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On the problem of bare-to-cased charge equivalency

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A B S T R A C T

Many explosives are covered with a steel casing. The fragmentation process of the casing dissipates part of the detonation energy and therefore cased charges yield lower overpressures and impulses than the same charges without a casing (bare charges). It is often required to assess the mass of an equivalent bare charge, which will produce similar impulses (at the same distances) to those of a given cased charge. Another pertinent parameter is the cased-to-bare impulse ratio, which is a direct measure of the effect of the casing on the resulted impulse. This paper deals with several aspects of the problem of a cased charge equivalency. A review of available models for the assessment of the ratio between the masses of the equivalent bare and cased charges is presented. The current study proposes a procedure to assess the mass ratio, which consists of relatively simple numerical simulations and of the blast waves scaling laws. The simulations are verified against experimental data and their results are compared with available models for the mass ratios. A relation between the mass ratio and the impulse ratio is also presented. Finally, examination of the effect of the casing material properties indicates that the casing-to-charge mass ratio is a key parameter in the assessment of the mass of an equivalent charge.

1. Introduction

The performance of an explosive charge may be quantified by its pressure–time and impulse–time curves. The impulse is the integration of the pressure with respect to time and it is considered as a very important parameter in the study and design of protective structures. A common source of explosive and impact load is a charge with a metal casing. After detonation, the casing expands and ruptures into many fragments. At this time, the gases are discharged through the spaces in the casing and propagate in the air. Experimental data show that there is a significant difference between the blast wave parameters of cased and bare charges [1–4]. When the charge is cased, part of the detonation energy is dissipated through the expansion and rupture of the casing. As a result, the blast wave parameters, and especially the peak impulse, will be lower than those that are caused by the same charge without casing (bare charge).

Analysis of blast-wave parameters that are caused by bare charges is commonly done with experimentally verified numerical simulations. Simulations of cased charges, however, are cumbersome and very expensive in terms of computational resources and time. This is because the casing has to be modeled with a very fine mesh that requires a very small time step. Yet, the propagation of the blast wave in the air takes relatively a much longer time than the fragmentation of the casing, and as a result, it is very hard and sometimes impossible to be simulated. This limitation can be overcome in pertinent analyses by finding a corresponding or 'equivalent' bare charge (without casing) that will produce a blast wave with the same parameters as that of the cased charge.

As in other engineering problems, scaling a phenomenon is a common and helpful practice [5]. It is generally employed to resolve budgetary limitations of full-scale experiments, and particularly those that involve explosions. The most common scaling form for the latter type of experiments is the "Hopkinson scaling" or "cube root scaling" [5–7], which is based on the "Buckingham π theorem". The scaling laws can also be used to evaluate the "equivalent charge" (as will be shown in the following text). According to these laws, two similar blast waves (caused by charges that have similar geometries with different dimensions, at the same atmosphere) will produce similar scaled parameters (e.g., impulse) at the same "scaled distance". The scaled distance is defined by the ratio $R/C^{1/3}$, where R is the distance and C is the mass of the charge. The scaling laws described above are applied in this study in the interpretation of results from a numerical investigation, for the comparison of the blast parameters of bare and cased charges.

It is evident that two similar bare charges with different masses will not produce the same impulse at the same distance. However, the scaling laws show that they will cause impulses that converge to the same scaled-impulse versus scaled-distance curve. When cased charges are considered, a common definition for an equivalent bare

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charge mass, C_e, is that at given scaled distances it produces scaled impulses that are equal to those caused by a given cased charge, C_c. I.e., C_e satisfies, at any given standoff distance R, the following equations:

$$\frac{I(C_c)}{C_e^{1/3}} = f\left(\frac{R}{C_e^{1/3}}\right) = \frac{I(C_e)}{C_e^{1/3}} \rightarrow I(C_e) = I(C_c) \tag{1}$$

where $f(R/C_e^{1/3})$ is a function of the scaled impulse–distance curve.

Hutchinson argued that this definition could be confusing [8] and thus he suggested another definition for the estimation of the impulse reduction due to the effect of the casing, i.e., Hutchinson suggested to define the ratio $I(C_c)/I(C_b = C_c)$, where it is noted that C_b is a bare charge. Hutchinson further argued that both ratios, the impulse ratio and the mass ratio (C_e/C_c), are equal [8].

The current work examines ways to evaluate the equivalent bare-to-cased mass ratio or the cased-to-bare impulse ratio. It consists of a calculation procedure, which is based on numerical simulations and employment of the scaling laws of blast waves. First, we review available models for an equivalent charge, C_e. These models are then examined through the proposed numerical procedure. The numerical calculations of this procedure are verified against published experimental data for bare charges. Then, the procedure is used to evaluate the equivalent bare charge masses and the impulse ratios for particular cases, for which there are also experimental data that allow further verification of the proposed procedure. The relation between the impulse ratio $I(C_c)/I(C_b = C_c)$ and the equivalent bare charge-to-cased charge mass ratio C_e/C_c is derived from the numerical results in order to check Hutchinson assumption (that they are equal). Finally, the effect of the casing material (and therefore, of its different mechanical properties) was examined through the numerical procedure.

