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Assessment of explosion effects in railway stations

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ABSTRACT: Numerical simulation tools have been developed suitable for the assessment of the physical vulnerabilities of rail transport infrastructures to explosion loads, mainly due to terrorist bomb attacks. The source term, the air medium and the structure are properly modeled using the computational framework of the explicit finite element code Europlexus. Several new features are added to the code. A case study of a rail station has been conducted, whose geometry has been reconstructed using a laser scanning technique. For several bombing scenarios the structural response is reliably determined, and through appropriate probit functions, the associated risk of human injuries has also been calculated.

1 INTRODUCTION

Land mass transport systems usually have an open architecture and widely dispersed assets, and measures like those used in aviation are seldom applicable. The recent terrorist attacks in Madrid, London, and Moscow have shown that rail transport constitutes a high-impact target, and have exposed its vulnerability. While security measures will always be taken for preventing and foiling such attacks, improved architectural design may also significantly contribute towards mitigating the effects of explosions. Thus reliable simulation tools for assessing structural vulnerabilities would be necessary.

Several investigations have been performed in the direction of assessing the risk in railway systems. Loukaitou-Sideris et al. (2006) compare the measures taken by four cities to reduce the risk in their metro lines and stations. As reported, increased surveillance and patrolling are mainly pursued, while strategies, such as the Crime Prevention Through Environmental Design (CPTED), start gaining acceptance and are incorporated into new station planning and design.

The number of deaths and injuries of the terrorist attack of March 2004 in Madrid is reported by Peral-Gutierrez et al. (2004). A comparison of the injuries from detonations in confined structures and in open-air is presented by Leibovici et al. (1996) showing that the mortality rate in confined spaces is higher. The reason is that the pressure of an air blast wave decays much slower inside a long tube-like train or metro tunnel than in open space. Therefore, both the response of the air medium inside the structure and the failure of the structure itself have to be considered for the determination of the risk in case of a blast.

Empirical formulas are available (Baker et al. 1983), for the calculation of the risk inside relatively simple rectangular structures. The maximum pressure and impulse of an air blast wave can also be used to determine the risk with more accuracy. These values can be taken from experimental and analytical formulas describing the development of air blast waves inside complex geometries, as shown by Smith & Rose (2006) for urban areas, where it is also postulated that shielding and channelling have to be considered in city streets. Experimental data for explosions between buildings are given for example by Smith et al. (1992). Bogosian et al. (1999) investigate the damage of complex buildings using a pressure-time function to describe the air blast wave, which is applied to multiple degree of freedom models, whose stiffness is determined using detailed finite element calculations.

More sophisticated Computational Fluid Dynamics (CFD) codes have also been employed for the determination of the behaviour of air inside complex structures. Remennikov & Rose (2005) present the results of such CFD calculations for complex city geometries, computing the loads to which buildings are subjected and determining their failure behaviour. Similar are also the methodologies of Langdon & Schleyer (2005), Luccioni et al. (2006) and Löhner et al. (2004). The interaction of air blast waves with buildings in combination with a damage criterion is shown by Luccioni et al. (2004). For urban environments, Van den Berg & Weerheijm (2006) investigate the blast in underground road tunnels with roof openings as venting areas.

Along the same direction, the blast analysis inside partially confined, large spaces, like those of a train station, is attempted in this work. The code Europlexus is used, which has the feature of efficiently treating fast fluid-structure interaction phenomena.

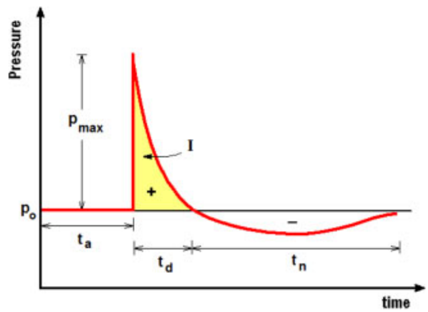

Figure 1. Idealised form of a pressure-time function.

