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Risk assessment of the fatality due to explosion in land mass transport infrastructure by fast transient dynamic analysis

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ABSTRACT

Terrorist attacks in New York have shocked the world community showing clearly the vulnerability of air transport in such events. However, the terrorist attacks in Madrid and London showed that land mass transport infrastructure is equally vulnerable in case of similar attacks. The fact that there has not been substantial investment in the domain of risk analysis and evaluation of the possible effects due to such events in land mass transportation infrastructure leaves large room for new developments that could eventually fill this gap. In the present work using the finite element code EUROPLEXUS there has been a large effort to perform a complete study of the land mass infrastructure in case of explosion events. This study includes a train station, a metro station and a metro carriage providing thus valuable simulation data for a variety of different situations. For the analysis of these structures it has been necessary to apply a laser scanning method for the acquisition of geometrical data, to improve the simulation capabilities of EUROPLEXUS by adding failure capabilities for specific finite elements, to implement new material models (e.g. glass), and to add new modules that achieve data post-processing for the calculation of fatal and non-fatal injuries risk. The aforementioned improvements are explained in the present work with emphasis in the newly developed risk analysis features of EUROPLEXUS.

1. Introduction

Simulation of explosion events has been reported in the literature especially in latest years. The development of finite element codes and computer hardware can now cope with the high requirements of such simulations in terms of computational power. During the last decades the European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre (JRC) has been involved in the development of EUROPLEXUS, a fast transient analysis finite element code specifically suited for the simulation of severe loading effects in major infrastructures of diverse nature. A large number of publications and case studies in the literature are focused in the industrial domain and especially in the process industries where phenomena related to gas explosions and in general accidents draw significant attention among the members of this community.

The interpretation of results of such analyses is a cumbersome procedure that in many cases does not provide a valuable insight for administrative staff. These analyses tend to be highly technical and thus do not help substantially decision makers and stakeholders to realize the real danger for human beings and eventually to take the necessary preventive measures. The modeling of such events is done implementing a number of different methods—experimental procedures in many cases are out of question. Particularly interesting is the work of Khan and Amyotte [1] that performed the modeling of the accident that occurred in BP Texas City refinery unit. Three different approaches have been implemented in order to model the effects of the explosion. In the first approach, a pentane vapor cloud in a semi-confined area is considered which is exploded upon its contact with the ignition source. The in-house software named SCOPE has been used for the evaluation of this scenario. In the second approach the vapor cloud explosion is followed by a jet fire. Again analytical based models have been used. Finally the third approach includes two different scenarios, one for a quasi open area explosion and one for a confined explosion that considers a highly congested space. The phenomenological models of approach 1 and 2 require an intense calculation effort whereas the overpressure model implemented in approach 3 is much simpler.

A similar case has been reported by Bubbico and Marchini [2] where an liquified petroleum gas (LPG) tank filling accident is considered. In this study, the main target was to investigate the

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series of phenomena that happen during an accidental release of LPG and the corresponding consequences when ignition occurs. However, the analysis was mainly based on analytical thermodynamical models for the propagation of the fire ball in the air. Although it is not absolutely comparable to the case shown in the present work, it lies within the category of events that lead to large infrastructure destruction and/or loss of human lives. However, the dominant destructive phenomenon is the high energy release that is expressed through radiation flux in the air.

The work of Feldgun et al. [3] where the simulation of internal blast loading in a buried line tunnel is shown seems to be closer to the scope of the present work. The study is particularly interesting considering that the detonation of the charge, wave propagation, soil–structure dynamic interaction as well as multiple gap opening/closure and wave propagation in the surrounding medium are considered. However, the geometrical modeling has taken place using axisymmetric representation. Although numerical schemes are applied, these are not pure finite element analysis techniques but more numerical solutions (Runge–Kutta) of the analytical formulation.

Particularly interesting for the present study is the work of Sklavounos and Rigas [4] that have studied ways of mitigating the effects of explosions inside tunnels. A number of vents have been conceptualized in order to relieve the internal pressure. Parameters such as the number of vents, their diameter as well as their angle with respect to the tunnel are evaluated in order to estimate their influence in the mitigation of the explosion effects. However, a quantitative risk approach that could be used as a measure of the effectiveness of this solution has not been implemented. A similar work (in terms of goals to be achieved) is presented also by van der Berg and Weerheijm [5] that studied the efficiency of open spaces in tunnel systems in mitigating explosion effects that occur from LPG pressure vessel rupture.

The lack of quantitative risk analysis for such devastating events has been partially tackled by Yet Pole and Cheng [6]. Instead of using traditional dispersion models that are based on a number of assumptions, a CFD analysis has been conducted for the dispersion of flammable chemical agents that explode upon ignition. Based on these calculations a risk analysis takes place using statistical data for human presence in certain areas as well as the number of events during a year. The overpressure and overpressure impulse values are used as death risk parameters.

