Simulation of laminated glass loaded by air blast waves

Martin LARCHER
Civil Engineer
Universität der Bundeswehr München
Neubiberg, Germany

Norbert GEBBEKEN
Professor
Universität der Bundeswehr München
Neubiberg, Germany

Martien TEICH
Civil Engineer
Universität der Bundeswehr München
Neubiberg, Germany

George SOLOMOS
Structural Engineer
European Laboratory for Structural Assessment
European Commission-Joint Research Centre
Ispra, Italy

Summary
Laminated glass is widely used in the building envelope and it can protect the interior of a structure from the influence of an air blast. In this study several numerical models are investigated in order to represent the failure of the glass as well as of the interlayer. Layered shell elements (e.g. Mindlin) with special failure criteria are efficiently employed. For the PVB an elastic-plastic material law is used. For the glass, after the failure at an integration point, stresses there are set to zero under tension, while the material can still react to compression. If the interlayer reaches the failure criterion of PVB, the element is eroded. Older and new experiments with laminated glass are used to validate the numerical results. The experiments include both the failure of the glass sheets and of the PVB interlayer. It is shown that the layered model can adequately represent the experiments, also in cases where the interlayer fails. Results of a full 3D solid model are also presented and discussed.

Keywords: Air blast wave; Laminated glass; Shock tube experiments; Layered shell model; Material law for Polyvinylbutyral.

1. Introduction
Glazing windows have to fulfil several and diverse demands. Security related buildings are, for example, usually designed against the loading of explosions from outside. Consequently, their glazing system has to resist also air blast waves. If the detonation occurs inside a structure (e.g. a train) the aim is different. The failure of the glass panel could result in a release surface for the air blast wave with beneficial effects, as, the pressure would be decreasing. In both cases, the behaviour of laminated glass, which is often used in such cases, has to be taken into account.

Laminated glass is built of two or more annealed or tempered glass sheets which are combined with one or more PVB interlayers. It should be noticed that several types of laminated glasses are manufactured, using different types of glass and interlayers. The aim of laminated glass is to prevent the splinters from flying away and injuring people. After the failure of the glass, the interlayer glues the splinters together. The failure of a laminated glass sheet can be distinguished in five phases (Figure 1):
1. Elastic behaviour of the glass plies.
2. The first glass ply is broken; the other glass ply is still intact. The interlayer is not damaged.
3. The second glass ply fails. The interlayer reacts elastically.
4. The interlayer reacts plastically. The splinters are glued onto the interlayer.
5. The interlayer fails by reaching failure strain or by cutting from the splinters.

While phase (1) and its limit can be modelled with several analytical and numerical methods, phases (2) to (5) are more complex to simulate.

1.1 Analytical Approaches

Behr [1] and Norville [2] show that the behaviour of laminated glass up to the failure of the first ply is similar to monolithic glass under fast dynamic loading. This simplification is used by Weggel [3] to determine the behaviour of laminated glass loaded by low level blast. A conventional facade is strengthened using laminated glass instead of monolithic glass and using structural silicone sealant instead of compression gaskets. The numerical results show a good accordance with experimental data.

Single degree of freedom (SDOF) methods are used by several authors in order to design glass which is loaded by air blast waves (see for example for not laminated glass TM5-1300 [4], and for laminated glass Morison [5], and Fischer [6]). The stiffness of the plate in the different failure phases can be determined with analytical or numerical methods and can be verified with experiments. The stiffness is used in a SDOF system in combination with damping elements. The SDOF methods are especially useful in the pre-design phase since the calculation time of a SDOF system is very small.

1.2 Numerical Approaches

Several models are used in the literature to model laminated glass with finite element codes using shell or solid elements.

Models with one shell element through the thickness use layered materials with integration points over the thickness. Wagner [7] uses a material model for the glass which allows a two dimensional failure. The simulation of the post-failure under bending loading can be done with a smeared model with two coincident shell elements (see application for windshields by Timmel [8]) where one shell element represents the behaviour of one glass ply and the interlayer, while the other shell element represents the second glass ply. These models are presented in detail later on.

