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Influence of the Shape of an Explosive Charge: Quantification of the Modification of the Pressure Field*)

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Abstract: Many scientific articles dealing with the detonation of explosive charges and their effects suppose that the charge is spherical and centrally initiated. Yet, when discussing the blast wave effect, the charge shape and the location of initiation could be as important as the composition or the mass of the considered explosive. Specifically, close to the charge, the shape may cause significant modifications of the pressure field compared to the predictions developed for spherical charges. Experiments have been carried out, using an emulsion explosive, TNT and C4, in order to quantify the shape effect. Unconfined, centrally initiated spherical and cylindrical charges with different length-to-diameter (L/D) ratios have been fired. The pressure in the median plane was recorded for different reduced distances. Results for spherical charges showed excellent agreement with well-known references. The expected change of the pressure field in the median plane of a cylindrical charge was observed, directly linked to the L/D ratio. Peak overpressure magnifications of up to almost 3 have been measured. The dimensions of the zone within which an increase of the blast wave effect is observed, have also been determined. A similar behaviour for TNT and C4 has been demonstrated; but a different behaviour has been observed for the emulsion explosive.

Keywords: shape effect, emulsion explosive, C4, TNT

1 Introduction

A large number of scientific authors present their experimental results concerning detonation of explosive charges focusing on the nature and the mass of the

*) Some results included in this article have been orally presented and are included in the Proceedings of the 17th NTREM Seminar at Pardubice, Czech Republic, 2014.

explosive. Often a TNT equivalent is also mentioned. The shape of the charge and the location of the detonator are rarely mentioned, since it is commonly supposed that the explosive charge is initiated centrally and that the charge is spherical or hemispherical (or behaves as such). To a first approximation, it may be acceptable to reduce the pressure field to a spherical one when the distances of interest are large enough (typically reduced distances > 4 to 5 $m/kg^{1/3}$).

Nonetheless, in the vicinity of the charge, the shape effect causes considerable discrepancies between expected and measured pressures, as previous publications have shown [1-3]. More specifically, in the case of cylindrical charges with length-to-diameter (L/D) ratios greater than one, the overpressure is highest in the radial direction. By contrast, for L/D ratios lower than one, it is highest in the axial direction [1, 4, 5]. Plooster [6], Katselis and Anderson [7], and Wu *et al.* [8] have also explained the effect of a detonator located at one extremity: the pressure field is then no longer symmetrical and the values of the peak overpressures are higher on the side opposite to the initiation.

Because of these physical phenomena, reference values and formulae for the prediction of the peak overpressure, positive impulse, reflected blast waves, fragment projection, *etc*., initially developed for spherical charges, become unreliable for other charge shapes. In a military context (landmines, rockets) or in industrial applications (ammunition destruction, civil engineering, accidental explosion), understanding these physical phenomena and quantifying them is necessary to avoid unwanted consequences or to improve the efficiency of the charges.

When an unconfined explosive is fired, the principal effects are the fireball and the blast wave. As the blast wave influences its environment in a larger zone than the fireball, we will focus only on the effects of the blast wave in this paper. The two representative parameters of the blast wave are the peak overpressure (P_{max}) and the first positive impulse (I^+). The fireball and the potential fragments resulting from confined charges will not be discussed.

One of the explosives which is often used in this type of work is an ammonium nitrate based emulsion. This type of explosive is well known for its non-ideal detonation behaviour. In contrast to TNT or C4, the emulsion explosive in a cylindrical shape is not as well documented, which explains the interest in this work.

2 Scope of the Work and Definitions

In this section, some essential notions used in this paper are explained. Cylindrical charge shapes have been selected in this study. They are characterized by the dimensionless length-to-diameter (L/D) ratio, with L the length of the cylinder and D its diameter. The shape effect is studied as a function of that L/D ratio. Taking advantage of the axisymmetry, pressures are measured at different distances in the radial direction in the median plane of the cylinder (Figure 1). This is the plane through the charge center, perpendicular to the charge axis. The center of the charge, where the detonator is located, will be considered as the origin of the distance to the sensors.

(a) (b)

Figure 1. Measurements in the median plane for a cylindrical charge. (a) View from above, (b) View from the side.

As different explosives are compared in this work, reduced distances (Z) and impulses (I_{red}) are used to represent the results. In these classical definitions, the TNT equivalent of the considered explosive is used.

Reduced distance and impulse are defined as:

$$Z = \frac{R}{\sqrt[3]{W_{EQTNT}}} = \frac{R}{\sqrt[3]{EQ_{TNT} W_{\mathrm{explo}}}} \qquad I^{+}_{red} = \frac{I^{+}}{\sqrt[3]{W_{EQTNT}}} = \frac{I^{+}}{\sqrt[3]{EQ_{TNT} W_{\mathrm{explo}}}}$$

where EQ_{TNT} is the TNT-equivalent of the considered explosive (for the considered parameter) and W_{explo} is the mass of the considered explosive.