A more complete approach on the risk analysis has been presented by Ferradás et al. [7]. Instead of using only the overpressure and the corresponding impulse to calculate death risk, three different lethal risk categories are identified: the death risk due to head impact, the death risk due to whole body impact and finally the death risk due to lung hemorrhage. Additionally, eardrum rupture is tackled as well. Although not being a lethal injury, this is very important for the rest of the lifetime for someone who witnesses an explosion event from a close range.

Concluding this short review, it becomes evident that focus has been so far given either on the analysis of the explosion phenomenon by using numerical tools, or on the risk consequences by means, however, of very simple tools in order to have in the best case scenario a good estimation of the overpressure and of the impulse. In the present work there is a significant effort to bridge this gap by presenting a complete set of tools starting from the explicit finite element analysis for explosions and introducing a relatively complete risk analysis based on the post-processing of the analysis results for the overpressure and the corresponding impulse. In the next sections the developments that took place in EUROPLEXUS in order to be able to provide reliable solution results for explosion events are presented as well as the risk module that is able to calculate both lethal and non-lethal risk probabilities. The analysis has taken place for a number of scenarios namely a train carriage, a train station and a metro line. The results are particularly encouraging and show the necessity for further developments of tools that can translate engineering values into something more meaningful for decision makers and administrators in the domain of public transport.

2. Numerical investigations

2.1. Introduction

Numerical simulations are performed with EUROPLEXUS (see [8]), an explicit finite element code for non-linear dynamic analysis. This finite element tool is a joint development between the French Commissariat à l' Énergie Atomique (CEA) and the Joint Research Centre (JRC). Among the main advantages of EUROPLEXUS over similar software tools is its ability to handle complex fluid structure interaction problems.

2.2. Air blast wave

We start with the description of the various available ways of modeling the explosion. In fact, these define the type of geometrical discretization and lead to vastly different calculation schemes that in some cases may require excessive calculation time.

- The *solid TNT model* describes the mechanical behavior 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 is therefore very expensive in terms of computational time. If the mesh is not fine enough, the pressure and the impulse values are unrealistically small.
- Model with a *bursting balloon* (see Larcher [9]). The pressure–time function resulting from a compressed balloon can match the curve of an air blast law. The amount of initial compression can be calibrated with the impulse. The computational time is smaller compared to the one for the solid TNT model.
- *Mapping* algorithm. A 1D calculation is used until the air blast wave reaches the closest structural surface. Then the values of the density, energy, velocity, and pressure are mapped onto a 3D mesh. The calculation time should be much shorter than for the solid TNT model. Alternatively, analytical values for the pressure and the particle velocity can be mapped to the fluid elements.
- *Load–time function*. Only the structure is modeled. It is loaded by a load–time function built with the pressure–time function presented previously. The calculation is relatively inexpensive. The method cannot represent reflections, shadowing and channelling.

In the present work the bursting balloon technique has been used. Among the advantages of this approach is that the explosive is in fact a zone of highly compressed fluid and thus it is possible to assign the bursting balloon properties to the corresponding portion of the fluid mesh.

2.3. Geometrical modeling and finite element discretization

The geometry of the structures that are evaluated in the present work has been acquired using a laser scanning technique. A laser scanner was placed at various spots inside or outside these structures and the whole geometry was stored as a cloud of points. The passage from the point cloud to continuous geometrical primitives, like surfaces and volumes, has been performed using the JRC-RECONSTRUCTOR [10], an in-house developed tool. The elaboration of the finite element model is performed in various steps. Using the point cloud data it is possible to construct the geometry in

AUTOCAD [11] using geometric entities (lines, surfaces, volumes). The geometric model is exported through IGES file format to SAMCEF FIELD [12] in order to perform the finite element discretization. However, in that step only the envelope of the structure is discretized.

The explosive is modeled using a sphere which is meshed starting from the mesh of a perfect icosahedron [13] with the diameter being exactly the one that – depending on the density of the solid charge – represents the desired mass of explosive. Using an iterative procedure that is built in CAST3M [14] (an in-house tool also developed in collaboration with CEA) the surface mesh of the explosive is further refined. The obtained result is a closed shell structure mesh that incorporates the explosive surface mesh. Using the built-in capabilities of SAMCEF FIELD it is possible to create the fluid mesh between the outer shell and the explosive surface using tetrahedral elements.

The element size of the solid explosive has to be relatively small and in many cases is much smaller than the one used for the structural parts. Thus in zones where the explosive is close to the coarse structural mesh, highly distorted fluid tetrahedral elements are created. One solution could be the complete remeshing of the whole structure with smaller elements, but this would lead to a huge increase of the computational time. Instead, a local remeshing is carried out in order to avoid this problem and at the same time to avoid the development of highly distorted elements. This procedure is based on a projection algorithm that inspects the size of the explosive elements projected over the structural mesh. Based on a certain criterion it is then decided whether the structural mesh has to be refined locally by splitting the existing triangular surface elements in half. This procedure has been implemented in CAST3M.

