for all limit states.

This report gives first an introduction to numerical simulations followed by a chapter on how finite element simulations can be used to assess the behaviour of laminated glass and windows. Recommendations for finite element simulations show the limits of the method and propose validation and verification procedures. Open questions for further research are discussed at the end of this report.

# 3. Objectives of numerical simulations

Even if there are several open questions in numerical simulations for blast-loaded laminated glass, there are several reasons why they could help the engineer in his or her work. The interaction between numerical simulations and their verification, validation and the approval of a design by experiment is shown in Figure 1. The figure shows the role of the numerical simulation like the finite element method or the single degree of freedom (SDOF) method in the experimental validation in order to achieve a design for a protective structure.

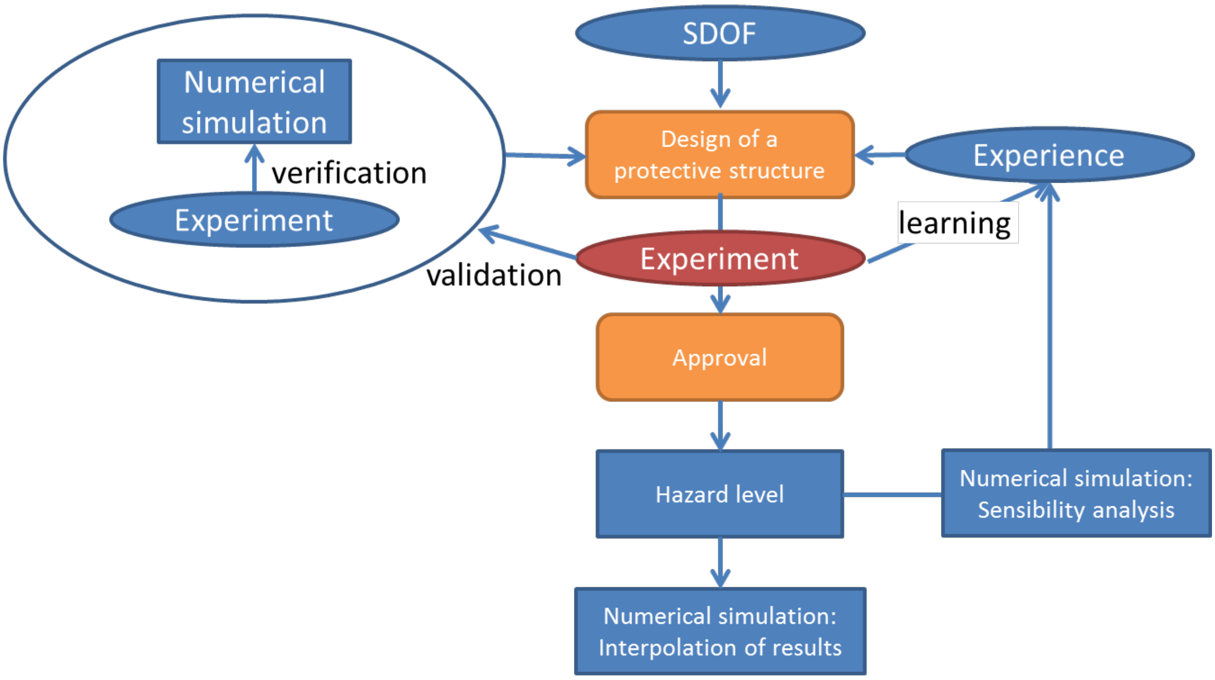



**Figure 1: Interaction between numerical simulations and experiments for the approval of protective structures**

Numerical simulations can help to understand the behaviour of the structure. While detailed experimental investigations are not easy to perform, numerical simulations can close that gap. Numerical simulations may help to develop new kinds of materials or structures. These structures can be tested numerically before expensive experiments are conducted.

Numerical simulations can help to investigate the different parameters of the windows relevant to the design. When a set of experiments has been conducted either to demonstrate the protective capacity of a specific window or to validate the numerical simulation, then further simulations can be used to investigate, for example, other sizes of the glass sheets and/or the loading or boundary conditions. Hence the number of experiments can also potentially be reduced by employing numerical simulations.

While an experimental investigation captures mainly one scenario or even only one pressure-time curve representing that scenario, numerical simulations can be used to investigate more threat scenarios. The place of the charge and its size can be varied easily in order to see the influence of those parameters. Also much larger structures can be taken into account like whole facades. Different types of facades could be tested such steel frame structure or cable-net facades.

Experimental investigations can be aided by using numerical simulations in advance in order to know the possible failure modes. Numerical simulations can support this process either in the design of a shock tube for testing windows or for the substructure for laminated glass in the case of arena tests.

Experimental research is needed [1] in order to understand the physical phenomena when choosing the appropriate modelling techniques and material laws. Further dedicated material tests are needed to obtain relevant material parameters for the material models.

Another approach is given by the SDOF method, where the window is represented by a single mass and a related stiffness. A huge number of experimental results are used to get data in order to model the non-linear stiffness properties of a spring. The method is presented in a previous report of the European Reference Network for Critical Infrastructure Protection (Erncip) thematic group [1]. The SDOF method cannot replace experimental investigations for a particular design.

# 4. Finite element method (FEM) best practices

Numerical methods have been developed in order to help engineers in understanding, analysing and predicting all physical phenomena occurring during different types of loading conditions. Numerical tools are of great importance, especially for dynamic loading, because fast dynamic events like blast loading are not easily understandable just by studying the damaged structure.

## 4.1. Implicit and explicit FEM

Numerical simulations can be advantageously used to predict the behaviour of glass undergoing blast-wave effects. These numerical simulations cannot replace experimental tests but they can be used in planning the tests, to predict experimental results and to carry out parametric studies by varying e.g. boundary conditions, the geometry of the structure, material properties or, explosive data. Most FEM solvers are based on a representation of structural components by elements. Typically, elements can be 1D (beams), 2D (shells) or 3D (bricks). Each corner (i.e. extremity) of an element is defined with a node. The association of all elements represents the structure and eventually the environment of the structure (boundary conditions or air) and is called the meshed structure.

### 4.1.1. Numerical schemes

Implicit and explicit time-integration schemes are the two main available methods used in dynamic finite element analysis [2]. The most appropriate method is selected based on the nature of the problem to be solved. While for earthquake loading and completely linear behaviour for fast dynamic loading, implicit methods are preferred, fast dynamics with non-linear behaviour is mainly calculated using the explicit time integration. This has several advantages, e.g. treating the non-linearities, the element erosion etc. see Table 1.

**Table 1: Features of several simulation models for dynamic loading of structures**

| | Implicit methods | Explicit methods |
|---|---|---|
| Stability | Unconditionally stable. Solution not dependent on the size of the time step. | Conditionally stable. Time increment must be small enough. |
| Time step sizes | Large time increments are possible. | Very small time increment needed. |
| Iterative methods | Needed for non-linear behaviour. | Not needed. |
| Applications | Linear and non-linear behaviour, slow dynamics, eigenfrequency analyses. | Highly non-linear behaviour, highly dynamics phenomena . |

For most of the applications presented in this report, explicit integration method is more suitable. More information about the general procedure of explicit methods is given in Belytschko [2].

#### 4.1.2. Solvers

The two main solvers are the Lagrangian solver and Eulerian solver (Figure 2).