As explained before, the non-homogeneous release of the energy around a cylindrical charge leads to considerable discrepancies between the spherical blast wave parameters and those for cylindrical charges.

2.1 Shape factor

The pressure field near the explosive charge has a characteristic shape which is directly linked to the L/D ratio, as shown in Figure 2. This means that for each L/D ratio and at every distance, a ratio P_{cyl}/P_{sph} can be defined. In this ratio P_{cyl} is the peak overpressure in the median plane around a cylindrical charge and P_{sph}

is the peak overpressure at the same reduced distance around a spherical charge. This ratio will be called the "shape factor" in what follows. A similar shape factor can be defined for the positive impulse: I^{+}_{cyl}/I^{+}_{sph}. The shape factor in the median plane is not constant as a function of the reduced distance. This is illustrated in Figure 3. Very close to the charge, it is greater than one, which means that the cylindrical shape has a magnifying effect in this plane. With increasing distance from the charge, the shape factor increases until it reaches its maximum value. This *maximum shape factor* is an important piece of information, because it gives an idea of how large the amplification of the effect is compared to a spherical charge. This maximum value depends on the L/D ratio. For larger distances, the shape factor decreases as the distance to the charge increases, accounting for the vanishing effect of the explosive shape.

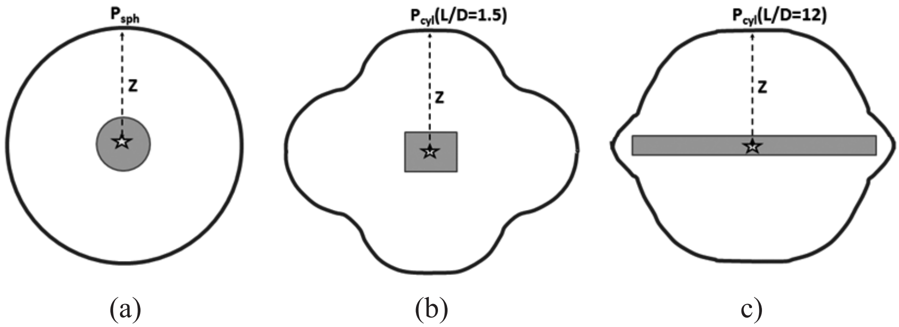


Figure 2. Pressure field near the charge for three different shapes (sphere, L/D=1.5, L/D=12).

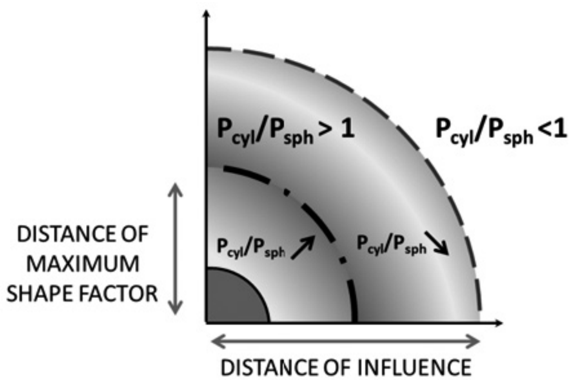


Figure 3. Definition of the distance of influence and the distance of maximum shape factor.

2.2 Distance of influence

At a certain (reduced) distance, the shape factor becomes equal to one. This particular distance was defined as the "(reduced) distance of influence", by Simoens *et al*. [9]. It delimits the zone within which the effects of a cylindrical charge remain more important than those produced by a spherical charge of the same mass of the same explosive. There is a typical distance of influence for the peak overpressure and another for the positive impulse. Beyond the distance of influence, a cylindrical charge produces a (slightly) lesser effect than a spherical charge. The influence distance is also a function of the L/D ratio.

Ideally, values for distance of influence and maximum shape factor should be mentioned in reference works. Depending on the application, we need to know to what extent the effects are magnified (maximum shape factor), or we need to know where these magnifying effects have vanished (influence distance). In some cases both types of information might be relevant.

As specified in previous sensitivity studies [3], both of these parameters may be influenced by the type of explosive, the shape of the charge, the location around the charge, the confinement and the physical parameters compared with a spherical one (peak overpressure or positive impulse).

3 Experimental Setup

3.1 Explosive charges

Three different explosives have been used during the experiments carried out in this study: an ammonium nitrate based emulsion, TNT and C4. While C4 and TNT are typical military explosives, the explosive emulsion is typically used in civil applications. The emulsion contained 80% ammonium nitrate, 10% water, 6% oil and an adequate emulsifier. Microballoons were added to make it cap-sensitive. It had a velocity of detonation of about 5500 m/s and a density of 1.15 ± 0.1 g/cm^3. It was very viscous, and therefore ideal to fill any shape of charge.

