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Velocity characteristics of fragments from prismatic casing under internal explosive loading

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ABSTRACT

In this study, a prismatic casing, which is a part of a variable geometry device, is designed to improve the effectiveness of its impact distribution. The fragment velocity of the casing is investigated experimentally by high-speed photography. The experimental data indicate that the fragment velocities are influenced by the rarefaction wave from both the axial and transverse directions. In addition, the Parallel for Multi-material in Cell 3D (pMMIC-3D) hydrocode, coupled with the Lagrangian marker-point weighted method, is used to numerically investigate the fragmentation process of the prismatic casing. The numerical results confirm the considerable influence of the rarefaction wave on the fragment velocity. Therefore, a correction formula is proposed to calculate the initial fragment velocity on the basis of the experimental data. The agreement between the numerical results and corrected results confirms that the correction formula can be used to predict the fragment distribution of such prismatic casings.

1. Introduction

In most ordnance fragmentation systems currently in use, the available impact distribution is rendered ineffective because of the lack of a method to achieve direction control [1]. A variable geometry device is designed to increase the capability for achieving fragment direction control and to ensure the distribution of a wide range of fragment particles over the target area. The device configuration can be cylindrical or polygonal. It is radially segmented into several sections, which are hinged together, and each section consists of a polygonal charge and metal casing. The device is usually unfolded and aimed at the target by detonating auxiliary charges, with its fragment side facing the target; the main charge is detonated simultaneously. Therefore, the fragment velocity distribution is an important design parameter for the device. It is necessary to investigate the initial and subsequent velocity distribution for increasing fragment direction control.

The explosive-driven fragmentation of ductile metals is a very complex phenomenon in which the fragmenting material undergoes plastic deformation because of the intense shock followed by high-rate plastic deformation, which ultimately leads to fracture. The topic of the fragmentation of metal casings has been of interest to many researchers for decades [2–7]. Goto et al. [8] presented a systematic approach to exploit an explosive-driven cylinder as not only an application-relevant fragmenting pipe bomb but also a dynamic test apparatus for controlled loading studies. Furthermore, the fragment velocity has always been a primary concern for many researchers. Gurney [2] from the Ballistics Research Laboratory published a report on the predicted velocity values of fragments generated from explosive-filled cylinders. The velocity derivation is based on an energy balance in which a cylinder of infinite length is filled with an explosive at a uniform density and is axially detonated simultaneously along its length. The Gurney formula takes the following form:

$$v_0 = \sqrt{2E}\cdot\sqrt{\beta/(1+0.5\beta)} \tag{1}$$

where v_0 and E are the initial casing velocity and the energy content of the explosive, respectively. In addition, $\beta = C/M$, where C and M are the explosive mass and casing mass, respectively. The term $\sqrt{2E}$ is normally referred to as the Gurney constant. The value of this constant varies with the explosive type and density. The values of this constant are empirically determined and can be found in the literature for a wide range of explosives [9]. Gurney assumed that all the parts of a metal casing rupture with the same initial fragment velocities; however, this assumption gives results that are different from those obtained from experimental data because the rarefaction wave generated at the ends are ignored. Zulkoski [10] developed a correction formula $C_f(x)$ by adopting an exponential form to describe the influence of the rarefaction wave at the ends on the initial fragment velocities; the formula is expressed as

$$C_f(x) = \left(1-e^{-2.3617x/d}\right)\left(1-0.288e^{-4.603(L-x)/d}\right) \tag{2}$$

where x is the axial distance from a certain point on the cylindrical casing to the detonation end, d is the diameter of the charge, and L is

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the length of the casing. The formula that predicts the initial fragment velocities while considering the rarefaction wave at the ends can be obtained by multiplying Eq. (1) with Eq. (2). Then, based on Zulkoski's research, Huang [11] proposed another correction formula, which is expressed as Eq. (3). Huang performed tests in which detonation is carried out at one end of the cylindrical casing, which is filled with an explosive charge. The correction coefficients are fitted by the experimental data obtained from the tests. Eq. (3) can be used to accurately calculate the initial fragment velocities along the axis of the cylindrical casing. Later, Grisaro [12] validated Eq. (3) by means of numerical simulation.

$$v_0(x) = \left(1-0.361e^{-1.111x/d}\right)\cdot\left(1-0.192e^{-3.03(L-x)/d}\right)\cdot\sqrt{2E}\cdot\sqrt{\beta/(1+0.5\beta)} \tag{3}$$

Although the available formulas can usually predict the fragment velocity of the cylinder casing, more complicated structures have hardly been evaluated. Thus, this paper presents a study of the fragment velocity caused by the explosion of a prismatic casing. The research activities carried out in this work can be summarised as follows. An experiment is performed to investigate the velocity characteristics of a prismatic casing with a waffle plate (PCWP) under interior blast loading using a high-speed camera. Numerical simulation is performed for the same explosive fragmentation geometry, which is modelled by the Parallel for Multi-material in Cell 3D (pMMIC-3D) hydrocode [13]. From the perspective of numerical simulation, the fragmentation driven by detonation is an intense fluid–solid coupling problem that involves high-rate strain and multiphase material interaction. Moreover, the waffle casing undergoes high-rate plastic deformation and dynamic fracture. Thus, an Eulerian formulation is necessary for the problem in spite of its weakness in terms of interface tracking. A coupled method based on mutual mapping between Lagrangian marker points and Eulerian meshes is proposed to track the interface and failure material for simulating the process of expansion, break-up, and production of high-speed fragments. The characteristics of the numerical fragment velocity distribution are in accordance with those obtained from the experimental data, and the results reveal that the rarefaction wave from the axial and transverse directions influences the fragment velocity distribution. A new correction formula is proposed to predict the initial velocities of fragments according to the experimental data. The corrected results are verified against the numerical simulation results, and a non-uniform velocity distribution is found along two directions. This illustrates that the correction formula can predict the fragment velocity of a prismatic casing.

