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Effects of U-notches on the dynamic fracture and fragmentation of explosively driven cylinders

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ABSTRACT

Metal cylinder specimens are explosively expanded to fragmentation and the effect of U-notches in walls are investigated on fragmentation behaviors and failure mechanisms of the cylinders experimentally and numerically. Fragments were recovered by sawdust and sorted into four categories according to fragment morphology and fracture mode. The shear fracture is pronounced in the low notch depth condition, while tensile fracture plays a leading role in higher notch depth. Moreover, mass percentage distribution of the fragments appears more affected by the notch depth than width. In addition, fragmentation energy and fragmentation toughness, considered as material properties, are discussed using Grady's energy-based theory. A suitable correction factor related to the width and depth of the notch is proposed to depict the effects of the U-notch. The effects of U-notches on the deformation and fracture behavior of cylinders are discussed with numerical simulations, indicating the stress concentration was noticeable at the notch tip, and the dynamic stress concentration factor (SCF) of the U-notch was less than that of the V-notch.

1. Introduction

Explosively driven fragmentation is a highly complex phenomenon in which the structure undergoes a rather complicated behavioral process of "expansion to deformation to fracture to fragmentation". The fragmentation process is much more involved than simple quasi-static uniaxial tensile fracture and shear fracture [1]. Numerous experimental methods have been used for fragmentation, including explosive cylinder technology [2] and expanding ring technology [3]. Since the cylindrical structure is widely used in the design of munitions and armaments, the dynamic fracture and fragmentation of this structure has been studied immensely since the Second World War. In the 1940s, Gurney [4], Mott [5], and Taylor [6] presented extensive studies establishing the theoretical foundations for this subject. Gurney derived empirical expressions for prediction of fragment velocities as a function of the ratio between the high explosive mass (C) and the metal cylinder mass (M), the energy of the high explosive available to drive the cylinder, and geometric factors. Mott estimated a statistical model for predicting average fragment sizes and fragment mass distributions. In the model, he proposed that the mechanism proceeded through random spatial and temporal occurrence of fractures resulting in a distribution of fragment lengths. A stress rarefaction wave propagates from the fracture while the fracture strain of the material achieves a mean value. The rarefaction unloads the material surrounding the fracture, preventing the possibility of further fracture in adjacent material. This process completes when the fracture-induced rarefaction waves subsume the entire cylinder. Taylor developed a model of fracture strain based on material tensile strength, internal pressure, and wall thickness of the steel cylinder. Studies on this topic, which has been researched for more than half a century, are extensive, and a large numbers of researchers [7–11] have contributed to this field. These early works laid the foundation for a field of study that continues to this day.

The performances of fragmentation warheads are usually described with characteristics of the fragment dispersion. These characteristics include mass and shape, projection angle and direction, velocity and distribution density of the fragments. In general, the natural fragmentation process leads to fracture of the cylinder wall into irregular and predominantly small fragments with low performance. In order to control the distribution of fragment masses and provide the desired terminal effects, many techniques have been utilized. The most famous method, cylinder grooving, has been used productively to control the phenomenon of dynamic deformation and dynamic fragmentation. Contrary to natural fragmentation, fragmentation controlled by weakening the cylinder structure with notches or grooves offers the possibility to adapt fragment parameters, such as size and mass, to the performance requirements in a very flexible way. Early fragmentation tests of notched-cylinder bombs were conducted by Philipchuk [12] in

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1953. The results indicated that better fragment size control could be achieved with internal notch depths up to at least 50% of the wall thickness. Then, Pearson [13] used the shear method to control fragmentation and developed a fragmentation model based on this method. Subsequently, the work reported by Lamborn [14] used external longitudinal and circumferential notches in cylinder walls to affect the break-up of cylinders upon detonation. These effects of notch geometry, hardness of wall material, pitch of notch, and the C/M ratio were discussed in his report. Then, Saunders [15] investigated the effects of the C/M ratio on the degree of control of fragmentation attainable by external longitudinal grooving, both unfilled and filled with an epoxy resin. Hiroe et al. [16] investigated the effects of wall materials, configuration, explosive energy, and initiated locations of fragmentation behavior of exploded notched cylinders both experimentally and numerically. Recently, an investigation on dynamic fracture trajectories of explosive cylinders with internal and external grooves was carried out by Li et al. [17]. Although the fragmentation behaviors and various effects have been determined over the past many years, however, the effects of U-notches on explosive-filled cylinders have not been fully explored.

