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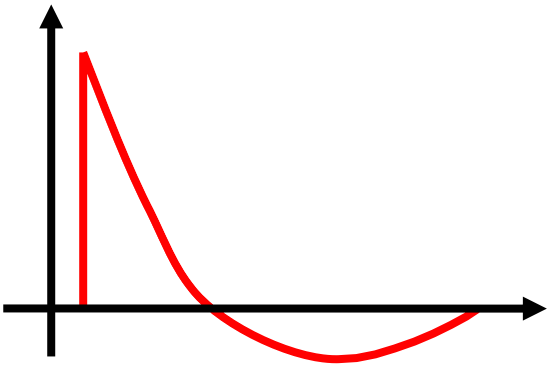
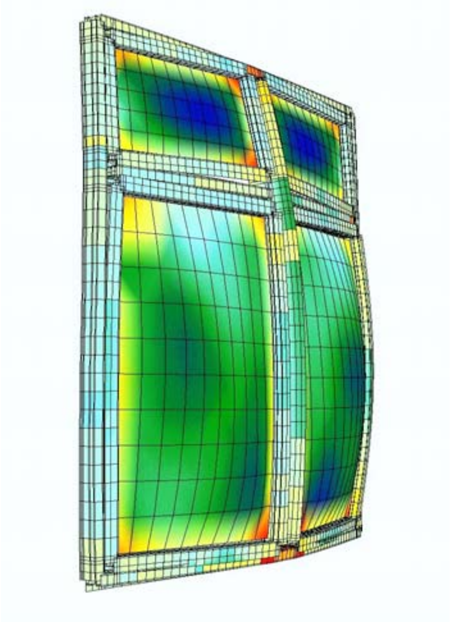
Computation of Blast Resistant Window and Facade Constructions





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Abstract:

This report describes blast loads acting on a window or a glass facade resulting from a detonation of an explosive device as well as computational simulations of the nonlinear behavior of complex facade constructions made out of many single components with attention to the different processes of fracture and damage. Purpose of the studies is to complete or replace the very expensive blast tests in order to determine safety against collapse by computational simulation.

1. Explosion hazards

In recent years terrorist attacks have increased all around the world. In case of an explosion especially close to modern glass-buildings more than 80% to 90 % of the injuries are caused by glass fragments and pieces of facades. For that reason enhancement of blast resistant window and facade construction is more important than ever before.

Fig. 1 Burst of a single window after an explosion (source: US Army Corps of Engineers)

Fig. 1 shows the failure of a normal non-protected window after an explosion. The enormous peril to people inside the room due to glass and framing fragments is quite obvious.

2. Evaluation of loading from blast wave

2.1 Theoretical blast wave parameters

For simple cases, e.g. fully reflected pressure at zero degrees on a vertical wall, parameters of the pressure-time-curve are well known. Diagrams and formulas may be extracted from various sources (e.g. ([2], [17]).

The values are based on a lot of tests under different conditions. Sometimes the values are different between two sources. Therefore the area of validity especially for scaled distances must be noted. Extrapolations could be incorrect and should be used carefully. The units (metric or US) of diagrams and formulas and the difference between side-on-pressure, free-air-pressure and reflected pressure are important. The values must be clearly specified to avoid mistakes.

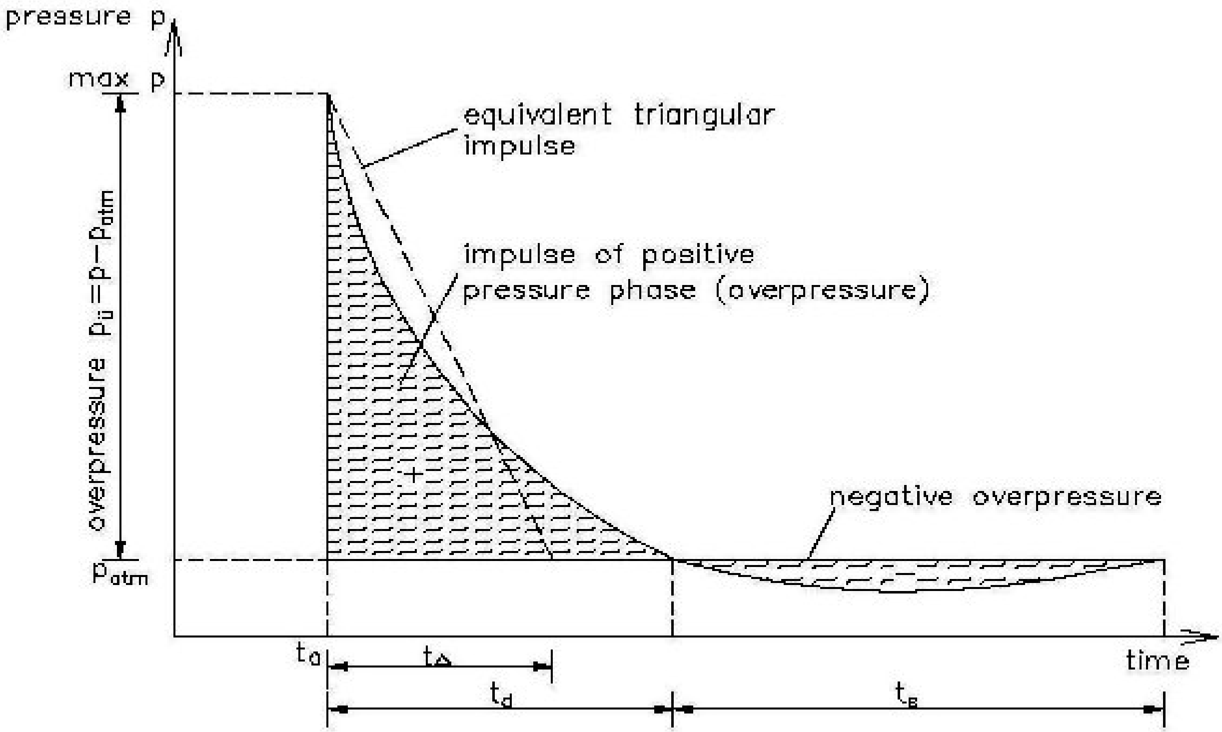


Fig. 2 Theoretical pressure-time-curve of a blast wave

The pressure-time-curve of a blast wave (fig. 2) is characterized by an abrupt pressure rising when the wave arrives at the target and a following exponential decay with a change into a negative pressure phase. For usual windows or facades the overpressure level $p_0 = {}_{max}p - p_{atm}$ is not the main important criterion. In this connection the impulse $I = \int p(t)\, dt$ is the basic parameter.

Usual computations consider only the positive pressure phase approximated by a triangular gradient. The suction phase is mostly unimportant in relation to flying debris towards to the protection area.

For windows which have to prevent debris on both sides of the construction (e.g. courtyards, buildings close to highly frequented traffic areas, overhead-glazing) the negative phase is also important. The longer duration time and the interaction with the pre-damaged structure could be critical.

Sometimes, especially for huge and weak constructions with a long vibration time the suction phase may decrease the maximal structural deflection.

For comparison of simulation with test results it is necessary to know the real pressure-time-history including the negative pressure phase.