2. Available models of an equivalent bare charge

Gurney, in his classic work, showed that the fragments velocity of cylindrical and spherical casings can be estimated by using simple energy balance of the charge and the casing [9]. Fano, as quoted by Fisher [4], followed Gurney's assumptions and assumed non uniform velocity of the gases (in a cylindrical charge), being zero at the center of the charge and increasing linearly up to a certain value at the charge–metal interface. Using this assumption and a suitable energy balance, he obtained a formula for the equivalent charge mass. In addition, he assumed a factor of 0.8 "to account for the fraction of the total detonation energy belonging to the gases and the case as kinetic energy at time of rupture of the case" [4]. In summary, Fano proposed the following equation for the equivalent bare charge:

$$\frac{C_e}{C_c} = 0.2 + \frac{0.8}{1 + 2M/C_c} \tag{2}$$

where M is the mass of the casing.

Fisher modified Fano's formula by making a different assumption of uniform gases velocity and obtained the following expression [4]:

$$\frac{C_e}{C_c} = 0.2 + \frac{0.8}{1 + M/C_c} \tag{3}$$

In the same report [4], Fisher modified his own formula and proposed the following empirical equation, which agrees better with experimental data:

$$\frac{C_e}{C_c} = \frac{1 + M/C_c(1 - M')}{1 + M/C_c} \tag{4}$$

where M' is a non-dimensional coefficient, equal to the minimum of M/C_c and 1.0 (note that with $M' = 0.8$, Eq. (4) converges to Eq. (3)).

Hutchinson noted on the above that using the factors "0.8" and "0.2" is redundant, because the derivation already included consideration of the kinetic energy that goes to the fragments [10]. He further rightfully noted that according to the Fano and Fisher formulas, for very large M/C_c ratios ($M/C_c \rightarrow \infty$), the equivalent bare charge does not converge to zero, as expected [11].

Hutchinson proposed another approach to evaluate the equivalent bare charge, according to which, the equivalent bare charge should be derived based on the conservation of momentum rather than energy. This approach yielded the following formula for an equivalent cylindrical bare charge:

$$\frac{C_e}{C_c} = \sqrt{\frac{0.5}{0.5 + M/C_c}} \tag{5}$$

The above models depend only on the casing-to-charge mass ratio. In the same work [11], Hutchinson followed Crowley's approach [12] to consider also the casing material and explosive type in the estimation of the equivalent bare charge, as follows:

$$\frac{C_e}{C_c} = 1 - \left(1 - \sqrt{\frac{0.5}{0.5 + M/C_c}}\right) f_m \tag{6}$$

where f_m is a factor that takes into account the casing material yield stress and the explosive type. Hutchinson derived an analytical expression for the factor f_m [11], which was not in good agreement with experimental data. Still, he showed that for each set of results with the same casing material and explosive type there is a unique value of f_m that yields good agreement.

In a later work, Hutchinson changed his approach for the equivalent bare charge [8]. He argued that the definition of an equivalent bare charge that will produce the same impulse at the same distance (see Eq. (5)) is confusing, and suggested the use of the ratio between the peak blast impulses from two charges with the same mass – cased and bare, I_c/I_b (i.e., $I(C_c)/I(C_b = C_c)$). He used his previous formula (Eq. (5)) to evaluate the impulse ratio instead of the equivalent bare-to-cased charges' mass ratio, as follows:

$$\frac{I_c}{I_b} = \sqrt{\frac{0.5}{0.5 + M/C_c}} \tag{7}$$

Hutchinson also showed that his equations, which do not consider properties of the casing material and the explosive type (Eqs. (5) and (7)), are valid for very ductile casings. He further argued that these casings are accelerated up to their ideal Gurney velocity before they fracture [8]. In many cases, the casing fractures before it is fully accelerated by the energy available from the explosive, and for these cases Hutchinson proposed the following formula [8]:

$$\frac{I_c}{I_b} = \sqrt{\frac{1}{2} + \frac{M}{C_c}\left(\frac{R_0}{R_f}\right)^{2(\gamma-1)} \Big/ \left(\frac{1}{2} + \frac{M}{C_c}\right)} \tag{8}$$

where γ is the heat capacity ratio, R_0 is the initial casing radius and R_f is the radius at fracture. He mentioned that the radius R_f can be estimated by the fracture strain of the casing material (however, he did not provide further details for this estimation). In his verification with experimental results, using high speed cameras, R_f/R_0 was assessed to be equal to 2 (i.e., the casing radius was increased to about twice its initial radius) [8].

In another research, Hutchinson [13] extended his approach to consider the casing material yield stress, as follows: