Influence of venting areas in tubular structures like train carriages subjected to internal explosions

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Abstract The influence of venting areas built from glass on the peak pressure and the impulse of explosions due to high explosives is investigated in this paper. The pressure-time function of an air blast wave resulting from a high explosive is different from that of a gas or dust explosion. Its peak pressure is higher but the duration of the positive phase is much shorter. The capability of making a structure fly away is therefore reduced. Apart from the pressure time function also the direction of the wave could have an influence. Starting from a certain distance to the explosion, calculations show that the air blast wave inside a tubular structure becomes one-dimensional. In such a case, the influence of venting areas parallel to the wave propagation direction is small. This is shown in the study by several calculations using fluid-structure interaction. The pressure peak and the impulse at selected points in a tubular structure are compared depending on the existence of openings, their dimension and position, and their number. Their effect is found to be small even in the case that the opening is near the explosion. In addition, the influence of venting areas in realistic train carriages is presented.

Keywords: Explosion inside structures, pressure release, venting area, safety of train carriages, underground transportation

1. Introduction

Several terrorist attacks have recently taken place inside land mass transport systems like trains and underground carriages. Several investigations have been made in the direction of assessing the risk inside trains. Loukaitou-Sideris et al. [1] compare the measures taken by four cities to reduce the risk in their metro lines and stations; policing and surveillance methods are mainly considered. The number of casualties of the terrorist attack in Madrid is reported by Gutierrez et al. [2]. A comparison of the injuries between detonations inside confined structures and open-air detonations is presented by Leibovici et al. [3] and shows that the mortality rate in confined spaces is higher. Larcher et al. [16] present a method for determining the probability of death inside structures and its use for rail transport systems. As commented, the possibilities to reduce the number of affected passengers are limited. One possibility is provided by internal structures like seats, windscreens etc. The total number of passengers has also a big influence on the extent of the zone with high probability of death.

Venting is another measure often proposed. Venting areas are parts of a structure, through which an overpressure resulting from an internal explosion can be released. Vents are designed to limit the overpressure inside a structure in case of an explosion. These parts are mainly lightweight so that the surface pressure needed to open them is low. Several such systems are available like rupture disks, bursting foils or explosion doors.

Venting areas are used successfully in laboratories for high explosives and ammunitions storage places, where at least one side is built lightweight. They are also used for vessels and pipelines where goods vulnerable to dust explosions are stored or transported (see several examples by Taveau [4]). A scenario with vessels, where also the risk is calculated, is given by van der Voort et al. [5]. Special products are available for extinguishing the flame from the vented explosion (Bartknecht [6]). Venting areas are also often used on offshore structures to reduce the impulse of the pressure wave (Fitzgerald [7]). European norms (EN standards) for systems that are vulnerable to dust [8] and gas [9] explosions are available. These standards have been developed in order to enhance safety by limiting the pressure wave escaping from vessels in case of an accident.

The influence of a venting system in urban tunnels has been presented by van den Berg and Weerheijm [10]. The rupture of a LPG pressure vessel (boiling liquid expanding vapour explosion) is simulated taking into account large openings (50 to 150 m long) in the roof of such a tunnel. The influence of the venting on the primary peak pressure is significant. Due to the loading and the geometry of the tunnel, a strong secondary peak pressure is generated. The peak pressure of the secondary pressure peak is reduced by only about 15 % using an opening of 150 m instead of 50 m.

Explosions resulting from high explosives (detonations) are different from gas or dust explosions (deflagration) since the latter have a lower detonation speed and take place over larger volumes. The peak overpressure generated by a gas or dust explosion may also be smaller but the duration of the positive phase may be quite longer (Corr and Tam [11]). Therefore, the lightweight structure of an explosion vent, which should fly away, has more time to react in case of a gas or dust explosion than for a solid explosive charge.

In this work, the influence of venting areas on explosions inside trains or similar systems is investigated through numerical simulations. Only detonations due to high (solid) explosives have been considered. The investigations first consider a simplified train geometry. The dimensions of the venting areas in this model are varied in order to assess their influence. Calculations with more detailed models of a train carriage and of a long train without internal structures are performed next, in order to check the influence of venting devices in a real train structure.

This paper presents the influence of venting areas in case of a detonation of solid explosives inside of closed structures. Explosions inside structures show a different behaviour in comparison to free-field conditions. Long, empty, tube-like structures are a special case. Inside such tubes the air blast wave cannot expand as much as it does under spherical or hemispherical conditions, and thus constrained, it almost becomes a 1D plane wave (channelling). Examples of such channelling may occur in narrow streets with buildings, in train carriages, and in tunnels.

