Blast wave on a parallelepipedic obstacle

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1. Introduction

In an industrial safety context, it is important to know the blast characteristics whenever an explosion occurs near a building. The problem arises from the impact of overpressure wave on structures that may be catastrophic under certain conditions. Overpressure histories as well as a series of parameters, namely the positive peak overpressure, the arrival time and the positive phase duration, are dependent on several data such as the charge type (gaseous or solid charge), the volume, and the location of the explosive charge (on the ground or at altitude).
Several works have been conducted on the properties of spherical blast waves into free air and reflected blasts on surfaces. The charge can be defined by a TNT charge (Kinney 1962, Baker & al 1983, Dewey 2004), or by a gaseous mixture (Brossard & al 1988). The TNT equivalency method of explosive sources makes it possible to express the energy release resulting from the detonation of a gas mixture in terms of TNT equivalent energy (Dewey, 2004). Application of the Hopkinson scaling law allows one to translate the adimensional laws at large scale: the amplitude of the pressure is the same for a large-scale structure; the times, impulses and distances are multiplicated by a factor k and the energy by k^3.
The purpose of this paper is to report the blast loading characteristics resulting from the detonation of a propane-oxygen stoichiometric mixture, and to validate the approach which consists in simulating TNT explosions at large scale by small scale experiments of gaseous explosions. Simulations are achieved by means of computational fluid dynamics (CFD). Here, a three-dimensional simulation of shock waves in free field and also in an obstructed terrain is implemented via the use of the CFD code Autodyn.

2. Experimental setup

The experimental investigation is achieved by means of small-scale experiments. The detonating gas (propane-oxygen stoichiometric mixture) is confined in a soap bubble (radius $0.03 \leq R_0 \leq 0.07$ m) on a large plane surface (length 1.80 m, width 1.20 m). The detonation is ignited by an exploding wire in the center of the hemispherical bubble. The pressure gauges (Kistler 603B) are distributed on the plane surface in front of the soap bubble with a radial distance r from the center of explosion Es ($0.07 \leq r \leq 0.7$ m). This experimental setup enables to observe the shock wave propagation in free field; it is then possible to study the pressure wave evolution in a flow field which is obstructed by a parallelepipedic PVC structure (Figure 1). Its length, width and height are 0.40 m, 0.18 m and 0.14 m respectively (Figure 2).

Figure 1. The PVC structure with the gauges and the experimental setup.

The different positions of the center of explosion in the plane of the surface are given in Figures 2 and 3. The angles $\theta_{xy} = 0°$ and $\theta_{xy} = 90°$ are defined with respect to the center of the parallelepipedic structure (Figure 2); $\theta_{xy} = 0°$ and $\theta_{xy} = 90°$ correspond respectively to the small face and the large face. Concerning the oblique reflections, another angle θ is defined so that the straight line (Δ) and the front face of the parallelepipedic structure are crossing at this angle θ (Figure 3).

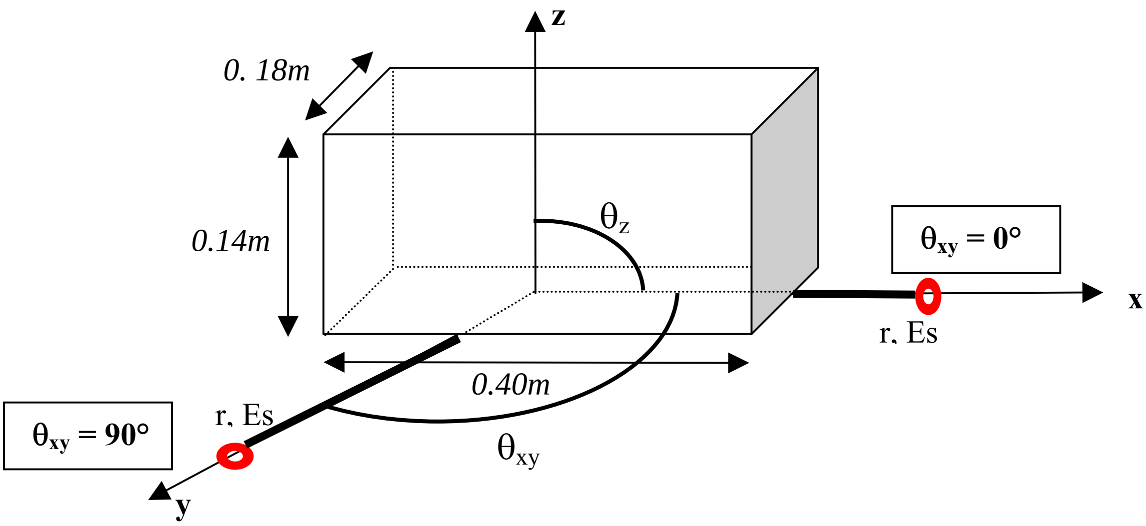


Figure 2. The experimental setup: the parallelepipedic structure and the different positions of the explosion source Es. (r = 0.10 – 0.15 – 0.20 cm, $\theta_z = 0°$).