The simulation of the explosion takes place using an Eulerian formulation for the explosive and for the fluid representing the air. Apart from the nature of the problem, the choice for an Eulerian formulation is based on the fact that the risk analysis requires the calculation of pressure and impulse of the air inside the volume of the structure at specific points and thus any Lagrangian movement of the finite element grid would lead to erroneous results. In Fig. 1 the three structures that are evaluated are depicted. The train station is composed from two principal domains that are connected through a short corridor. The waiting area is about 50 m × 30 m and the corridor about 120 m × 10 m. The metro station is about 130 m × 10 m and finally the train carriage is 25 m × 3 m. Due to the large number of elements used in the discretization and in order to avoid visualization problems, the outlines of the elements are omitted.

2.4. Material failure models

In EUROPLEXUS different material models exist for large strain analysis of metals up to failure. The structural elements of the station as well as the metro line carriage are modeled as metallic (steel/aluminum) elements with rather ductile characteristics. The material model used is based on isotropic hardening formulation in order to describe the elastoplastic behavior, however failure is also added. Strain rate effects are not considered. In the work of Lemaitre [15] one can find arguments for the inclusion or not of strain rate effects for metals.

2.5. Laminated glass

The laminated glass used in the metro line carriage and in the metro station is modeled by using layered elements with a special failure criterion (see also Müller and Wagner [16]). After the failure of the glass, the stresses are set to 0.0 Pa if the strains are positive (traction). The material can still react to compression. The failure behavior of the interlayer of the laminated glass cannot be described with a coarse element mesh, which is needed due to the large dimensions of the complete train numerical model. A displacement criterion is used instead for the failure of the interlayer.

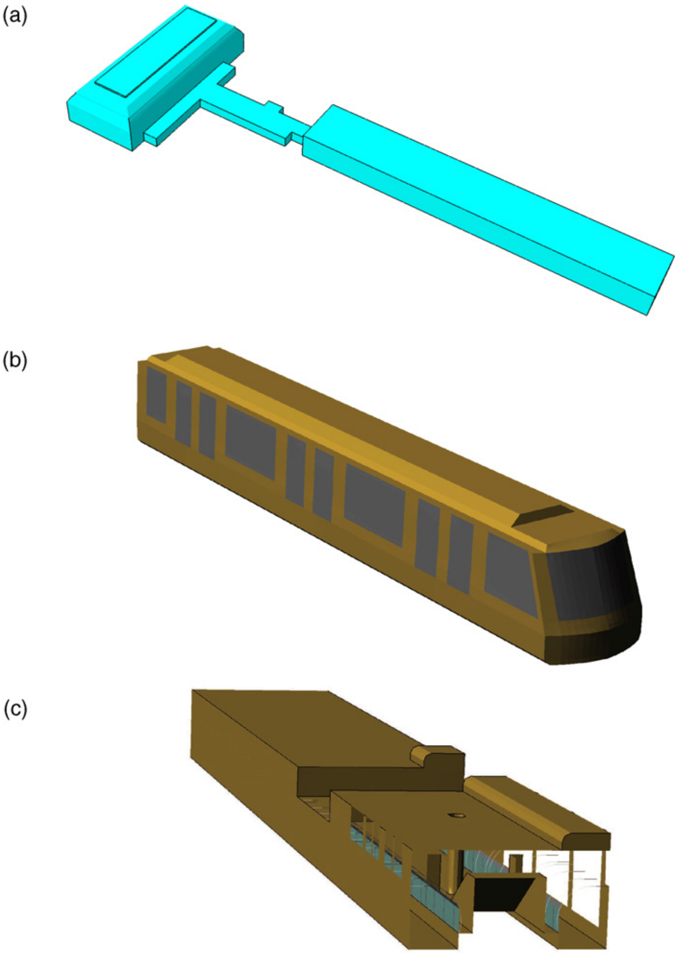


Fig. 1. (a) Train station model, (b) metro line carriage model and (c) metro line station model.

2.6. Explosive material

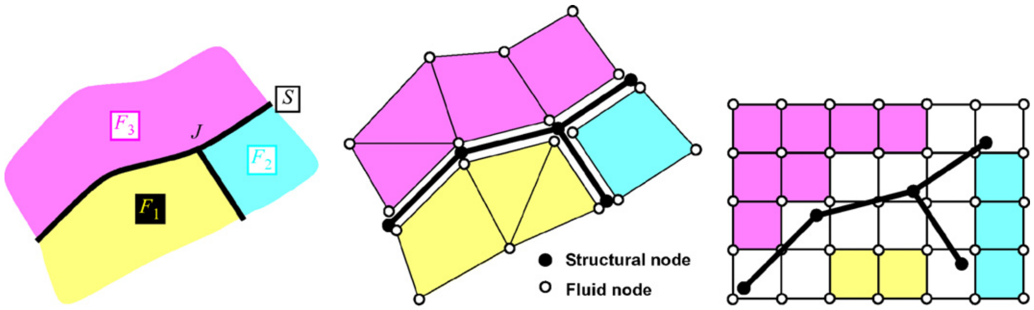
The explosive has been modeled implementing the JWL formulation. This model includes the parameter of the detonation speed and the detonation coordinates. In several analyses where the bursting balloon is used, although the explosive is not modeled, the initial higher pressure for the domain of the fluid representing the balloon is provided through a calibration based on the JWL model. The model is described mathematically by Eq. (1).