3. Numerical investigations

All numerical calculations presented below are performed with EUROPLEXUS [14], an explicit finite element code for non-linear dynamic analysis. The code is developed in collaboration between the French Atomic Energy Commission (CEA) and the Joint Research Centre of the European Commission (JRC). The main focus of EUROPLEXUS is fluid-structure interaction in fast dynamics.

3.1 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 Jones-Wilkins-Lee (JWL) equation. A fine mesh is essential to obtain realistic results. The calculation becomes therefore very time consuming. If the mesh is not fine enough, then peak pressure and impulse are underpredicted.

- Model with a **compressed balloon** (Larcher [15]) replacing "equivalently" the solid explosive. The pressure-time function resulting from a compressed balloon can easily match the curve of an air blast wave. The level of the initial compression can be calibrated to fit 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 by properly selecting the parameters of a pressure-time function (e.g. modified Friedlander equation (e.g. Baker [12]). The time needed for calculation is relatively small. However, this method cannot represent reflections, shadowing and channelling.
- The choice among these methods depends on the scope of the analysis. Here, the charge is represented using a compressed balloon since a simple load-time function cannot be used to determine the venting characteristics in long tubular geometries, where channelling effects are essential. Instead, a full fluid-structure interaction calculation is needed, where the compressed balloon technique provides both sufficient accuracy and computational efficiency.

3.2 Fluid-structure interaction

Fluid-structure interaction (FSI) is modelled in EUROPLEXUS using a quite powerful automatic algorithm, which does not require matching nodes for the structure and the fluid. The two meshes are fully independent and a continuous and even structured fluid mesh can be adopted. At each time of the computation, a topological search is performed of the fluid nodes, which are reasonably close to the structure. Thanks to optimisation of the fluid-structure interaction routines, computation times for the simplified geometry and the realistic trains considered here are acceptable: each simulation takes between 6 hours (simplified model) and 1 week on a normal desktop PC.

4. Simplified train model

4.1 Investigated geometry

A simple geometry is first employed to investigate the influence of venting areas (Fig. 1). This geometry should represent a simplified train and is loaded by an internal air blast wave using an 8 kg TNT equivalent, which is realistic for a terrorist attack in such an environment.

The geometry of the structure consists of a tube with rectangular cross-section 3 x 3 m and a length of 15 m. The deflections of the tube in case of a channelled one-dimensional blast wave along its axis are relatively small. The structure is therefore considered rigid in order to minimize the number of parameters examined. The fluid is modelled using the non-conforming fluid-structure interaction presented in Section 3.2. The structure is completely filled by fluid (air). An additional fluid layer of 0.45 m thickness (not shown in Fig. 1) is added all around the structure. All the exterior surfaces of this fluid layer are modelled as absorbing boundaries in order to avoid reflections due to venting effects through the opening. The fluid (air) is modelled using the ideal gas equation and, as mentioned above, the explosive is represented using the balloon model.

The openings are placed centrally at mid length in the "roof" of the tube with a width of 3 m and lengths of 0.5, 1.0, and 2.0 m, respectively. The resulting peak pressure and impulse are compared with the situation in a closed tube (no opening) and in a completely open tube (no roof).

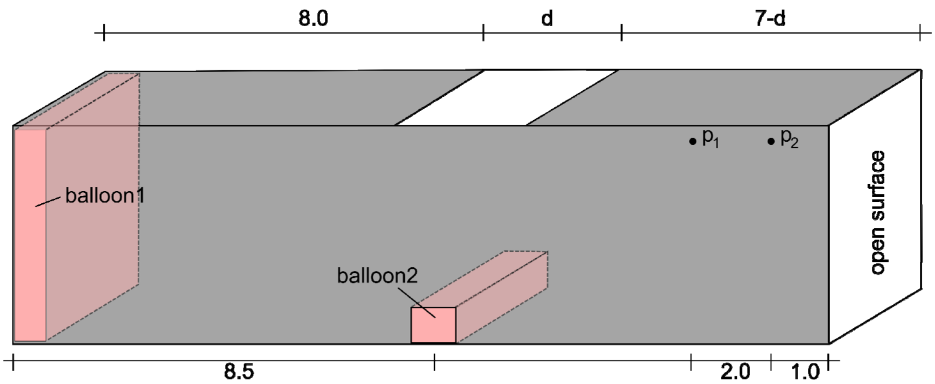

Fig. 1 Simplified train model, geometry, full length 15 m

The charge is placed at two different positions. In the first investigation the charge is located at one extremity of the tube (Fig. 1, balloon 1, lateral explosion). The pressure wave resulting from this explosion follows the tube and reaches the opening at a distance of 8 m. This situation should represent the case where a nearly one-dimensional air blast wave (due to channelling) propagates parallel to a venting area. In the second case, the influence of a venting area orthogonal to the air blast wave is investigated and the charge is placed directly under the vent (Fig. 1, balloon 2, central explosion).