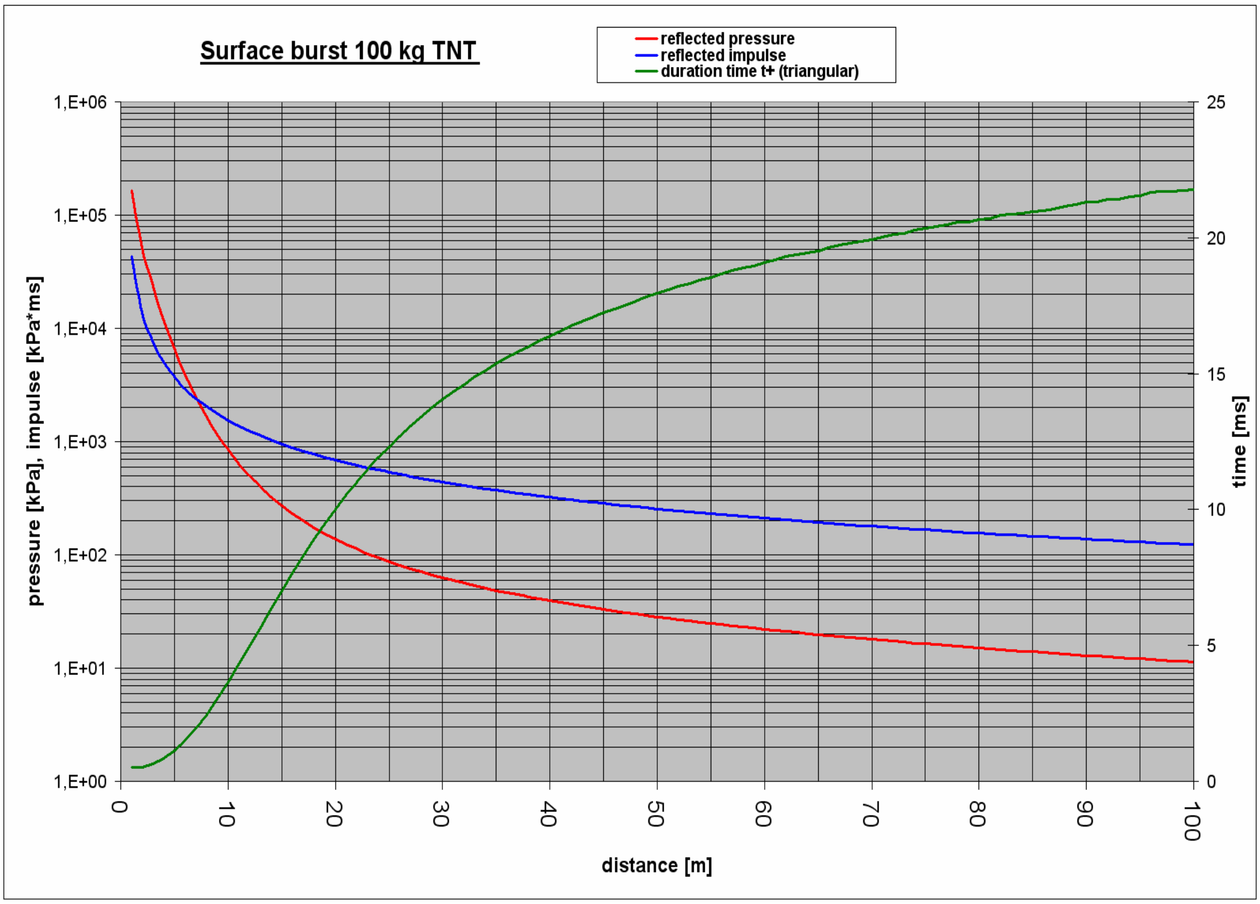


Fig. 3 Theoretical dependence of pressure, impulse and duration with distance from explosion

Fig. 3 shows the relationship of fully reflected overpressure, fully reflected impulse and positive duration time for a hemispherical surface burst of 100 kg TNT versus standoff distance.
The outcome of the ideal hemispherical wave propagation is an extreme dependence on standoff distance.

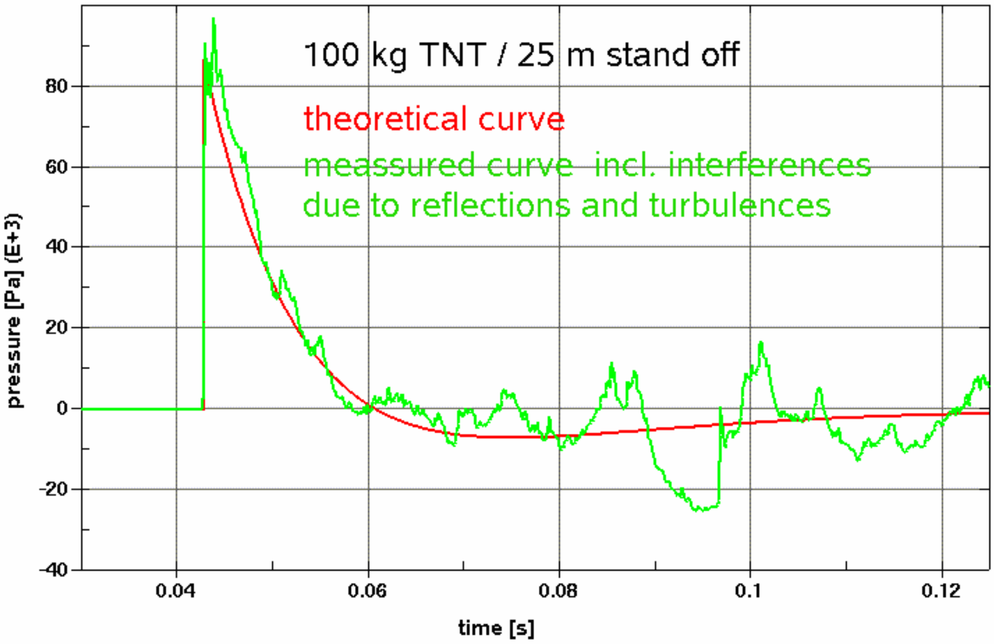


Fig. 4 Measured and computed pressure-time-curve (measurement source: Bollrath PRO FORCE)

Measurements on test objects show in comparison to the theoretical curves for all nearly ideal test conditions marked variations. This is caused by turbulences and suction effects from the edges of the test cubicle and interaction with the testing ground. Another reason is the detonation process itself, which is not ideal and steady in reality. These interferences in the form of single pressure peaks do not highly effect the reaction of normal windows and facades because of the extremely short action time.
Significant variations especially in impulse und duration time, results from complex geometrical structures or special geometrical shapes (e.g. inside corner, canopy). Therefore more detailed considerations are recommended.

2.2 Blast wave propagation and influence factors

For the numerical simulation and dimensioning of a complex and fragile construction like a window or a glass-facade, it is very important to know the realistic pressure-time-curves for specified scenarios.
In fig. 5 an example of a numerical blast wave propagation including interaction with buildings is shown.
The computation was performed by using the code LSDYNA [1]. The wave propagation, the reflection on ground, later on the small and finally on the main building is clearly visible.
Direction, magnitude, height of detonation above ground and interactions of the wave with the ground and obstacles like the small building are very important for the resultant p-t-curves on different parts of the main building and the courtyard.

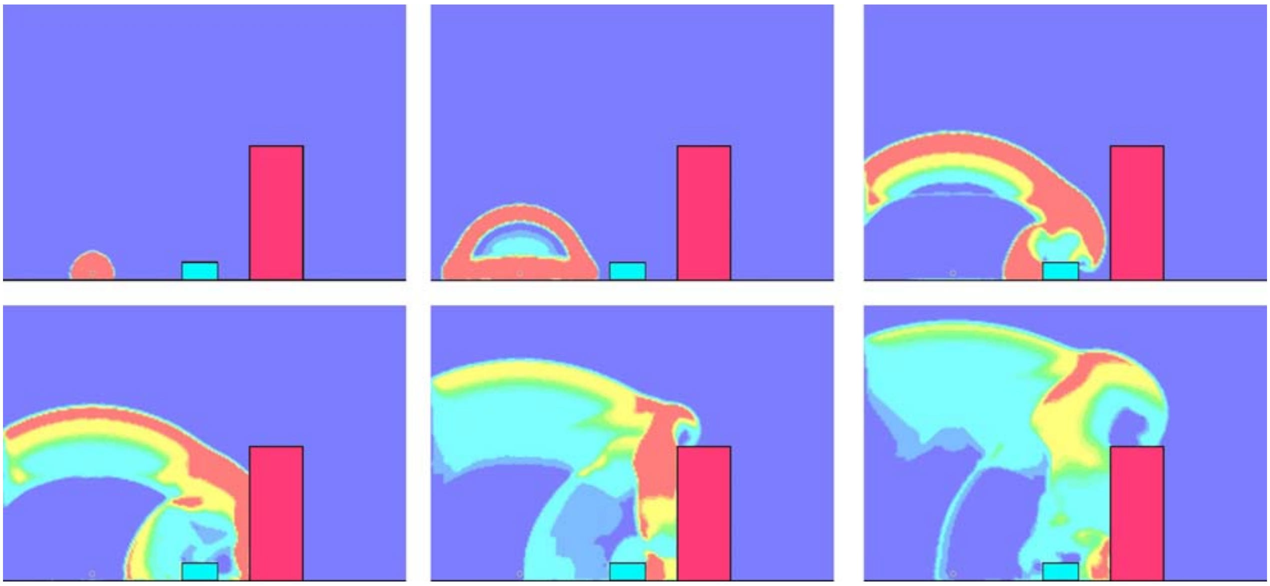


Fig. 5 Computational simulation of blast wave propagation

In the case of a real explosion, mass, height and distance of the charge, type and form of obstacles mainly determine magnitude and form of the impulse.
For special and important targets, like embassies, power plants, subway stations, great bridges and so on, it makes sense to work out some studies or computations under consideration of the specific local conditions, risk potential and safety requirements.

For instance it is possible to check the reduction resulting from a blast wall of the pressure and the impulse at different building parts (fig. 6). The distances between charge and wall and between wall and building as well as the height of the wall are very important for the result.
The simulation outputs are values for design and dimensioning of the blast-protection-wall and the facade. Of course distance and height of the wall can be optimized that way.

