SIMULATIONS OF A METRO CARRIAGE EXPOSED TO AN INTERNAL DETONATION

Martin LARCHER
Joint Research Centre, IPSC
European Laboratory for Structural Assessment, I-21027 Ispra, Italy

Abstract : *Land mass transport systems have an open architecture and are therefore vulnerable to terrorist attack. The access to metros, for example, cannot be controlled against explosive materials like it is done for airplanes. An approach to determine the risk in a case of a detonation inside a train is done here numerically using EUROPLEXUS.*

INTRODUCTION

The terrorist attacks in recent years, for example in Madrid and in London, have shown that train carriages are vulnerable to detonations. The explicit finite element code EUROPLEXUS is used here to determine the deformations and the failure behaviour of a train carriage exposed to an air blast wave. The structure of the underground carriage investigated is shown in Figure 1. Similar investigations are being done to assess the behaviour of a railway station and of a metro station in a case of internal explosions but which are not presented here.

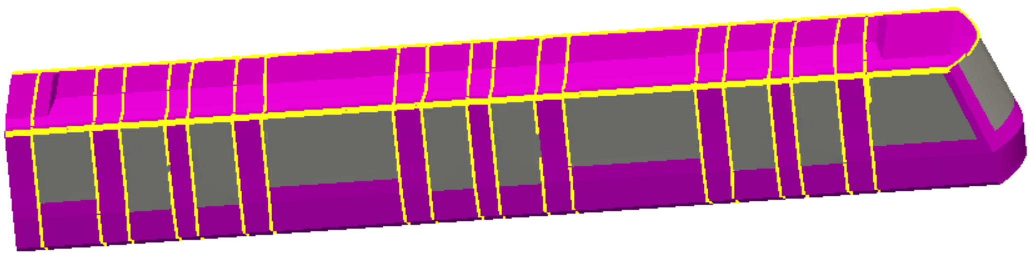

Figure 1 Structure of the train using frames (yellow)

AIR BLAST WAVES

Air blast waves result from a rapid release of energy. Here, the air blast waves investigated result from the detonation of a solid explosive. Similar investigations are possible for detonations due to gas combustion.

The pressure magnitude of an air blast wave arriving at a certain point depends on the distance and size of the charge. An idealised form of a pressure-time function at a certain distance from the explosive is shown in Figure 2.

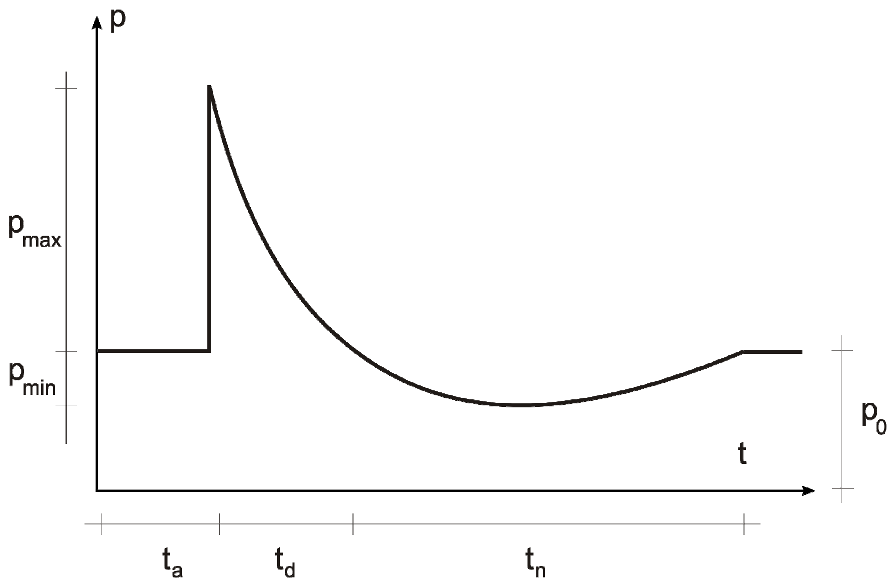

Figure 2 Pressure history of an air blast wave

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. This period is defined as the time from the beginning of the explosion including the time of the detonation itself.
- The pressure attains its maximum (**peak overpressure p_{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 **minimum (negative) pressure p_{min}**. The **duration of the negative** phase is denoted as t_n.
- The overpressure 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 greatly altered by the morphology of the medium encountered along its propagation, especially due to reflections by rigid obstacles. The effects of the reflection depend on the geometry, the size and the angle of incidence. The situation is much more complicated if there are several reflection boundaries, as it happens between buildings or inside the underground carriages investigated.