The peak pressure and the impulse are measured at two points p_1 and p_2 at a distance of 12 m and 14 m from the left end of the tube, i.e. the distance from the measuring points to the beginning of the opening is 4 and 6 m respectively. The total number of brick fluid elements is about 240,000; the number of structural elements (quadrilateral shells) is about 18,000.

4.2 Results

The pressure wave for three different configurations of the opening in comparison to the completely closed tube is shown in Fig. 2 for the explosion at the left end of the tube (balloon 1). The air blast wave reaches the opening at t = 12 ms, when it is nearly one-dimensional. A small part of the pressure is released through the openings. At t = 16 ms the blast wave profiles for the different openings show some small differences. While the blast wave for the case without any opening is still perfectly one-dimensional the air blast wave for the case of an opening of 2 m exhibits a peak in the lower part of the tube. At t = 20 ms these differences among roofs with and without openings are still observable, but they are overall quite small.

The influence of the venting area on the peak (total) pressure for point p_1 and point p_2 is shown in Fig. 3. The peak pressure and the impulse are scaled using the values of the case without opening. It can be seen that the peak pressure at point p_1 is reduced by 6 % by using an opening of 2 m. For an opening of 1 m the peak pressure is only reduced by 3 % and for an opening of 0.5 m by 1.3 %. The reduction of the peak pressure can also be compared with the situation without any roof, where the reduction is about 30 %. The reductions of the peak pressure for point p_2 are for all cases in a similar range as those for point p_1.

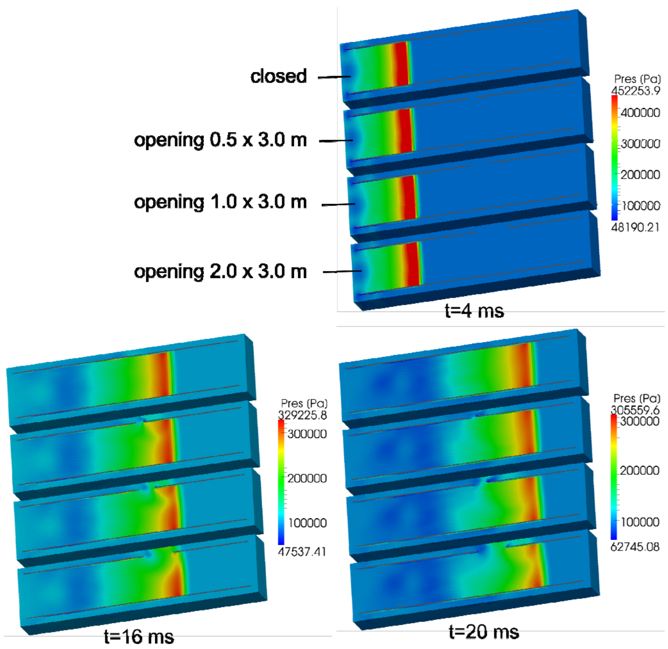

Fig. 2 Development of the pressure in case of a lateral explosion (balloon 1), for various venting areas

