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Numerical and reduced-scale experimental investigation of blast wave shape in underground transportation infrastructure

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ABSTRACT

When an explosion occurs in a tunnel, the study of the blast wave quickly becomes complicated, owing to the multiple propagation patterns of the blast wave (incident wave, regular and Mach reflections) and to the geometrical conditions. Considering this problem, two patterns can be revealed. Near the explosive, the well-known free-field pressure wave can be observed. After multiple reflections on the tunnel's walls, this overpressure behaves like a one-dimensional (1D) wave. One aim of this paper is to determine the position of this transition spherical-to-planar wave propagation in a tunnel using both numerical and reduced-scale experiments, and thereby validate the dedicated law established in a previous work.

For this purpose, a detonation of TNT in a tunnel with a cross-section of up to 55 m^2 is considered. Results show good agreement between the numerical simulations and experiments. The transition zone between the three-dimensional (3D) and the 1D wave is well detected. An application to a simplified subway station is also investigated which shows that significant planar waves can be transmitted to the neighboring stations via the junction tunnels.

1. Introduction

In urban areas, many tunnels and covered ways can be found, built for road and rail traffic. These geometrical configurations can be considered as tunnels of various lengths and cross sections. As hazardous materials or explosive devices may transit in these areas, the risk of accidents due to the explosion of reactive materials must be considered. Explosions might come from solid detonating materials, gas or flammable gas–air mixtures. The effects of such explosions, resulting from accidents or deliberate acts, are increased by the semi-confined configuration of the tunnels. The front-wave shape is strongly dependent on the geometry and the overpressures can produce severe injuries or lethal issues.

Blast waves have been studied by many authors, in the free-field, and in confined or semi-confined areas. In this case, two patterns can be found: one in a free field, before any perturbing reflection, the other one including multiple reflections. For the first propagation pattern, in the free-field case, different authors have proposed suitable laws, allowing the overpressure peak to be determined on the basis of the radial distance and the quantity of energy released by solid explosive (Baker et al., 1983; Brode, 1955). More recently, Chang and Young (2010) have given different expressions of the incident pressure wave depending on the explosive mass and the radial distance. In the case of flammable gas–air mixture detonations, Brossard et al. (1995) have proposed a polynomial fitting of the blast wave, including the incident angle and allowing

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the application times and the negative pressure for incident and reflected waves to be determined. The TM5 manual (TM5-1300, 1990) is useful in approaching the blast phenomena and their consequences on structures.

The second propagation pattern concerns confined or semi-confined explosions. The approach is more complex, and was mostly investigated by using numerical tools. Among others, numerical codes, such as AUTODYN (Zyskowski et al., 2004), LS-DYNA (He et al., 2011), EUROPLEXUS (Larcher et al., 2010), CONWEP (Rouquand, 2012) or self-developed CFD (computational fluid dynamics) codes as used by Benselama et al. (2009), require substantial computer resources to provide realistic simulations. In the different tunnel studies, many authors have focused on the mechanical effects of an explosion on the structure of the tunnels whereas a few have presented the behavior of the blast wave in the tunnel. Some of these studies include computations with obstacles and venting devices. For a semi-confined configuration, Ripley (2004) has discussed the small-scale modeling of explosive blasts in urban scenarios using both experiments and numerical simulations. Working specifically on tunnels, He et al. (2011) used LS-DYNA to study the mechanical behavior of subway stations made of concrete submitted to an explosion of 50 kg of TNT (trinitrotoluene). Buonsanti and Leonardi (2013) used a finite element method to describe the behavior of a tunnel submitted to the blast generated by the explosion of an LPG (liquefied petroleum gas) tank, coupling the thermal and mechanical aspects. Van den Berg and Weerheijm (2006) also computed the consequences of a pressure vessel exploding in a tunnel system with branched ducts for smoke evacuation. Larcher et al. (2010) studied venting protection systems in trains with explosions of up to 25 kg of TNT. Solomos et al. (2010) have computed the damage of an explosion of 250 kg of TNT in a railway station using a CFD method. Rigas and Sklavounos (2005) have also used a CFD method to simulate the pressure wave propagation in a small-scale branched tunnel. Computations may lead to good approaches and give a better knowledge of the phenomena with realistic representations.