Some authors present 3D models with solid elements which allow using a detailed material law for the interlayer. The number of degrees of freedom increases rapidly. Wei [9], for example, uses a viscoelastic material model for PVB taking into account the strain rate effect. Since the failure of the glass is not considered, the results can only be used to define the starting point of the cracking. He postulates that the negative phase of the air blast wave has a big influence on the failure of the glass since the stresses at the negative peak are much higher. The influence of the negative phase of an air blast wave is analyzed by Teich & Gebbeken [24] for elastic structures and by Krauthammer [10] for conventional glass. The negative phase has a significant influence if the scaled distance is large since the negative pressure can be in the same range of the positive one.

Some investigations are presented which show the behaviour of laminated safety glass loaded by air.
blast waves. Weggel [11] presents experiments and numerical investigations for the low level of blast. A conventional facade is strengthened using laminated glass instead of monolithic glass and by using structural silicone sealant instead of compression gaskets. The properties of the PVB interlayer are ignored due to results by Norville [2].

Wei [9] presents finite element calculations using a viscoelastic material model for PVB taking into account the strain rate effect. Examples and calculations with failure criteria of conventional glass are shown, for example, by Wagner [7].

2. Structures Loaded by Air Blast Waves

2.1 Air Blast Waves

Air blast waves result from a rapid release of energy. The magnitude of the pressure of an air blast wave that arrives at a certain point depends on the distance and on the size of the charge. An idealised form of a pressure-time function at a certain distance from the explosive is shown in Figure 2.

The main characteristics of a free field air blast wave are the following:

- The shock wave of the air blast wave arrives at the point under consideration at the **arrival time** $t_a$.
- The pressure attains its maximum (peak overpressure $p_{\text{max}}$) very fast (extremely short rise time). The pressure then starts decreasing until it reaches the **reference pressure** $p_0$ (in most cases the atmospheric pressure).
- The duration of the positive phase $t_d$ is the time taken to reach this reference pressure. After this point the pressure drops below the reference pressure to the **maximum negative pressure** $p_{\text{min}}$. The **duration of the negative phase** is denoted as $t_n$.
- The overpressure impulse (positive impulse) is the integral of the overpressure curve over the positive phase $t_d$.

The idealised (free air blast) form of the pressure wave in Figure 2 can be significantly altered by the morphology of the medium encountered along its propagation. For instance, the incident peak pressure can be increased up to 8 times if the wave is reflected by a rigid obstacle. The effects of the reflection depend on the geometry, material, size and the angle of incidence (Gebbeken [25] for more details). The situation is much more complicated if there are several reflection boundaries, as it happens in urban environments.

2.2 Experimental, Analytical and Numerical Data

A widely used way of describing the shape of the air blast pulse is the so-called modified Friedlander equation, which proposes a function for the positive phase of the air blast wave. The pressure $p$ at time $t$ can be calculated by:

$$p(t) = p_0 + p_{\text{max}} \left( 1 - \frac{t}{t_d} \right) \frac{t}{t_a}$$

All parameters of equation (1) can be taken from several diagrams and equations (e.g. Baker [12], Kingery [13]). Kingery presents equations for the peak overpressure, the duration of the positive
phase, the positive impulse, and the arrival time. All these values are available for incident and reflected waves for spherical (free field) as well as for hemispherical conditions.

The negative phase (negative peak pressure and time of duration of the negative phase) can be described with a diagram proposed by Drake [14], obtained from experimental data. A bilinear function for the negative part of the air blast wave is used in this work.

The decay of the pressure-time function can be changed with the form parameter $b$ of Equation (1). Several diagrams from the literature can be used for this parameter, for example, Baker [15].

3. Experimental investigations

3.1 Experiments without Failure of the Interlayer

Kranzer [16] presents experiments of a 7.5 mm thick laminated glass sheet loaded by different blast loads. The experiments are carried out with Seismoplast PETN, whose explosive energy is 1.4 times higher than TNT. The experiment using 0.125 kg in a distance of 2 m is used for the calculations and the comparison. The pressure history for this experiment can be represented with a charge of 0.09 kg TNT in a distance of 1.8 m (spherical conditions, reflected).