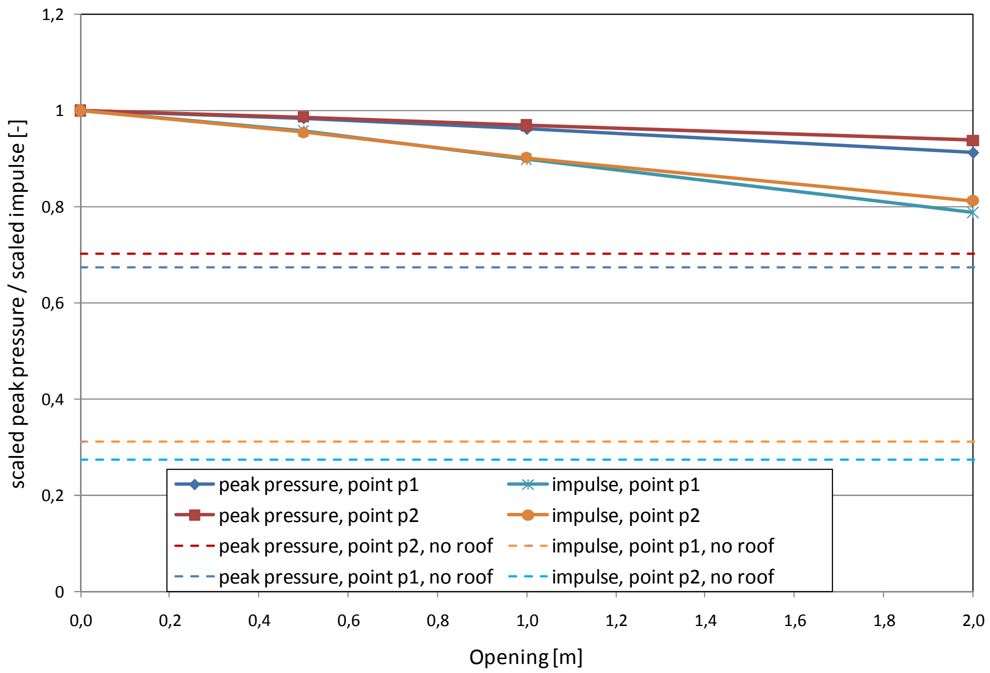

Fig. 3 Scaled peak total pressure and scaled impulse

The reduction of the impulse is higher (see also Fig. 3). It reaches 21 % at point p_1 and 19 % at point p_2 for the opening of 2 m. For the opening of 1 m the reduction is about 10 %. For the case without roof, the impulse is reduced by 69 % at point p_1 and 72 % at point p_2.

The blast wave behaviour in case of an explosion that takes place near the venting area (balloon2, Fig. 1) is similar.

If the dimensions of the openings are compared with the situation inside a train carriage it is obvious that an opening of 2 x 3 m as venting area is not realistic. On the other hand, the reduction of the peak pressure and the impulse in case of an assumed opening of 1 m is relatively small for realistic charges of a terrorist attack.

These parametric studies indicate that the influence of venting areas, in the geometrical configurations presented, is generally small and that they cannot be used to efficiently reduce the probability of death and with it the vulnerability of a transport system to internal explosions. As seen, even for a spherical wave, i.e. for a wave not yet reflected by the structure and impacting normally to the venting area, any realistic opening is too small to efficiently reduce the pressure. The situation would be even worse, if the venting area is closed by a lightweight structure acting as a venting device. As can be shown using a diaphragm of glass material, the pressure release in such a case is even smaller.

5. Influence of venting areas in realistic train carriages

The influence of venting areas in realistic trains is investigated using a single train. While in the previous calculations the venting areas were always open and no venting device was present, in the following calculations with train carriages glass windows should work as venting devices. Before the pressure wave can be released, the venting devices must be ruptured. Therefore, the pressure has to reach a certain level in order to start opening the glass device.

5.1 Train carriage

A symmetric train carriage (two planes of symmetry) is used; only one fourth is modelled (Fig. 4) when the explosive is positioned at its centre. The train carriage has a full length of 25.2 m, a full width of 3.0 m and a height of 3.0 m. Its model is built of a frame structure on which an aluminium sheet of a thickness of 4 mm is welded. The windows are built either from annealed glass with a thickness of 6 mm in order to examine the influence of their failure. The floor of the train is treated as rigid. The doors are built from the same glass as the windows and have a size of 2.2 x 1.3 m.

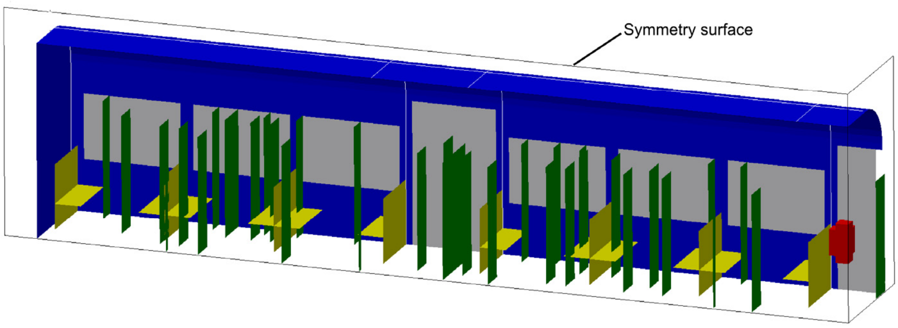

Fig. 4 Geometry of the train carriage (one fourth): structure (blue), windows (grey), seats (yellow), passengers (green) and balloon (red)