Experimental works on tunnel explosions are hardly ever found in literature, as has already been outlined by some authors (Liu et al., 2008). The results of some full scale experiments can be found in the works of Forsén et al. (2012), who studied explosions in Swedish military tunnels, and in a report of the US army (Joachim-Charles, 1990). The METRO project (Ingason and Nilsson, 2012) is a recent and large collaborative project about tunnels, and in addition to smoke, fire and other problems, one part of this work is devoted to damage to underground transportation, including explosions occurring inside the trains. Using plastic explosive PE4, very close to the plastic explosive C4, the influence of rigid obstacles in small scale tunnels has been experimentally studied by Smith et al. (1998). To summarize the state of the art on this subject, experimental data on time-dependent pressures, arrival times in tunnels or subway stations and air-blast shape in tunnels due to an explosive device do not seem to be published often in the literature.

In a confined domain, before any reflection on obstacles, a blast wave propagates as in a free-field. In this phase, the blast wave is spherical and the maximum peak of overpressure can be described with a free-field decay law (Henrych, 1979). After reflection on the walls, the wave exhibits a different shape which can be predicted by a driven decay law dedicated to planar waves (Silvestrini et al., 2009). So, by knowing the transition zone between those two different propagation patterns, one can determine the incident overpressure at any location in the tunnel. This was investigated by Benselama et al. (2010), who proposed a suitable law to locate the transition zone issued from numerical simulations of the detonation of TNT in a tunnel. Benselama et al. (2010) also showed that planar waves can spread over long distances with small damping effects on the incident overpressures. So, the spatial evolution of the incident overpressure shows a less steep slope than in the spherical case.

In this paper, the proposed study is to determine this transition zone, by using both numerical simulations and reduced-scale experiments of the detonation of a flammable gas–air mixture in a tunnel. Finally, application to underground stations (metro) is proposed, where the objective consists in predicting whether a significant blast wave can be transmitted or not to a neighboring station via a junction tunnel.

2. Description of the numerical solver and the experimental method

2.1. *The numerical solver*

Blast wave propagation in air is governed by the unsteady Euler equations, which, in the present study, are solved by a home-made solver developed at the University of Valenciennes (Waymel et al., 2006; Benselama et al., 2009). The numerical method on which this software's solver is based, is an unstructured finite-volume cell-centered approach using the traditional upwind scheme and a two-stage explicit time integration technique, which gives an accuracy of the second-order in both space and time. In order to prevent numerical oscillations, which may occur in regions with strong gradients, the minmod limiter was used. The spatial discretization was performed with an automatic Cartesian grid generator (Deister et al., 2002).

2.2. *The experimental methodology*

2.2.1. *Scale models and similarity law*

In detonics, working on real scale structures is very expensive and the quantities of explosive used can be substantial. So, these full scale experiments often involve working in a restricted and secured area, due to the high levels of pressure produced, flying shrapnel and the use of sensitive explosive devices. An alternative experimental method consists in using reduced scale models, which allow experimental works to be safely performed in research laboratories. A previous work (Pennetier et al., 2004) presented the evaluation of the vulnerability of a vehicle facing the action of a landmine. This work was realized using a 1/10th scale model on which pressure and impulse fields were determined. Considering the Hopkinson similarity law, it is well established that for homothetic detonations, the whole history of the pressure field is identical for both the actual and reduced scale and the application times are multiplied by the scale ratio of the experiment (Kinney and Gilbert, 1962). The lengths must be within the scale factor. Consequently, the masses of the explosive, being the product of density and volume, have to be within the cubic root of the scale factor. This law has been verified, using propane–oxygen mixtures, with tests over a large range of flammable mixture volumes (1.6–510 m^3) (Brossard, 1982).