A widely used way of describing the form of the air blast wave is the so-called modified Friedlander equation (see e.g. Baker [1]), which proposes a function for the positive phase of the air blast wave. The parameters of this equation can be taken from the literature (e.g. Kingery [2]).

NUMERICAL SIMULATIONS

EUROPLEXUS

All numerical calculations presented are performed with EUROPLEXUS, 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). A commercial version of the code is distributed by SAMTECH as part of its SAMCEF software.
The main focus of EUROPLEXUS is on fluid-structure interaction in fast dynamics. Several developments have been done in the recent years to provide ad-hoc procedures for the calculation of structures loaded by air blast waves.

SIMULATION OF 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 (see Figure 3). These methods differ in the number of finite elements used and, accordingly, in the computation time.

- **Pressure-time function** (command AIRB): The structure is loaded by a pressure-time function. The calculation is relatively inexpensive. The method cannot represent reflections, shadowing and channelling.
- Model with a **compressed balloon** (bubble model; see Larcher [5]; material BUBB). The pressure-time function resulting from a compressed bubble 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 the one for the solid TNT model.
- 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 expensive. If the mesh is not fine enough, the pressures and the impulse are too small.

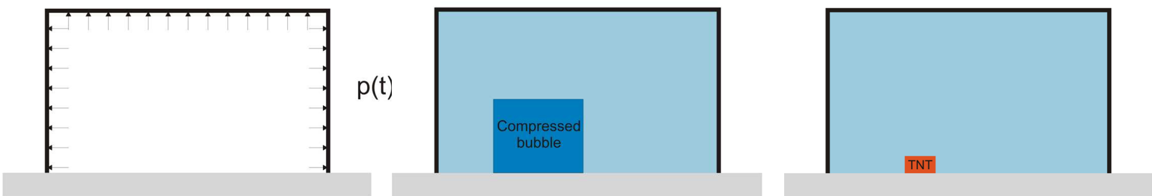

Figure 3 Numerical models for air blast waves: pressure-time function, compressed balloon, solid TNT

The choice among these methods depends on the scope of the analysis. The pressure-time function can be used here to calculate the behaviour of the structure itself, disregarding multiple reflections and channelling. However, the risk (e.g. of death) inside a structure can only estimated using a full fluid-structure calculation. The bubble model is used herein to reduce the computation time in comparison to the solid TNT model.

A non-conforming fluid-structure interaction algorithm (FLSR model) is used here. The fluid and the structure are meshed independently. This simplifies modelling since the carriage can simply be set into a regular box of fluid. This method is the only feasible one in the particular case of failure with erosion of structural elements.

LAMINATED GLASS

The most recent train carriages use laminated glass for the glazing. Laminated glass is built by two annealed or tempered glass sheets, which are combined with a PVB interlayer. The aim of laminated glass is to prevent flying splinters, which could injure people. After the failure of the glass, the interlayer glues the splinters together.
Layered shell elements with special failure criterion can be used very efficiently for the simulation of laminated glass, which is used very often to construct train carriages. After failure of the glass, the stresses are set to 0.0 if the strains are positive (tension). The material can still react to compression stress. If the interlayer reaches the failure criterion of PVB, the element is eroded (deleted from calculation). The material model is implemented in EUROPLEXUS as material LSGL.
It can be shown (Larcher [6]) that the element size has only a small influence on the displacements of a glass sheet loaded by air blast waves. The failure of the interlayer, which indicates the failure of the whole glass sheet, can only be described using small elements. Such small elements can not be used for the calculation of a big structure like an underground carriage. Since the failure of the interlayer can not be determined using big elements, a displacement criterion (see for example Morison [7]) is used with 30% of the span of the window (command FAIL DISP). The elements at the border of the glass sheets are eroded after reaching the failure limit.