Previous investigations (Larcher et al. [16]) have shown that the presence of passengers has a significant influence on the behaviour of pressure waves. Therefore, 150 passengers have been modelled (rather crudely representing their masses and stiffness) and are distributed uniformly along the carriage. The passengers are not connected to the floor since the friction in case of an air blast wave is negligible.

Seats are also modelled roughly, using simplified structures of aluminium with thickness of 4 mm, length of 0.4 m, and height of 1 m. In all calculations the possibility of contact between the train and the passengers is neglected in order to speed up the computation time. The influence of such contact on the behaviour of the air blast wave is estimated to be very small.

The probability of death (risk of death) is calculated for all fluid elements following the procedure given by Larcher et al. [16]. The risk is determined with empirical formulas available in the literature involving the impulse and the peak pressure of each fluid element. Since these main parameters of an air blast wave are employed in order to determine the risk, the value of the risk can also be used as a mean of assessing the effectiveness of venting areas. Fig. 5 presents the resulting window failures for a change of 2 kg TNT and the risk of death through a vertical cross-section. At a certain time, all windows are failed. In addition, for comparison purposes the corresponding cases with no windows have been run: in these calculations the same material is used for the windows as for the structure in order to avoid failure of the windows (closed, “unbreakable” windows). The differences between the two calculations are very small. The risk in case of closed windows is slightly higher, but not significantly. The failing windows don't reduce the risk of death enough to be considered as effective venting devices.

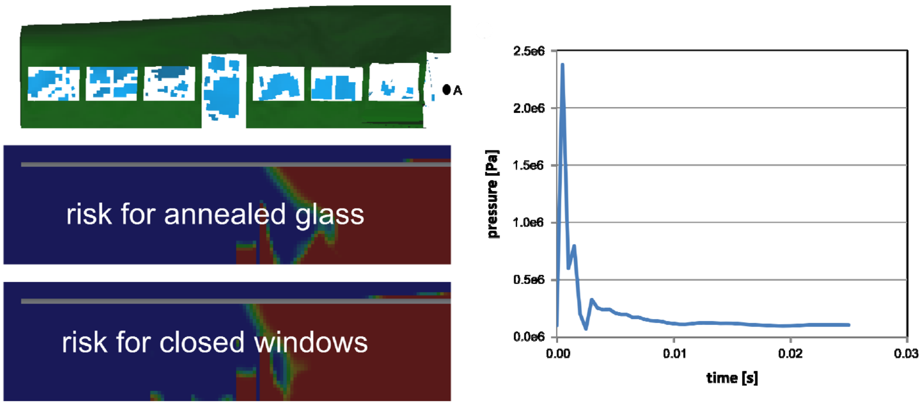

Fig. 5 Failure of the windows, risk map for train with windows and train with closed, “unbreakable” windows, pressure-time curve near the window inside the train (point A)

6. Conclusions

It is well known from the literature that venting areas are a practical and efficient measure for mitigating explosion effects and for reducing the vulnerability of structures exposed to the risk of gas or dust explosions.

This work investigated the influence of venting areas exposed to blast waves from high explosives (solid charges) for structures of the size of a train carriage and for charges between 2 and 25 kg TNT equivalent. Is has been shown that their influence is noticeable but relatively small for a free venting area, even for large sizes of the opening. For a realistic opening of 3 x 1 m, for example, the reduction for a small charge (2 kg TNT) is about 18 % but for a bigger charge (25 kg TNT) it is only about 8 %. The mitigation of the blast wave becomes even smaller when the wave is one dimensional, due to channelling effects.

For real train carriages it is mainly the windows that could play the role of a venting area. Calculations have shown that the reduction of death risk inside the carriage is not significant, when these additional fragile structures are used. Due to inertia, these structures react too slowly to provide a significant mitigation of risk in case of a very rapid explosion such as that resulting from solid charges.

Therefore, frangible elements used for venting areas cannot be considered as a particularly effective means of mitigating internal high explosion effects. However, it can never be wrong to include them anyway in trains because, besides a partial release of the pressure, they may also serve as emergency exits in case of an accident.

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