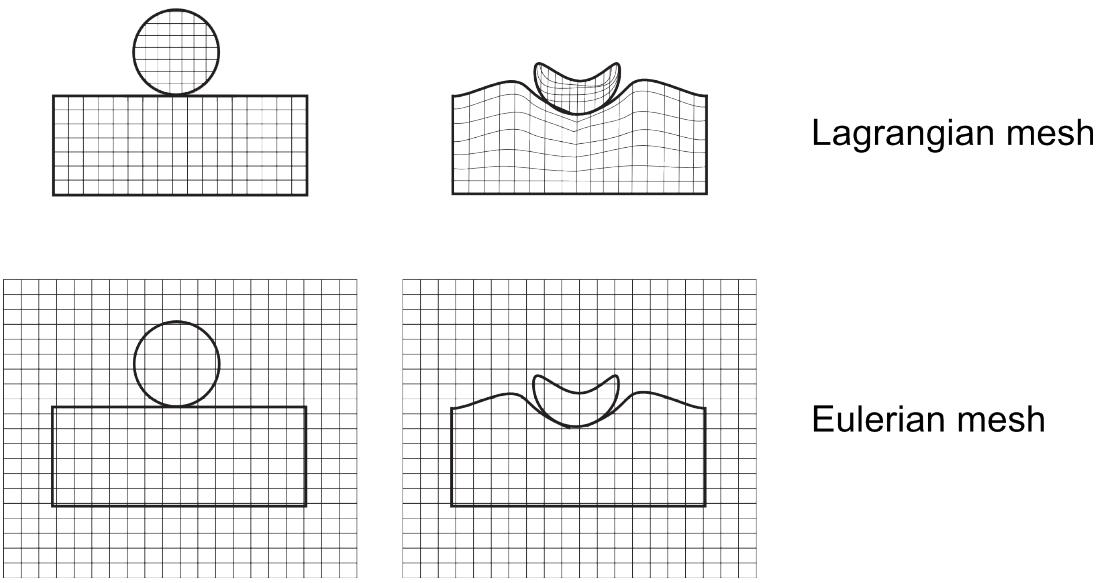



**Figure 2: Lagrange solver (top); Eulerian solver (bottom)**

The **Lagrangian solver** is the most commonly used in structural FEM analysis. The mesh represents the structure and its deformation. For example, during blast loading, the structure may undergo large deformations and the calculation mesh may be highly deformed when generating the premature stopping calculation (Figure 2, top).

To overcome this difficulty, the **Eulerian formulation** can be used instead of the standard Lagrangian approach. In the Euler solver the mesh (the grid) is fixed and the materials (solids, liquids and gases) flow through the grid (Figure 2 bottom). Eulerian analyses are effective for applications involving extreme deformation, up to and including fluid flow. In those applications, traditional Lagrangian elements would become highly distorted and lose accuracy. Liquid sloshing, gas flow and most of the penetration problems can be handled effectively using an Eulerian analysis.

In order to improve the quality of the numerical approach, many modern codes include **coupled Euler–Lagrange** analysis (also ALE approach). In this case the space domain is separated into two parts. One part is devoted to the Lagrangian solver and the second part is kept for the Eulerian solver. This coupled approach is very useful in simulating, in a single run, the shock-wave propagation and the structure response. Eulerian–Lagrangian contacts allow the Eulerian materials to be combined with traditional non-linear Lagrangian analyses.

Another possibility to improve the accuracy of fluid-structure interaction is to use mesh adaptivity (**automatic mesh refinement AMR**). The idea is to use a very fine fluid mesh near the structures and in zones with a high pressure gradient in order to better capture the details of the development of the wave in such regions.

New methods appear in a high-speed/deformation simulation domain. One of them is the **smoothed particle hydrodynamics** (SPH) method. SPH is a numerical method that is part of the larger family of mesh-free methods. For these methods it is not necessary to define nodes and elements as is normally done in a finite element analysis. It is necessary to define a collection of points representing a given body. In SPH these points are commonly referred to as particles or pseudo-particles. SPH is a fully Lagrangian modelling scheme permitting the discretisation of a prescribed set of continuum equations by interpolating the properties directly at a discrete set of points distributed over the solution domain without the need to define a spatial mesh. A Lagrangian solver coupled with the absence of a fixed mesh permits problem solving associated with fluid flow and structural interaction involving large deformations, failure and rupture of the structure.

### 4.1.3. Synthesis

Table 2 lists in alphabetical order some well-known software with their respective time-integration method. They could be separated between commercial, company-developed or free. The name of the company which develops the named software is noted in parentheses.

**Table 2: Non-exhaustive FEM codes lists with their time-integration methods and discretisation capabilities [1]**

| Software | Implicit Method | Explicit Method | Discretisation | | | Other features |
|---|---|---|---|---|---|---|
| Commercial software | | | Lag | Eul | Eul/Lag | |
| ABAQUS (Dassault Systems) | X | X | X | X | X | SPH,AMR |
| ANSYS (ANSYS) | X | X | X | | | |
| Apollo Blast Simulator (EMI) | | X | | X | | AMR |
| ASTER (EDF) | X | | X | | | |
| AUTODYN (ANSYS) | | X | X | X | X | SPH |
| CASTEM (CEA) | X | X | X | | | |
| COMSOL (Comsol) | X | X | | | | |
| EUROPLEXUS (CEA + JRC) | | X | X | X | X | SPH, AMR |
| IMPETUS (Impetus) | | X | X | | | SPH |
| LS-DYNA (LSTC) | X | X | X | X | X | SPH, AMR |
| NASTRAN (MSC) | X | X | X | | | |
| OURANOS (CEA) | | X | X | X | X | |
| PAM CRASH (ESI) | X | X | X | | | |
| RADIOSS (Altair Engineering) | X | X | X | | | |
| SOPHIA (EMI) | | X | X | | | SPH |

## 4.2. Simulation of the air-blast loading

### 4.2.1. Coupled and decoupled approach

Structural analyses methods (based on FEM) for blast-wave loaded structures can be divided into two main groups:

- decoupled approach
- coupled approach.

### 4.2.2. Decoupled approach

In the decoupled approach the pressure loading is calculated separately from the structural response either by analytical, empirical equations or by previous fluid dynamics simulations. The pressure is then used as a loading function to the structural-analysis model. The individual pressure function presents the pressure at the structure surface as a function of time. For example, the properties of the loading function are dependent on the scaled distance from the detonation point to the considered element of the structural-analysis model [1].

The decoupled approach is usually used:

- when the time response of the structure is longer than the duration of the positive phase (the relevant natural frequency of the structure usually determines this parameter);
- when the deformation of the structure doesn't significantly affect the pressure signal.

#### 4.2.3. Coupled approach

The structural effects of explosions can be simulated using a coupled Eulerian/Lagrangian finite element analysis technique. By this approach, the real phenomenon of interaction between the air (shock wave) and the flexible structure ~~is~~ analysed. The main difference from the decoupled approach is that the blast wave generates stress and displacements within the structure but the structure is also able to interact with and modify the blast wave. This simulation type is time costly in terms of computational resources because it needs to solve both Lagrangian and Eulerian equations at each time increment. This type of simulation is used especially when the flexibility significantly influences the loading profile.

#### 4.2.4. Modelling detonation and shock waves

There are several approaches to simulate the detonation and shock-wave loading of structures, as shown in Figure 3 and Table 3 (Larcher [3]). Far-field explosions can often be modelled using **pressure-time functions** that can be taken from several textbooks or reports in combination with the so-called modified Friedlander equation. (e.g. Kinney [4], Kingery [5]). These functions are applied to the structure. Fluid is not considered in the calculation with this type of simulation. The influence of reflections, shadowing and channelling is often not taken into account. The advantage of this method is that due to the small number of elements the calculation time is small. Often the formulas of the pressure-time function are already implemented in explicit codes; i.e. the use of them is very easy. The negative phase of an air-blast wave is seldom considered by using these functions. In some cases this is important especially for lightweight structures like windows.