TRAIN

Two different structures are used to define the cladding of the train: a relatively stiff honeycomb structure (see Figure 4; Zheng [9]) and a frame structure with aluminum sheets welded on it. Since the honeycomb structure itself cannot be modelled for the train carriage due to the too small elements needed, it is modelled using layered shell elements having the same stiffness and density as the honeycomb structure. The cross section of the frame structure has the standard profile IPE80. These profiles are placed near the doors and at the upper border of the carriage.

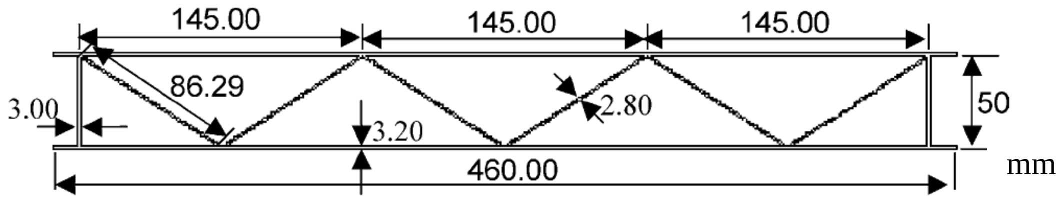

Figure 4 Honeycomb structure for the train (see Zheng [9])

RISK

Calculations can also be used to estimate the risk inside the train. Both the risk of eardrum rupture and the risk of death can be calculated. The internal routine for the risk assessment (command RISK; see Giannopoulos [3]) uses the pressure and the impulse inside each element. The probability functions for each fatality case of the risk are calculated using the procedure of Ferradás [4]. The total probability from these functions is determined using Yet-Pole [8].

RESULTS OF THE CALCULATIONS

The calculation of the train carriages is performed using 0.5 kg or 10 kg TNT. The resulting displacements of the structure are compared in Figure 5. A detonation of 10 kg TNT leads to a complete failure of the structure around the explosive. Most of the windows are also failed due to reaching the displacement criterion. The end of the carriage is also destroyed due to the channelling effect inside and the reflection of the wave at the end of the carriage. A detonation of 0.5 kg TNT doesn't result in failure of the structure. The displacements of the windows are large. This indicates that the windows are broken but the interlayer is still intact. The interlayer prevents the splinters from flying away. Since the windows are still intact, there is also no release surface for the air blast wave.