$$P = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_1 V}\right)e^{-R_2 V} + \omega\rho e_{\mathrm{int}} \qquad (1)$$

where ρ is the current density, e_{int} is the current internal energy per unit mass and V is the ratio ρ_{sol}/ρ where ρ_{sol} is the density of the solid explosive, while A, B, R_1, R_2 and ω are model parameters. The pressure calculated from this model is used in order to derive the initial overpressure and density of the explosive bubble. Further analysis of these parameters exceeds the scope of this paper.

2.7. Fluid–structure interaction

As mentioned, EUROPLEXUS contains quite powerful automatic FSI algorithms, see Fig. 2a and b, developed and validated over the last decades by application to industrial problems (Casadei et al.



(a) Continuous FS domain (b) Discretized (FSA model) (c) Discretized (new model)

Fig. 2. Two alternative approaches for the modeling of a FSI problem. (a) Continuous FS domain, (b) discretized (FSA model) and (c) discretized (new model).

[18–20]). However, the simulation of terrorist attacks up to possible complete failure and fragmentation of some structural components introduces a new challenge, for which a new dedicated FSI model has been developed along the following lines (see Casadei [21]). The fluid and structural sub-domains are topologically uncoupled (independent). Each sub-domain is discretized separately and the two meshes are simply superposed, see Fig. 2c. At each time instant of the computation, a topological search is performed (by suitable optimized algorithms) of the fluid nodes which are reasonably close to the structure. Along the fluid–structure interfaces the continuity of normal velocity and normal stress (before failure) are imposed.

2.8. Risk analysis module

The formulation of the fatal injury risk for the occupants of a train station in case of an explosion event is based on the work of Ferradás et al. [7]. In general two different parameters can be considered responsible for the development of lethal injuries: the impulse of the explosion and the overpressure. However, the latter is distinguished into side-on overpressure and effective overpressure. The difference between the two exists only when the position of the human body with respect to the pressure wave is considered. However, this information is not available in the present study and for this reason there is no distinction between the two and the absolute value of the overpressure is used. This of course overestimates the potential damage on the human body with respect to the calculations of Ferradás et al. [7]. The equations used are:

$$\begin{aligned} P_{\max}(x,y,z) &= \max\|P(x,y,z,t)-P_{\mathrm{ref}}\| \\ I(x,y,z) &= \int_0^t (P(x,y,z,t)-P_{\mathrm{ref}})dt \end{aligned} \qquad (2)$$

where $P_{\max}(x, y, z)$, is the maximum overpressure that occurs at each point inside the volume under investigation, $I(x, y, z)$ is the pressure impulse and finally P_{ref} is the reference pressure before the explosion occurs. Based on these values the “Personnel Casualty Probit Functions” are evaluated. Three different causes of death are recognized and represented by the following probit functions:

$$\begin{aligned} Y_1 &= 5-8.49\ln\left(\frac{2430}{P_{\max}}+\frac{4\times10^8}{P_{\max}I}\right) \\ Y_2 &= 5-2.44\ln\left(\frac{7380}{P_{\max}}+\frac{1.3\times10^9}{P_{\max}I}\right) \\ Y_3 &= -77.1+6.91\ln P_{\max} \end{aligned} \qquad (3)$$

Y_1 is the death probit function due to displacement and head impact, Y_2 the one for displacement and whole body impact and finally Y_3 is the one for lung haemorrhage. These are the three main fatality causes in case of explosion. However, in the present work the eardrum rupture probability is also considered which, although not being fatal, is very important for the rest of the lifetime of the victims that have witnessed from a closed range such an event. This is described by the following probit function:

$$Y_4(x,y,z) = -12.6+1.524\ln(P_{\max}(x,y,z)) \qquad (4)$$

Pressure and impulse in Eq. (2) are expressed in Pa and Pa s respectively. The personnel death percentage due to each of the previous mentioned causes is expressed by the following equation (see [6]):

$$P_{\mathrm{Di}}(x,y,z) = \frac{1}{(2\pi)^{1/2}}\int_{-\infty}^{Y_i(x,y,z)} e^{(-u^2/2)}\,du \qquad (5)$$

Finally the individual risk (*IR*) per incident is calculated by Eq. (6), assuming that distribution of persons inside the volume being investigated is uniform. If data on the actual distribution of persons are available, the corresponding weighting factor can be of course assigned.

$$IR = \min\left[\sum_{i=1}^{3} P_{Di}(x,y,z),\ 1.0\right] \qquad (6)$$

The formulation presented in the previous paragraphs has been implemented in EUROPLEXUS. In the next paragraphs the corresponding results are presented. The pressure inside the volume that is being examined remains constant until the pressure wave arrives. For that initial time period the individual risk is set to zero.

3. Analysis

3.1. Introduction

The analysis of the behavior of the previously mentioned structures is performed based on an Eulerian formulation without considering the structural part, except for the train carriage analysis. The air is modeled using the JWL material model from EUROPLEXUS (the equation of state is shown in the previous paragrapsh) with the appropriate material properties. All the analyses have been conducted using a 64-bit PC under Windows XP with 4 Intel Xeon CPUs 5110 running at 1.6 GHz clock rate with 32 GB of

Table 1
Material properties for air and explosive.

Property	Symbol	Unit	Air	Explosive
Density	ρ_0	kg/m^3	1.3	1630
Internal energy	e_{int}	J/kg	2.198e5	4.52e6
JWL coefficient	A	Pa	3.738e11	3.738e11
JWL coefficient	B	Pa	3.749e9	3.749e9
JWL coefficient	R_1	–	4.15	4.15
JWL coefficient	R_2	–	0.9	0.9
Specific heat ratio	γ	–	1.35	1.35
Detonation speed	D	m/s	–	6930

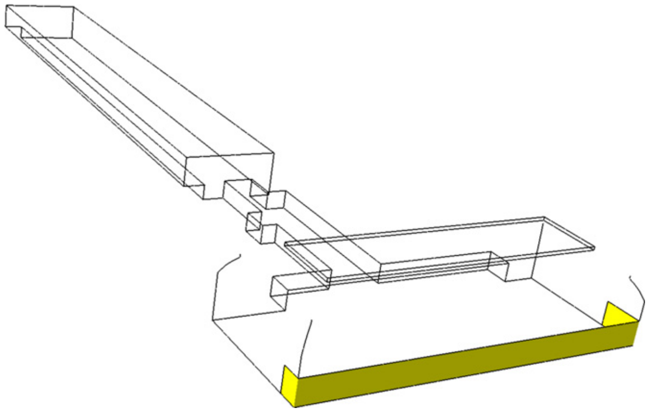


Fig. 3. Absorbing boundary (in yellow) simulating the opening of the train station. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

RAM. In Table 1 the material properties for air are presented as well as some data for the explosive formulation.

3.2. *Train station*

In order to extract both eardrum and death risk values due to an explosion in the train station an Eulerian formulation has been used for the fluid mesh. Internal structural elements are not considered. The size and the geometry of the structure dictates a behavior that is closer to an open space explosion rather than to a confined one and thus features like chairs, etc. are not expected to play an important role. The fluid mesh is conforming to the external envelope mesh on which the appropriate boundary conditions are set. Areas of the station that are communicating with the external environment are modeled using an absorbing boundary condition, as shown in Fig. 3.

The model consists of 391,214 tetrahedral elements (FL34) and 861 absorbing boundary elements (CL3I). The amount of explosive used is 16.3 kg and is meshed using 1302 tetrahedral elements. The explosive is represented by a bubble that has an initial radius of 0.25 m and initial density of 197.6 kg/m^3 (see previous definitions for the explosive modeling). The analysis simulated a period of 250 ms and the CPU analysis time has been 46,431 s. In Fig. 4 the geometry and the position of the explosive are shown in the middle of the main hall.

The risk analysis performed for this structure reveals the areas for which death risk and eardrum risk is high. The results obtained at the end of the simulation time are shown in Fig. 5 for the death risk and in Fig. 6 for the eardrum rupture risk. From these figures it is evident that for a large part of the station the death risk is very high as well as the eardrum rupture risk (this is quasi 100%). However, the sudden change of geometry between the main part of the station and the corridor seems to play a very important role in reducing the devastating effects of the explosion. At this part of the structure the death risk is highly reduced providing a relatively safer area for the occupants of the station, although the eardrum rupture risk is still very high. It is also worth noticing spots at corners where enhanced values of death risk are encountered due to reflection phenomena.

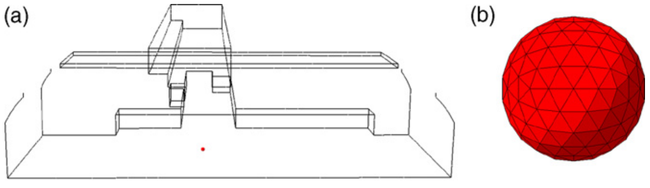


Fig. 4. (a) Position of the explosive and (b) explosive mesh.