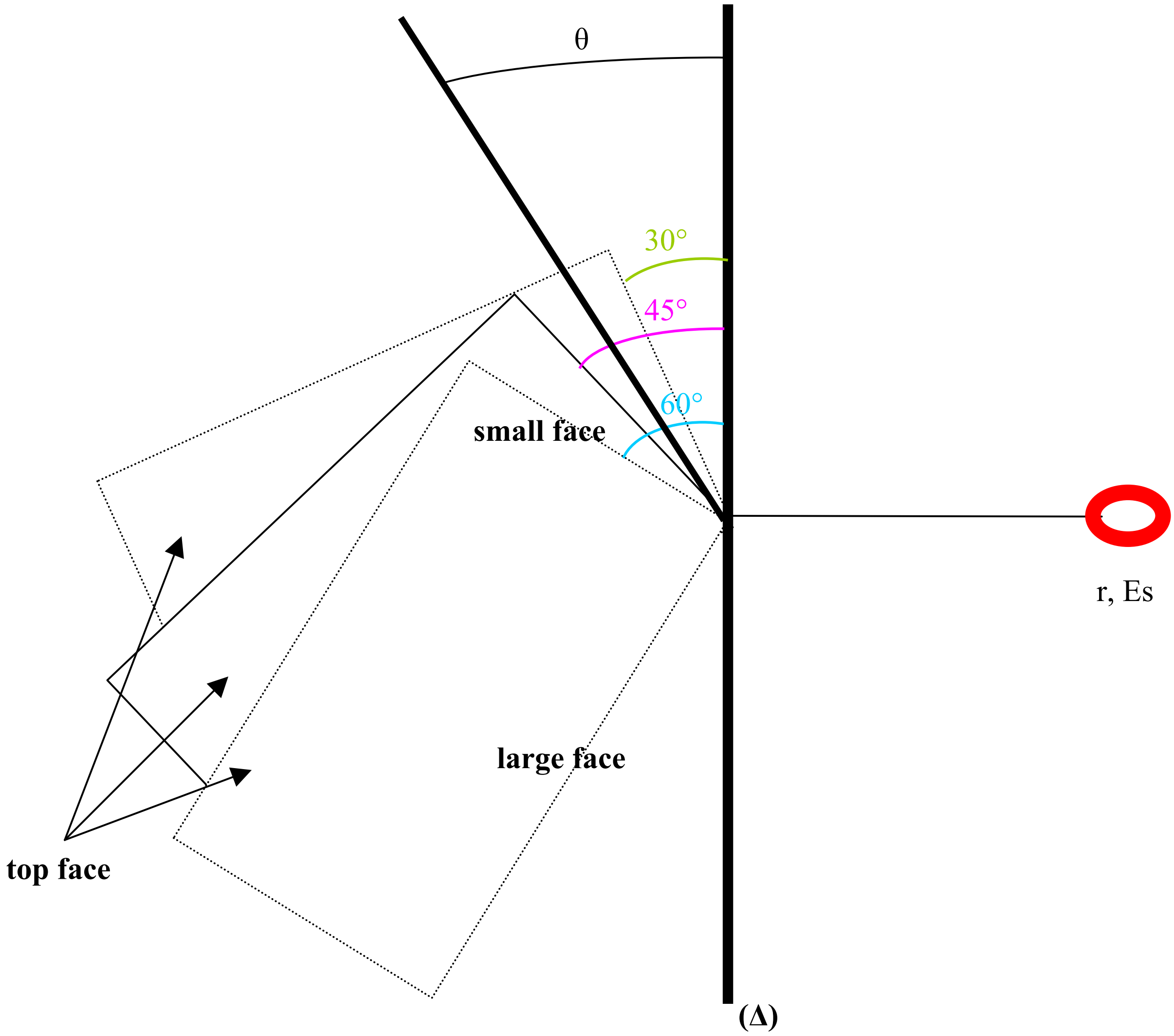
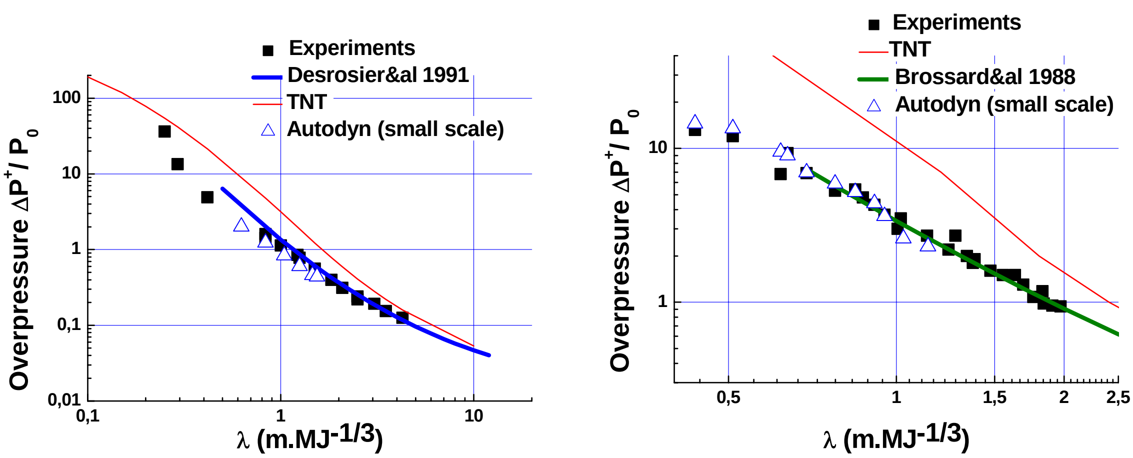