The glass sheets have a dimension of 1.1 m x 0.9 m. The laminated glass is made of two annealed glass plies, each with a thickness of 3 mm (float glass) and an interlayer of PVB with a thickness of 1.52 mm. All sheets are clamped to the rigid frame by 50 mm wide rubber strips with a thickness of 4 mm. The static Young's modulus of the rubber specified is approximately 3.5 MPa. The loaded area of the sheet is 1.0 m x 0.8 m. The pressure is recorded at two points.

3.2 Experiments with Failure of the Interlayer

The experiments of Kranzer [16] did not result in a failure of the interlayer since the tensile strain in the interlayer was relatively small. Two experiments using a higher air blast load were carried out by Hooper [17]. An amount of 15 kg C-4 was used with two different standoff distances (10 m and 13 m). Each window had a size of 1.5 m x 1.2 m with a thickness of 7.5 mm. The laminated safety glass (LSG) was made of two annealed glass plies each with a thickness of 3 mm. The PVB interlayer had a thickness of 1.52 mm. The window was bonded with 6 mm thick and 20 mm wide silicone strips to a steel frame.

Several values of the TNT equivalent are documented in the literature for C-4. A value of 1.2 is used here to determine the pressure-time function.

The displacements of the windows were recorded with a high speed camera in such a way that the deformation of the whole sheet and the angle between the glass and the frame can be determined using a 3D digital image correlation.

The response of the laminated glass sheets depends on the distance from the charge. The laminated glass with a 10 m standoff distance failed before the rebound had started. The deflections of the other glass sheet with a standoff distance of 13 m were smaller and the panel failed much later.

The third case is used to verify the calculations with the help of two experiments from Morison [5] using also 7.5 mm thick laminated glass panels with a size of 1.25 x 1.55 m. The given pressure histories of both experiments are similar to each other and can be used to determine the charge, which was approximately 60 kg TNT at a distance of 12 m (spherical condition). Both glass panels fail during the experiment with a maximum deflection of approx. 32 % of the panel span.

3.3 New Experiments

The publically available basis for the verification of numerical calculations is small, and most of these experiments are using float (annealed) glass with a glass thickness of 3 mm and an interlayer thickness of 1.52 mm. Therefore, five new experiments have been performed using glass panes with a dimension of 890 mm x 1090 mm and a total thickness of 14 mm. The glazing was made of 6 mm heat-strengthened glass according to EN 1863, 2.28 mm PVB, and 6 mm heat-strengthened glass.

The tests were performed according to the European Standards DIN EN 13541. Particular attention has been paid to the clamping construction since it can be very important for the response of the
laminated glass panel, and consequently for the verification of the simulations. The procedures and setup of the shock tube testing are described in DIN EN 13123-1 and DIN EN 13124-1.

The experiments are conducted at the Ernst-Mach-Institut Freiburg, Germany at their test site in Efringen-Kirchen. A shock tube with a length of approx. 50 m is used. The basic functioning is as follows. A pressure chamber is filled with compressed air. After reaching a certain pressure level, the membrane is cut, using a small charge of explosive, and the compressed air of the chamber is released. The pressure wave resulting from this release is similar to an air blast wave. Depending on the overpressure of the pressure chamber and the diameter of the chamber (and of the membrane) several scenarios can be simulated. Charges between 100 kg and 2500 kg TNT in a distance of 35 m to 50 m are possible. The resulting overpressure of the reflected pressure wave is between 5 kPa and 260 kPa.

The test specimens are clamped in a special construction at the end of the tube where different frames can be fixed. Here, the standard frame according to EN 13124-1 is used.

Of the five tests performed only one is used here for calculations and comparisons, which has a maximum pressure of 150 kPa an impulse of 2037 Pa·s and a duration of 0.036 s. In this experiment the interlayer failed.

4. Numerical Investigations

The numerical calculations presented here are performed with EUROPLEXUS [18], which is an explicit finite element code for non-linear dynamic analysis. The program is developed in collaboration between the French Atomic Energy Commission (CEA) and the Joint Research Centre (JRC). The main focus of EUROPLEXUS is the fluid-structure interaction in fast dynamics.