2. Experimental

An experiment is performed to investigate the velocity distribution of pre-formed fragments of a prismatic casing under interior blast loading. A high-speed camera is employed to record the experimental process, and the fragment velocity distribution is approximately determined from the camera images, as will be described later.

2.1. Experimental setup

Fig. 1 shows the top view of the experimental setup. The dispersion and perforation of fragments are recorded by the high-speed camera. For safety reasons, the camera is located inside a protection box equipped with an explosion-proof glass window. The steel target is 4 m long, 2 m high, and 6 mm thick. The PCWP is placed on a 1 m-high shelf. To facilitate the detection of regularly shaped fragments, the fragment side facing the target is embedded with a piece of 5 mm-thick pre-formed waffle plate made from 30CrMnSi steel. The plate is cut with 1 mm-wide and 3 mm-deep crossed grooves. The plate is divided into 15 rows and 5 ranks according to the grooves, generating a total of 75 fragments. Each of them has a 10 mm side length. The physical photograph of the PCWP is shown in Fig. 2(a). Fig. 2(b) shows a simplified model, whose shape is similar to that of a triangular prism. The mass of the steel plate is 462.1 g. The dynamite filled in the casing is Composition B and is detonated

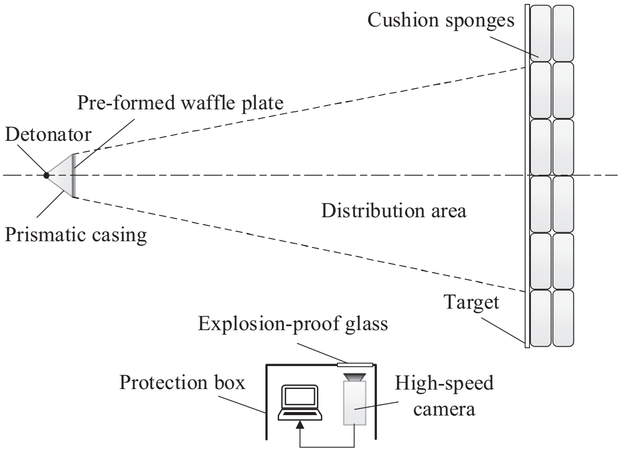

Fig. 1. Schematic view of experimental setup (top view).

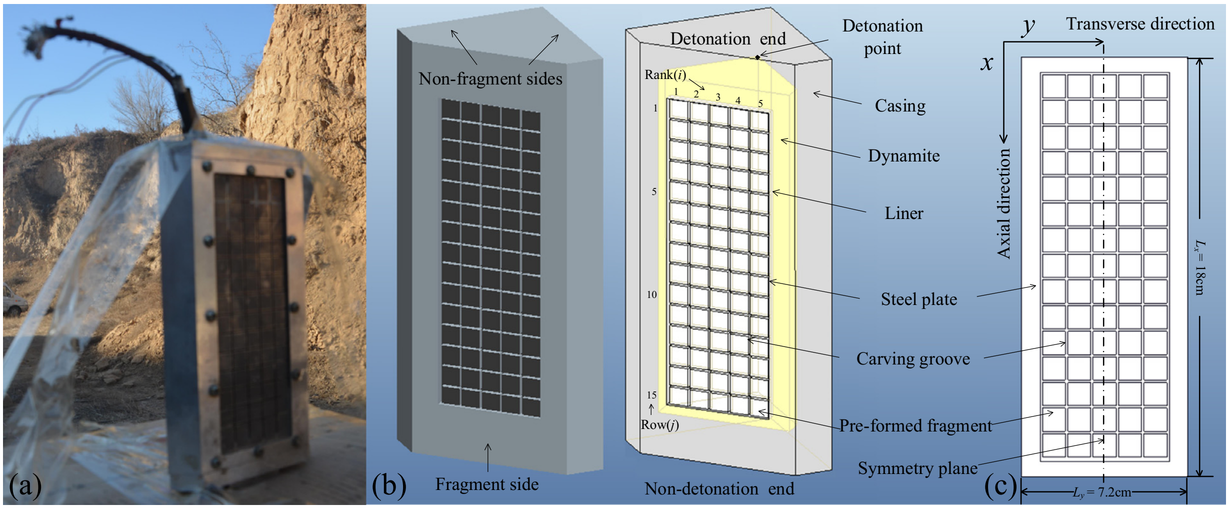

Fig. 2. Triangular prismatic casing with half-pre-fabricated fragment: (a) photograph, (b) model, and (c) waffle plate.