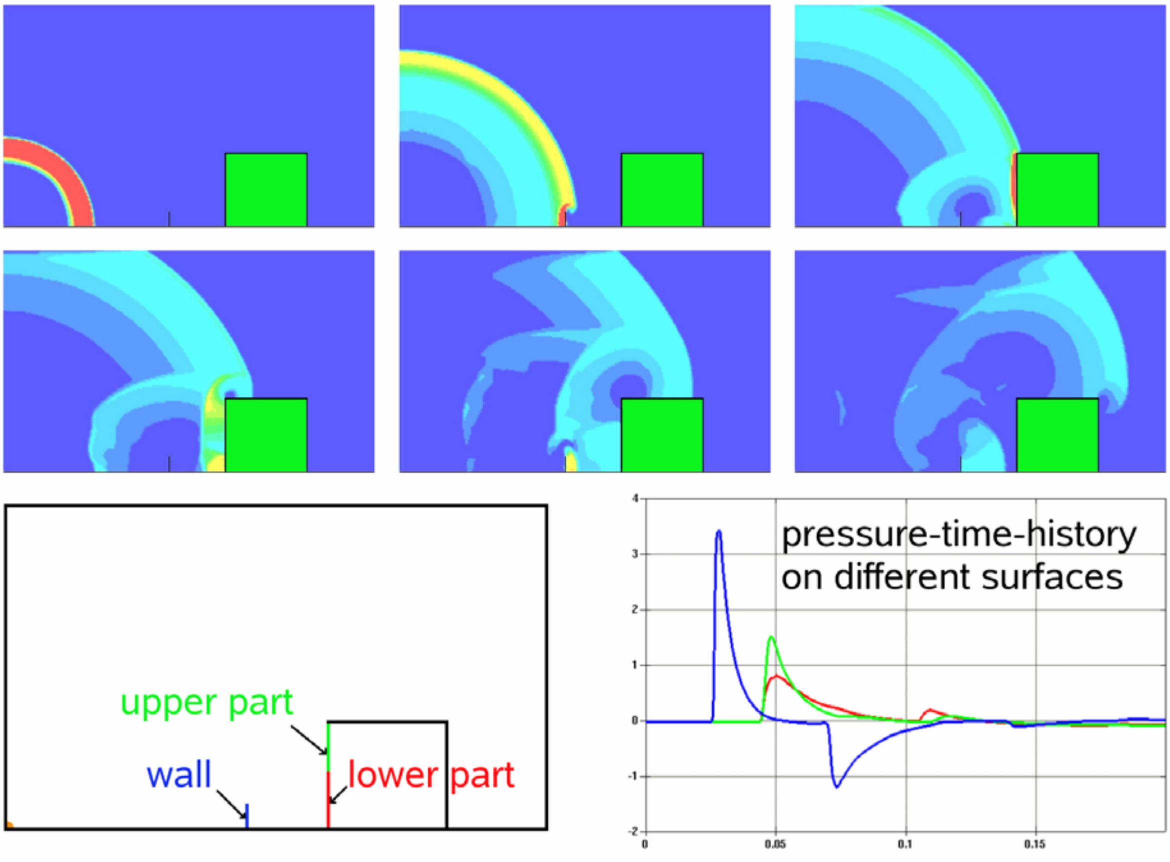


Fig. 6 Influence of a blast protection wall, computer simulation

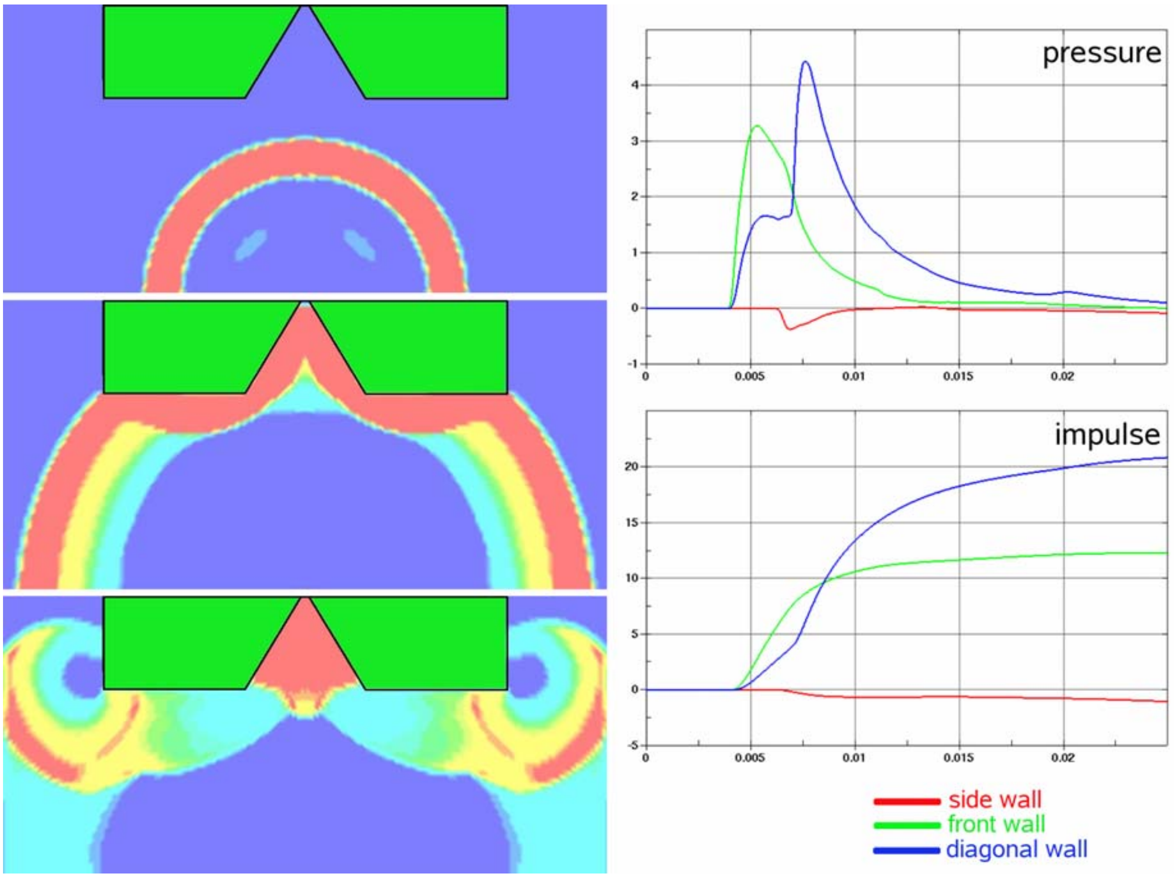


Fig. 7 Blast wave reflection at an inside corner of a building with curves for pressure and impulse

Building setoffs like canopies, entry areas, opened courtyards or inside corners may be unfavorable geometries from the point of view of force protection. The impulse will increase because of the impeded pressure outflow in the lateral direction. For closely arranged buildings there is the peril of multi reflection phenomena influence (small streets etc.).

In usual tender documents only values for maximum overpressure and impulse are specified without consideration of special local conditions.
In many cases this is insufficient and the outcome may be a wrong protection level. Sometimes the result is an uneconomic design, but mostly hazard will increase because of effects mentioned above.
Attention should be paid to the high numerical effort for spatial and chronological discretization due to the supersonic wave propagation and the quite abruptly pressure rising at the front of the wave. Thereby a lot of numerical problems become more important (time step control, energy conservation during advection steps etc.). Execution and post processing of these calculations require some special experiences.
Already during the primary design phase of new buildings possible threats should be investigated for integration of possible safety measures.
For enhancement of blast protection, the exterior building shape, the arrangement of rooms dependent on utilization, redundant load bearing systems etc. could be well adapted at an early planning.

3. State of standardization

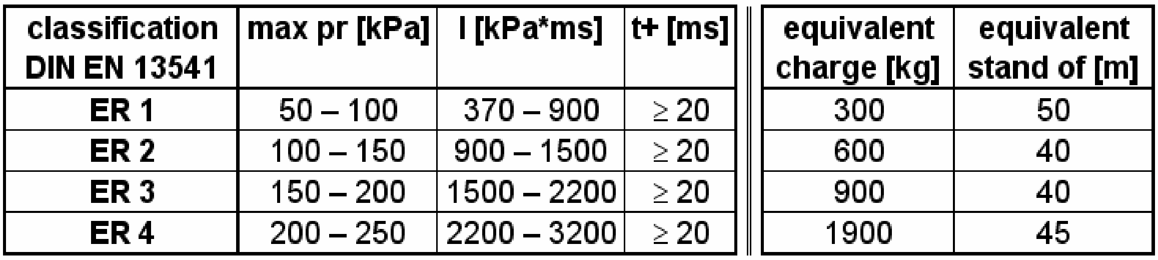
To the subject “force protection of windows and facades” in Germany the following standard guidelines are in use:

Current German standards:
- DIN EN 13123-1 (2001) and DIN 13124-1 (2001), shock tube tests, [6], [7]
- DIN EN 13123-2 (2004), DIN 13124-2 (2004), arena air blast tests, [6], [7]
- DIN EN 13541 (2001), Glass in building, Security glass, Testing and classification ….. [8]
- DIN 1055-9 (2003), Special loadings on structures - Part 9 [9]

European Standard (draft):
- ISO/DIS 16933 (2004), arena air blast tests, [10]
- ISO/DIS 16934 (2004), shock tube tests, [11]

US-guidelines:
- ASTM F 1642, GSA-TS01 (2003), [12]

The available standards include limits for pressure, impulse and minimum duration time. On the basis of comparison of measured test results with the standard values constructions can be classified.
With regard to specification the standards are not uniform. Equal specification names refer to different requirements (cp. ISO/DIS 16934 vs. DIN EN 13541 specification ER).
Especially the shock tube test standards are made for comparison of different small constructions in existing test areas. The limit values are not very useful for real scenarios. For clarification table 1 shows classification and associated values for pressure impulse and duration time according to DIN EN 13541. The additional denoted values for charge and standoff distances point at unrealistic events. They are the result of the typical long duration time of shock tube tests.