Spherical and cylindrical charges with a range of different L/D ratios and masses have been fired. The different charges are specified in Table 1 and some are shown in Figure 4. Thin plastic spherical containers and cardboard cylinders were assumed to represent no confinement; the charges were considered as bare charges.

Table 1. Shapes and masses of the different charges used in this study (masses in gram)

L/D	0.7	1	1.42	1.85	3.62	4.37	5.4	7.2	8.33	11.1	14.8	Sphere
Emul-sion	-	1600	-	1600	1050 1600	-	1600	-	1600	1220 1600	1600	1600
TNT*	2000	-	-	-	-	-	-	2000	-	-	-	1000 2000
C4*	-	400	1000	-	-	1000	-	-	-	-	-	50 1000

* Experiments performed in collaboration with Institut Saint Louis (ISL)

(a) (b) (c) (d) (e) (f) (g)

Figure 4. Some of the explosive charges: (a) Emulsion, L/D = 1, (b) Emulsion, L/D = 3.62, (c) Emulsion, L/D = 14.8, (d) Emulsion, spherical, (e) TNT, L/D = 0.7, (f) TNT, spherical, (g) C4, L/D = 1.42.

The average densities of the charges were 1.63 g/cm^3 for TNT and 1.5 g/cm^3 for C4. A booster of 100 g of C4 was used to initiate the TNT charges. This mass is included in the total mass of TNT.

Furthermore, in order to efficiently post-process the results, a TNT equivalent was needed for each explosive. Table 2 summarizes the TNT equivalents used in this work for peak overpressure and positive impulse. These numbers have been determined based on the experimental peak overpressure and positive impulse measured during the shots with TNT instead of on data from reference works. This explains why the values in Table 2 deviate slightly from those in other references [3, 10].

Table 2. TNT equivalent for the explosive emulsion and for C4

Parameter	Emulsion	C4
Peak overpressure (P_{max})	1.0	1.5
Positive impulse (I^+)	1.3	1.4

3.2 Instrumentation

Shock pressure profiles were measured using PCB® piezo-electric blast pencil sensors. Blast wave peak pressures could be measured up to 40 bar. This value limits the closest (reduced) measuring distance from the charge to about Z = 0.5 m/kg$^{1/3}$. Twelve blast wave signals were measured during each experiment. Redundancy in the measured signals was needed because of the unavoidable scattering in the results, certainly for the very short distances (0.5-2.5 m/kg$^{1/3}$).

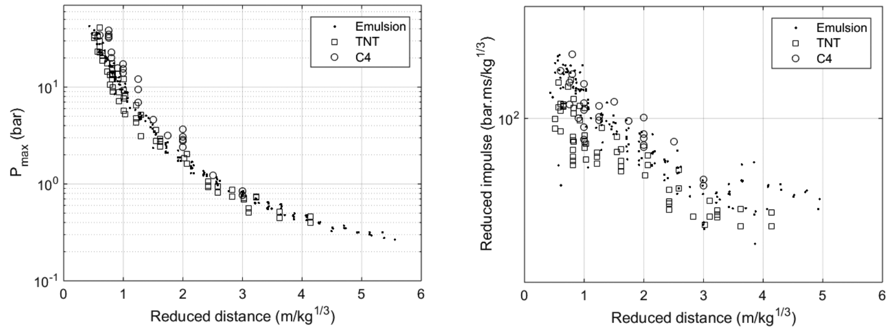
3.3 Setup

All cylindrical charges were placed/hung vertically. The detonator was always placed at the charge center irrespective of the charge shape in order to obtain a symmetrical pressure field. All pressure gauges and the charge center were placed at a height of 150 cm above the ground to ensure that no reflection from the ground disturbed the record of the incident aerial blast wave. This condition limits the maximum measuring distance. It has been observed that the Mach stem does not disturb the pressures of the recorded blast waves or reduced distances up to 5.5 m/kg$^{1/3}$.