2 AIR BLAST WAVES

In the present study, air blast waves result from the detonation of a solid high-explosive charge (a TNT equivalent). 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 1.

As seen, the main characteristics of a free-field air blast are: the arrival time t_a (it includes the detonation time itself), the peak overpressure p_{max} over the reference pressure p_0 (atmospheric pressure), the duration of the positive phase t_d, the minimum pressure, and the duration of the negative phase t_n. The positive impulse I is the integral of the overpressure curve over the positive phase t_d.

The form of the pressure wave of Figure 1 can be greatly altered by the morphology of the medium encountered along its propagation. For instance, incident peak pressure can be substantially increased if the wave is reflected by a rigid obstacle. 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 happens between or inside buildings. Obviously these arguments make clear that in confined environments simplified models that relate the peak overpressure to the distance from the explosion can lead to grossly erroneous estimates.

It is widely accepted to describe the positive phase of the free-field air blast wave by the modified Friedlander equation (Baker 1973), where the pressure p at time t can be expressed as:

$$p(t) = p_0 + p_{max\left(1-\frac{t}{t_d}\right)}^{-b\frac{t}{t_d}} \tag{1}$$

The decay mode of the pressure with time depends on the constant b. All parameters of Equation 1 can be taken from appropriate diagrams and equations, e.g. Baker (1973), Kingery (1984), software CONWEP (1991), the US Army Manual TM5-855-1 (1986), for free field conditions and spherical and hemi-spherical charge shapes.

3 NUMERICAL INVESTIGATIONS

3.1 *Computational environment*

Numerical simulations are performed within Europlexus (2010), an explicit finite element code for non-linear dynamic analysis. This finite element tool has been jointly developed by the French Commissariat a l'Energie Atomique (CEA) and the Joint Research Centre (JRC). Among the main advantages of Europlexus over similar software is its ability to handle complex fluid-structure interaction problems.

3.2 *Air blast wave loading*

There are available various ways of modeling explosions and blast loading, which, in turn, define also the type of geometrical discretization. Three of them have been considered in this study.

- The solid TNT model. It 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 is therefore very expensive in terms of computation time.
- The bursting balloon model (Larcher et al. 2010). The pressure-time function resulting from the release of a compressed balloon can match the air blast history. The amount of initial compression can be calibrated with the impulse. The computational time is smaller compared to that of the solid TNT model.
- Load-time function. Only the structure is modeled and loaded by an appropriately scaled pressure-time function, as presented previously in Figure 1. The calculation is relatively inexpensive. Clearly, since the air is neglected, the method cannot represent reflections, shadowing and channelling.

In the present work the bursting balloon technique has been preferably used. The advantages of this approach lie in the fact that for big structures and spaces (e.g. a rail station) larger dimension elements can be used, and thus the computation time becomes reasonable, while at the same time both the structure and the fluid are modelled.

3.3 *Geometrical modeling and discretization*

A relatively old typical train station has been selected for evaluation. The geometry of its structures has been acquired using a 3D laser scanning technique. A laser scanner was placed at various positions inside and outside these structures and the whole geometry was stored as a cloud of points. These points were next transformed to continuous geometrical primitives, like surfaces and volumes, using the JRC-RECONSTRUCTOR (Boström et al., 2008), an in-house developed tool, and a final elaboration of these data yielded the finite element model for the structure, depicted in Figure 2. It is composed of two principal domains which are connected through a short, narrow passage. The dimensions of the waiting hall area are

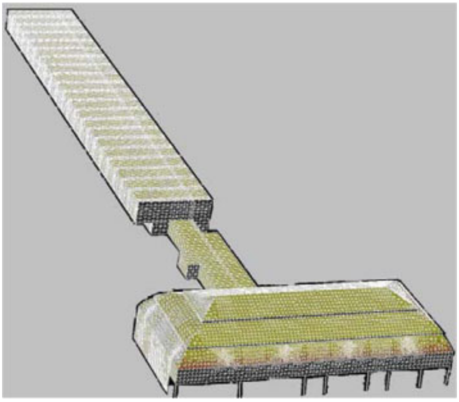

Figure 2. Geometrical finite element model of structure consisting of a main hall and a long corridor.

about $50 \times 30 \times 12$ m and those of the long corridor about $100 \times 10 \times 8$ m.