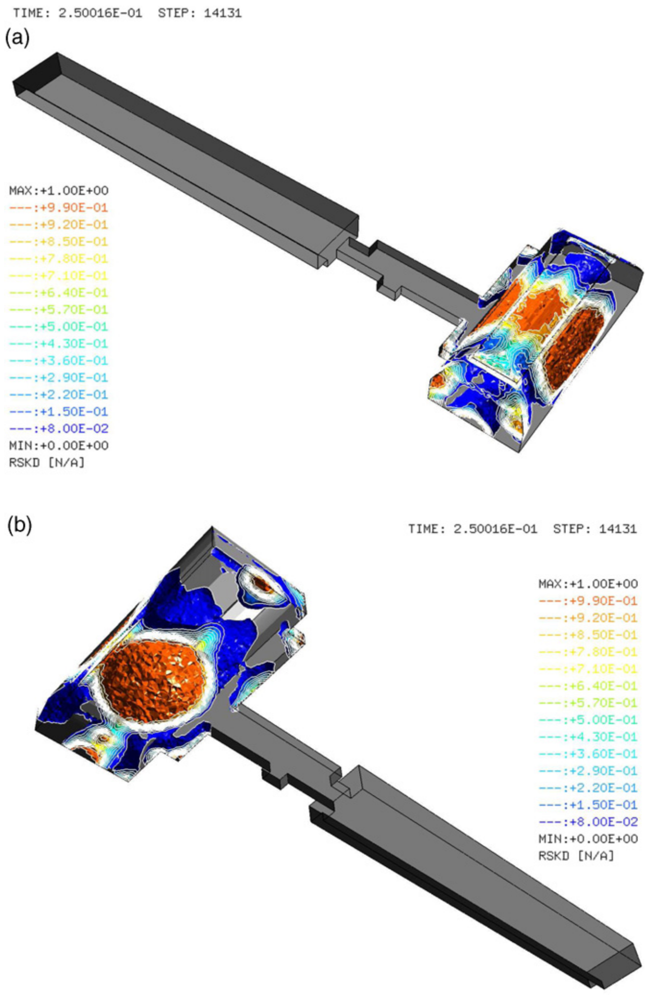


Fig. 5. Death risk values (a) upper view and (b) bottom view.

3.3. *Metro line*

A similar analysis was also performed for a metro line station. This structure can be considered to perform similarly to a shock tube due to its large length (130 m) and relatively narrow cross-section. This may enhance the effect of the explosion considering that the attenuation of the pressure wave is limited. The air consists of 1,116,455 tetrahedral elements (the same type as for the station analysis) from which 9564 elements represent the explosive bubble. However, the explosive mesh in this analysis is very detailed leading to a very small time step and as a consequence to a very long calculation time that was 1,584,729 s (18.2 days). The explosive mass is again 16.3 kg of TNT equivalent. The bubble diameter is 0.5 m and the initial density is 185.8 kg/m^3. The position of the explosive bubble inside the metro station is shown in Fig. 7, approximately in the middle of the long central platform.

Death risk and eardrum rupture risk values are calculated showing clearly that at positions where the geometry changes sharply there is a high attenuation of death risk. This is not the case for eardrum rupture due to the amount of the explosive which is by far sufficient to provoke such damage over the whole domain. Death risk and eardrum rupture risk values are shown in Figs. 8 and 9 respectively.

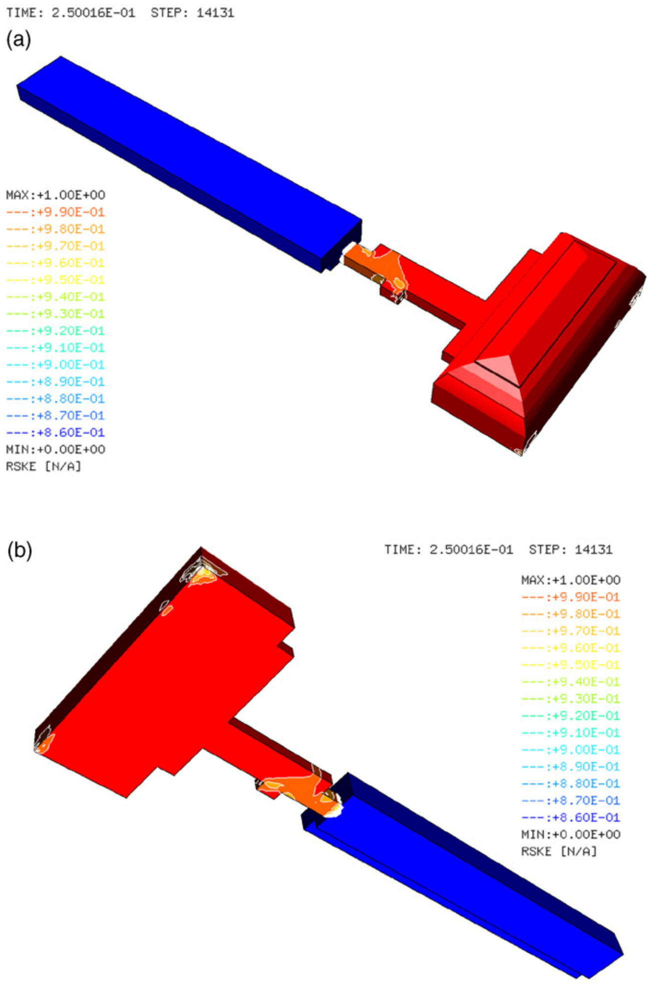


Fig. 6. Eardrum risk values (a) upper view and (b) bottom view.