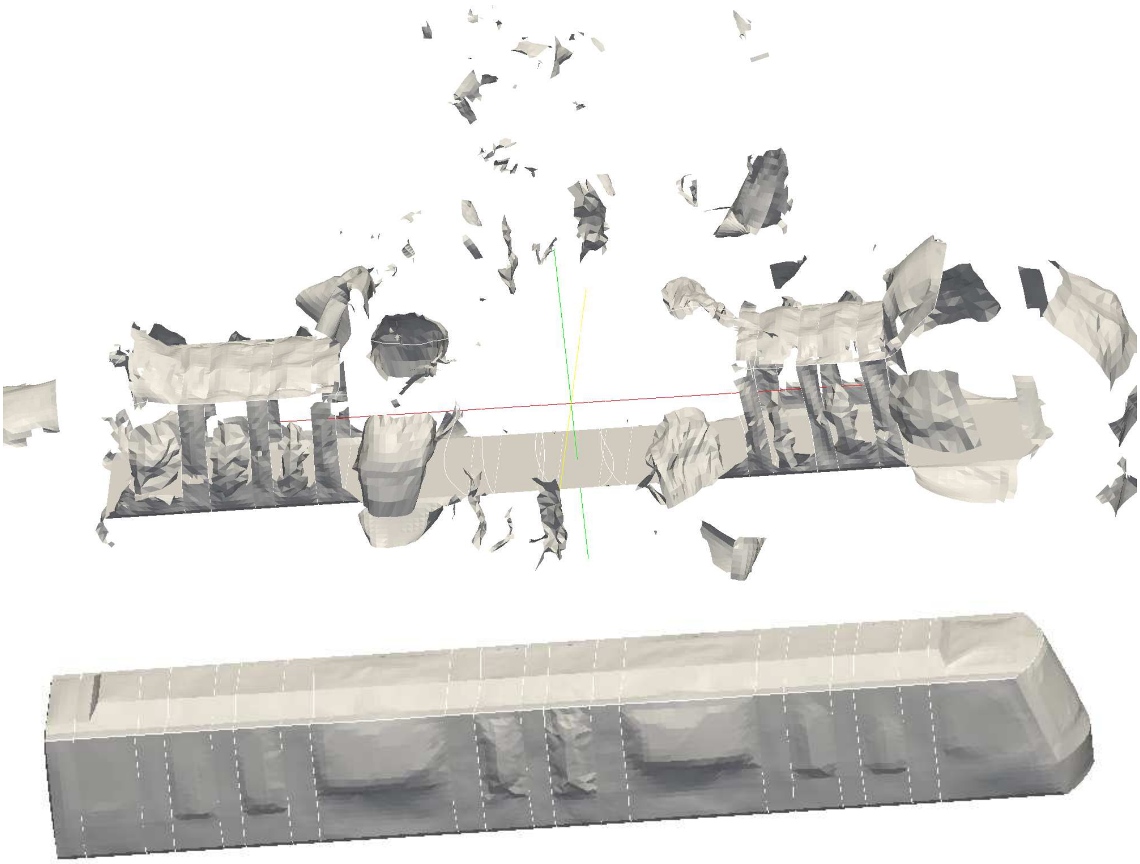

Figure 5 Displacements after 6 ms for 10 kg TNT (top) and after 20 ms for 0.5 kg TNT (bottom), frame structure

The comparison of the frame structure and of the honeycomb (sandwich) structure (see Figure 6) shows that the later is much stiffer. Apart from the fact that all windows are failed, the local failure around the explosive is small.

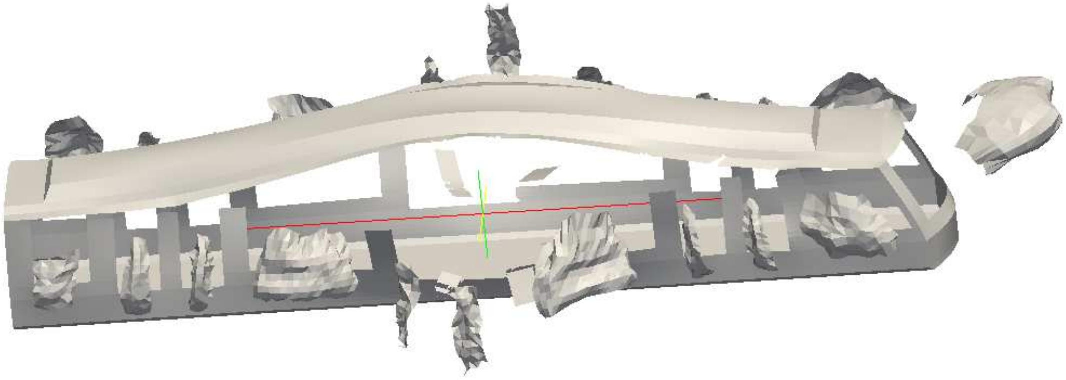

Figure 6 Displacements after 20 ms for 10 kg TNT, sandwich structure

The fluid calculations performed can also be used to determine the risk for humans inside the structure. The risk of death and the risk of eardrum rupture are 1.0 in the whole carriage in the case of 10 kg TNT (see Figure 7). It can be shown that the risk can be reduced using internal walls like doors. A train carriage with such internal walls using the same laminated glass as for the windows shows that only half of the carriage is exposed to a risk of 1.0 (Figure 8). The part of the carriage which is shadowed by resisting glass walls has a smaller risk.