classification DIN EN 13541	max pr [kPa]	I [kPa*ms]	t+ [ms]	equivalent charge [kg]	equivalent stand of [m]
ER 1	50 – 100	370 – 900	≥ 20	300	50
ER 2	100 – 150	900 – 1500	≥ 20	600	40
ER 3	150 – 200	1500 – 2200	≥ 20	900	40
ER 4	200 – 250	2200 – 3200	≥ 20	1900	45

Table 1 Classification acc. to DIN EN 13541 for shock tube tests with specification of equivalent arena blast

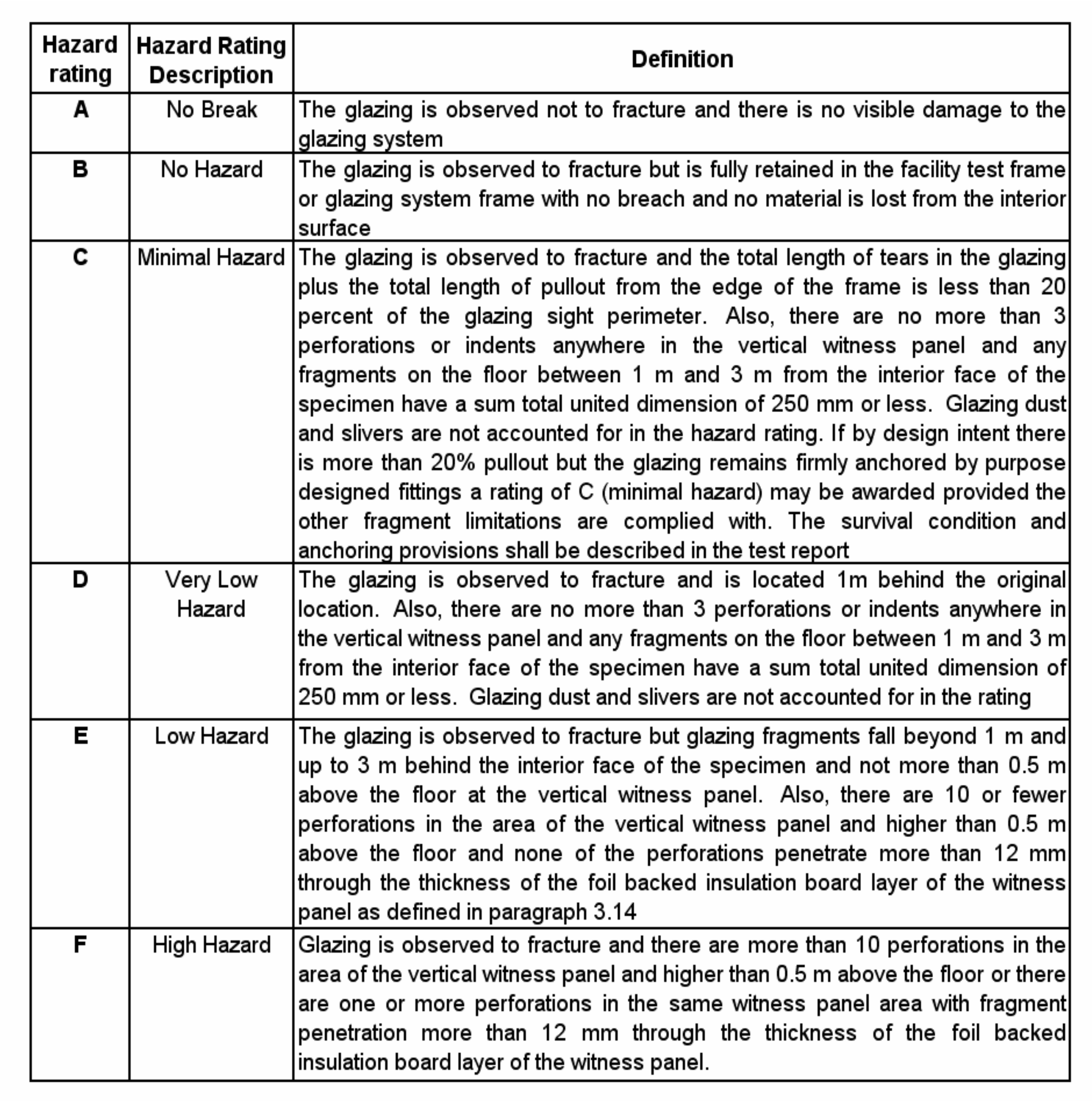
Basically the existing standards are only useful for experimental comparison and specification of different constructions. They do not sufficiently enter into the question of determination of realistic blast and blast resistance parameters.

The standards are not made for numerical handling of explosion problems. Only DIN 1055-9 gives some general information to this topic.

For numerical simulation and realistic prediction of reaction of windows and facades it would be more reasonable to determine hypothetical charges and detonation sites. In comparison with direct specification of blast parameters and global protection levels it would be possible to consider the special building situation and local hazards inside and outside of the buildings (cp. chapter 2.2).

For each building or construction it is necessary to specify a permitted hazard level, depending on what kind of damage is acceptable after an explosion.

Standard ISO/DIS 16933, Table 2 contains a hazard rating system from level A “no hazard” up to level F “high hazard” (table 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 is fully retained in the facility test frame or glazing system frame with no breach and no material is lost from the interior surface
C	Minimal Hazard	The glazing is observed to fracture and the total length of tears in the glazing plus the total length of pullout from the edge of the frame is less than 20 percent of the glazing sight perimeter. Also, there are no more than 3 perforations or indents anywhere in the vertical 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 20% pullout but the glazing remains firmly anchored by purpose designed fittings a rating of C (minimal hazard) may be awarded provided the other fragment limitations are complied with. The survival condition and anchoring provisions shall be described in the test report
D	Very Low Hazard	The glazing is observed to fracture and is located 1m behind the original location. Also, there are no more than 3 perforations or indents anywhere in the vertical 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 but glazing fragments fall beyond 1 m and up to 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 perforations in the area of the vertical witness panel and higher than 0.5 m above the floor and none of the perforations penetrate more than 12 mm through the thickness of the foil backed insulation board layer of the witness panel as defined in paragraph 3.14
F	High Hazard	Glazing is observed to fracture and there are more than 10 perforations in the area of the vertical witness panel and 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 through the thickness of the foil backed insulation board layer of the witness panel.

Table 2 Hazard levels acc. to ISO / DIS 16933

In other countries tender documents often are based on the requirements of the „Standard Test Method for Glazing and Window Systems“ of the US General Services Administration / GSA and performance conditions 1 to 5.

4. Estimation of the dynamic behavior of structures

For a first dynamic estimation of a complex structure it would be helpful to know the response of a single-degree-of-freedom-system with the same dominating natural frequency loaded by a triangular pulse.

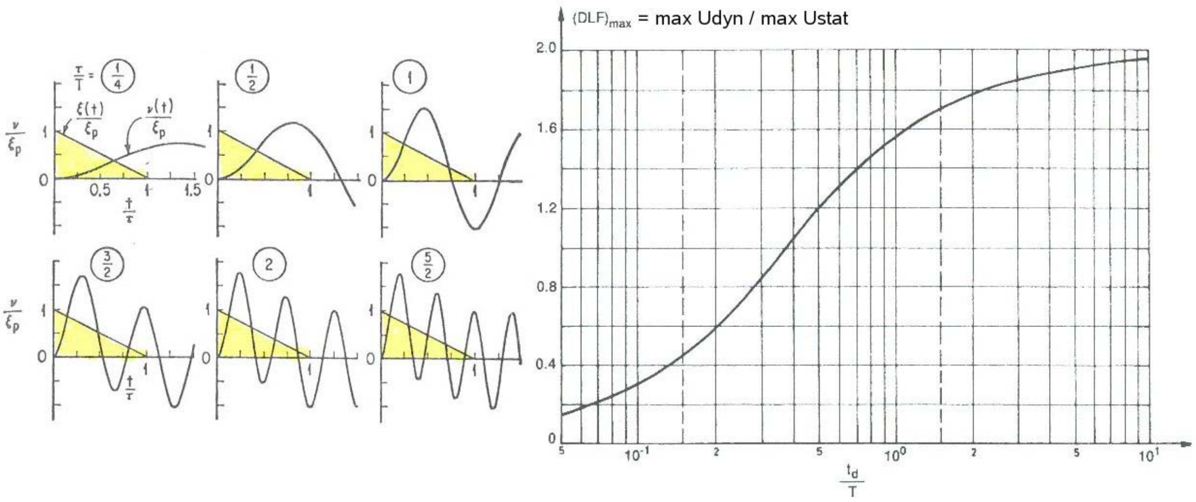


Fig. 8 Dynamic correction factor for a linear-elastic-vibration system (from [13])

In fig. 8 the response of an elastic SDOF-system is shown in dependence of the ratio pulse time t_d / natural period T. It shows the strong dependence of dynamic reaction from the ratio t_d/T.
If t_d/T is >> 1 the dynamic displacement may reach the double value of static displacement from the peak load. That is similar to the dynamic response of a suddenly acting load according to a jump function.
For short pulse times and long natural vibration times (in case of blast wave acting on a large facade construction), the dynamic response may decrease to values lower then 1/10 of the max. static response. The extreme variation of the response for different structures is clearly visible.