4 Results and Discussion

4.1 Spherical charges and comparison with existing models

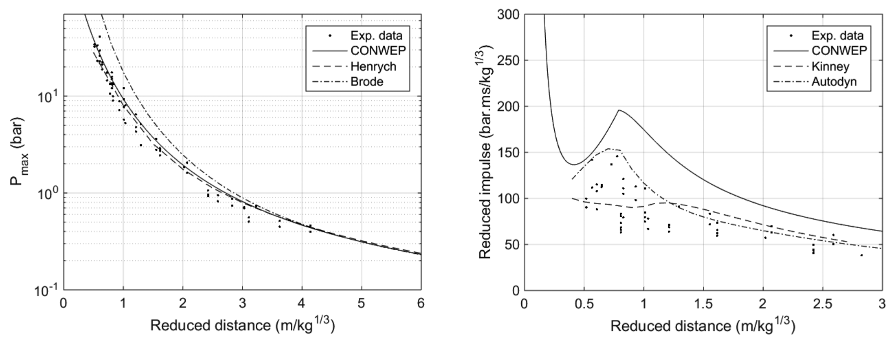
The results for spherical charges of the three explosives are summarized in Figure 5. No TNT-equivalent has been applied to express the experimental results. The TNT-equivalents for the emulsion explosive and C4 as given in Table 2 were determined using these data. Considering the peak overpressures in Figure 5(a), it is clear that the three explosives show consistent behaviour over the entire range of reduced distances. As expected, C4 produces a higher peak overpressure than TNT, while TNT and the emulsion explosive show similar effects. A relatively small scatter is also observed. This confirms the reproducibility of the different shots and measurements. The conclusions are qualitatively similar for the first (reduced) positive impulse (Figure 5(b)). The scatter is significantly larger than for the peak overpressure. The emulsion explosive produces a higher impulse than TNT. As expected C4 has the highest impulse. Figure 5(b) reflects the difficulty of accurately measuring the first positive impulse. The measured pressure profile is far from the perfect theoretical shape, especially at very short range (Z below 1 m/kg$^{1/3}$). The possible non-ideality of the detonation and of the behaviour of the pressure sensors themselves may be reasons for this difference.



(a) (b)

Figure 5. Experimental results for the spherical charges for (a) peak overpressure, and (b) reduced impulse.

Many researchers have developed models and reference data for spherical charges of TNT. Figure 6 shows the comparison between our experimental TNT data and some reference models: CONWEP [10], Kinney-Graham [11, 12], Henrych [13], and Brode [14] for peak overpressure, and CONWEP [10], Kinney [11] and Autodyn [15] for impulse. These models are known to be efficient for representing the detonation of spherical TNT charges, in free field, for reduced distances above 3-4 m/kg$^{1/3}$.



(a) (b)

Figure 6. Comparison between experimental results and different reference models for spherical charges of TNT for (a) peak overpressure, and (b) positive impulse.

From the results for peak overpressure in this work (see Figure 6(a)), it appears that the TNT experimental charges and the models of CONWEP, Kinney-Graham and Henrych show good agreement for the entire range of the distances considered. The Brode model however does not match well with the experimental data for distances below 3-4 m/kg$^{1/3}$, which may be accepted as the limit for distinguishing between the near field and the far field. This again confirms the validity of the experimental data.

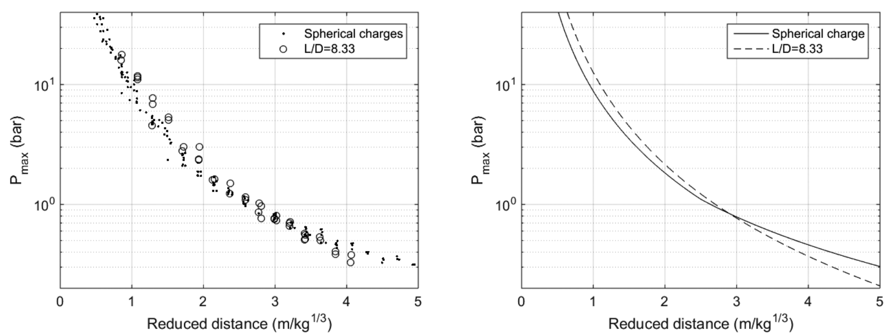
For impulse (see Figure 6(b)), more important differences exist between the references. The experimental data fit better to the Kinney and Autodyn predictions, whereas CONWEP seems to overestimate the impulse.

Because these experimental data for the spherical charges of the emulsion explosive, TNT and C4 are reproducible, coherent and fit well to known references, they can be used with confidence for comparison with the experimental cylindrical data and thus for the calculation of shape factors and influence distances.

4.2 Results for the emulsion explosive

4.2.1 Preliminary discussion

When determining the shape factor and the reduced influence distance, any scattering in the data represents a real inconvenience and an important limit to the accuracy. A precise determination of the distance where overpressure or impulse for the cylindrical charge passes below that of the spherical case (*i.e.* the influence distance) is difficult. Therefore, curves have been fitted through the experimental data points. These fitted curves were then used for the determination of the influence distance.



(a) (b)

Figure 7. (a) Raw and (b) fitted data for different charges for the peak overpressure.

An example is given in Figure 7 for measurements of peak overpressure around an explosive charge of the emulsion explosive with L/D = 8.33. After curve fitting, the distance of influence can clearly be identified, whereas this was difficult based on the raw data points. This technique has been applied to all of the experimental results.

It may also be noticed from these experimental data that the peak overpressures for cylindrical charges are lower than those of spherical charges beyond the reduced influence distance. This means that the shape effect does not completely vanish for large distances, but that the effect is rather reversed. The same observation can be made for the first positive impulse.

4.2.2 Influence distance

Figure 8 summarizes the experimental results for all of the shots with 1600 g of the emulsion explosive. The graphs reveal that the distances of influence increase with increasing L/D ratio. The increase for the positive impulse is not as important as for the peak overpressure. In both cases the increase seems to come to cease for large L/D ratios. The influence distance becomes more or less constant for the largest L/D ratios in the tests.

