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Numerical simulation of the natural fragmentation of explosively loaded thick walled cylinders

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Abstract

The ability to predict the natural fragmentation of an explosively loaded metal casing would represent a significant achievement. Physically-based material models permit the use of small scale laboratory tests to characterise and validate their parameters. The model can then be directly employed to understand and design the system of interest and identify the experiments required for validation of the predictions across a wide area of the performance space. This is fundamentally different to the use of phenomenologically based material algorithms which require a much wider range of characterisation and validation tests to be able to predict a reduced area of the performance space. Eulerians numerical simulation methods are used to describe the fragmentation of thick walled EN24 steel cylinders filled with PBXN-109 explosive. The methodology to characterise the constitutive response of the material using the physically based Armstrong–Zerilli constitutive model and the Goldthorpe path dependent fracture model is described, and the results are presented. The ability of an Eulerian hydrocode to describe the fragmentation process and reproduce the experimentally observed fragment mass and velocity distributions is presented and discussed. Finally the suitability of the current experimental analysis methodology for simulation validation is addressed.

Keywords: Fragmentation; Numerical simulation; Euler; Material model

1. Introduction

The natural fragmentation of a shell, projectile or munition under the dynamic loading regimes of impact and detonation waves is of considerable interest to the warhead designer, the system designer and the ultimate end user who has to deploy it. Knowledge of the physics and dynamic material properties as drivers of the fragmentation process allows for their effective exploitation in a weapon design. The fragmentation is an important element in defining the Critical Effects Radius (CER) of a system, its potential for collateral damage, and hence its possible deployment roles in different theatres of operation.

The Weapons Science & Technology Centre (WSTC) meets the needs of the MOD and Industry in the provision of complex weapons research and technology. It delivers an appropriate balance of timely exploitable technology, innovation and the sustainment of UK sovereign capability and expert advice to support future procurements.

The WSTC was set up and established during 2008 and has been a successful change programme delivering a partnering approach to the management of complex weapons research in the UK. It has over 41 partners that comprise a mix of industrial primes, technology and sub-system providers, subject matter experts, consultants and academia.

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The WSTC recognised that the ability to predict natural fragmentation using numerical simulation would represent a significant cost effective design capability. It therefore defined a research requirement to understand the ability of a number of different numerical simulation methodologies to describe the fragmentation of explosively loaded steel cylinders and predict the number of fragments generated including their masses and angular distributions. The numerical methods studied in the programme included, Euler, Euler–Lagrange and Smoothed Particle Hydrodynamics (SPH). The programme was led by Raytheon Systems Limited (RSL). This paper is concerned with the Euler element of the programme performed by QinetiQ. It describes the ability of the in-house Eulerian hydrocode GRIM to predict the experimentally observed fragmentation pattern, the issues identified and the work to understand them. The secondary objective of the study was to determine the effectiveness of the current experimental methods to characterise the fragmentation process and fragment distributions as a method for validating numerical simulations.

2. Background

The primary requirement of the study was to investigate the ability of different numerical schemes to reproduce the experimentally observed fragmentation pattern of a simple explosively loaded steel cylinder. This included the number and masses of the fragments and their angular distribution. The ability of the experimental method to provide an accurate measurement of the fragmentation process was also a factor in the study.

An additional objective was to understand the behaviour of the different material and fracture models used in the simulations and the material testing required to characterise them. In the case of the fracture algorithm, this includes the initiation of the fracture process, post fracture development and identification of fragments.

There has been some significant work to develop models to predict the natural fragmentation process of metals since the seminal work by Mott [1]. Grady [2,3] developed an energy based approach to predict the size of fragments based on strain rate and a fragmentation toughness constant for the material. This methodology has also been applied to brittle materials with some success [4].

The work of Brannon [5] on ceramics has made a significant contribution to the numerical simulation of fragmentation. In a brittle material, the concept of a critical flaw that acts to initiate fracture is well established. It implies that there is therefore a volume of material associated with this critical flaw size and that the failure is size dependent. The standard approach to characterising the critical flaw size from material tests therefore is to apply Weibull statistics to assign a probability of failure of the material. Brannon, in simulating the impact of a projectile with a ceramic target, used the numerical cell volume as the control volume and Weibull statistics to seed the cell with a failure probability, which was initiated using a random number generator. The method led to a significant improvement in the ability of the simulation to describe the experimental results. This approach has been extended to ductile metal fragmentation, with the numerical mesh seeded with failure sites which are initiated using a probability function [6,7]. Variations of this approach were used in the other numerical methods investigated in this study. As they were not employed in the QinetiQ study, they will not be discussed here.

The experimental study of the natural fragmentation of metal cased explosive charges and shells has also been reported in Refs. [8–10]. The work by Hiro et al. [10]. is very useful in understanding the roles of cylinder wall thickness and defined crack initiation sites on fragment size and distribution. The work of Chhabildas et al. [8] on an AERMET® 100 steel cylinder with similar dimensions to the charges in this study is also particularly relevant.

3. Experiments

The experimental programme was performed at QinetiQ Shoeburyness, UK, and consisted of three firings. The fragment spatial distribution, fragment mass distribution and fragment velocity spatial distribution were measured for each firing.

The experimental layout is shown in Fig. 1. The cylinder was located at the centre of the arena mounted on a polystyrene block. The centre of the cylinder was at a height of 1.5 m above the ground. The charge was initiated by an electrical bridge wire detonator fitted to the top of the cylinder. A velocity foil on the cylinder captured the start of case rupture.

Strawboards to capture fragments were located at a distance of 3 m from the centre of the cylinder. The strawboard array was 3048 mm high by 2032 mm wide and spanned 37.4° in azimuth and 53.9° in elevation. The strawboard was fitted with velocity foils residing in 11 5° angular (polar) zones. The coordinate system and ITOP angular zones for recording fragmentation data are shown in Fig. 2. The origin of the coordinate system is at the centre of the cylinder. The centre of the strawboard is aligned with the centre of the cylinder. The ITOP angular zones that coincide with the strawboard (Angular Zones 14 to 24 inclusive) are shown in Fig. 3.

The ITOP protocol [11] is a NATO standard that has been established to provide a standardised methodology for characterising and measuring naturally fragmenting weapons.

A soft fragment recovery system and additional instrumentation, including blast gauges and high speed cameras, were included in the arena to recover undamaged fragments and to provide additional information on the early time expansion of the cylinders, fragment formation and motion for velocity determination.

4. Fragmentation cylinders

The cylinders for the experiments were manufactured by QinetiQ Fort Halstead, UK, and were made from EN24W steel