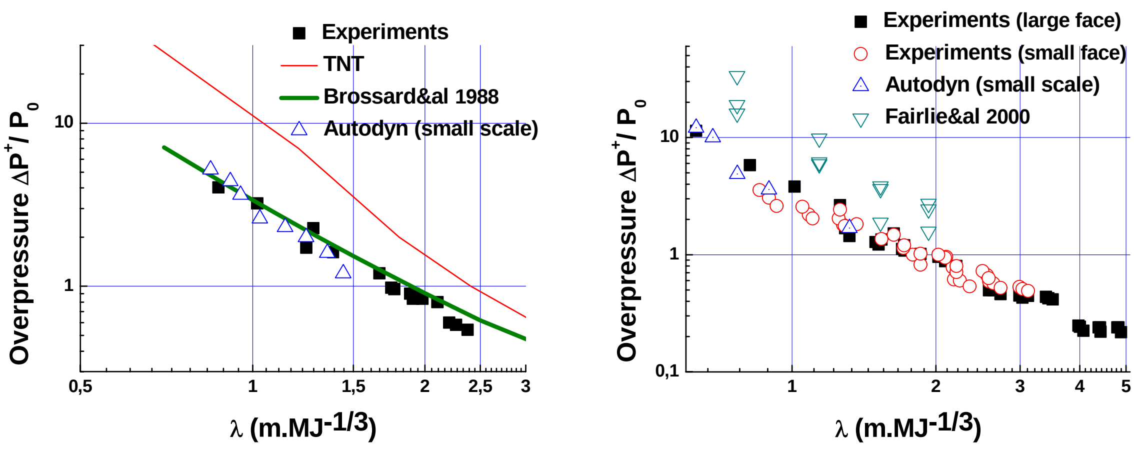
Figure 3. Top view of the parallelepipedic structure: position of the explosive charge defined with the angle θ.

3. Results expressed as function of radial reduced distance λ (m.MJ$^{-1/3}$)



(a) Incident overpressure

(b) Reflected overpressure, $\theta_{xy} = 0°$



(c) Reflected overpressure, $\theta_{xy} = 90°$ **(d)** Reflected overpressure, $\theta = 45°$

Figure 4. Blast loadings for experimental, numerical and analytic models: positive overpressure $\Delta P^+ / P_0$ as a function of reduced radial distance λ (m.MJ$^{-1/3}$).

When it is possible, the experimental data are compared (Figure 4) with the similar TNT curves (TM5-1300 1969; Baker & al. 1983). An energy equivalency can be deduced by comparison. The positive phases of the incident, reflected pressures and impulses are equivalent for TNT (energy E_{TNT}) and gaseous charges (E_{gas}) if the energies are related by $E_{gas} = 2.3\ E_{TNT}$. In this part, we present the overpressure results versus the radial reduced distance λ. Nevertheless, the other characteristics of pressure wave (positive impulse and time duration) have been also correlated as a function of λ with the same energy equivalency. (Table1). We have also reported on this curves other similar results from different authors (Brossard & al 1988, Fairlie & al 2000, Desrosier & al 1991) so that we can compare them with our results. In its paper, GE Fairlie (Fairlie & al 2000) presents experimental tests and simulations of the channelling of a blast wave down a street type geometry (Figure 5): a 13g TNT equivalent charge (10 times higher than our equivalent charge) is detonated at the center of this street geometry (the streets cross at right angles), so that we can compare its results with our results (Figure 4.d).