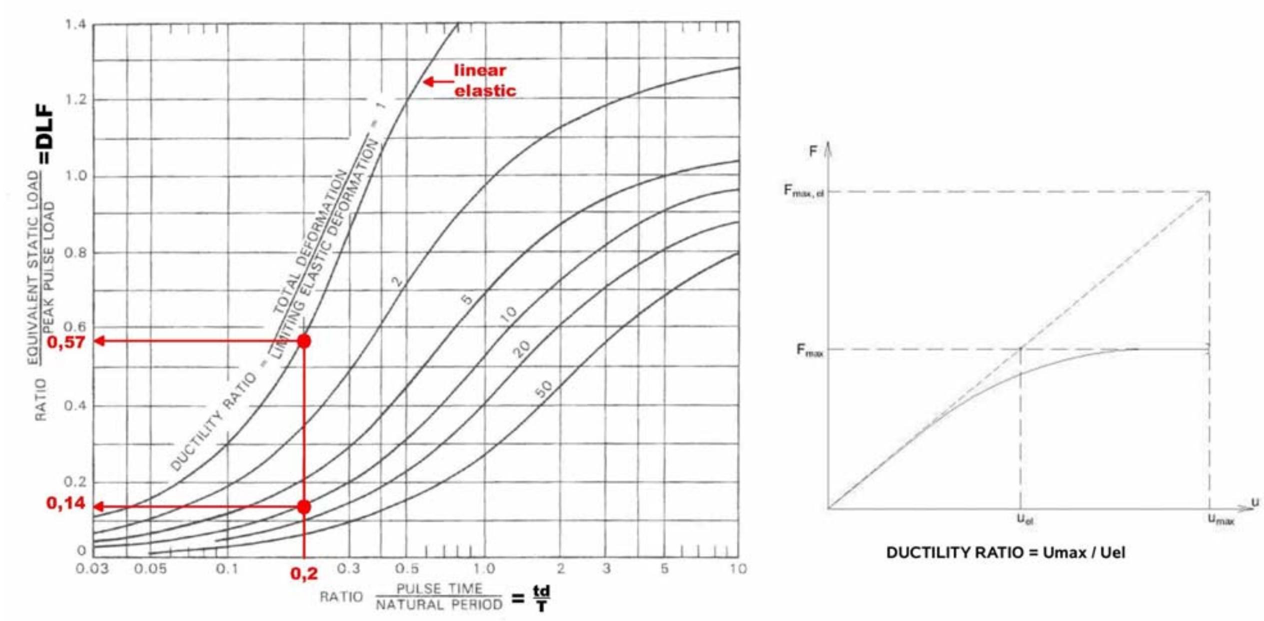


Fig. 9 Dynamic correction factor for an elastic-plastic vibration system (from [2])

In case of a ductile or elastic-plastic structure response e.g. for laminated glass or thermally insulated aluminum profiles the dynamic correction factor decreases again. Due to the large plastic profile deformation after reaching the yield stress and cracks in laminated glass panes without failure a lot of energy is dissipated and the natural period of the panes increases. The diagram (fig. 9) shows the dependency of the dynamic factor DLF from the structure ductility ratio.
For example at a ratio td/T = 0,2 and a ductility ratio of 10 the dynamic correction factor decreases from 0,57 to 0,14.
Certainly rough estimations like these are only useful to receive a first impression of the structure response. Proper predictions of the real behavior including failure limits are not possible. In fact the different parts of a window have a very different ductility. In addition windows are multi-degree-of-freedom-systems with a lot of nonlinear material properties. Therefore in most cases an approximation with a SDOF is not sufficient for prediction of the different failure modes and limits.
On the other hand it is important to combine the different materials and connections in a way to optimize vibration behaviour and maximize energy dissipation by avoiding complete failure at the same time.

5. Damage levels and failure modes

For a numerical simulation it is necessary to classify the construction to a hazard level (table 2) according to the associated damage degree.
The numerical effort of calculations depends on this rating.

Level A (no breakage, no visible damage):

- Linear-elastic material and verification of yield stress limits for short-time loading
- Calculations via equivalent static loads by diagrams and tables may be sufficient in simple cases
- Sometimes it makes sense to carry out geometric nonlinear calculations for consideration of membrane effects at large elastic deformations
- Normal charges and standoffs cause massive and expensive constructions.
- Mostly level A is not realistic or practicable. In real cases there is a high risk by primary fragments from the bomb casing at usually required distances. Therefore visible damage may not be excluded.

Level B / C: (breakage of laminated glass and plastic deformation permitted):

- Using of nonlinear material laws and plastic deformation capability
- Equivalent static systems are not suitable
- Utilization of local energy dissipation and damping effects
- Material models and parameters especially for high strain rates are mostly unknown and only available by special material tests
- Common practice because of the favorable cost-hazard ratio

Level D to F (flying fragments permitted):

- Exact modeling of failure criteria’s of all parts and connections with details are necessary
- Extreme fine mesh is required
- Precisely determinated contact conditions / friction / offset etc. is necessary
- Because of the large range of outside influences and material properties it is improbable even for “correct simulations” to verify the detailed results by single tests
- Actual test results for that level are mostly not reproducible in detail

For level B to C the basic requirement is the correct mapping of nonlinear materials and parts as far as possible. All details which are important for the different failure modes should be considered. Therefore a lot of material data is required. At the best they can be extracted from special dynamic tests of single construction parts (see chapter 6.2.1).
Comparisons or verifications which are dealing with equivalent static substitution on a high level should be keenly checked. It is not possible to handle highly nonlinear problems by simple linear approximations in a proper way.
Dynamic simulations and tests show that these practices often generate insufficient and sometimes unsafe results even for comparison of the reaction of nearly similar small construction elements because transient and different strain levels of the single construction parts are not considered.

Finally it is possible to carry out simulations of complete failure and post damage behavior.
For example the failure of the glazing bite of a laminated glass pane is shown in fig. 10. The laminated pane is additionally fixed by a special fixing construction. The procedure of failure, the movement of the pane and the connection forces can be received from such a computation.

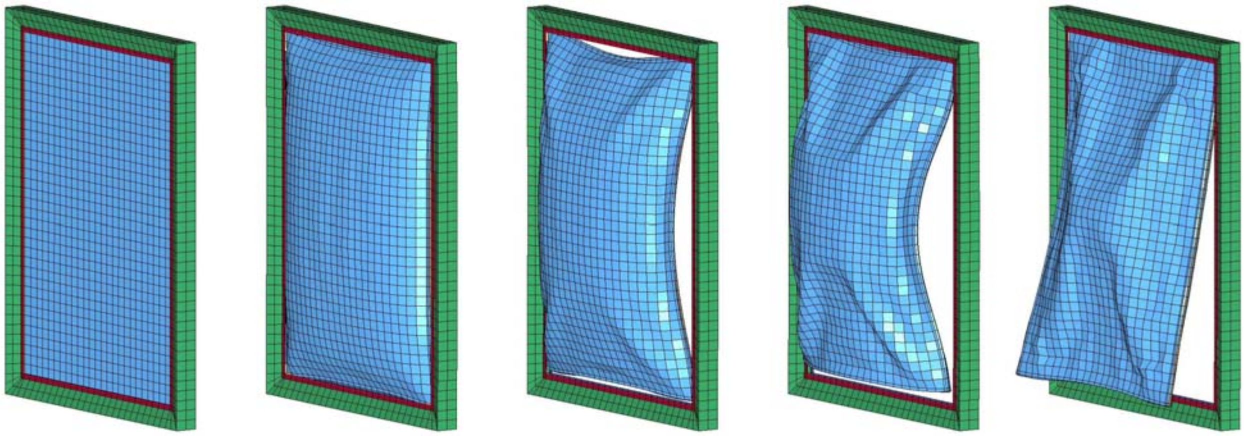


Fig. 10 Window with integrated glass catcher

For typical windows at level B to C the following failure modes are important for tests and simulations:

- Fracture of glazing
- Crack of PVB interlayer
- Separation of splinters from the rear side of the window
- Pullout from the edges of the frame or failure of structural sealant glazing
- Failure of fittings
- Composite failure in thermally insulated profiles, crack or fracture of fiber-reinforced plastic connections
- Collapse of profile connections
- Local crack or buckling of aluminum profiles due to high plastic strains
- Anchorage failure

The failure limit of more complex facade constructions depends on the balanced combination of single parts. The combination of ductile and non-ductile elements have to ensure that the ductile parts of the system dissipate a maximum of energy due to plastic deformation without failure of the non-ductile elements. Therefore these non-ductile elements need a higher elastic stress limit in order to avoid sudden failure.

6. Dynamic FE-Computations

The numerical handling of the above mentioned effects in one system requires a complex model including all geometrical and material details.
For example it is not sufficient to use beam elements for the frames because they do not include effects of local buckling and failure of thermal insulation etc. 3D-models by using shell- and solid-elements and nonlinear material models allow the consideration of local bending forces in transverse direction, effects of local buckling, local influences of fittings, composite failure in thermally insulated profiles, contact problems on gasket strips and overlap of profiles.
By means of numerical simulations the number of high expensive explosion tests can be reduced. Realized comparisons of numerical prognoses with test results approve the high standard of the computational model.
For nearly similar constructions or details in new combinations it is possible to use advanced numerical simulations instead of additional tests.

