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Spatial mass distribution of fragments striking a protective structure

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ABSTRACT

Fragmentation of cased charges is of interest in the design of protective structures. To assess the global response of a protective structure due to the fragments impact, their spatial mass distribution should be evaluated. Experimental results indicate that this distribution is not uniform, as commonly assumed. In this paper, a simplified model is proposed to depict the non-uniform spatial distribution over a protective wall. This distribution is characterized by an 'intense strip', which is stricken by relatively large fragment masses. Numerical simulations are presented to evaluate the model parameters for cases of various standoff distances and impact angles (which result from the angle between the charge longitudinal axis and the ground). The model parameters obtained in this method also agree very well with reported experimental findings. The simplified fragments mass distribution is shown to be more realistic than the commonly used, uniform one.

1. Introduction

1.1. Background

Characterization of the effects caused by detonation of an explosive charge is of interest in assessing the response of a structure to extreme loads. In most cases, the explosive charge is covered with a casing, which is usually made of metal. After detonation, a blast wave is generated, and fracture of the casing results in many metal fragments with different masses and velocities. The prediction of the fragments impact from the cased charge is important for the evaluation of the expected structural damage. Commonly, a cylindrical case, filled with explosive charge and detonated at one end, is considered. This shape is a simplification of a more complicated realistic shape and it is used in many researches [1–4]. After detonation, the casing expands to about twice its initial radius before it fractures into a large number of fragments [5]. The fragments initial velocities are 1000–3000 m/s, depending on the masses of the charge and of the casing. The velocity decreases with distance due to drag forces in the air [6], but within a certain range the velocity reduction is negligible. Characteristics of the fragments impact on a structure are set according to their shape, mass, ballistic path and velocity. Impact of the fragments creates local structural damage due to their penetration into the structure. In addition to this damage, the total momentum of the fragments is transferred to the structural element and thus, the structure is exposed to combined loading of blast and fragments impact. Therefore, it is important to know the spatial distribution of the fragments, as well as their mass and velocity distributions, for the evaluation of the structural vulnerability to the fragments impact.

The fragments initial velocity (V_0) is related to the maximum casing velocity. It is usually calculated by the well-known Gurney formula [7] and taken as constant along the longitudinal axis of the cylindrical charge. In reality, it is only nearly constant, because, for a cylindrical charge that detonates at one end, the velocities near the charge edges are lower than the Gurney velocity [3,4].

Fragmentation analysis commonly deals with the mass distribution of the fragments but not with their spatial mass distribution. Studies of the fragments spatial distribution are very rare (see following text).

The above observations point to the importance of the fragments spatial mass distribution over the structure they strike. However, fragmentation is a very complicated phenomenon (e.g., [8]) and therefore it is difficult to predict the mass distribution of the fragments. Although discussed in several works, mass distribution from experimental data of cased charges is not commonly published due to classification issues, which makes its calculation validation rather challenging. For design purposes, the well-known Mott mass distribution is usually used [6]. Based on statistical considerations, Mott provided a formula to predict a cumulative mass distribution of the fragments, which was based on statistical and physical considerations. Design manuals provide empirical constants for the Mott distribution, which depend on the explosive type and charge dimensions. The mass distribution is very hard to predict by numerical simulations, because the fragmentation phenomenon includes statistical aspects and the material behavior should be accurately known.

Design of protective structures usually considers a single ‘design

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fragment', which represents a realistic, worst case scenario of a fragment impact. The point of interest is a minimum wall thickness to prevent scabbing or perforation by the impact of the 'design fragment'. The definition of a 'design fragment' refers to a fragment mass, which is larger than the masses of a certain percentage of the other fragments. Consequently, a 'confidence level' is defined as the criterion to identify the 'design fragment' [6], where a 95%% is commonly used for this estimation [8].

1.2. *Fragment spatial distribution*

When analyzing scabbing or perforation of a protective wall by fragments or projectile impact, it is reasonable to consider a single fragment with the highest mass and velocity. However, a more realistic scenario than that of the single 'design fragment' is the impact of multiple fragments, especially when looking at the global structural response due to the impact of fragments and blast. In this case, the fragments spatial distribution over a barrier is very important; yet, it has not been extensively studied or reported. In the following text, findings related to the fragments spatial distribution from previous works are presented.

Huang et al. [4] published flash-radiograph photos during the expansion process of a cylindrical charge after detonation (Fig. 1). They observed that most of the fragments were formed at the cylinder edge ('region 1' in Fig. 1) and that the fragments in this region were the smallest. They also observed that the narrowest fragments were found in a region marked as 'region 4' in Fig. 1. Thus, according to their photos it is likely that the spatial distribution by such pattern of fragmentation would not be uniform.