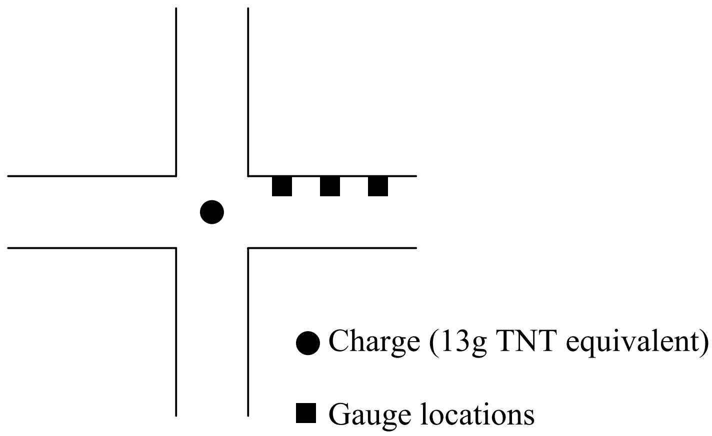


Figure 5. Plan of Cross-Roads Small Scale Experiment Geometry (Fairlie & al 2000)

In Brossard's paper (Brossard & al 1988), the purpose is to supply several useful curves as a function of the single parameter ($\lambda = R/E^{1/3}$) in the range 0.5 - 20, that are similar to those established for TNT: these results concern the detonation of gaseous charges and take into account both the positive and the negative phases of the pressure signal of the reflected wave on a plane surface. This pressure signal characterizes the dynamic load imposed by the blast wave. The pressure wave is generated by a hemispherical charge (radius $0.025 \leq R_0 \leq 0.12$ m) of stoichiometric propane-oxygen mixture confined in a soap bubble as in our experimental setup. The paper of C. Desrosier (Desrosier & al 1991) describes a quite similar experimental investigation at reduced scale. But the detonating gas, confined in a hemispherical charge (radius $0.05 \leq R_0 \leq 0.08$ m), is ignited at different locations inside the charge at ground level. The data are correlated as a function of the single parameter ($\lambda = R/E^{1/3}$) in the range 0.5 – 12.

All our experimental data are well-correlated as functions of the reduced radial distance λ in the range 0.29 – 4. (Figure 4). The least-squares second-order polynomials are then deduced for each series of data: first in free field, then for normal reflection with $\theta_{xy} = 0$ and 90°, and finally oblique reflection with $\theta = 45°$ (see Table 1).

The three characteristics of the incident and reflected pressure signals are defined as follows:

- $\mathbf{\Delta P^+ / P_0}$ = peak overpressure of positive phase;
- $\mathbf{I^+/E^{1/3}}$ = impulse of positive phase;
- $\mathbf{t^+/E^{1/3}}$ = duration of positive phase.

$$\ln\left(\frac{\Delta P^+}{P_0}\right) = a + b(\ln\lambda) + c(\ln\lambda)^2 \text{, and } \ln\left(\frac{Y^+}{\sqrt[3]{E}}\right) = A + B(\ln\lambda) + C(\ln\lambda)^2 \quad \text{with } Y = I^+ \text{ or } Y = t^+$$

	Free field $0.29 \leq \lambda\ (m.MJ^{-1/3}) \leq 4.27$	**θ_{xy} = 0 and 90°** $0.43 \leq \lambda\ (m.MJ^{-1/3}) \leq 1.97$	**θ = 45°** $0.63 \leq \lambda\ (m.MJ^{-1/3}) \leq 4.88$
Positive overpressure $\Delta P^+ / P_0$	a = 0.0884 b = -1.7631 c = 0.16428	a = 1.2001 b = -2.025 c = 0.18	a = 1.1411 b = -1.909 c = 0.1464
Positive impulse $I^+/E^{1/3}$ (bar.ms.MJ$^{-1/3}$)	A = -1.1936 B = -0.864 C = 0.19386	A = 0.0646 B = -1.496 C = -0.11397	A = -0.5989 B = -0.855 C = -0.02982
Positive phase duration $t^+/E^{1/3}$ (ms.MJ$^{-1/3}$)	A = 0.0955 B = 0.1335 C = 0.324	A = 0.1183 B = 0.2313 C = 0.3199	A = -0.4599 B = 1.03 C = -0.29764

Table 1. Characteristics of incident and reflected pressure waves: least-squares polynomials.