In the case of more complex structures (as is often encountered inside urban areas or for near-field detonations) the spherical pressure-time history will not give accurate enough results. Decoupled approaches with separate fluid calculations or coupled approaches using fluid-structure interaction should be used. The behaviour of the explosive (**solid trinitrotoluene (TNT)**) can be considered using the Jones–Wilkins–Lee (JWL) equation of state together with an ideal gas model for the air. More details about these models are given e.g. by Baudin [6]. Simulations which also take into account the behaviour of the explosive itself need very small elements. Often such small elements are not usable in large zones of investigation. A **mapping algorithm** to map a fine 1D result to a coarser 3D mesh can close that gap. Other possibilities are given by the **compressed balloon** model where a balloon with higher pressure is released (Larcher [3]). This model is not physical but it shows similar pressure waves in comparison to real air-blast waves.

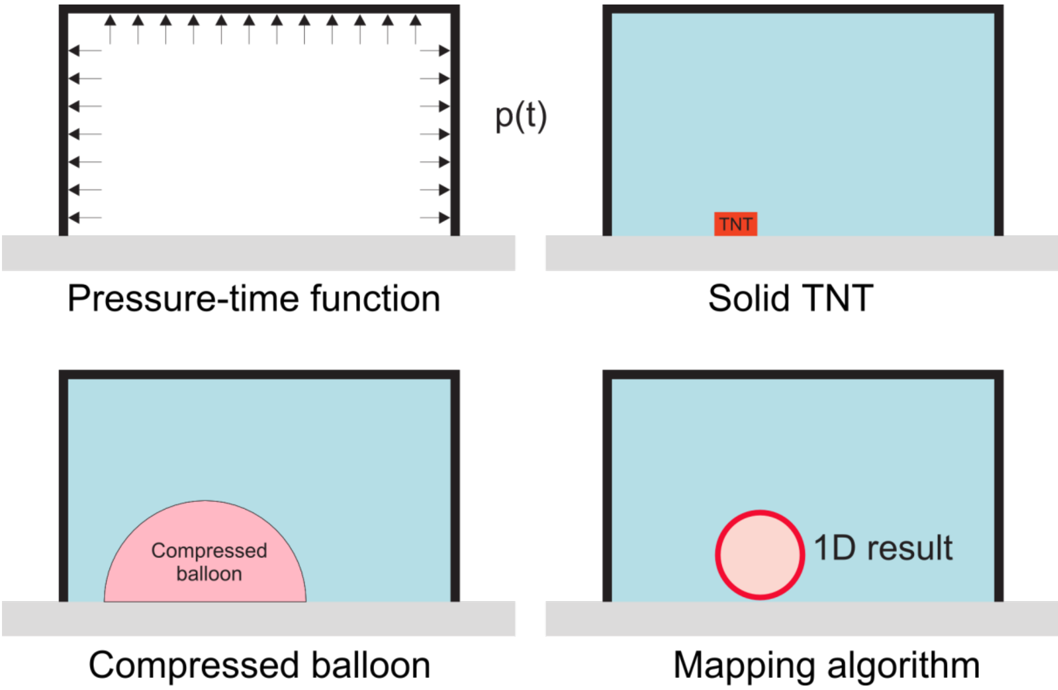



**Figure 3: Simulation approaches for load evaluation**

**Table 3: Advantages and disadvantages of several simulation methods for air-blast waves**

| Model | Applications | Accuracy | Calculation time |
|---|---|---|---|
| Pressure-time curve | Not suitable for reflections, shadowing | Depending on the case | Very short |
| Solid TNT | Large structures not possible | Very high, when small elements are used | Very long |
| Mapping algorithm | Large and complex structures are possible | Very high | Intermediate |
| Compressed balloon | Large and complex structures are possible | High, but not a physical model | Intermediate |

## 4.3. Material modelling

The simulation of air-blast loaded facades must consider all relevant structural parts of the facade. The first one is the glass itself which is described later in detail. Next is the modelling of the sealant and the frame of the window. Both of them are part of the boundary condition of the glass and should be modelled in detail since this condition has a strong influence on the glass failure behaviour. If the anchoring elements and the wall take part in the glass response, they must be included in the model.

If the window is part of a glazed facade it is recommended to model also the facade system since this system is often more flexible than a stiff concrete wall and it adsorbs a part of the blast energy via plastic deformations. These deformations of the facade can result in additional damage to the windows.

Double-glazing systems are more complicated to model since the gas between the glass panes generally transmits the loading to the second glass ply. After strong deformations both glass panes could also come into contact. Retrofitting systems with, for example anti-shatter film, can also be numerically modelled, but this will not be described here.

A crucial parameter in the numerical simulation of explosion effects is the definition and modelling of the material mechanical properties [1]. The blast waves can cause significant structural deformation exceeding the linear domain and this implies that one has to deal with concepts such as plasticity, visco-plasticity, large strains, high strain rate, failure and fragmentation etc. Features of the modelling of the main structural materials of laminated glass windows, such as the glass and the inter-layer as well as steel and aluminium used for the frames will be presented.

### 4.3.1. Glass

Glass is often the most fragile part of a structure and is therefore the most important part in order to protect critical infrastructure and its occupants. There are three different types of glass: annealed (AN), heat-strengthened (HS), and fully tempered (FT) glass (Figure 4). They can be distinguished by their average tensile failure strength which lies between 70 and 250 megapascals (MPa). The strength of one particular glass type shows strong variations due to micro-flaws. Dynamic glass strength still needs more investigations, but some experiments show a higher dynamic strength than the static one (Peroni [7]). The compressive strength of glass is much higher than the tensile one.

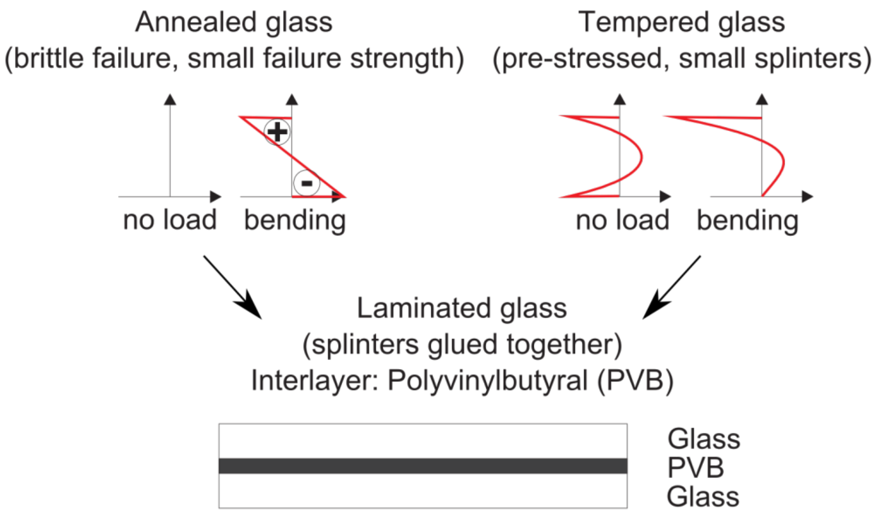



**Figure 4: Glass types**

### 4.3.2. Annealed glass (AN)

This glass is cooled slowly in a controlled way in order to relieve internal stresses. The strength of this relatively inexpensive glass is small (Figure 4) and the variation in strength is large. It is widely used for windows in cases where security against impacts and blasts is not important and where failure and the splinters produced do not affect human bodies (Beason [8], Overend [9]).

### 4.3.3. Fully tempered or toughened glass (FT)

Toughened glass or tempered glass is two or more times stronger than annealed glass. The production is done in such a way that residual stresses remain in the glass but in a manner that contributes to the increase of its bending strength. Both surfaces of the glass pane remain under compression, and when loaded by a pressure the induced tensile stresses are practically overcome by the existing residual compression, and thus the surface of the glass does not really enter in tension. The variation of the failure strength is smaller in comparison to annealed glass.

### 4.3.4. Heat-strengthened glass (HS)

Heat-strengthened (HS) glass is glass that has been heat treated in order to induce surface compression, but not to the extent of a tempered glass. The failure strength is therefore between the above two glass types.