As mentioned above, for representing a certain TNT quantity (while the JWL law has also been tried) the bursting balloon model has mainly been used. The air inside this balloon behaves as a perfect gas, and the diameter and internal energy (or initial pressure) of the balloon are properly chosen so as to generate a far-field blast impulse equivalent to that produced by the TNT charge under consideration.

The full simulation of the explosion is performed using an Eulerian formulation for the explosive and for the fluid representing the air. Apart from the nature of the problem, this choice is justified by the fact that the subsequent risk analysis requires the calculation of pressure and impulse of the air inside the volume of the structure.

3.4 *Fluid-Structure interaction*

Appropriate modelling of fluid-structure interaction (FSI) phenomena has been a central issue in the numerical simulations considered in this work, as Europlexus contains quite powerful automatic FSI algorithms. However, the simulation of terrorist attacks up to possible complete failure and fragmentation of some structural components introduces a new issue, for which a novel dedicated FSI model has been developed (Casadei 2008, Giannopoulos 2010). The fluid and structural sub-domains are topologically uncoupled (independent). Each sub-domain is discretized separately and the two meshes are simply superposed. 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, and appropriate FSI coupling conditions are imposed.

4 RISK ANALYSIS MODULE

The formulation of human injuries risk is based on the work of González Ferradás et al. (2008), Yet-Pole (2008) and Mannan (2005). It uses the peak overpressure p_{max} (Pa) and the positive impulse I (Pa · s) calculated inside each fluid finite element in order to determine the probability of eardrum rupture and the probability of death.

Three different causes of death are considered through the following probit functions:

$$Y_1 = 5 - 8.49\, ln\left(\frac{2430}{p_{max}} + \frac{4\times10^8}{p_{max} I}\right) \quad (2)$$

$$Y_2 = 5 - 2.44\, ln\left(\frac{7380}{p_{max}} + \frac{1.3\times10^9}{p_{max} I}\right) \quad (3)$$

$$Y_3 = 5 - 5.74\, ln\left(\frac{4.2\times10^5}{p_{max}} + \frac{1694}{I}\right) \quad (4)$$

Y_1 is the death probit function due to head impact, Y_2 is the one for whole body impact and Y_3 is the one for lung haemorrhage. A probit function for body impact by flying debris has not yet been implemented. The probit function of eardrum rupture Y_4 is described through the equation:

$$Y_4 = -12.6 + 1.524\, ln(p_{max}\square) \quad (5)$$

The probability of occurrence R (or the percentage of the affected population) of the corresponding injury is next determined for each of the above probit functions using Equation 6 (González Ferradás et al. 2008), which is a very good approximation of the relevant cumulative normal distribution, $i = 1{,}4$:

$$R_i = -3.25Y_i^3 + 48.76Y_i^2 - 206.6Y_i + 270.35 \quad (6)$$

Plausible influence and interaction of the different causes of death is treated in a simplified manner by considering the maximum of the relevant three probabilities. Clearly, since pressure-time histories are needed, a full FSI calculation is required for such kind of analysis.

5 SIMULATIONS

5.1 *Introduction*

Several material models exist in Europlexus for large strain analysis of metals up to failure. The structural elements of the station (columns, roof trusses) are modeled as metallic (steel) elements with rather ductile characteristics. The material model used is based on isotropic hardening formulation in order to describe the elastoplastic behaviour, however failure is also added. Strain rate effects are not considered. The floor is rigid.