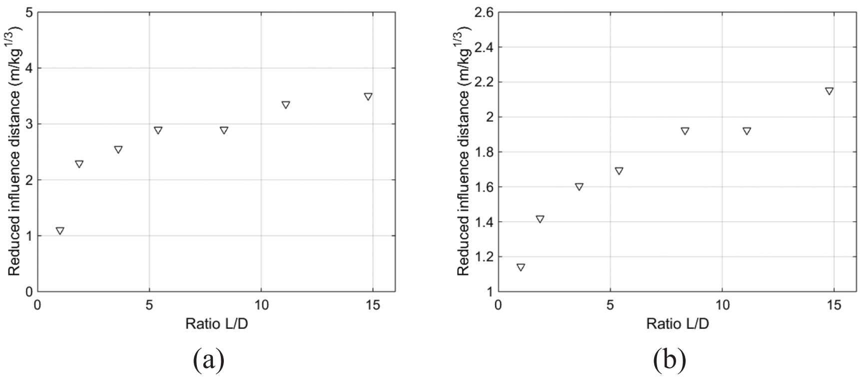


Figure 8. Influence distances for the emulsion explosive for (a) peak overpressure, and (b) reduced impulse.

For the cylindrical charges initiated centrally, a cylindrical blast wave leaves the charge at the median plane. For a theoretical infinitely long cylinder (with infinite mass), the energy decreases according to $1/r^2$, with r being the distance from the charge center. As the energy decreases with $1/r^3$ in the spherical case, the cylindrical case leads to higher pressures and impulses in the median plane for all distances. However, real cylindrical charges have a finite length, and the side effects from the extremities (bridge waves) will at some point start affecting the cylindrical blast wave in the median plane, reducing its intensity. At some point, the additional cylindrical effect will have disappeared (*i.e.* influence distance). Moreover, as all explosive charges considered in this paragraph have an identical mass, the diameter of the cylindrical charges decreases with increasing L/D ratio. This means that the amount of energy released in the median plane decreases with an increasing L/D ratio. At the same time, the extremities are further away from the charge center, and the bridge wave has to travel a longer distance before affecting the cylindrical blast wave in the median plane. A combination of these two effects explains the aspect of the graphs in Figure 8. One can expect that the influence distance starts decreasing for very large L/D ratios, as the section of the explosive charge becomes so small that the cylindrical blast wave is no longer stronger than in the spherical case. This decrease has not been observed experimentally, and one can assume that the L/D ratio for this decrease must be larger than 15. An additional potential problem in experiments with large L/D ratios could be that the diameter of the cylindrical charge becomes smaller than the critical diameter of the explosive, which would add another physical phenomenon to the discussion. In this work however, the recorded detonation velocities show that the value remains constant for all L/D ratios considered.

4.2.3 Maximum shape factor

As mentioned in the first section, it is not only the influence distance that can be of interest, but in some cases the maximum shape factor can also be of importance. Figure 9 gives the evolution of the shape factors as a function of distance for different cylindrical charges of the emulsion explosive. Note that the distances where these curves pass below 1 are the influence distances.

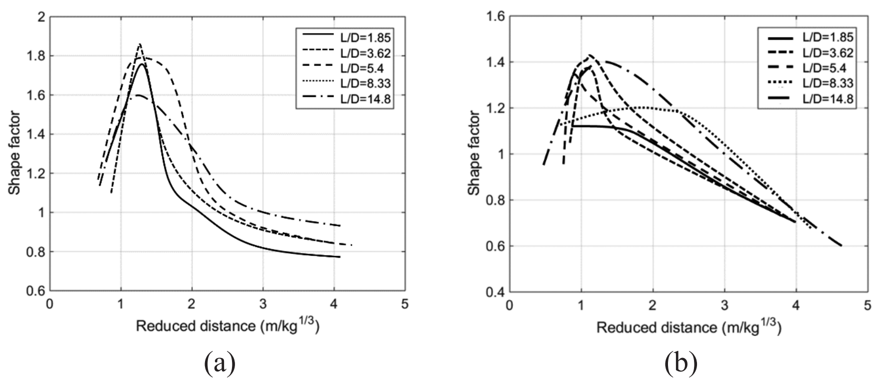


Figure 9. Shape factor as a function of reduced distance for the emulsion explosive for (a) peak overpressure, and (b) reduced impulse.