### 4.3.5. Laminated glass

Laminated glass is a combination of two or more glass sheets with one or more polymer inter-layers. Several types of laminated glass have been manufactured, with different types of glass materials, e.g. annealed glass and tempered glass, and with various inter-layers, such as polyvinyl-butyral (PVB), SentryGlas®Plus and ethylene-vinyl acetate (EVA). Laminated glass has the advantage that, following its failure due to blast loading, the produced fragments remain stuck to the inter-layer, as graphically illustrated in Figure 5. Thus practically no splinters are formed and the risk of human injuries is contained.

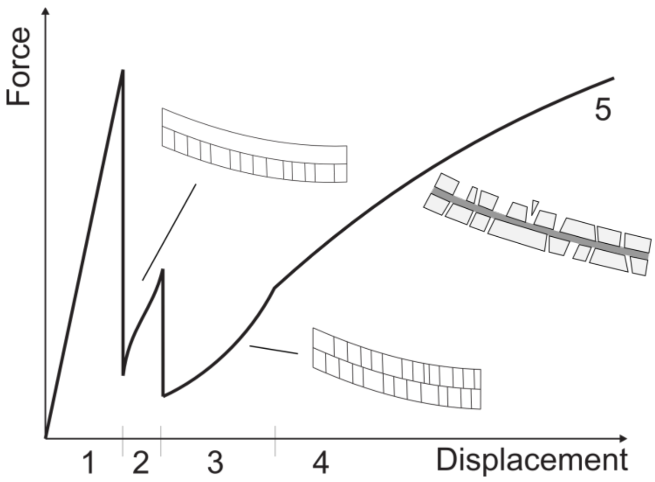



**Figure 5: Phases of failure of laminated glass**

#### 4.3.5.1. Inter-layer types

**Polyvinylbutyral (PVB).** The long-time behaviour of PVB is visco-elastic, while the short-time behaviour is closer to elastic-plastic or brittle. Like other plastic materials, PVB shows failure at large strains (approximately 200 %), which indicates the need for a hyper-elastic material law. The Poisson ratio of the almost incompressible material is nearly 0.5, which can cause numerical problems if the material law is not adequately formulated.

**Ionoplast Polymers (e.g. SentryGlass).** This polymer has five times the tear strength, 100 times the rigidity of conventional PVB. Good impact strength/toughness over broad range of temperatures but it is very expensive (three to four times more expensive than PVB). The material's behaviour under high strain rates is still not investigated [15].

**Polycarbonate.** The material itself shows very good bullet resistance. The material can be easily scratched. The scratch and blast resistance is increased by using it in combination with glass layers. The polycarbonate layers are then much thicker in comparison to PVB.

#### 4.3.5.2. Example of FEM for laminated glass

Three model types can be adopted for calculating the response of laminated glass under air-blast loads, as shown in Figure 6.

(a) **Layered elements with a special failure criterion**. After glass failure, the stresses are set to zero if the strains are greater than zero (tension) but the material can still react to compressive stress. If the inter-layer reaches the failure criterion of PVB, the element is eroded (Müller [10]).

(b) **Smeared model.** This is used to simulate post-failure behaviour (Timmel [11]). Two coincident shells are used with two different material laws. The thickness, density and Young's modulus of these two shell elements are calculated in such a way that the combination of the two shell elements represents the behaviour of the sheet before failure.

The behaviour of the laminate after failure of one of the glass plies is represented by only one of the shell elements (Timmel [11]).

(c) **The 3D solid model.** This simulation requires very fine meshes, resulting in a long calculation time. The same material laws can be used as for layered shell elements. Some authors present 3D models with solid elements which allow using a detailed material law for the inter-layer (Wei [12], 2006; Bennison [13], [14]).

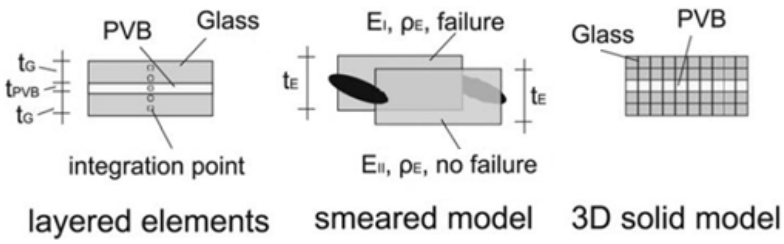



**Figure 6: Models used for the simulation of laminated glass**

The influence of large strains and large strain rates should be considered for blast and impact loaded laminated glass (Morison [16], Iwasaki [17], Bennison [14]; Figure 7).

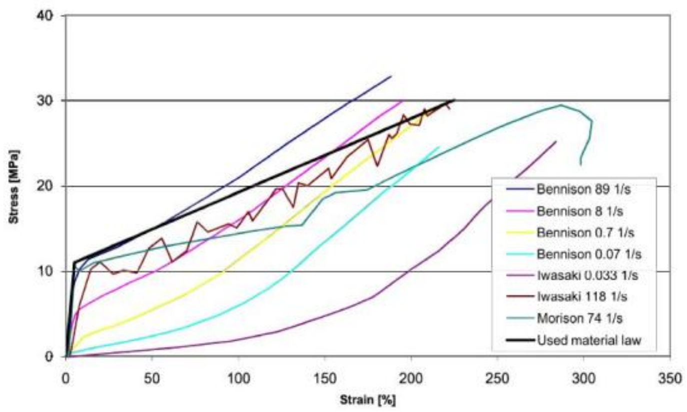



**Figure 7: Behaviour of PVB at different strain rates**

Visco-elastic materials show more elastic-plastic behaviour below the glassy point. The glassy point refers to the conditions (temperature, loading rate) where a transition occurs from the glassy state to a rubbery state. Since the behaviour of such materials under higher strain rates is often similar to the behaviour at lower temperatures, an elastic-plastic material law could be a first approximation. Further investigations should be done to identify the unloading behaviour of this material under higher strain rates.

The interfacial adhesion between the glass and the inter-layer is produced by heating in combination with the application of high pressure. The mechanisms for the chemical adhesion depend on chemical and hydrogen bonding. The gluing forces of PVB are relatively high, and de-bonding is not usually considered for blast-loaded laminated glass. An example of material data for the material parts of laminated glass is given in Table 4. It is important to mention that these are examples and values may actually vary. The deviation especially of the values for the glass strength is high. Stewart [18] also gives values of strength resistance based on a probability for a failure of 0.8 %. In such a case the strength must be chosen to about 28 MPa which is much smaller than the mean value given in Table 4.

**Table 4: Typical material properties for glass and PVB as given by Stewart [18]**

| Property | Annealed glass | Tempered glass | PVB |
|---|---|---|---|
| Initial Young's modulus [Pa] | 7.0e10 | 7.0e10 | 2.2e8 |
| Poisson ratio | 0.23 | 0.23 | 0.45 |
| Elastic limit [Pa] | 84e6 | 196e6 | 11e6 |
| Density [kilograms (Kg)/cubic metres ($m^3$)] | 2500 | 2500 | 1100 |
| Failure strain | 0.0012 | 0.00228 | 2.0 |
| Failure stress [Pa] | 84e6 | 196e6 | 28e6 |

### 4.3.6. Metallic materials

Metallic materials like steel, iron and aluminium constitute an important part of contemporary constructions. In the case of explosion events the deformations of the structural elements are very likely to enter the plastic domain and phenomena like strain hardening and material failure should be taken into account. Several models have been developed to describe the behaviour of metallic materials under severe dynamic loading conditions such as the Ludwik model (Moras [19]), the Cowper–Symonds model, Armstrong-Zerilli model (Zerilli, et al.[20]) and Johnson–Cook model (Johnson, et al. [21]) which appears to be the most commonly used one. Since the strain rate of the metal part of the structures is small and the strain-rate effect of metals is small also classical plastic material laws can be used.

### 4.3.7. Rubber-like materials

In addition to the resistance of the glass itself, the connection between the glass and the supporting structure must also resist the air-blast wave. If the joint or framing structure is not strong enough, the pane could get detached and enter the building at high velocity and injure occupants. Structural silicone sealant is commonly used to bond the laminate to a framing structure [33]. The laminate is restrained at two or four edges of the pane with a silicone-bonded joint on one or both faces of the laminate. Securing all four edges on both sides is the recommended practice for blast resistance with a silicone joint of at least 35 mm in depth. There are also other methods of restraining laminated glass, such as rubber gaskets, glazing tape and mechanical point fixings. These systems are generally considered to give inferior blast protection to silicone bonded edges (Hooper [22]).

The elastic support of these rubber materials of the windows can be modelled by solid elements sharing some of the node elements of the laminated glass. If the frame should be set as rigid, the nodes at the top and at the bottom could be fixed. An elastic material law can be used. Larcher [23] uses a value for the Young’s modulus of 3.5 MPa which represents the stiffness of the testing frame according to the standards. However, the influence of the support fixing must be assessed by conducting parametric studies with different boundary conditions.

# 5. Recommendations for the simulation of blast-loaded laminated glass

The first decision concerns the appropriate simulation model regarding the loading since this has many influences on the following possibilities. Table 3 could provide a good indication of which model is appropriate. In the case of far-field detonations the loading by a pressure-time curve is often the most suitable way, since the calculation time is so small that structural components can be investigated in detail. In the case of a more complex fluid structure around the structural part of interest, the more complex pressure-time curve is often converted into a standard one in order to facilitate the simulation. This question has to be discussed together with the operator since the scenario of the hazard must also be chosen appropriately.

Fluid-structure interaction simulations must be checked very carefully. The pressure-time curve at a distance where the spherical or hemispherical wave is not yet influenced by any obstacle should be compared with analytical values given for example in Kinney [4] or Kingery [5] in order to check if the element sizes of the simulation are fine enough to simulate the blast wave.

## 5.1. Components modelled

All important components must be modelled in order to represent the response of the structure, i.e. all components which take part on the resistance, the failure and the movement of the structure. This means that the laminated glass itself is sufficient to be simulated only for some particular cases. In all other cases, the connection to the frame with an elastomer, the frame itself and the connection of the frame to the structure must be considered. In the case of possibly opening frames the hinges must also be included in the investigation.

## 5.2. Material models

Only material laws corresponding to the chosen structural modelling lead to successful simulations. The first question is what damage state should be investigated. If only the first crack of the laminated glass should be determined, the smeared model or even one continuous glass ply through the thickness could be enough. If the behaviour after the cracking of the glass and with it the interaction between splinters and the inter-layer are also to be investigated then even more complex models need to be chosen. Its detailed failure behaviour is still not yet known and should be investigated in the future.

The importance of the choice of the material law for metallic parts is minor. Due to the small strain-rate effect, elastic-plastic material laws with an erosion criterion often fit very well to the needs of the simulation, but the implementation of the fixings of the frame could be more complicated. One possibility here is to set a fixed boundary condition and measure the maximum force of the boundary. This value can be compared with experimental values to determine a possible failure of the fixing.

## 5.3. Model verification

Also the meshes should be conforming to some rules which are presented in the following sections.

### 5.3.1. Shell and solid elements

The element type and material model should be chosen according to the expected failure mode. It should be especially noted that non-linear transverse shear deformation is not necessarily taken into consideration in a shell element.

Most of shell elements should be defined using four node elements. Three node elements should be used with care since their behaviour can be different from what is expected. A large amount of three node element verification with these elements should be done. More recommendations concerning the element shape are given in Table 5.

Solid elements are generally defined using eight node elements (hexahedron). The use of tetrahedron elements is helpful for complex geometry meshing but may need more elements to reach sufficient quality result.

The element size must be investigated in a convergence study. Its result should be validated with an experiment to show the capability of the model to represent the expected behaviour. Cracks in the glass are often represented by element erosion and therefore small element sizes are needed.

The element size of shell elements has some limitations. In general, shell elements with dimensions smaller than the order of the thickness are not usable. The minimum element size depends on the formulation of the shell element and must be checked for each element type and sometimes together with its material parameters.

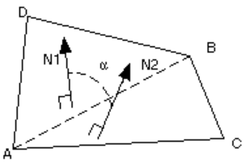
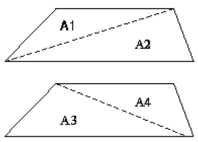
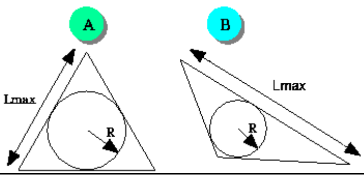
### 5.3.2. Main mesh verification

In order to help FEM users, a acertain number of intrinsic parameters related to mesh quality should be taken into account.

Table 5 below represents typical parameters to be checked before the simulation. The main commercial codes provide their own quality check that might help engineer to design the numerical model.

**Table 5: Mesh conformity recommendations for shell and solid elements [29]**

| Mesh size | |
|---|---|
| Mesh uniformity. | Its admitted mesh is as homogenous as possible. In the case of mesh size modification, the size of two adjacent elements should not differ by more than 1.5 times (ratio of element size). |
| Minimum number of integration point. | In the case of linear material model, three integration points may be sufficient. In the |

| | |
|---|---|
| | case of non-linear deformation, the number of integration points should be seven or more. In case of a layered structure, the number of integration points should follow previous rule per ply. |
| Skew<br>Measures the deviation of an element's corners from 90° for quadrilateral elements and 60° for triangular elements. | Quadrilateral: $\text{Skew} = \sum_{i=1}^{4}(90 - \alpha_i)$<br>Triangular: $\text{Skew} = \sum_{i=1}^{3}(60 - \alpha_i)$ |
| Warp<br>Measures the deviation in an element face from a maximum allowable planar warp. |  |
| Taper<br>$A_a = 0.25\times(A_1 + A_2 + A_3 + A_4)$<br>$\left\lvert\frac{A_i - A_a}{A_a}\right\rvert > 0.5$ |  |
| Aspect ratio: | Measures the ratio of the maximum element edge length to the minimum length. |
| Stretch: (example for triangular element)<br>stretch=(R/Lmax) $_{actual}$ * (Lmax/R) $_{target}$<br>A: Target, B: Actual |  |

### 5.3.3. Model check

In addition with element check, some specific checks must be done prior to and after the simulation. Several good recommendations about tests for explicit finite element simulations are given in the European Committee for Standardisation (CEN) standard CEN/TR 16303 [30].

The following tests could be done prior to a simulation.

- Mass model check (mass check of each component, material).
- Boundary condition modelling: e.g. comparing external loads with internal reaction forces.
- Checking of nodes not connected to any element or of coincident nodes.
- Convergence study: simulation of mesh refinement sensitivity.
- Singularities and over constrained models. This is a typical numerical problem when using implicit solver (static or dynamic). It can be checked by solving the eigenvalue [31].
- Modal analysis
    - Used to evaluate the mesh refinement. If the eigenvalues and eigenmodes differ too much from the theoretical values, this can suggest an insufficient mesh refinement on this component.

- Used to evaluate bad conditioning connections between the model components: if internal energy is not equal to zero, it can come from bad connection between nodes.

The following checks could be done during and after a simulation run [30].

- Plausibility of the result.
- Time step size should be small enough to represent the explosive loading but not too small to produce wrong results.
- Total energy check.
- Hourglass energy check.
- In case of mass scaling: Added mass should be controlled during the run (use of added mass cannot be banished but must be limited).
- Contact energy check.
- Capacity of the material model to represent the behaviour under the elevated strain rates in the simulation.
- Erosion criteria check.
- Negative volumes.
- Visible check of pressures, stresses, displacements.