A brittle material model and element erosion techniques are used for the glass tiles of the roof. The laminated glass used in the metro station is modelled by using layered elements with a special failure criterion. After the failure of the glass, the stresses are set to zero if the strains are positive (traction), but the material can still react to compression. The failure behaviour of the interlayer of the laminated glass requires a fine meshing. Since a rather coarse element mesh is implemented (due to the large dimensions of the complete numerical model), a displacement criterion is used instead for the failure of the interlayer.

5.2 *Case study scenario*

Several scenarios with different quantities of explosive have been run. Two cases for the same explosive charge of approximately 250 kg TNT equivalent, placed on the floor at the center of the main hall, are presented in Figures 3 and 4. Figure 3 is based on the results of the pressure-time function approach, where only the structure can be considered. Figure 4 is based on the results of the more sophisticated bursting balloon approach, where both the fluid and the structure are included.

It is observed that both approaches manage to reproduce the main characteristics of the expected structural behaviour, such as large deformations, failure of the roof, fragmentation, projectile formation and motion. The deformation and damage pattern of the structure at the selected four time instants is quite similar. This is also true for the whole response period and for the picture of the final damage. Thus it can be concluded that for structures directly exposed to an air blast the pressure-time functions can provide a good and inexpensive way for calculating their behaviour. However, this approach is not sufficient if the blast waves arrive indirectly to the structure (reflections, channeling), or if information about the pressure field is required.

As described above, in the comprehensive simulation, with the bursting balloon approach, an Eulerian formulation has been used for the fluid mesh. 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. The complete model consists of about 4000000 fluid brick elements, 175000 absorbing boundary elements and 55000 elements for the structure.

The risk analysis performed for this structure reveals the areas for which the human injury risk is high. The results obtained at the end of the simulation time are shown for the three-dimensional space in Figure 5 for the death risk and in Figure 6 for the eardrum rupture risk, respectively. From these figures it is evident that for a large part of the main hall the death risk is very high, and the eardrum rupture risk is almost 100% everywhere. However, the abrupt change of geometry between the main hall of the station and the corridor appears to play a very important role in reducing the devastating effects of the explosion. At this section of the structure the death risk is substantially reduced, providing a relatively safe area for the occupants of the station under this scenario. The eardrum rupture risk remains still very high along a large part of the corridor. For the main hall (Fig. 5) it is also worth noticing spots at corners where enhanced values of death risk are encountered due to wave reflection phenomena.

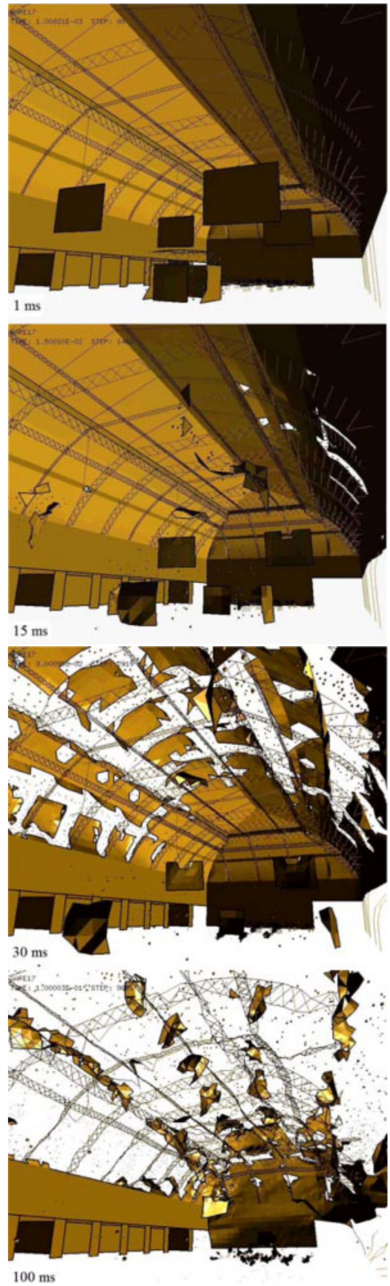

Figure 3. Structural response at four time instants using the pressure-time functions approach.