Two more examples of the fragmentation process from numerical simulations can be seen in Fig. 2. The figure shows results from Ugrčić [9] and from Xiangshao et al. [10]. It can be observed from the figure that the heaviest and narrowest fragments are located in the middle part of the charge, while at the edges there are smaller fragments. These results qualitatively agree with the experimental result of Huang et al. [4]. Ugrčić also tried to examine a possible correlation between each fragment's velocity and its mass but did not find any [9].

Krapp and Predebon [11] reported experiments, in which the fragment masses within given ranges of angles were recovered and plotted as a function of the spatial angle, measured from the longitudinal axis of a cylindrical charge, as described in Fig. 3. One can observe from Fig. 3 that there were heavy fragments in the middle part of the cylinder, while the lightweight fragments were located near the cylinder edges.

From the above examples of experimental and numerical calculations, it seems that although fragmentation of a cylindrical charge is random in some manner, it is characterized by heavier fragments in the middle part of the cylinder, and by many small fragments at the edges. Findings of the spatial fragments distribution over a surface they strike are presented in the following text.

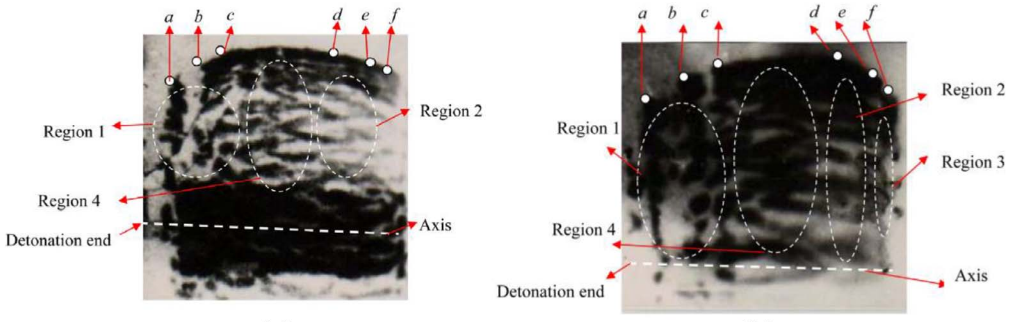
Cullis et al. [12] performed a single experiment and a corresponding numerical simulation of a detonated cylindrical charge. They put several witness plates at a given radius around the charge, to document the fragments impact. From their results, one can observe that the number of fragments was different over the height of each plate, which indicates a non-uniform fragments spatial mass distribution.

Arnold and Rottenkolber [13] performed experiments in which witness plates were placed to record the fragments impact due to a cased charge detonation. Fig. 4a shows an example of the recorded fragments impact from their experiments. It can be observed that there is a large mass of fragments that impacted within a limited area, marked in the figure by the dashed lines (the specific location of the dashed lines is explained in detail in Section 2), while the other area is impacted by large number of small fragments.

Bejar [14] conducted a statistical analysis of the fragments impact on a round target from explosion of a vertical cylindrical charge. He considered an infinitely long charge and studied the fragments distribution over the target. He then assumed that the fragments mass distribution is proportional to the ratio between the target area and a section of a cylindrical shape with a radius, which is equal to the distance between the target and the charge. That is, he used geometric considerations that correspond to the axial symmetry of the problem, which he analyzed, to evaluate the number of the fragments impacting the target. Yet, he further assumed that their spatial distribution over the target area is random.

Works that deal with the combined loading of blast and fragments, ordinarily apply simplifications in the characterization of the loading, i.e., of the pressure time-history of the blast and the mass, velocity and spatial distributions of the fragments. Such simplifications include the assumption that the spatial mass distribution of the fragments is uniform (e.g. [8,15,16]). According to this assumption, protective walls located within a certain range of distances from the charge, will be loaded by the same uniform distribution of the 'design fragment' (e.g. [8]). The above numerical and experimental observations suggest that unlike the common assumption in works that deal with the structural response to blast and fragments load, the fragments spatial mass distribution over a protective wall is likely to be non-uniform, and not uniform or random as commonly considered.

This paper presents a study of the spatial mass distribution of fragments, initiated from an end detonation of a cylindrical cased charge, over a vertical, plane protective wall. The aim of the study was to derive a reasonable, yet simplified, more realistic fragments spatial mass distribution over a protective wall, which can be considered for a more reliable global analysis of the wall. Note that the simplified approach for assessing the spatial distribution of the fragments, which is proposed in this paper, does not include a detailed analysis of the casing fragmentation. This is a different topic, which is out of the scope of this paper (i.e., this study does not pretend to predict accurately this detailed and complicated fragmentation). First, the simplified model is proposed together with its assumptions. Next, numerical simulations of the detonation of a cased charge are conducted to present and evaluate the model parameters, which are then also calculated from



(a) (b)

Fig. 1. Flash-radiograph photos at (a) 21.6 μs and (b) 44.2 μs after detonation [4].