## 5.4. Model validation

### 5.4.1. Structure response

Since the results of numerical simulations depend on the model used, the material laws, the element size and the appropriate boundary conditions (Figure 1), they can differ from the experimental ones. A validation of the numerical results is therefore very important. This should be done with experiments showing the same failure limit under a comparable loading characteristic (e.g. cracks in the glass, failure of the inter-layer).

Most of the experiments done in the past were confidential since they belong to the manufacturer or they cannot be published due to security reasons. Some experiments are presented in the literature and an overview of publicly available experiments is shown by Larcher [32].

The following aspects should be considered, especially when the numerical model should be validated or the results are reused for further optimisation of the design.

- Displacements; time dependent, maximum displacements, permanent displacement.
- Failure mode (Cracks, holes, window opening) taking into account the hazard level.
- Fragmented area.
- Opening mechanism still usable.

# 6. Open gaps in research

The simulation of laminated glass loaded by air-blast waves is still a demanding task. It is not yet possible to capture all effects of the failure of laminated glass. Several scientific questions are still to be solved. Most of them are not only numerical problems but also connected to questions about the behaviour of the material under fast dynamic conditions. Nevertheless, simulations can be useful to investigate and analyse the general response of the laminated glass element to the blast loading.

## 6.1. Simulation of tempered glass

The failure strength of annealed glass is difficult to determine since the statistical variation is very large. The mean value of the tensile failure stress for annealed glass is for example about 80 MPa (Table 4). Experimental investigations show variations between 20 and 140 MPa. This variation is smaller in case of tempered glass. Nevertheless, the numerical simulation of tempered glass is also not easy if the pre-stressing of the glass has to be taken into account. This would help to understand the failure behaviour of tempered glass more. The experimental determination of the pre-stressing and its numerical modelling are difficult since the area of the window is much bigger than its thickness.

An example of dynamic loading on glass panel is given below (Figure 8, courtesy of the *Commissariat à l'énergie atomique et aux énergies alternatives*, CEA/Gramat, France):

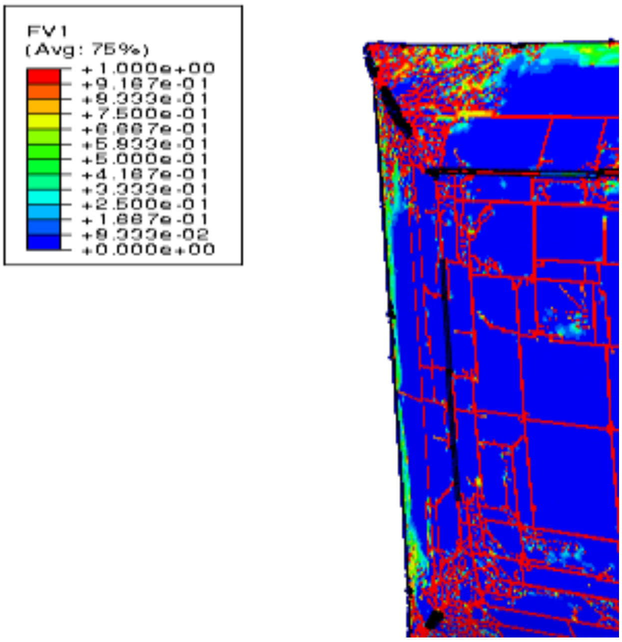



**Figure 8: Glass failure simulated with user material model (PRM model — CEA)**

## 6.2. High strain-rate behaviour of glass and inter-layer

The high strain-rate behaviour of concrete and many metals is well known. Concrete for example shows an increase of tensile strength up to five times, whereas the strain-rate behaviour of aluminium is negligible. Only some preliminary studies about the behaviour of glass under high strain rates are available [7]. A difficulty of fast loading experiments with glass is the production of proper test specimens whose surfaces are not damaged by the cutting process. In addition, due to the statistical variation of the strength under static conditions and most probably also under dynamic conditions, the evaluation of the influence of the strain rate can only be done by using a very large number of experiments.

The situation of the behaviour of inter-layers under high strain rates is also not well known. Figure 7 shows some data available for PVB. They show a plastic loading part under high strain conditions but most probably the material reacts, not plastic for unloading, i.e. there are no plastic strains after the loading. More material investigations are necessary to develop a suitable material law for different material types of the inter-layer.

The behaviour of the composite structure under high strain rates should also be investigated in more detail. It could also be possible that the composite structure changes some of the material behaviours under high strain rates.

## 6.3. Simulation of the cracks in the glass

The composite structure after the failure of the glass changes completely. The behaviour of the inter-layer may be neglected until the failure of the glass under high strain rates, since the shear connection under fast dynamics of the inter-layer is quite good (below glassy point). After the failure the interaction between the inter-layer and the glass fragments is very important. It can be observed in experiments that the delamination of splinters is very small. The only fragments that were found are either very big (broken glass together with the inter-layer, sizes from 10 centimetres (cm) to the size of the panel) or very small (smaller than a millimetre (mm)). The very small splinters most probably do not have any connection to the inter-layer.

The simulation of the glass cracks and the splinters is a challenging task. A classical method for such a question is element erosion. Elements that reach a certain failure limit are not taken into account any more (eroded) in the simulation. In order to get small crack thicknesses, the element size must be very small. For shell elements this element size is limited by the thickness of the plate. Very detailed and expensive 3D calculations could be helpful. Another possibility could be to split the elements just before the crack starts to open, but the general limit of the element size is not changed. There are some quite new numerical methods that can represent cracks in a material also when it goes through one element (e.g. XFEM, EFG). It is not clear whether these methods are suitable for the crack propagation problem of laminated glass. Since the number of cracks is very high in the case of blast-loaded laminated glass, a damage material law could also be used. Such a law would have to represent the combination of glass splinters and inter-layer by reducing the stiffness.

## 6.4. Damage definition

All recent standards define a hazard level in order to compare several laminated glass products. This is done mainly via the number of glass fragments that are flying into the room behind the window. In order to compare the experimental hazard level with the numerical simulation, the damage of the laminated glass and the sizes of the splinters must be taken into account. This is not easy since the development of the glass cracks is already complex. The trajectory of the fragments must be followed to get the hazard level.

An example of fragment flight simulated with Abaqus software is shown on Figure 9.