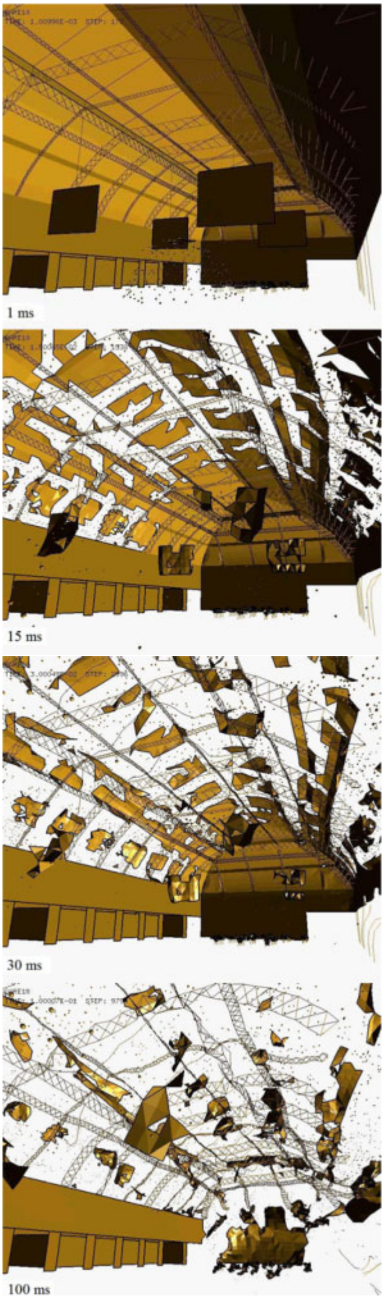

Figure 4. Structural response at four time instants using the full fluid-structure interaction approach.

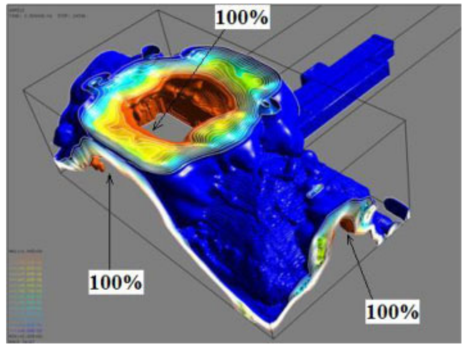

Figure 5. Top view of death risk contours for the main hall and corridor.

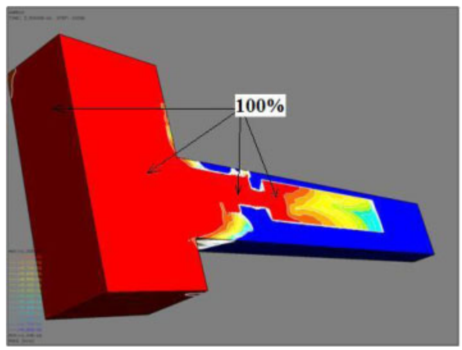

Figure 6. Bottom view of eardrum rupture risk contours for the main hall and corridor.

6 CONCLUSIONS

In the present work the finite element modeling of a large structure representing a train station has been elaborated and the numerical simulation of a terrorist bomb attack scenario has been conducted. Attention is drawn to the fact that several simplifying assumptions have been made with regards to material and structural properties.

The Europlexus code used has proven to be an efficient and robust computation platform. Several modelling approaches have been presented and implemented in the code. It has been found that the bursting balloon model demonstrates definite advantages when explosion effects in such large spaces are simulated. At the same time it allows a comprehensive study to be carried out by including both the fluid and the structure.

A number of additional simulation features have been introduced and their theoretical basis explained, with focus on the newly developed human injuries risk analysis module. It is thought that such risk analysis capabilities can be a useful tool for decision makers, transport operators and stakeholders etc. in order for them to assess the risks of certain events and perform cost-benefit analyses of contemplated interventions.

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