A similar characteristic behaviour can be observed in all of the experimental curves for peak overpressure (Figure 9(a)). For Z up to 0.8-1 m/kg$^{1/3}$, there is a rapid increase of the shape factor, which quickly reaches its maximum value. In this range of distances, measurements are very sensitive to small errors for all L/D ratios. This was especially noticed during the TNT and C4 tests. The maximum shape factor was found to increase with increasing L/D ratios up to about L/D ratios of 3 to 5. The highest shape factor of about 1.8 was obtained for L/D ratios around 4, which means that the shape effect is significant. For larger L/D ratios the maximum shape factor decreases with increasing L/D ratios. From L/D ratios of 5.40 and higher, a plateau appears in the evolution of the shape factor. The maximum shape factor is found over a particular range of distances. The plateau tends to widen as L/D increases. Finally one can notice that the final decrease of the shape factor converges to a unique slope for high L/D.

To recapitulate, one can see that the highest shape factor for overpressure is obtained for L/D ratios around 4, but only in a small zone around the charge. For the highest L/D ratios, the maximum effect is slightly less important, but the zone where this maximum is reached is larger.

Similar conclusions can be drawn for the shape factor based on the first positive impulse (Figure 9(b)). The maximum value in this case is about 1.4. This value is reached for all of the tested L/D ratios.

4.3 Results for other explosives

4.3.1 Cylindrical shape and similitude parameters

The Hopkinson-Cranz similitude parameters are commonly used to calculate reduced distances, impulses, times, *etc*., in order to make them independent of the mass of the explosive. Nevertheless, these similitude parameters have been developed for spherical charges which are characterized by a single geometrical parameter, the radius; and where energy is released in a spherical way, proportional to the reciprocal of the cube of the radius. One might question the use of the same method for cylindrical charges, where there is no spherical symmetry.

Figure 10 summarizes the reduced distances of influence obtained with three different masses: 1050, 1220 and 1600 g. The experimental data from Figure 10 suggest that the same concept can be used, at least for masses of the same order of magnitude. It is clear that the use of reduced distances allows values independent of the mass to be obtained. Within the range of the masses studied, the Hopkinson-Cranz similitude parameters can thus be legitimately used for cylindrical charges. This also allows the results for different explosives to be compared, as the difference in explosive can be considered by taking a different TNT-equivalent mass.

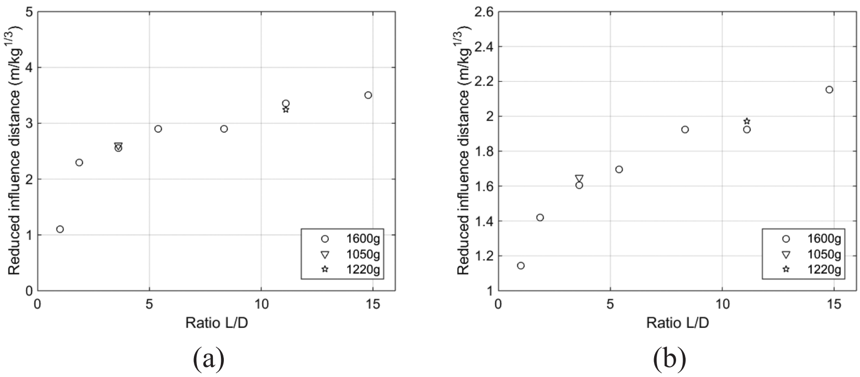
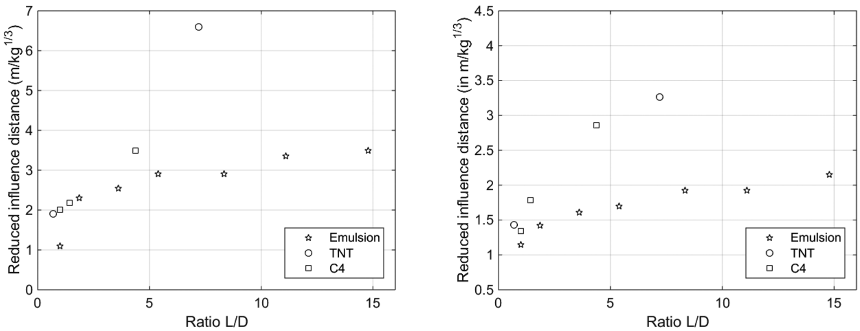


Figure 10. Reduced distance of influence for different masses of the emulsion explosive (a) for the peak overpressure, and (b) the positive impulse.

4.3.2 Influence distance

Figure 11 adds the experimental results for the reduced influence distances obtained for TNT and C4 to Figure 8. As demonstrated in the previous paragraph, the use of previously mentioned TNT-equivalents and of a reduced distance allows a comparison between the different explosives to be made. At a first glance, all of the curves show a continuous and consistent increase in the distance of influence with increasing L/D ratio. TNT and C4 behave in the same pattern: a constant increase in the reduced distances of influence from 2 to 6 m/kg$^{1/3}$ for an increase in L/D from 1 to 8, in terms of the peak overpressure; from 1.5 to 3-3.5 m/kg$^{1/3}$ for L/D from 1 to 8, in terms of the positive impulse. One should note that the largest reduced distance in the experiments with cylindrical charges of TNT and C4 was about 3.5 m/kg$^{1/3}$. The influence distances for TNT and C4 in Figure 11 are based on extrapolations of the measured data, and are therefore subject to possible additional errors. Measurements at longer distances should allow the quality of the extrapolations to be verified.

Another observation from Figures 11(a) and 11(b) is the clear distinction in behaviour between the emulsion explosive and the pair TNT/C4, for ratios above L/D = 2. Generally speaking, the influence distance of the emulsion explosive is smaller than that of TNT and C4, and the increase in the function of L/D is also slower. Yet, it has previously been demonstrated that the results for spherical charges of TNT and the emulsion explosive were very similar, at least for the peak overpressure. This means that the shape effect depends on the nature of the explosive. As mentioned before, a possible decrease in the velocity of detonation of the emulsion for small diameters has been excluded as the main cause. This tends to indicate that the shape effect for this type of emulsion explosive is clearly different from typical military explosives, which indicates an influence of the nature of the explosive charge on the shape effect.



(a) (b)

Figure 11. Reduced distance of influence for (a) the peak overpressure, and (b) the positive impulse, determined from the experimental data for the emulsion explosive, TNT and C4.

Eventually, more experiments with emulsions, and also with TNT, C4 or a similar explosive with high brisance, should be performed to confirm these conclusions.

4.3.3 Maximum shape factor

From the measured data for TNT and C4, the shape factor can also be represented as a function of distance from the charge. Curves similar to those in Figure 9 were found. Despite the similarities in the distances of influence for TNT and C4, it appears experimentally that the maximum shape factor for TNT is slightly higher than that for C4 (2.9 for TNT against 2.6 for C4). The distances from the charge where these maximum values are reached, are about the same as for the emulsion explosive.

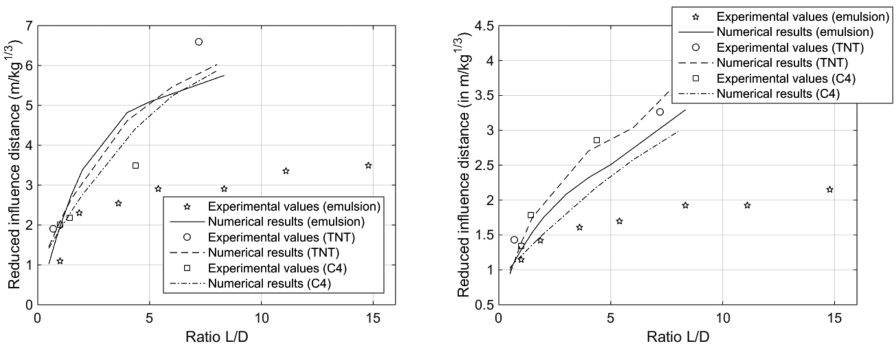
4.4 Comparison with numerical simulations

4.4.1 Numerical models

A series of numerical simulations has been performed to support the experimental conclusions. These numerical simulations were performed with ANSYS AutoDyn v.14. JWL equations of state were used to model the explosives [16]. For TNT and C4, the standard material database was used. The cylindrical shape with central initiation allows 2D axisymmetric models to be run. A uniform Eulerian mesh was chosen. The procedures to determine the distances of influence and the shape factor were identical to those used for the experimental data.

4.4.2 Distances of influence

In Figure 12, a comparison is made between the reduced influence distances obtained experimentally and numerically. Although relatively good agreement for the TNT and C4 charges is observed, some differences do appear between the experimental and the numerical values. Some factors which may explain these are: an uncertainty in the experimental charge densities, the limited representativeness of the experimental data and the approximation due to the use of a single TNT equivalent for the whole range of reduced distances. In a first approximation, one could state that the numerical simulations are good representations of the experiments for TNT and C4. However, as will be discussed later, some non-negligible differences exist between the numerical and the experimental data.