4.1 Simulation Methods for Air Blast Waves

There are several methods of numerical modelling that can be used in order to load a structure with an air blast wave. These methods differ in the number of elements used and, accordingly, in the calculation time.

- **The solid TNT model** describes the mechanical behaviour of the explosive with a material law, e.g. the JWL equation. A fine mesh is essential to obtain realistic results. The calculation is therefore very time consuming. If the mesh is not fine enough, the pressures and the impulse are too small.

- Model with a **compressed balloon** (Larcher [19]). The pressure-time function resulting from a compressed balloon can easily match the curve of an air blast wave. The size of the compression can be calibrated with the impulse. The calculation time is smaller than for the solid TNT model.

- **Load-time function**. The structure is loaded by a load-time function built with the pressure-time function presented in Section 2.2. The calculation is relatively inexpensive. The method cannot represent reflections, shadowing and channelling.

The choice among these methods depends on the scope of the analysis. Here, the load is applied with a load-time function since the origin of the explosion is far away from the glass sheet.

4.2 Simulation Models for Laminated Glass

Several models can be adopted for the calculation of the response of laminated glass under air blast loads. Whereas smeared models can represent the behaviour of laminated safety glass only until the failure of the second glass sheet (which often occurs together with the failure of the first glass sheet), the layered element model can represent its behaviour after this point. In addition to these models, a real 3D model is being used next in this investigation. Not investigated are models using 3 shell elements through the thickness and combinations of shell and solid elements.

**Layered elements with special failure criterion** can be used very efficiently. After the failure of the glass, the stresses in a fixed direction are set to zero if the strains in this direction are greater than zero (tension). The material can still react to compressive stress in this direction. If the stresses in the direction normal to the direction of the fixed crack also reach the failure limit, only
compression stresses can be transmitted. If the interlayer reaches the failure criterion of PVB, the element is deleted. A similar model is implemented in LS-Dyna and is used by Wagner [7] to calculate blast loaded windows yielding a good correlation between numerical and experimental results.

The simulation of the post-failure behaviour under bending can also be performed with a smeared model (Timmel [8]). Two coincident shells are used with two different material laws. Thickness, density and Young's modulus of these two shell elements are calculated in such a way that both shell elements represent the behaviour of the sheet before the failure. The behaviour of the sheet after the failure of one of the glass plies is represented by one of the shell elements. Therefore, the stiffness of the shell element, which fails after the breakage of one of the glass plies, is smaller than the stiffness of the other shell element. The implementation of this material law is straightforward.

The simulation with a 3D solid model requires very fine meshes resulting in a long calculation time. The same material laws can be used as for the layered shell elements.

4.3 Material Law for Glass

The failure of glass is brittle. Architectural glasses fail at stresses between 8 and 45 MPa, whereas the environmental and loading conditions have a big overall influence. The failure of glass depends on the flaws on the glass surface (Griffith-flaw). Griffith [20] postulated that fracture starts at these flaws which are statistically distributed over the surface. Therefore, the failure of a glass panel can be represented by a one or two-parameter Weibull distribution, as shown by Beason [21], and the failure strength can be determined depending on a specified probability of failure. The strain rate effect of glass is based on the fact that flaws need time to grow to cracks. Its influence on blast analysis of not laminated glass is probably significant.

In the investigations shown, an elastic material law in combination with a failure strength is used.

4.4 Material Laws for PVB

Experiments show that the loading time has a big influence on the mechanical behaviour of Polyvinylbutyral (PVB). The long-time behaviour of PVB is viscoelastic, while the short-time behaviour is closer to elastoplastic or brittle. Like other plastic materials, PVB shows failure at large strains (appr. 300 %) which indicates the need of a hyperelastic 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.

The Young's modulus of PVB under high strain rates can be measured using standard tensile tests. Such tests have been performed by Morison [5], Iwasaki [22], and Bennison [23], Figure 3. All tests show that the behaviour of PVB under small strain rates is viscoelastic. This behaviour changes when loading the PVB at higher strain rates. The material becomes more and more elastoplastic, and the Young's modulus increases dramatically. The hardening parameter corresponds with the Young's modulus for small strain rates. The strain limit appears similar to the static one.