3.4. Metro line carriage

The metro line carriage analysis differs with respect to the rest of the analyses presented above. The meshing of the air is not conforming but it is elaborated, as explained in the previous paragraphs, independently from the structure. The reason for elaborating this kind of meshing is that the metro carriage is highly deformable and thus the destruction of structural elements should be taken into account otherwise the analysis would be unrealistic. Considering failure of elements would immediately imply that the analysis would have stopped at exactly this point if a conforming fluid mesh had been chosen. The train carriage analysis can thus

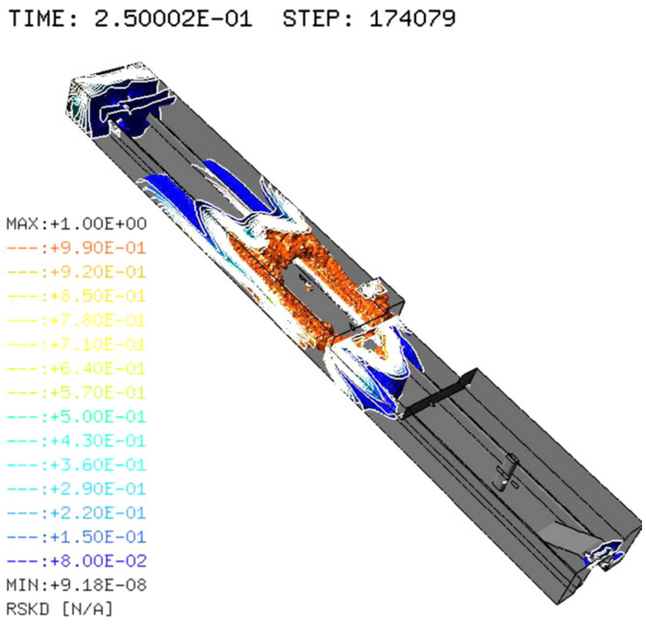


Fig. 8. Death risk value.

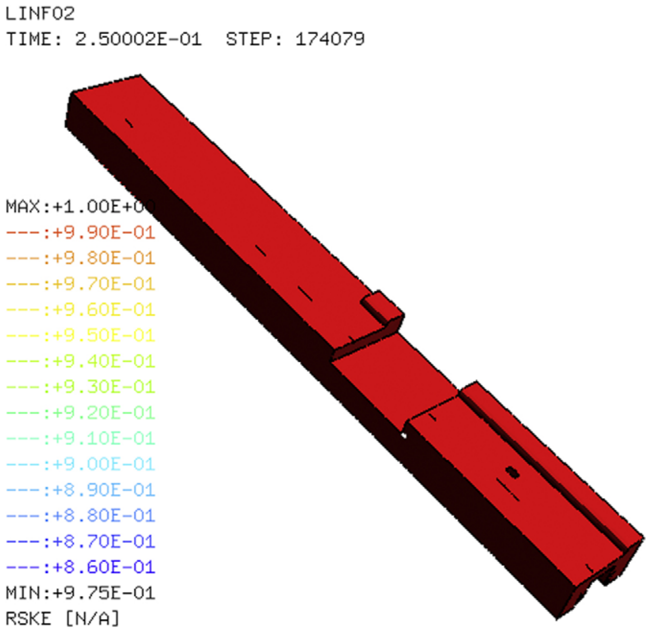


Fig. 9. Eardrum risk value.

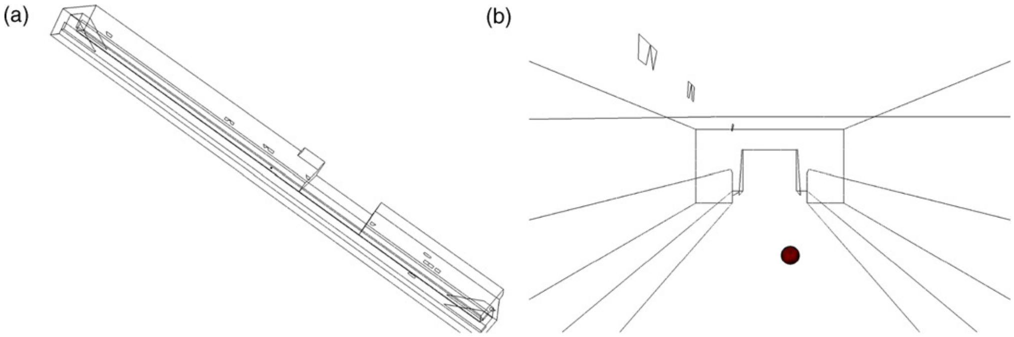


Fig. 7. (a) Metro line geometry and (b) position of the explosive.

Table 2
Material properties for structure and glass for the metro line carriage.