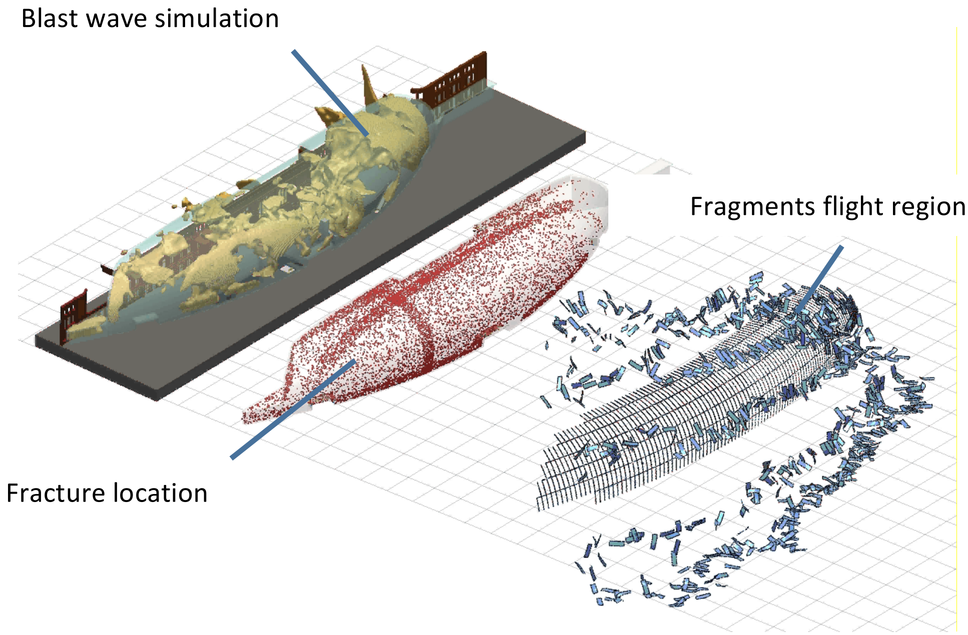



**Figure 9: Glass structure damage (fragment flight) — Courtesy CEA Gramat**

## 6.5. Support conditions

The support conditions of laminated glass are very important in studying failure behaviour. Laminated windows fail either by reaching a maximum deflection in the middle or by a failure at the boundaries (e.g. pull-out, shear). Several boundary conditions are possible. Windows are mainly fixed into the frame by using an elastomer. The behaviour of the elastomer under high strain and high strain-rate conditions should be investigated. For modern architecture often point fixings are preferred. Their failure behaviour is also not yet investigated in detail. The connection of the frame to the stiff structure is also important. The fast pull-out of fixings in such a case should be investigated.

## 6.6. Insulated glass

The environmental aspect of our buildings becomes more and more important. Even if the number of buildings that use laminated glass for safety or security reasons is small, it should also be possible in such cases to use laminated insulated glass. There are products on the market where an exterior normal glass is combined with an internal laminated glass. In the case of an air-blast loading two questions are important: first, the influence of the air between the two plates, which loads the second plate. Second, the fragments of the first plate after its failure that add an additional mass and impulse to the laminated glass.

## 6.7. Experiments for validation

There is indeed a lack of published experiments that can be used for validation purposes. Most of the experiments in the past were confidential. It would help the development of numerical models if a larger set of experiments of blast-loaded laminated glass with different dimensions, thickness and inter-layer materials were available. Different types of experiments should be defined.

- Full scale experiment on assemblies (windows or facade).
- Small scale experiment of specific material.

Experimental setups are presented in the report [1] related to experimental validation.

Small scale experiments can be done on specific test facilities in order to characterise material behaviour, especially in the high dynamic loading domain.

## 7. Conclusions

Numerical simulations can be a powerful and cost effective tool for assessing the resistance of glass structures to blast loading. As stressed, key parameters for the quality of the simulations are the verification and validation of the numerical models and input parameters, and should therefore be independent from the chosen actual numerical code.

Numerical methods and models should be validated against experimental data, and engineering judgement is certainly needed in defining the validation cases. Simplified models are a valuable first step when judging the reliability of both the test results and the more comprehensive finite element numerical simulations.

When conducting such simulations, experience is required in choosing the appropriate modelling techniques, boundary/support conditions and material laws. It is crucial to remember that blast waves can cause significant structural deformation exceeding the material linear domain and this implies that one has to deal with concepts such as plasticity, visco-plasticity, large strains, high strain rate, failure and fragmentation etc. Currently, numerical simulations can provide stresses, deformation and a global pattern of failure of the glass component but it is not possible to reliably calculate the size and speed of fragments. However, this constitutes a valuable and efficient tool in understanding the sequence of damage initiation and development.

Further research is necessary in order to understand the physical phenomena relevant for the given task of the failure of the laminated glass. Therefore, dedicated tests are needed to investigate the mechanical behaviour of such components and to obtain relevant parameters and material models.

Additional work on the best practices in numerical simulations for blast-loaded laminated glass will be carried out by the Erncip Resistance of structures to explosive effects thematic group during 2015, with the aim of producing proposals for work on European harmonisation, if appropriate.

## References

[1] Stolz, A., van Doormaal, A., Haberacker, C., Hüsken, G., Larcher, M., Saarenheimo, A., Solomos, G., Thamie, L., and Valsamos, G., *Resistance of structures to explosion effects: Review report of testing methods Erncip thematic area resistance of structures to explosion effects. Deliverable D1*, Publications Office of the European Union, 2013.

[2] Belytschko, T., Liu, W.K., and Moran, B., *Nonlinear Finite Elements for Continua and Structures*, John Wiley&Sons, Chichester, 2000.

[3] Larcher, M. and Casadei, F., 'Explosions in complex geometries — a comparison of several approaches', *International Journal of Protective Structures*, 1(2):169–195, 2010.

[4] Kinney, G.F. and Graham, K.J., *Explosive Shocks in Air*, Springer, Berlin; Heidelberg; New York; Tokyo, 1985.

[5] Kingery. C.N. and Bulmash, G., 'Airblast parameters from TNT spherical air burst and hemispherical surface burst. Technical report', Defence Technical Information Centre, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, 1984.

[6] Baudin, G. and Serradeill, R., 'Review of Jones-Wilkins-Lee equation of state', *EPJ Web of Conferences*, 10:00021, 2010.

[7] Peroni, M., Solomos, G., Pizzinato, V. and Larcher, M., 'Experimental investigation of high strain-rate behaviour of glass', *Applied Mechanics and Materials*, 82:63–68, 2011.

[8] Beason, W.L. and Morgan, J.R., 'Glass failure prediction model', *Journal of Structural Engineering*, 110(2):197–212, 1984.

[9] Overend, M., Parke, G.A.R., and Buhagiar, D., 'Predicting failure in glass – A general crack growth model', *Journal of Structural Engineering*, 133(8):1146–1155, 2007.

[10] Müller, R., and Wagner, M., 'Berechnung sprengwirkungshemmender Fenster- und Fassadenkonstruktionen', *Bauingenieur*, 81(11):475–487, 2008.

[11] Timmel, M., Kolling, S., Osterrieder, P., and Du Bois, P.A., 'A finite element model for impact simulation with laminated glass', *International Journal of Impact Engineering*, 34:1465–1478, 2007.

[12] Wei, J., and Dharani, L., 'Response of laminated architectural glazing subjected to blast loading', *International Journal of Impact Engineering*, 32:2032–2047, 2006.

[13] Bennison, S.J., Jagota, A. and Smith, C.A., ‘Fracture of glass/poly(vinyl butyral) (butacite) laminates in biaxial flexure’, *Journal of the American Ceramic Society*, 82(7):1761–1770, 1999.

[14] Bennison, S., Sloan, J.G., Kistunas, D.F., Buehler, P.J., Amos, T. and Smith, C.A., ‘Laminated glass for blast mitigation: Role of interlayer properties’, In *Glass Processing Days*, 2005.

[15] Ungureanu, V., ‘Laminated glass and interlayers in Advanced design of glass structures’, *European Erasmus Mundus Master Course Sustainable Constructions under Natural Hazards and Catastrophic Events,* 2014. http://www.ct.upt.ro/suscos/files/2013-2015/1E05/2E5_Glass_structures_L3_2014_VU.pdf

[16] Morison, C., Zobec, M. and Frenceschet, A., ‘The measurement of PVB properties at high strain rates, and their application in the design of laminated glass under bomb blast‘, *ISIEMS 2007, International Symposium on Interaction of the Effects of Munitions with Structures, 17-21 September, Orlando, US*, 2007.

[17] Iwasaki, R., Sato, C., Latailladeand, J.L. and Viot, P., ‘Experimental study on the interface fracture toughness of PVB (polyvinyl butyral)/glass at high strain rates’, *International Journal of Crashworthiness*, 12(3):293–298, 2007.

[18] Stewart, M.G. and Netherton, M.D., ‘Security risks and probabilistic risk assessment of glazing subject to explosive blast loading’ *Reliability Engineering and System Safety*, 93(4):627–638, 2008.

[19] Moras, B., ‘Constitutive equations of strain rate sensitive materials for the automotive industry. Plexis-3c implementation report’ *Technical report, JRC Technical Note* N. I.99.54, 1999.

[20] Zerilli, F.J. and Armstrong, R.W., ‘Dislocation-mechanics-based constitutive relations for material dynamics calculations’, *Journal of Applied Physics*, 61:1816–1825, 1987.

[21] Johnson, G.R. and Cook, W.H., ‘A constitutive model and data from metals subjected to large strains, high strain rates and high temperatures’, *Proc. 7th Int. Symp. on Ballistics,* The Hague, Netherlands, 1983.

[22] Hooper, P., Dear, J., Blackman, B., Smith, D., Hadden, D. and Sukhram, R., ‘Strength of structural silicone glazing joints under blast loading’*Department of Defense Explosives Safety Board Seminar, 12-14 August,* Palm Springs, CA, United States, 2008.

[23] Larcher, M. and Solomos, G., *Laminated glass loaded by air blast waves — experiments and numerical simulations. Technical report, Joint Research Centre*, Publications Office of the European Union, Luxembourg, 2010.

[24] Weerheijm, J. and Van Doormaal, J. C. A. M., ‘Tensile failure of concrete at high loading rates: New test data on strength and fracture energy from instrumented spalling tests’, *International Journal of Impact Engineering* Vol. 34, pp. 609–626, 2007.

[25] Hordijk, D. A., *Local approach to fatigue of concrete*. Thesis. Technische Universiteit Delft. ISBN 90-9004519-8. 201 p, 1991.

[26] Schuler, H., Mayrhofer, C., Thoma, K., ‘Experimental determinations of damage parameter and implementation into a new damage law’, *Proceedings of 11th international symposium on interaction of the effects of munitions with structures*, Mannheim, May 5–9, 2003.

[27] Bischoff, P.H. and Perry, S.H., ‘Compression behaviour of concrete at high strain rates’, *Materials and Structures*, Vol. 24, pp. 425–450, 1991.

[28] Malvar, L.J. and Crawford, J.E., ‘Dynamic increase factors for concrete’, *Twenty-Eighth DDESB Seminar*, Orlando, FL, 1998, pp. 1–17, 1998.

[29] IDEAS Simulation: Finite Element Modelling User Guide.

[30] CEN. Road restraint systems — guidelines for computational mechanics of crash testing against vehicle restraint system: Cen/tr 16303, 2012.

[31] Abaqus Analysis User Manual.

[32] Larcher, M., Solomos, G., Casadei, F. and Gebbeken, N., ‘Experimental and numerical investigations of laminated glass subjected to blast loading’, *International Journal of Impact Engineering*, 39:42–50, 2012.

[33] Hidallana-Gamage, Thambiratnam, D. and Perera, N. *Influence of Structural Sealant Joints on the Blast Performance of Laminated Glass Panels,* J. Perform. Constr. Facil. 2014.

## List of standards

[1] CEN, 2001. EN 13123-1: Windows, Doors and Shutters — Explosion Resistance — Requirements and classification — Part 1: Shock Tube.
[2] CEN, 2001. EN 13123-2: Windows, Doors and Shutters — Explosion Resistance — Requirements and classification — Part 2: Range test.
[3] CEN, 2001. EN 13124-2: Windows, Doors and Shutters — Explosion Resistance — Test Method — Part 1: Shock Tube.
[4] CEN, 2001. EN 13124-2: Windows, Doors and Shutters — Explosion Resistance — Test Method — Part 2: Range test.
[5] ISO 16934: 2007 Glass in Building — Explosion-resistant Security Glazing — Test and Classification by Shock-tube Loading.
[6] ISO 16933:2007/Cor1:2008 Glass in building — Explosion-resistant security glazing — Test and classification for arena air-blast loading.
[7] GSA-US General Services Administration 2003. Standard Test Method for Glazing and Window Systems Subject to Dynamic Overpressure Loadings, GSA-TS01-2003.

## List of figures

Figure 1: Interaction between numerical simulations and experiments for the approval of protective structures ........ 8

Figure 2: Lagrange solver (top); Eulerian solver (bottom) ........ 10

Figure 3: Simulation approaches for load evaluation ........ 14

Figure 4: Glass types ........ 16

Figure 5: Phases of failure of laminated glass ........ 17

Figure 6: Models used for the simulation of laminated glass ........ 18

Figure 7: Behaviour of PVB at different strain rates ........ 18

Figure 8: Glass failure simulated with user material model (PRM model — CEA) ........ 24

Figure 9: Glass structure damage (fragment flight) – Courtesy CEA Gramat ........ 26

## List of tables

Table 1: Features of several simulation models for dynamic loading of structures ........ 10

Table 2: Non-exhaustive FEM codes lists with their time-integration methods and discretisation capabilities [1] ........ 12

Table 3: Advantages and disadvantages of several simulation methods for air-blast waves ........ 14

Table 4: Typical material properties for glass and PVB as given by Stewart [18] ........ 19

Table 5: Mesh conformity recommendations for shell and solid elements [29] ........ 21

# List of acronyms

| | |
|---|---|
| AMR | automatic mesh refinement |
| EFG | element free galerkin |
| FEM | finite element method |
| PVB | Polyvinylbutyral |
| SDOF | single degree of freedom method |
| SPH | smoothed particle hydrodynamics |
| XFEM | extended finite element method |

European Commission
EUR 27137 EN – Joint Research Centre – Institute for the Protection and Security of the Citizen

Title: Numerical simulations for classification of blast loaded laminated glass: possibilities, limitations and recommendations

Authors: Kevin C.
Ans van Doormaal, TNO
Christof Haberacker, WTD 52
Götz Hüsken, BAM
Martin Larcher, European Commission
Arja Saarenheimo, VTT
George Solomos, European Commission
Alexander Stolz, Fraunhofer Institute
Laurent Thamie, CEA
Chiara Bedon, University of Trieste .

2014 – 39 pp. – 21.0 x 29.7 cm

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

ISBN 978-92-79-46172-9

doi:10.2788/083832

Abstract

It is important to protect critical buildings (shopping centres, government buildings and embassies), infrastructure and utilities, train and underground stations against being damaged, destroyed or disrupted by deliberate acts of terrorism, criminal activity and malicious behaviour. Normal regulations and building guidelines do not generally take into account these threats. The introduction of appropriate regulations or guidelines, where deemed necessary, should, enhance the resilience of buildings and infrastructure against explosion incidents. In order to protect the built infrastructure, methods are required to quantify the resistance of structural components against explosive loading and to assess the hazards resulting from the failure of an element. The applicable state-of-the-art techniques may include either experimental or numerical methods, or a combination of both. Therefore, the thematic group (TG) on the resistance of structures to explosion effects was formed in order to bring the required expertise together, make it commonly available and to find and define harmonised methods and solutions which can be provided to the decision-makers responsible for critical infrastructure protection. The current report summarizes existing best practices for the numerical finite element modelling of blast loading, including the important topics of domain discretisation, implicit/explicit formulation, Lagrangian/Eulerian solvers, the mathematical description of the material behaviour etc. Furthermore recommendations for the modelling of laminated glass elements are formulated and knowledge gaps in this application area are pointed out. Hence the report builds the basis for an actual evaluation of the different numerical methods, their suitability to certain problems, and their capability to support/complement the experimental testing of glass components. It thus provides helpful information to design architects and engineers, and more generally to critical infrastructure stakeholders, responsible for the structural integrity and security of the infrastructure in case of an explosion.

LB-NA-27137-EN-N

## JRC Mission

As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new methods, tools and standards, and sharing its know-how with the Member States, the scientific community and international partners.

*Serving society*
*Stimulating innovation*
*Supporting legislation*

doi:10.2788/083832

ISBN 978-92-79-46172-9

Publications Office