4. Results expressed as function of impact angle $\frac{\tau.R_0}{X}$ (°)

In this second approach, the three parameters of the blast wave generated by the detonating vapour cloud are well-correlated as functions of another parameter, $\frac{\tau.R_0}{X}$. R_0(m) is the radius of the hemispherical gaseous charge, τ(°) the angle formed by the gauge (Figure 6), the explosion source and the ground and X(m) the height from the ground to the gauge.

As in the first approach (section 3), the purpose is to provide the researcher with a practical and simple methodology for predicting the dynamics loads on the mechanical structure. In both cases, the data are correlated and fitted by least-square second-order polynomials (Figure 7). The advantage of this method is that:

- at any point of the two faces directly exposed to the explosion,
- whatever the chemical energy release E,
- whatever the position of the explosion source Es,

the pressure history can be quantified in terms of positive overpressure, positive impulse and positive duration phase.

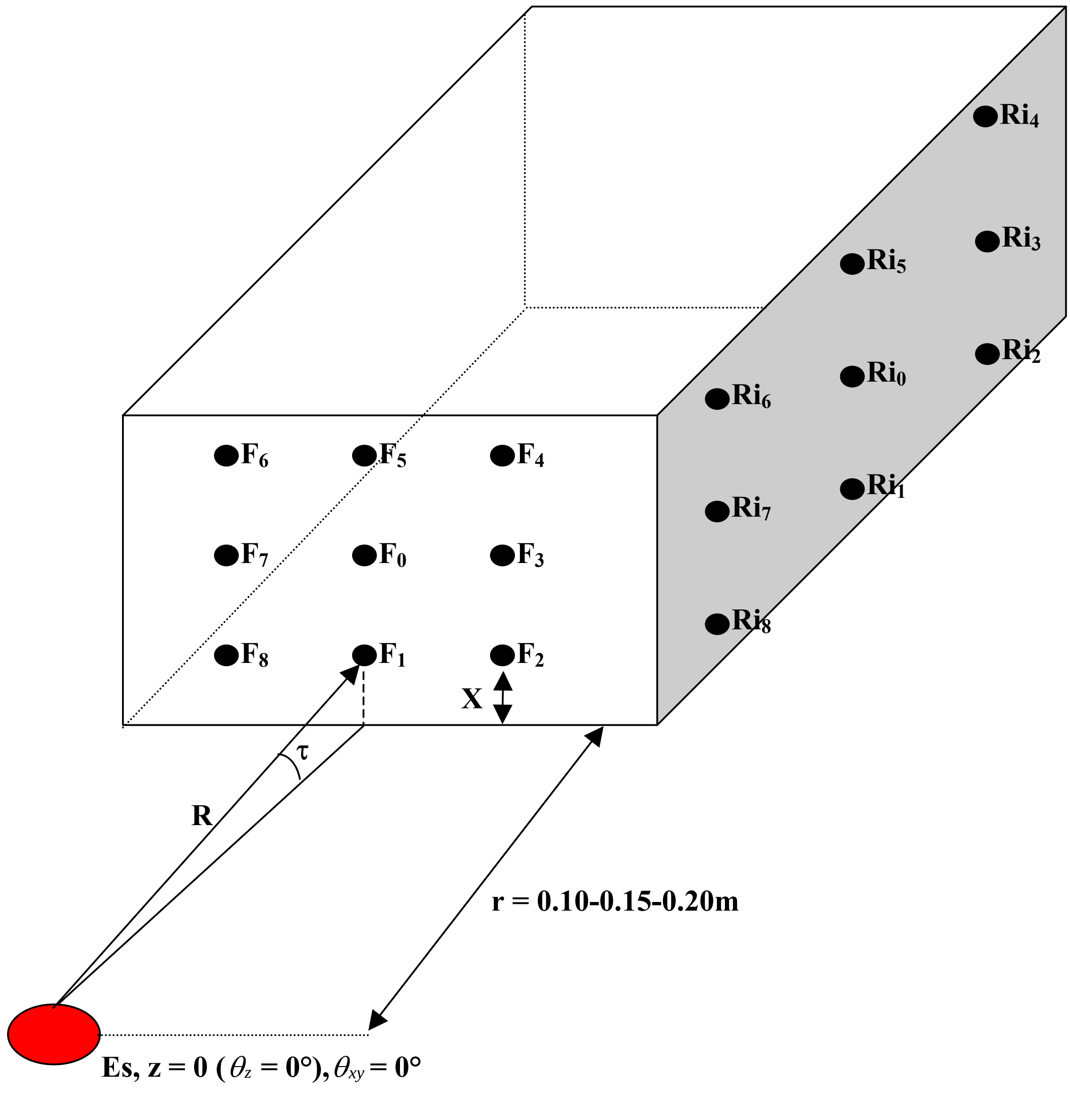
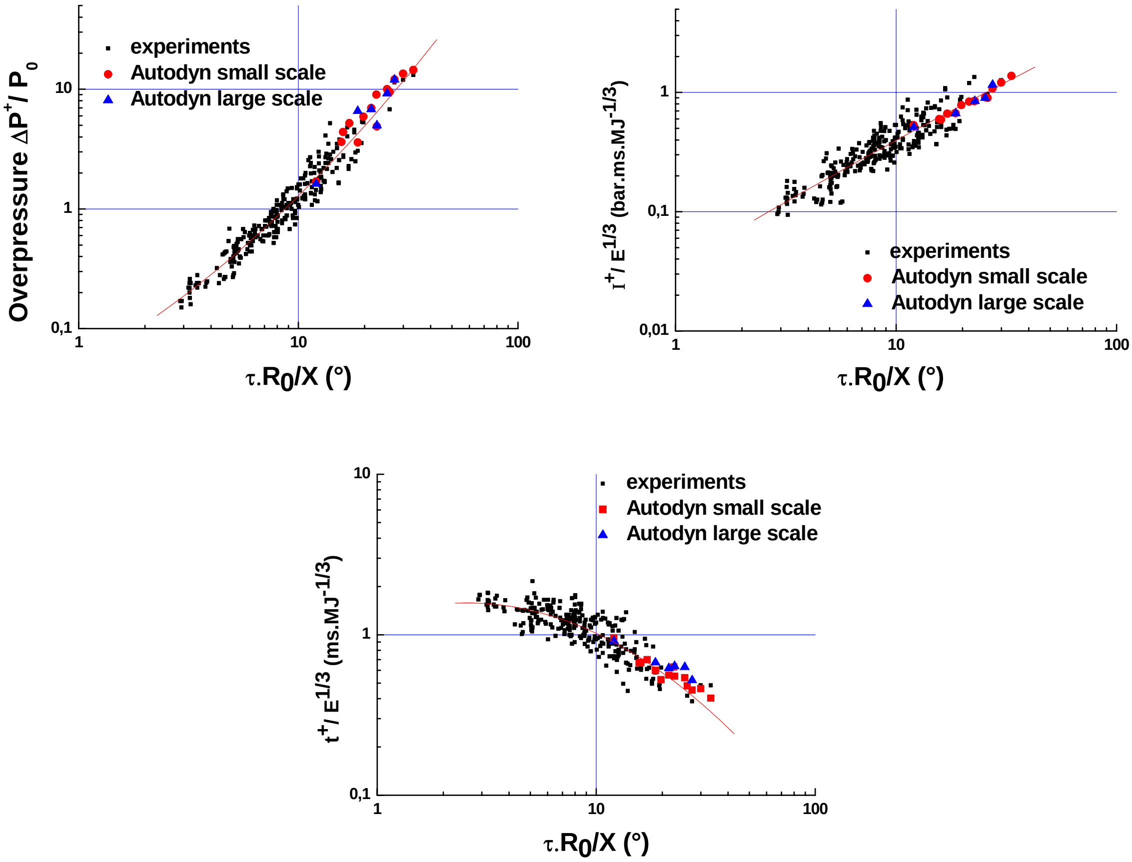


Figure 6. Location of gauges on the parallelepipedic structure, $\theta_{xy} = 0°$ et $\theta_z = 0°$ (z=0)



$$
\left.
\begin{aligned}
&\ln\left(\frac{\Delta P_r^{\,+}}{P_0}\right) = -2.9922 + 1.00456\left(\ln\frac{\tau.R_0}{X}\right) + 0.17603\left(\ln\frac{\tau.R_0}{X}\right)^2 \\
&\ln\left(\frac{I^+}{\sqrt[3]{E}}\right) = -3.35638 + 1.10589\left(\ln\frac{\tau.R_0}{X}\right) - 0.021693\left(\ln\frac{\tau.R_0}{X}\right)^2 \\
&\ln\left(\frac{t^+}{\sqrt[3]{E}}\right) = -0.240689 + 0.45541\left(\ln\frac{\tau.R_0}{X}\right) - 0.23929\left(\ln\frac{\tau.R_0}{X}\right)^2
\end{aligned}
\right\}\quad 2.9 < \frac{\tau.R_0}{X}\ (^\circ) < 33.38
$$

Figure 7. Blast loadings for experimental models: overpressure $\Delta P^+ / P_0$, positive impulse $I^+/E^{1/3}$ and positive phase duration $t^+/E^{1/3}$ as a function of the parameter $\frac{\tau.R_0}{X}$.