Fig. 3 Behaviour of PVB at different strain rates (Morison [5], Iwasaki [22], Bennison [23])
Table 1 Material parameters for glass and PVB

<table>
<thead>
<tr>
<th>Sample</th>
<th>Glass</th>
<th>PVB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Young's modulus [N/mm²]</td>
<td>70000</td>
<td>220</td>
</tr>
<tr>
<td>Poisson ratio [-]</td>
<td>0.23</td>
<td>0.495</td>
</tr>
<tr>
<td>Elastic limit [N/mm²]</td>
<td>-</td>
<td>11.0</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>2500</td>
<td>1100</td>
</tr>
<tr>
<td>Failure strain [-]</td>
<td>0.0012</td>
<td>2.0</td>
</tr>
<tr>
<td>Failure stress [N/mm²]</td>
<td>84.0</td>
<td>28.0</td>
</tr>
</tbody>
</table>

In the calculations presented an elasto-plastic material (Figure 3) is used for the PVB with the parameters shown in Table 1.

The interfacial adhesion between the glass and the interlayer is produced by heating in combination with higher pressure. The gluing forces of PVB are relatively high. A debonding is therefore not considered.

4.5 Simulation of the Support of the Window

The support of the windows as in the experiments is built up with solid elements, which use the same nodes as the shell elements. The nodes on the top and on the bottom are fixed. An elastic material law is used with a Young's modulus of 3.5 N/mm².

5. Comparison of Numerical and Experimental Results

5.1 Experiments without Failure of the Interlayer (Kranzer)

Several calculations are performed by the authors to simulate the experiment of Kranzer [16] (0.125 kg explosive). The mesh of the glass sheet is built up with tetrahedral elements (Discrete Kirchhoff Triangle). It can be shown (Figure 4) that the smeared as well as the layered model result in a relatively good agreement with the experimental values.

A convergence study is performed for the model investigated. Figure 4 shows that the results are independent from the size of the elements if the elements are small enough (smaller than 2 cm). The crack pattern can be described better with smaller elements as shown in Figure 5. The comparison with the experimental cracks shows a good agreement. The circumferential cracks as well as the radial crack are well represented by the numerical results. The part in the centre of the sheet remains undamaged in the experiment, which is not retrieved by the calculation.

![Fig. 4 Smeared model, layered model, 3D model; influence of the element size (Experiment of Kranzer [16])]
5.2 Experiments with Failure of the Interlayer (Hooper)

The behaviour of the PVB interlayer is much more important in cases when the interlayer has to sustain big tension strains, e.g. Hooper [17]. The material law shown in section 4.4 is used to describe the behaviour of PVB. The displacement history of the experiment as well as of the numerical simulations is shown for the standoff distance of 10 m in Figure 6. Clearly, the results of the smeared model do not reproduce the experimental data.

The calculations with the layered model also take into account the failure behaviour of the interlayer. The model shows such a failure in the numerical calculation at $t = 0.009$ s. The failure in the experiment was recorded at $t = 0.0085$ s (from the arrival of the air blast wave at the structure). As seen, the displacement history of this experiment can be described very well with the layered shell elements, under the condition that the element size is chosen small enough.
5.3 Experiments with Failure of the Interlayer (New Experiment)

The numerical models are also used to simulate the new experiment described in Section 3.3. The calculation with the layered model shows an adequate result. In comparison to the experiment, the numerical resulting failure of the interlayer starts earlier. The 3D model cannot represent the behaviour of the laminated glass in this case. Several numerical instabilities make the calculation fail much before the failure of the interlayer in the experiment.

Fig. 7 Layered model, 3D model (New Experiment)

6. Conclusion

The paper presents a comparison between experiments and numerical simulations for air blast loaded laminated glass. It can be shown that a smeared model can only be used for cases where the interlayer is not broken after the loading. The 3D model can represent most of the experiments but the calculations are very time consuming. The layered model can efficiently represent all experiments presented. In addition, the results of a new experiment are shown which were also compared with numerical simulations. The investigations exclude the cases where only one of the glass plies has failed. These calculations need a special procedure since they cannot be represented using the layered model.

7. References