6.1 Used FE-Codes and application ranges

Earlier computations with customarily implicit codes for nonlinear structural analysis by using beam elements for the facade profiles and bilinear springs without transmission of tension forces for the connection of glass and frame have some significant disadvantages in case of a geometric nonlinear simulation. Application of shell and solid elements instead of beam elements cause a significant increasing of the number of elements. So only one beam-element is substituted by about 20 shell-elements. In order to avoid numerical instabilities the time steps have to be very small due to the extreme load modifications and the high velocities of light construction parts. The numerical effort of the implicit solution for every time step is quite enormous. Often numerical instabilities lead to abnormal terminations after hours of computation. That is why it was not possible to improve this model for consideration of local failure modes, crack of laminated glass panes, nonlinear material models etc. These problems can be solved by an explicit code.

The code LS-Dyna by LSTC [13] was used for the following development of the simulation model. It is a well known program for crash simulation. The above mentioned numerical problems due to large deflections in short times, nonlinear materials etc. are avoided by the explicit approach. The number of elements is not so important by using an implicit solution. In addition to the conformance of these requirements the code offers a lot of features for definition of contact problems, material and element models etc. Another base for the choice was the possibility to analyze blast wave propagations and flow effects including the structure interaction (ALE / FSI, CFD)

6.2 Modeling

6.2.1 Thermally insulated aluminium profiles

The profiles and strips are simulated by shell- and solid-elements. The element approach and the material model for aluminum and fiber-reinforced plastic including buckling and composite failure are calibrated by simulation of force-deflection-tests (company Bollrath [16] fig. 11).

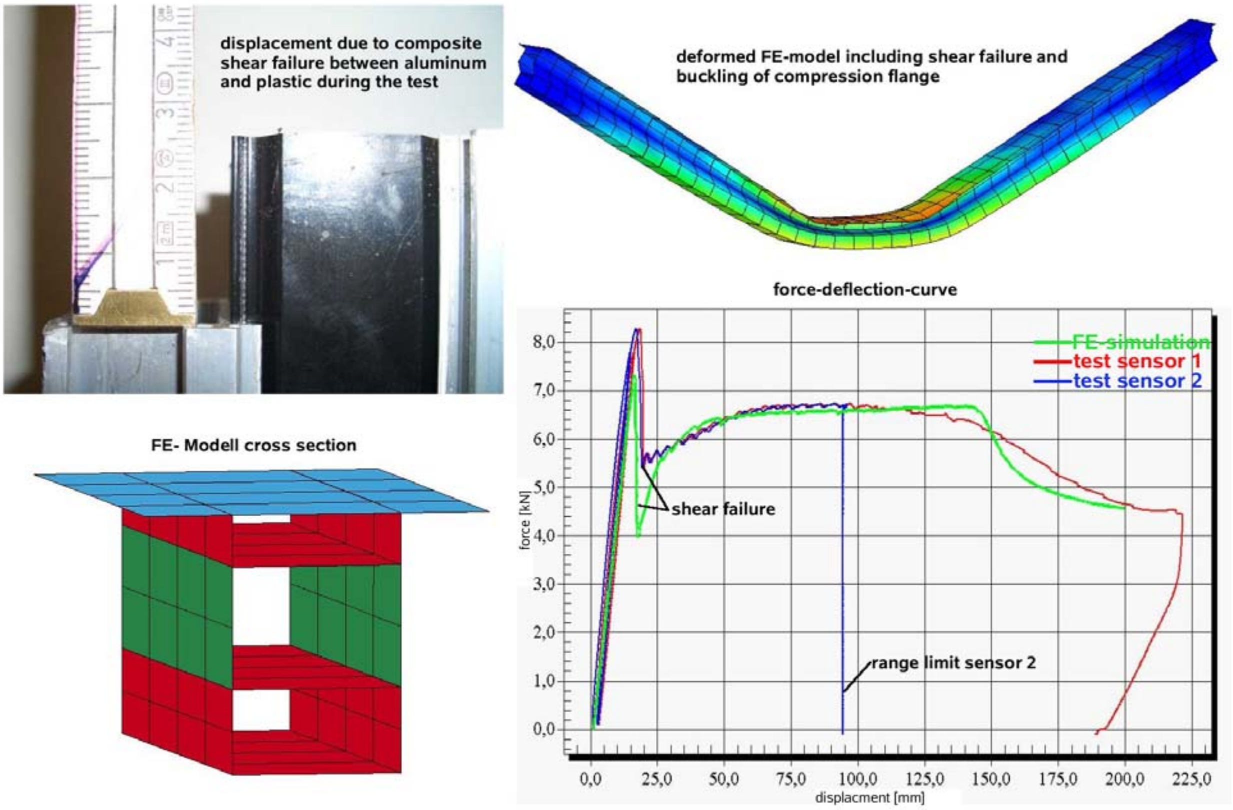


Fig. 11 Force-deflection-curve of a simple facade profile, comparison of test with computation

Elastic deflection, composite shear failure, plastic deflection, local buckling in outer aluminum part and plastic, local crack in case of too large strains are computed in good correlation to the test results.

6.2.2 New material model for laminated glass

Essential for numerical simulation of laminated glass is different structural behavior before and after cracking of the glass layers. Until appearance of the first crack, linear elastic behavior is assumed. Because of the short load duration time it is maintainable to neglect shear deflections in the PVB-layer.
After reaching the elastic tension stress limit the glass breaches. After this only the foil can carry tensile forces. The glass layers are only active in case of compression.
For the simulation of laminated glass 4-node shell elements are used. Depending on mesh refinement “Belytschko-Tsay elements” or fully integrated shell elements are used (element type 2 and 16 [1]). In this connection bending and membrane stiffness as well are considered.
First computations by using coincident elements [14] showed unrealistic shear forces at the joint between glass and supporting frame. In addition to the considered bending stiffness E*I in case of large deflections the influence of the different membrane stiffness for tension and compression E*A increases. The complex nonlinear stiffness is not implemented sufficiently in this approach and especially the compression stiffness is underestimated.
For a more realistic reproduction of the structural behavior a new material model for shells was developed (*MAT_USER_DEFINED _MATERIAL_MODELS [1]). In a first step, via the LS-Dyna integration rule (*INTEGRATION_SHELL [1] single integration points across the element are defined and weighted by the associated thickness. Every point is combined with the material parameters for glass or PVB in accordance to its position in the different layers. Before a crack appears at every time-step the linear elastic principal stresses in both directions and the associated angle are computed in this model. After reaching the defined tensile stress limit a crack algorithm will be activated and a crack perpendicularly to the stress direction will be performed. The stresses of all glass integration points will be set to zero and the crack angle will be stored. After that the strains in the now fixed direction are computed and added up during the following time steps and only in case of compression non-zero normal and shear stress values are considered for the next time step. Tensile stresses in glass points are not allowed. Optionally the second main stress direction works separate in the same way. In this direction tensile stresses are furthermore allowed until the stress limit is reached too.
PVB Integration points are linear elastic in general. This is maintainable because of the existing blast test results. The behaviour of the foil becomes more and more elastic by increasing strain rates and there is no clear permanent deformation visible after the test despite of measured large elastic displacements during the tests. At the other hand especially for strain rate dependency there is no material data available at present.
After reaching the defined equivalent stress limit for PVB-points the whole element will be deleted. The composite action of foils and glass between the cracks is included via a modification factor of the foil elastic modulus. A comparison between the new model and test results show a significant lower shear force in the glue of wet glassed test elements. The values are much closer to the available material data for high strain rates [15].
The computed time-deflection-history is in a good match to the measured results of the tested constructions.

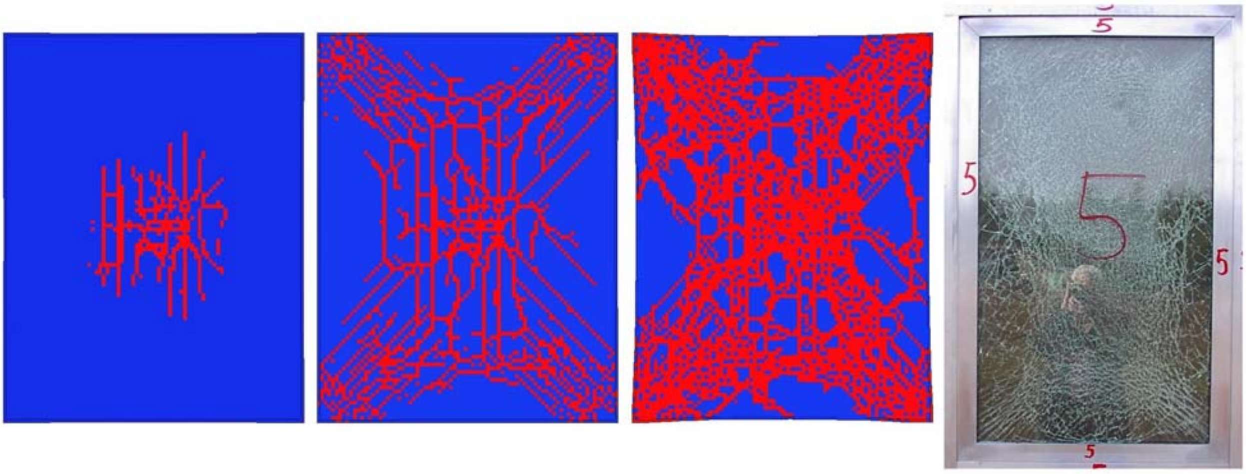


Fig. 12 Propagation of cracks in a laminated glass pane / model and test

Fig. 12 shows the crack propagation in a blast loaded pane. The broken elements at different time steps are red colored. Development and distribution are close to the high speed video test results [16].

Possibly occurring small shear deformations within the foil-layer before the pane cracks are not included in this model. However the experimental stress limit of glass is highly unsteady, but numerical simulations of cracked panes by different stress limits point out a secondarily influence relating to deformation and supporting forces. That’s why in our opinion it makes no sense to develop more complex models only for consideration of shear deformations.
A solid-element-approach with more elements across the thickness of the glass pane requires a lot of elements and nodes. Realistic calculations require nonlinear material models including the failure history. It is not sufficient to delete single glass solids because they would be missed in case of compression.
The numerical effort for complex facades including some double glassed windows is increasing drastic without attainment of significant better results.
Maybe it will be possible to improve the model with thick shell elements. But still today this is only a suggestion for research.

6.2.3 Insulated glass and frames

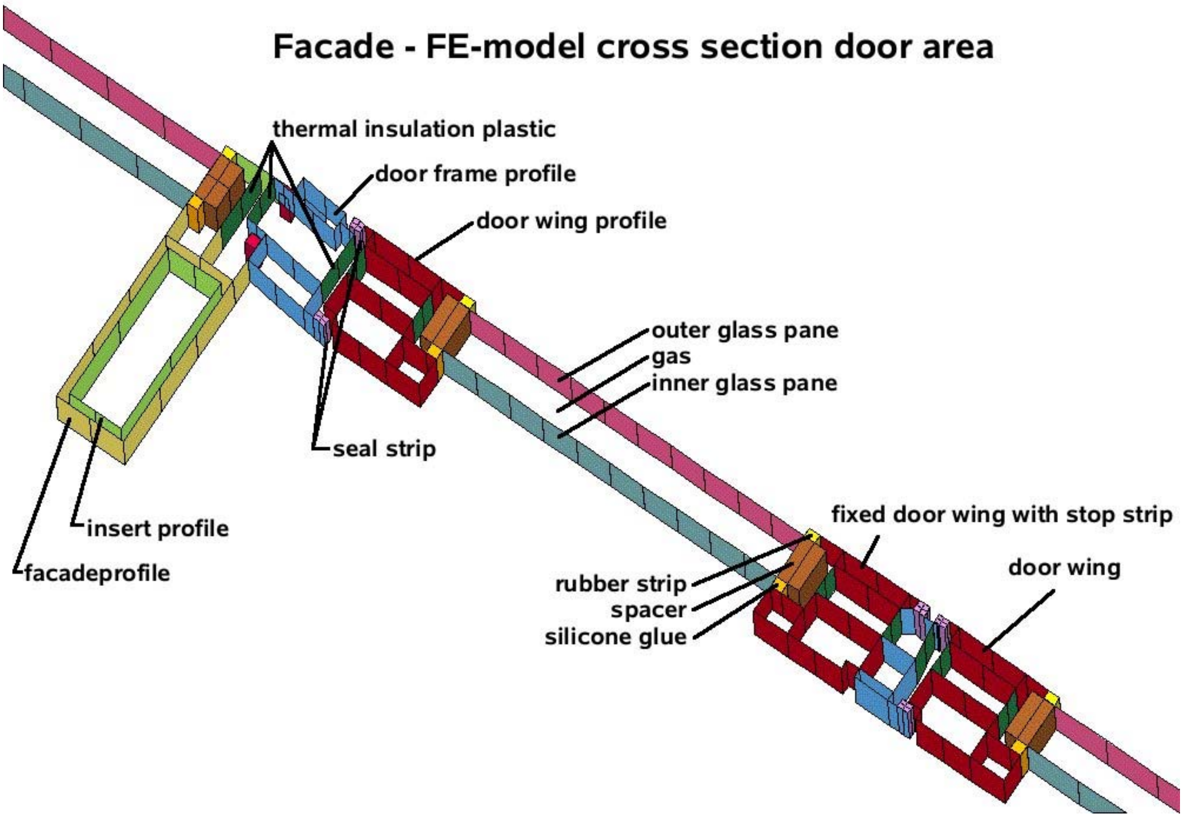


Fig. 13 Facade - cross section with frame and insulated glass pane (FE-model)

The interaction of the inner and outer pane due to the enclosed gas is considered by a volume-pressure control. The deflection of the outer pane leads to a reduction of the internal gas volume and an increasing pressure. The pressure acts on both panes.
Possible contact between the panes is checked in every time step and will be considered by special contact forces on the surfaces.
The panes are supported via elastomer or thick adhesives at the aluminum profiles. In case of wet glazing constructions nonlinear solid elements for the glue [15] connect glass and frame. In case of dry glazing an additional contact including friction will be defined. At fig. 13 the different FE-parts of a typical facade are shown. The effort to create regular FE-meshes including all details is enormous and requires special mesh algorithms.

6.2.4 Locking mechanism and connections

The locking mechanism works by overlapping of special elements. The bearing capacity depends on the available overlapping length. Value and direction of the supporting forces distinguish between several construction types. Profile fittings and anchoring elements work in the same way, but at all there is a great variation of ductility ratios of single points. It depends on different materials and overlaps.
These elements are approximated by nonlinear discrete spring elements (*MAT_NONLINEAR_PLASTIC-_DISCRETE_BEAM*, [1]). The springs for all 6 degrees of freedom can be characterized by separate nonlinear curves and 2 independent failure criteria for forces / moments and displacements / rotations. For both modes the degrees of freedom can be combined arbitrary.
It is a high finical effort to test all different single elements and connections of various manufactures under high dynamic loads. Another problem is the practical measurement setup during the dynamic tests due to the inertia of the elements and the experimental equipment. However in this field more effort in testing and research is desirable.

6.3 Load assumption

Real measured pressure-time-histories are unsteady due to different influences like turbulent flow, reflection effects, form of charge, position of blasting cap, basement etc. Discrepancies of 10 or 15 % are not unusual.
That’s why the numerical reproduction of tests is based on measured discrete pressure-time-functions .If there are no measured results available or for design calculations theoretic values by LS-Dyna function *LOAD_BLAST are used (fig. 4).

6.4 Example

Numerical simulations for new constructions are based on calibrated models of accomplished tests. The simulations are adapted to the tests [16] by variation of material data until the structural behavior is nearly similar to the measured data and the high speed video record. These variations are necessary because of the quite insufficient material data for some parts. Especially the interaction and stiffness of small pieces like bolds and fittings is not yet tested sufficiently.

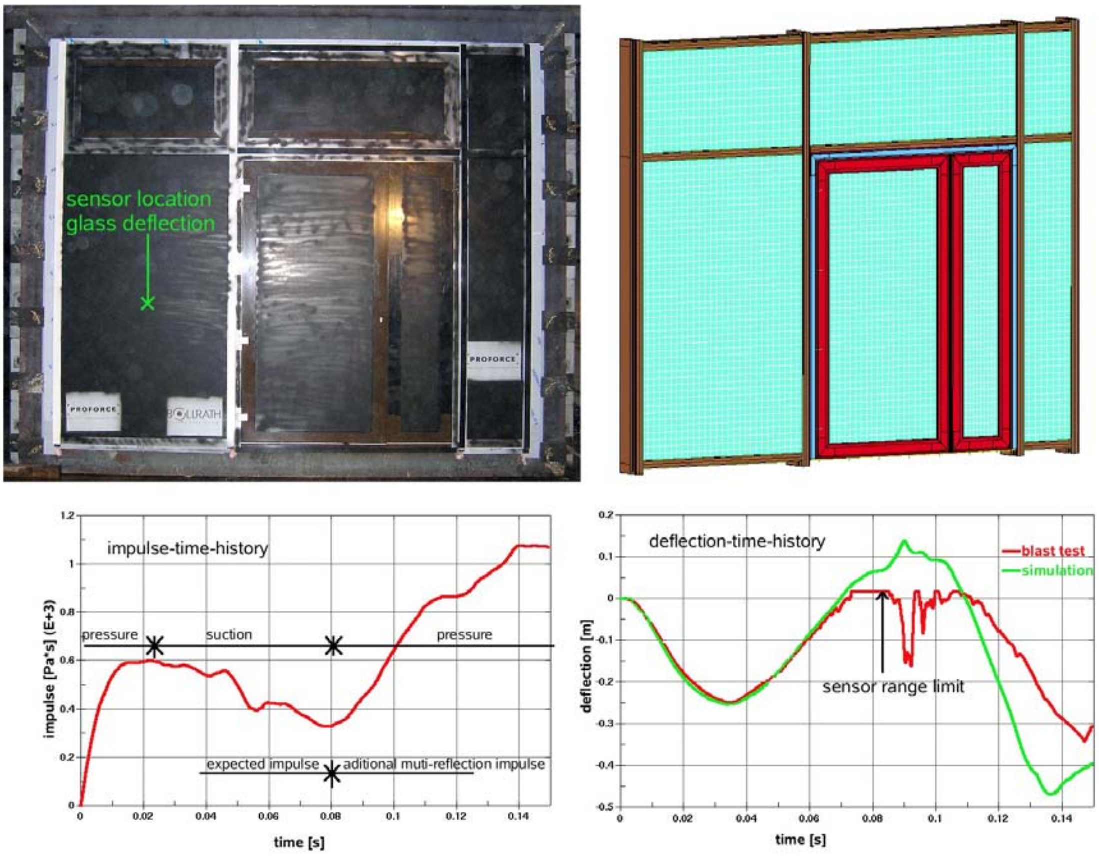


Fig. 14 Simulation of blast test (test results company Bollrath / PRO FORCE 2006) with comparison of deflection

A complex example for simulation and prediction of the structural behavior is the facade shown in fig. 14. The total dimension of the blast resistant facade element is 3,6 x 3,1 m. In the middle of the element an asymmetric double door is integrated. The maximum glass dimension is 1,3 x 2,2 m. For this element in preparation for the blast test a numerical simulation with theoretical load assumptions was performed. The simulation results were used for dimensioning of profiles, glazing and anchoring and some special safety construction details.

During the blast test the acting pressure at the structure surface at different points was recorded. The dynamic deflection of the left window was determined by laser-distance-measurement inside the test cubicle. Additionally of course the test was documented via high speed video.

The test was performed in a special underground blast shelter. Due to the unattended reflections at different shelter surfaces the structure was loaded by a multi-reflection blast wave. The first 15 ms overpressure phase was followed by a 65 ms suction phase. Pressure and impulse of the test where close to an open air surface burst with a charge of 100 kg TNT at 25 m distance. The unattended reflections lead to a second overpressure phase. This phase contained almost the same impulse as the first wave and acted on the pre-damaged structure (fig. 14 down left).

After the test, the structure was computed once more in consideration of the measured load-curve including the second overpressure phase. For all the complex models the correlation between measured results of glass displacement and numerical simulation was in good accordance (fig. 14 down right).

The computed permanent plastic deformation of the aluminum-profiles, the tears in the PVB-foil and the failure of some profile connections are close to the test results (fig. 15). Particularly the observed horizontal tear occurs in the test as well as in the simulation.

Without consideration of the flexible glass support, a vertical tear was first expected. The time dependent deformation behavior of the profiles and the opening of the door due to the multi-reflection-phenomena correspond with the high speed video data. With exception of glass breakage, the damage has occurred in the second overpressure phase.

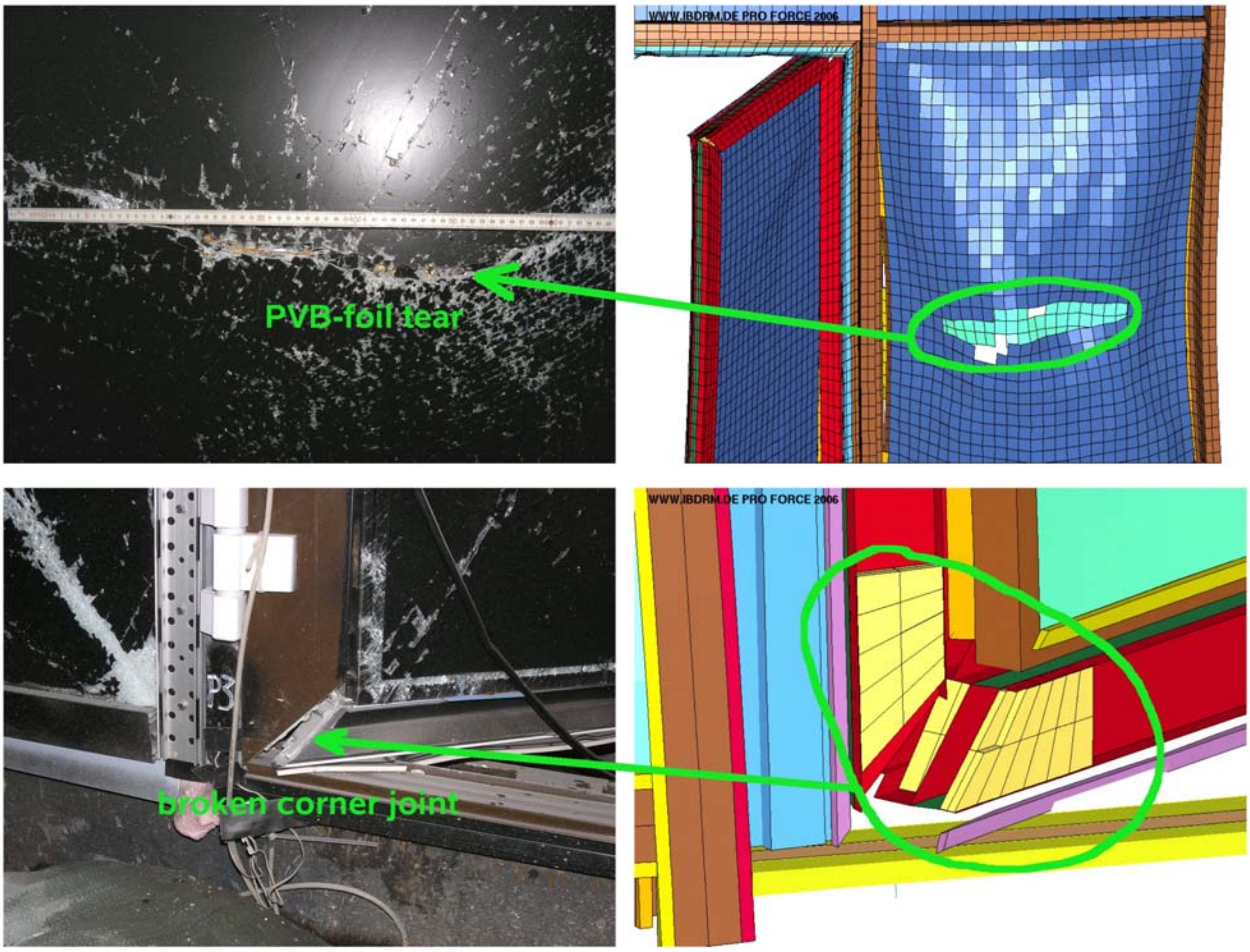


Fig. 15 Comparison test - computation details membrane failure and breakage of joint

As the test shows, it is possible to reduce local stress maxima by special adjustment of single elements and ductility´s by using numerical simulations. The risk of premature failure of fittings, bearings etc. will be reduced and a high ductile behavior of the element will be ensured. Due to those computations large facade systems with high safety level, economic material usage and a minimum of expensive combined testing can be developed. For the complete new structure in fig 15 with large thin panes and slim profiles only one verification test was necessary.

For the presented structure with 45000 elements and 150 ms examination time the computation time took about 9 hours. Depending on element approach, element number and size, elastic modulus and density the automatically configured time step size varies in a large degree. Because of that, a regular mesh is indispensable.

For computation of blast wave propagation and for interaction of waves and structures (FSI) in 3D high numbers of elements are necessary. The computation time may reach up to days depending on the hardware.

The showed computations where performed by LS-DYNA v. 970, operation system SUSE Linux 64-bit and AMD Athlon 64 4000+ CPU 2,4 GHz with 4 GB RAM.

7. Future developments and suggestions for research

The future developments aim to more discrete numerical models with consideration of more realistic rate dependency of material data and failure criteria.

For this, a lot of research on single components and materials including plastic behavior at high strain rates is required. Some suggestions are named in the list below.

- Strain rate dependency of different materials and composites
- Development and validation of strain rate depended material laws for different PVB-foils in addition to broken glass
- Acceleration limits for debris separation on the rear side of laminated glass panes
- Influence of glass crack propagation velocity
- Behavior of glue and elastomer glass support, adhesive tensile strength, friction coefficients, failure criteria for combination of normal and shear forces
- Ductility of fittings including local profile influences like gaps etc.
- Composite values for aluminum plastic profile connections for short term loads
- Research of insulated glass interspace pressure distribution in case of fast deflection

8. Summary

By using the presented sophisticated models for simulation of blast and blast effects on structures it is possible to predict behavior and failure of constructions in a more realistic way.

Especially the determination of realistic pressure-time-curves and hints for multi reflection phenomena etc. are not considered in the international blast protection standards.

Accomplished projects indicate that single results of idealized explosion test arrangements for arena air blast tests or shock tube tests are usable only in strong limitation for real applications. Small discrepancies in size, anchoring, glass bite, profile connection and combination etc. may cause totally different failure modes. By means of advanced numerical simulation it is possible to check the influence of modifications and make the real construction as safe as necessary and economical as well. For instance, not in every case it is valid to say “similar but smaller parts are safe because of successful tested large reference elements”.

For further improvement of the simulation models a lot of material data of single components including high strain rates is required.

The prospects for computational simulation of blast loaded windows and facades including the nonlinear interaction of all important details close to the real structure behavior have been elucidated. The still predominant skepticism against advanced numerical simulation methods to replace or complete blast tests appears widely inappropriate.

Numerical simulation tools as explained in this article enable the designing engineer to develop large and economic facade constructions with a high safety against blast effects.

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