In the present study, a series of conditions for testing were designed to investigate the effects of U-notches on dynamic fracture and fragmentation of explosively driven cylinders. The tests were performed on AISI 1045 steel with heat treatment. Fragments were sorted and measured, and the fracture was calculated. Moreover, the fragmentation energy was discussed and a derived expression of the factor was suggested using Grady's energy-based theory. Finally, the observed deformation and fracture behaviors are reproduced by numerical simulation using LS-DYNA software.

2. Experimental procedures

2.1. Experiment assembly

The developed experiment assembly for axially uniform or axially phased rapid expansion of cylinders driven by explosives is illustrated in Fig. 1. The casing, a stacked set of cylinders made of steel, is filled with explosive charge and a copper sleeve is placed before and after the array in order to confine the detonation wave passing down the cylinders. It is well known that there is significant difference between the dispersion angles of the fragments located in the center of the charge's surface and the ones located on its edges. The reason is rarefaction waves influencing the detonation gas near the ends. The phenomenon is called end effect. In order to minimize end effects influence on ejection angles of fragments, the use of a LY-12 aluminum cover, confining the detonation gas, was proposed. The end cover, made of LY-12 aluminum, is placed at the end of the array to protect cylinders from rarefaction waves. A plane wave generator is bonded to the end of the high explosive cylinder and is detonated at its apex with a detonator. The purpose of this plane wave generator is to provide near-planar detonation to the main charge. This caused cylinder walls to expand radially outward under the same conditions, thus resulting in similar strain variation in the longitudinal direction.

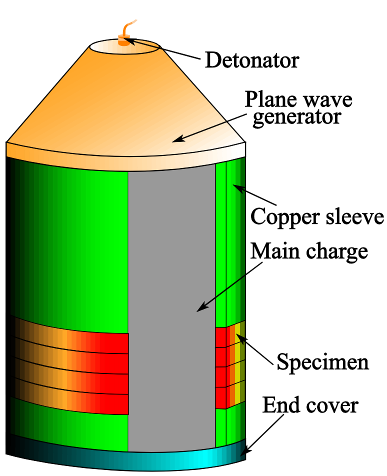

Fig. 1. Schematics of test assembly. The specimens, a stacked set of cylinders made of steel, are filled with main explosive charge and a copper sleeve is placed before and after the array.

2.2. Specimen design

Fig. 2 shows a basic test specimen used in the experiments. The cylinder consists of a 100 mm outer diameter with a 10 mm wall thickness, and the height t of the cylinder is 5 mm in order to achieve a plane-stress condition, approximately. An axis-symmetric cylinder, notched longitudinally, is used for the testing. The angle θ of adjacent external notches, as notches, is evenly spaced at 18°. The angle between adjacent external and internal notches is $\theta/2$. The profile of the notch is U-shaped with width w and depth d. The materials and dimensions of the notches are given in Table 1. The cylinder material, AISI 1045 steel, is a medium carbon steel and the chemical constituents and mechanical properties are summarized in Table 2.

2.3. Test setup

The test setup is illustrated in Fig. 3. The recovering unit consisted of sawdust placed in a semi-circle with a 2 m radius, which is designed to collect cylinder fragments softly. The height and thickness of the recovering unit are 1.5 m and 1.2 m, respectively. Three trigger circuits connected to an oscilloscope (OSC) measure the velocities of the fragments. The trigger consists of two copper foils and insulating foam. Electrical signals are recorded by the OSC as a fragment penetrates the trigger circuits. Three signals were obtained in the experiment. Based on the time interval of each two signals and a fixed distance between the triggers, the fragment velocity was calculated by the ratio of the distance to the time interval.

3. Experimental results and analysis

3.1. Fragment categories

About 70% of the fragments were successfully recovered and minimized any unintentional damage by the sawdust (Fig. 4). Two main types of fracture have been observed in the dynamic fracture of cylinders, namely, shear fracture at approximately 45° to the circumference of the wall, and tensile fracture along the radial direction of the wall. The fragments recovered from cylinders with different sized notches were sorted into four main categories based on fragment morphology and fracture mode (Fig. 5). These categories are:

(1) Tensile-mode fragment.
(2) Shear-mode fragment.
(3) Mix-mode fragment.
(4) End fragment.

As Fig. 5 shows, the tensile-mode fragments were the result of cracks, which formed and grew from the root of adjacent external notches or adjacent external and internal notches. The sizes of tensile-mode fragments consisted of two categories, large and small,