5. Modelling

The code used in the study is Autodyn. This code is a finite difference, a finite volume and a finite element method explicit programme.

Autodyn permits to model the detonation of a solid charge (see Figures 8 and 9). Simulations enable one to achieve gas detonations at very small and large scales, which can not be reached by means of experiments. Consequently, to perform the numerical analyses of the conducted experiments, the energy release E resulting from the detonation of the propane-oxygen mixture must be expressed in terms of TNT equivalent energy.

For the mixture considered: $C_3H_8 + 5\ O_2$, the enthalpy of the reaction is equal to $\Delta H_R^* = 3H_{CO_2}^* + 4H_{H_2O}^* - H_{C_3H_8}^* = 2.044\ MJ$ and the chemical energy $E_{v,\ gaz}$ released by the unit of volume expressed by $E_{V,gaz} = \frac{\Delta H_r^*}{6V_{mol}}$ (J / m^3) where $V_{mol} = 24.66 \times 10^{-3}\ m^3$ / mol.

Then, by making use of the formulation $E_{gaz} = E_{V,gaz} \frac{4}{3} \Pi R_0^3$ where R_0 is the bubble radius, the energy released by different bubbles is calculated.

After that, the experimental data are compared (Figure 4) with the similar TNT curves (TM5-1300 1969; Baker & al. 1983). An energy equivalency can be deduced by comparison. The positive phases of the incident, reflected pressures and impulses are equivalent for TNT (energy E_{TNT}) and gaseous charges (E_{gas}) if the energies are related by $E_{gas} = 2.3\ E_{TNT}$.
Finally, knowing the TNT energy release, $E_{TNT,\ m}$ = 4690 kJ/kg (Lannoy, 1984) the TNT equivalent mass is determined:

$$E_{gas} = 2.3\ E_{TNT}$$

$$\leftrightarrow \quad \frac{\Delta H_r^*}{6V_{mol}} \frac{4}{3} \Pi R_0^3 = 2.3\ m_{TNT}\ E_{TNT,\ m}$$

$$\leftrightarrow \quad m_{TNT} = 1.8\ \frac{\Delta H_r^*}{6V_{mol}}\ R_0^3\ \frac{1}{E_{TNT,m}}$$

As the energy equivalency $E_{gas} = 2.3\ E_{TNT}$ has been determined, it is now possible to simulate the explosion of a gaseous mixture by a TNT charge. Indeed, the equivalent released mass of TNT produces the same pressure levels than the gaseous explosive charge. For example, for the 0.06-m radius hemisphere which confines the mixture within the stoichiometric composition, the TNT equivalent mass is approximately equal to 1.3 g. The Autodyn results seem to be well-correlated to relevant experimental measurements (Figure 8).