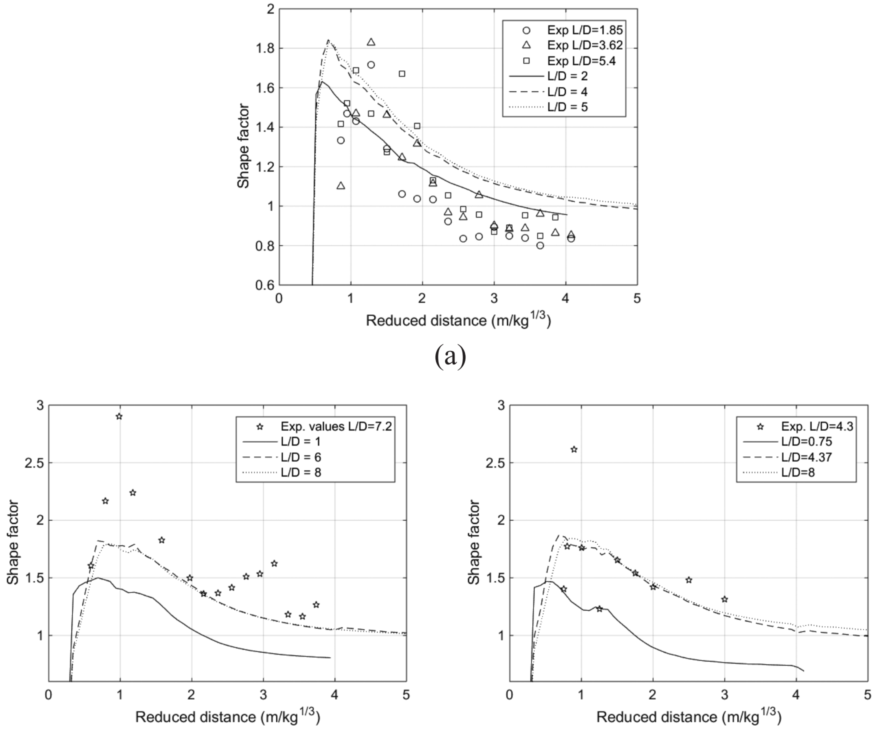


(a) (b)

Figure 12. Comparison between experimental and numerical distances of influence for (a) peak overpressure, and for (b) positive impulse.

There was absolutely no agreement, however, between the numerical and the experimental results for the emulsion explosive. Whereas experimentally the emulsion explosive deviates significantly from the other explosives, numerically it does not. The numerical decrease of the shape factor as a function of distance is much slower in the numerical simulations than in the experimental measurements, as can also be observed in Figure 13(a). A possible reason for this is the use of the

JWL equation of state to describe the emulsion explosive. This type of equation might not be the best choice to simulate the non-ideal behaviour of an ammonium nitrate based explosive. However, this numerical model is surprisingly capable of numerically predicting the pressures around a spherical charge compared to the experimental data. Better chosen parameters or a better chosen equation of state to describe the emulsion explosive might greatly reduce the difference between the numerical and experimental results.



(a)

(b) (c)

Figure 13. Experimental and numerical shape factors based on overpressure (a) for the emulsion explosive , (b) for TNT, and (c) for C4.

4.4.3 Maximum shape factor

In Figure 13, a comparison is made between the experimental and numerical shape factors (based on peak overpressure) as a function of distance. For the emulsion explosive, the experimental maximum shape factor of 1.8 is also found numerically, despite the differences in the distances. For TNT and C4, the maximum shape factor is largely underestimated numerically.

For shape factors based on impulse, the results are slightly better, certainly with respect to the maximum value of the shape factor.

5 Conclusions

Experiments have been carried out with cylindrical charges of an emulsion explosive, TNT and C4, with length-to-diameter ratios ranging from 1 to 14.8. Peak overpressure and positive impulse were identified and selected as the key parameters and have been successfully measured. Comparison of the experimental data with commonly used models (CONWEP, Kinney-Graham, Henrych…) shows good agreement for the peak overpressure, even very close to the charge.

It has been shown that on the median plane, for explosive charges with a given L/D ratio, there is a significant increase of the shock parameters, both peak overpressure and first positive impulse. This increase has been quantified as the shape factor, which is a function of the L/D ratio. For the emulsion explosive, the shape factor for peak pressure reaches a value of 1.8 for an L/D ratio of about 4. The maximum shape factor for impulse is about 1.4. This increased effect is significant up to relatively large distances before it vanishes. That distance is also L/D dependent. Large L/D ratios cause smaller increases in the explosive effects, but they are observed in a larger zone around the charge.

A study of the influence of the mass of the explosive for cylindrical charges has revealed that, within the range studied, the similitude parameters, commonly used for spherical charges, can be extended to cylindrical charges. Consequently, a comparison of different explosives using their TNT-equivalent mass is relevant.

Concerning the distances of influence, major differences have been observed between the emulsion explosive and the pair TNT/C4. TNT and C4 seem to exhibit similar behaviour for both parameters (P_{max} and I^+), with larger influence distances than the emulsion explosive and a more rapid increase in the distance of influence with increasing L/D.

The evolution of the shape factor as a function of distance to the charge has shown similar behaviour for the three explosives considered. The maximum shape factors for TNT and C4 were found to be slightly less than 3 for the L/D ratios considered.

Comparisons with numerical simulations demonstrated good qualitative and quantitative agreements for TNT charges, rather good agreement for C4 charges and no agreement for the emulsion explosive for L/D ratios larger than 2. Either the parameters in the JWL equation for the emulsion explosive should be adapted, or another equation of state, more convenient for emulsion explosives, should be used in numerical models.

Emulsion explosives require specific approaches; these are not military, highly brisant explosives and need specific models, distinct from those based on TNT charges. In this context, the tests performed during this study may become a benchmark for any future project.

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