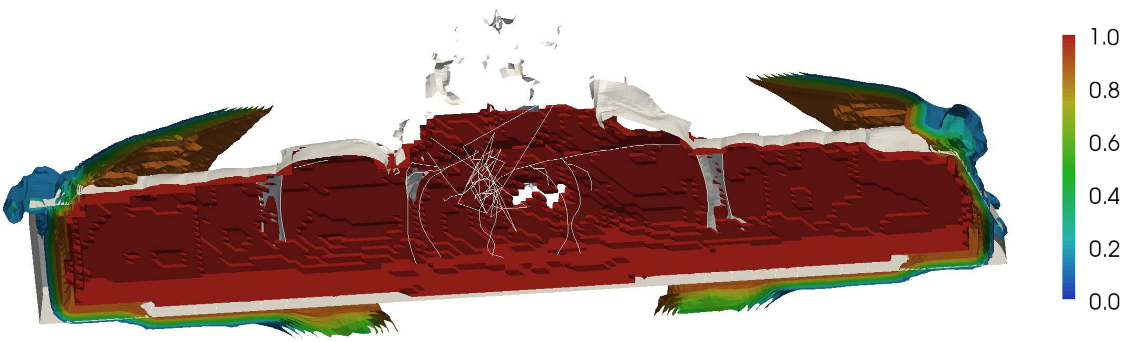

Figure 7 Risk of death, frame structure, 10 kg TNT

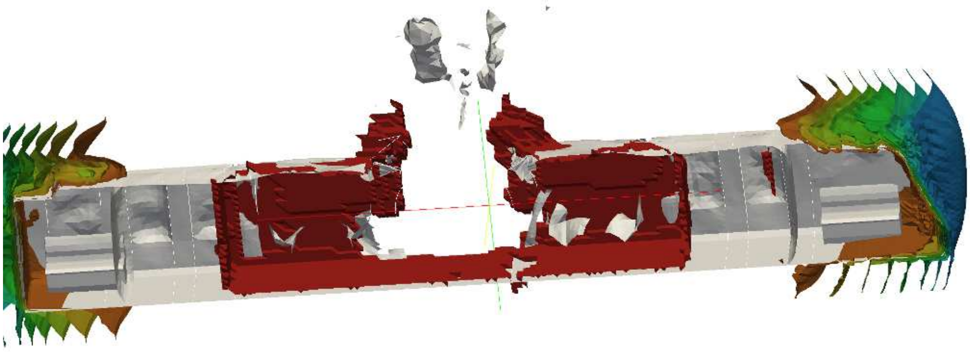

Figure 8 Risk of death, frame structure using internal glass walls, 10 kg TNT

The distribution of the risk in the case of 0.5 kg TNT is shown in Figure 9 and Figure 10. The risk of eardrum rupture is a little bit smaller. But it reaches also 0.9 in the whole train. One reason could be that the roof of the carriage is not opened due to the explosion and the air blast wave can not release. The region with a risk of death is much smaller for 0.5 kg than for 10 kg TNT. It is observable that the risk of death is increased at the end of the train since the air blast wave is reflected there. The reflection leads to a much higher impulse and pressure.