Property	Symbol	Unit	Structure	Glass	Interlayer
Density	ρ_0	kg/m^3	2700	2500	1100
Young modulus	E	Pa	7e10	7e10	2.2e8
Poisson ratio	ν		0.3	0.23	0.495
Material model	–	–	Von Mises	Linear elastic	Von Mises
Elasticity limit	E_y	Pa	200e6	–	11e6

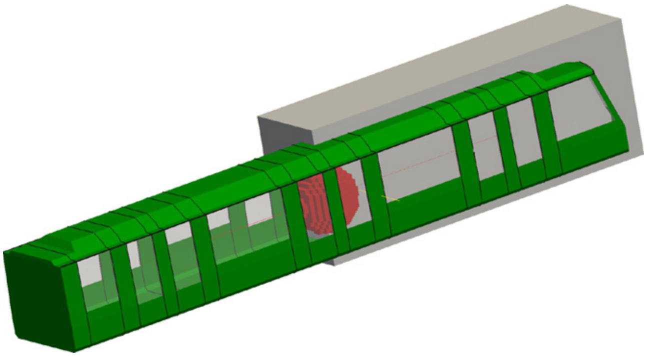


Fig. 10. Structural, fluid and explosive mesh of the metro line carriage.

be considered as a typical case of a fluid–structure interaction (FSI) analysis.

The carriage is built using 45,788 triangular shell elements (DKT3, Kirchhoff formulation), 2254 beam elements and the fluid uses a non-conforming mesh with 192,000 elements which is in fact a block of fluid elements that encompasses the whole structure. The thickness of the aluminum sheet (side-walls and roof of carriage), welded on the beams (IPE80) is set to 3 mm. The laminated glass, which is used for the windows, has a thickness of 8 mm. The charge is modeled using the bubble with a radius of 0.7 m. The material properties used are presented in Table 2, while the train and the corresponding fluid and explosive meshes are shown in Fig. 10.

In Fig. 11 the death and eardrum rupture risk are almost 100% for all points inside the train. The explosive charge chosen (10 kg of TNT equivalent) is obviously high enough to kill all carriage occupants. This result is particularly interesting since this amount of explosive can be easily carried in a backpack. Such results can help decision makers and administrative staff because they can better appreciate the real dangers from such attacks and take the right measures to prevent as much as possible such events. However, additional studies (see [9]) have shown that the use of internal separation walls can largely mitigate the explosion effects in the carriage.

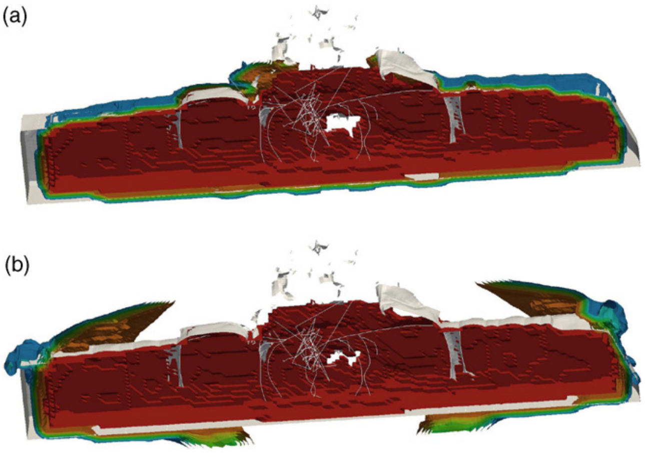


Fig. 11. Risk values. (a) Death risk and (b) eardrum rupture risk.

4. Conclusions

In the present work the finite element modeling of a train station, metro line station and metro carriage have been elaborated and the simulation of a possible terrorist attack has been conducted using EUROPLEXUS. A number of additional developments have been demonstrated showing the theoretical elements behind the simulation with focus on the newly developed risk analysis capabilities of the aforementioned software. Based on the long experience of ELSA Unit in the domain of transient analysis using numerical methods the next step towards integration of purely technical analysis with administrative and security issues is demonstrated using risk analysis as the appropriate interface. It is clear that risk analysis can be a very useful tool for decision makers, administrative staff, stakeholders, etc. in order to appreciate the risks and eventually the financial cost of certain events. Especially for non-specialized technical personnel, risk analysis is the right way in order to transform highly technical engineering results into something more meaningful and easier to grasp. In the domain of terrorist attacks this is translated into quantitative results about the death and heavy injuries risk. The present work has clearly demonstrated the link between pure engineering analysis results and risk values. Although risk analysis studies for devastating events have been performed in the past, the particularity and innovative aspect of the present work is that the risk analysis is coupled with the explicit finite element analysis software EUROPLEXUS and thus purely technical data are directly transformed into isosurfaces of death and eardrum rupture risk values. The analysis of a metro station, train station and metro carriage implementing different techniques (conforming and non-conforming mesh for the fluid) showed clearly that the same explosive mass can be devastating for certain structures while for others the survivability is much higher. This is obvious, however it complicates the development of control points that give access to different kind of structures (metro station and metro carriage) since each structure requires a different level of security. In any case, such results can represent a valuable tool for decision makers in order to adapt to the ever increasing threat of terrorist attacks in mass transport infrastructure.

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