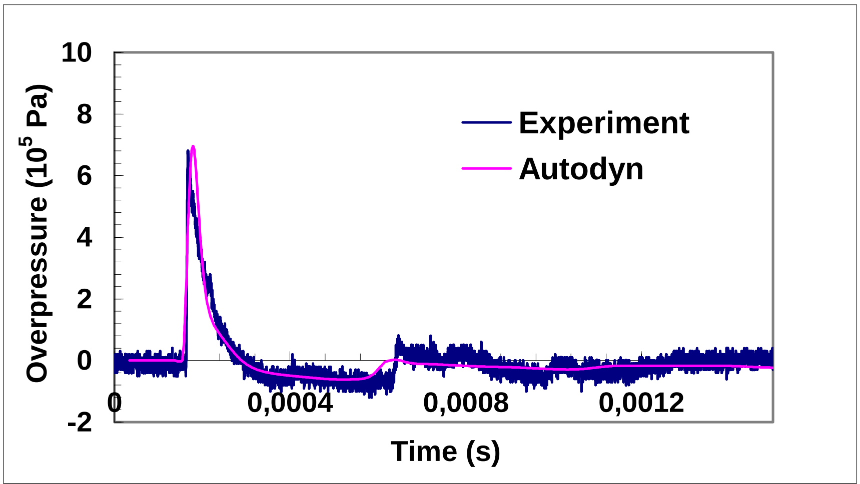
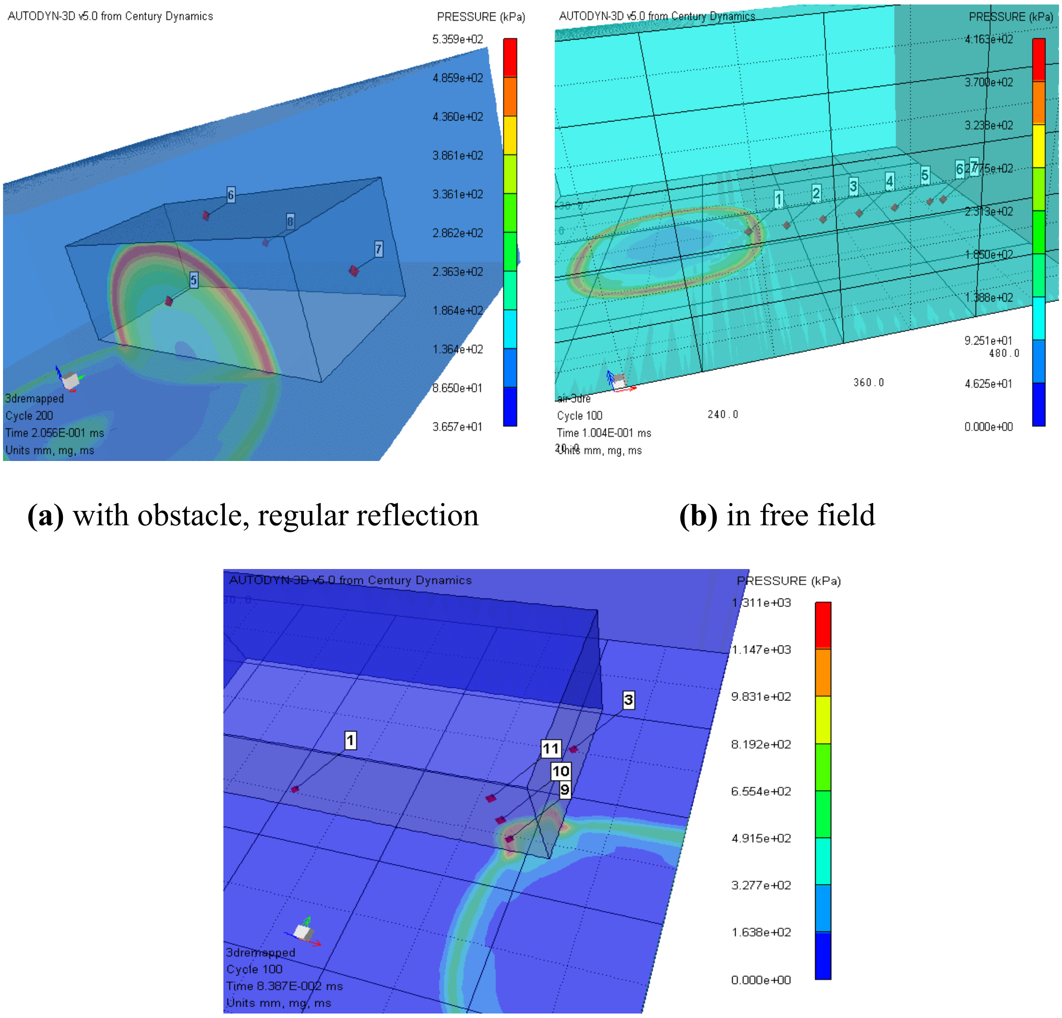


Figure 8. Reflected pressure wave profile: experimental and numerical models (gauge located at the center of the face, R_0 = 0.06 m, r = 0.15 m, small scale)



(a) with obstacle, regular reflection

(b) in free field

(c) with obstacle, oblique reflection

Figure 9. Last stages of pressure wave development in three-dimension and some gauge locations (small scale).

6. Conclusion

Several adimensional laws are expressed as function of radial reduced distance λ and impact angle $\frac{\tau . R_0}{X}$. These relationships, validated at small scale, allow to determine the propagation of a blast wave and its interaction on a structure as function of the position of the explosive charge in different configurations. Consequently, the blast wave’s characteristics can be predicted at large scale by applying Hopkinson law: the amplitude of the pressure is the same for a large-scale structure; the times, impulses and distances are multiplicated by a factor k and the energy by k^3.

7. Acknowledgements

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8. References

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