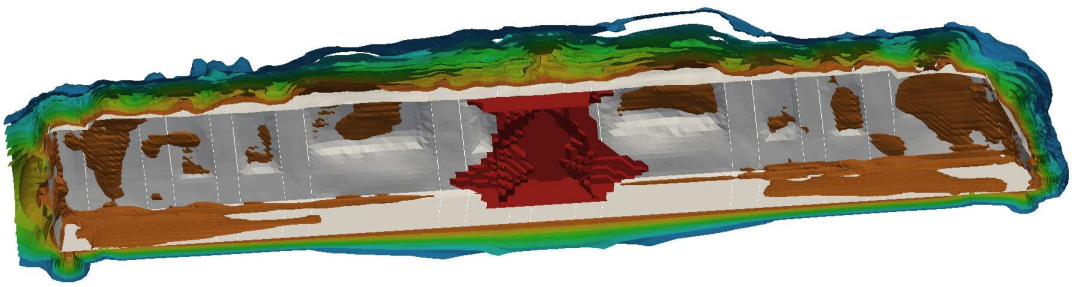

Figure 9 Risk of eardrum rupture, frame structure, 0.5 kg TNT

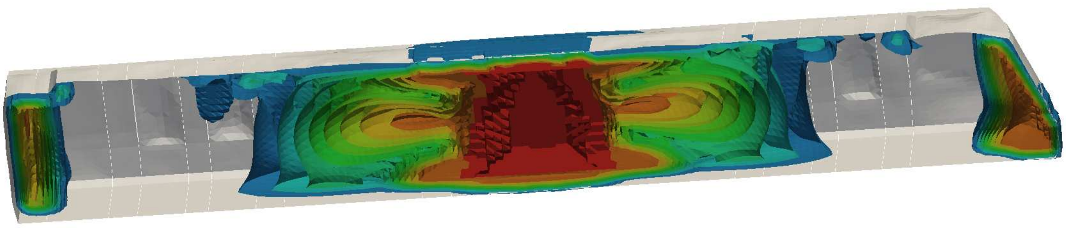

Figure 10 Risk of death, frame structure, 0.5 kg TNT

CONCLUSION

This paper presents investigations about explosions inside an underground carriage, which could occur during a terrorist attack. Two main constructions of train carriages are investigated: a frame construction with a thin metal sheet welded on it and a sandwich structure.

The charge in the fluid-structure calculations is modelled using a compressed balloon model. The displacements and the risk inside the carriage are presented.

For further calculations the following recommendations can be given:

- Fluid-structure interaction is needed to consider channelling and to determine the risk inside a structure.
- A compressed balloon model can be used instead of the JWL equation to model the behaviour of the explosive so that the computations are much more cost efficient.
- A simple model for the laminated glass is sufficient in order to represent the failure behaviour.

Further investigations should be done to define the behaviour of different internal structures using a simplified model.

The displacement erosion criterion should be verified to assess whether it can be describe a shear failure of laminated glass. An erosion criterion based on the maximum curvature might result in a more realistic behaviour of the laminated glass.

REFERENCES

[1] Baker, Wilfrid E.: Explosions in the Air, University of Texas Pr., Austin, 1973.

[2] Kingery, Charles N., Bulmash, Gerald: Airblast Parameters from TNT Spherical Air Burst and Hemispherical Surface Burst; Defence Technical Information Center, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland; 1984.

[3] Giannopoulos, G.: Risk Assessment of Explosion Events Using Europlexus. JRC Technical Note, Pubsy JRC50385, Ispra 2009.

[4] González Ferradás, E.; Díaz Alonso, F.; Doval Miñarro, M.; Miñana Aznar, A.; Ruiz Gimeno, J. and Sánchez Pérez, J.F.: Consequence analysis by means of characteristic curves to determine the damage to humans from bursting spherical vessels. Process safety and environmental protection 86 (2008), pp. 121–129.

[5] Larcher, M.: Simulation of Air Blast Waves in Urban Environment. JRC Technical Note, Pubsy JRC43400, Ispra 2008.

[6] Larcher, M.: Simulation of Several Glass Types Loaded by Air Blast Waves. JRC Technical Note, Pubsy JRC48420, Ispra 2008.

[7] Morison, Colin; Zobec, Marc and Frenceschet, Alberto: 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.-21.09., Orlando, US, 2007.

[8] Yet-Pole, I.; Cheng Te-Lung: The development of a 3D risk analysis method. Journal of hazardous materials 153 (2008), pp. 600–608.

[9] Zheng, L.; Petry, D.; Wierzbicki, T.; Rapp, H.: Fracture prediction in 4-point bending of an extruded aluminum panel. Thin-Walled Structures 43, pp. 565–590, 2005.