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Mild steel plates impacted by hard projectiles

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ABSTRACT

The evaluation of ballistic resistance of steel targets is important due to its direct application to the safety of defense protective structures such as bunkers for military personnel, shelters for arms and explosives as well as safety of nuclear containment against missile impact. Experiments on penetration of 23 mm hard projectiles into mild steel plates were performed for 500 mm square plates with 30, 50, 60, and 150 mm total thicknesses. Results for ballistic limits obtained from existing empirical and analytical relations are compared with those from experiments. In addition, numerical simulations to predict the experimental results were made. Erosion (cell removal) criteria were established in order to realize simulation. Effect of the erosion strain value for which cells are removed on the prediction of penetration into steel plates was investigated. The numerical results show that erosion strain value has a significant effect on the prediction of perforation into steel plates.

1. Introduction

A common method of guarding against possible impact damage when weight and space are not at a premium is to use a bulky shield (thin to intermediately thick metallic targets) to protect sensitive areas [1]. The evaluation of ballistic resistance of metallic targets is important due to its direct application to the safety of defense protective structures such as bunkers for military personnel, shelters for arms and explosives as well as safety of nuclear containment against missile impact [2]. The ballistic limit of a target, in general terms, is the greatest projectile velocity the target can withstand without perforation occurring [1]. Precise definitions of this parameter vary depending on the interpretation of the term perforation, a more detailed discussion concerning these terms can be found in [3].

The behavior of armor plates subjected to impact by projectiles, for velocities including and exceeding ballistic limits, has been investigated: experimentally, analytically, and numerically using explicit finite element code which, if properly validated, could be considered as the most potent approach for predicting ballistic limits of armor plates and for designing optimized as well as innovative solutions [4]. To ascertain the predictive capabilities of numerical simulations, validation experiments are required, despite the extreme high cost and the significant amount of time requirement for experimental setup and specimen preparation.

Literature survey on experimental studies for determining ballistic limit of plates and the residual velocity of the projectile for incident velocities higher than the ballistic limit has been covered in many comprehensive reviews [1,3,5–8]. In normal impact studies that have appeared in literature, the plate thicknesses have generally been small, less than 12 mm [9]. In the experiments performed by Gupta and Madhu [9], the maximum thickness of the aluminum AL3 plates was 40 mm. Because plates of higher thickness were not available, they included some of multi-layered target results to help determine ballistic thickness from extrapolation of the residual velocity–plate thickness curve. Experiments on multi-layered targets available in literature are rather few [10], and the benefits of using multi-layered plates as against monolithic plates of equal thickness are not clear as yet [9]. Analytical and experimental study on the ballistic resistance of multi-layered plates both adjacent and spaced made on steel and aluminum [9–13] showed that the ballistic resistance of the monolithic target was greater than or at least equal to that of the layered target of corresponding total thickness. On the other hand, Corran et al. [7] found that layers placed in contact were superior to monolithic single layer plates if the adoption of multiple layers changed the response of the plates from being one dominated by plate bending and shearing to one dominated by membrane stretching.

If the objective of engineering design of perforation-resistant armor plates is the estimation of ballistic limit and residual velocity rather than predicting the detailed geometry of failure, a number of empirical or semi-empirical relations [3,14–19] have been developed to facilitate this objective. However, most of these relations rely on empirical material parameters, which are difficult to determine [19]. Some of these empirical formulae were developed many years ago such as the

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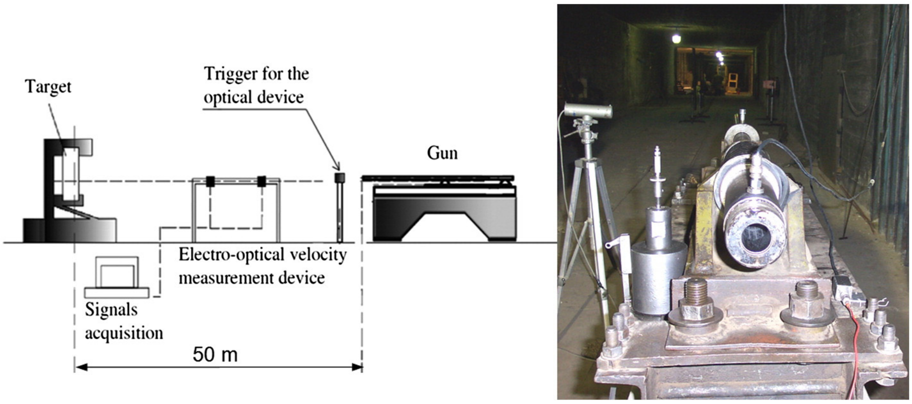

Fig. 1. Scheme of the experimental set-up.

well-known Robins–Euler formula [1,20]. Recently, Raguraman et al. [19] introduced two relations employing standard material parameters (i.e. mass and diameter of projectile, impact velocity and angle of impact, and plate thickness) for predicting residual velocity of small caliber projectiles and ballistic limit. The empirical constant appearing in their relations was determined by regression analysis of test data for mild steel target plates.

If the objective of engineering design is the prediction of detailed geometry of failure, the finite element method has become an increasingly useful tool for the analysis of impact events, and current commercial codes such as AUTODYN [21,22], LS-DAYN [23], and ABAQUS [24] are well suited to dealing with problems involving large deformations and elevated strain rates [25]. However, erroneous results can be obtained due to the use of models that are ill-suited to the problem, failure to recognize numerical instabilities (which may be attributed to physical phenomena), poor mesh specification, and use of inappropriate property data and constitutive relations [26].

Severe element distortion problem is observed in finite element mesh while performing numerical simulations of high velocity steel projectile penetration targets. This problem of element distortion in the Lagrangian formulation of finite element method can be resolved by using element erosion approach that is applied by defining failure parameters as a condition for element elimination. Borvik et al. [27] stated that in the highly complex non-linear finite element simulations the material behavior is not the only matter causing problems, several challenges are associated with the numerical approach itself. Among these challenges is the erosion criterion and special care must be taken in order to avoid errors and premature termination of the analysis. Schwer and Day [28] presented several techniques (for example; rezoning, element erosion, tunnel, local modified symmetry constraint and NABOR node techniques) to solve the element distortion problem. Among these various approaches element erosion method is widely used because of its simplicity in implementation. It gives a visual representation of the material fracture and damage in numerical analysis, which makes it possible to understand material failure in more details for high velocity impact problems. In the element erosion method, severely distorted elements are removed or eroded from further analysis to allow the projectile to penetrate into the target. The elimination process is performed based on some failure criteria such as, maximum or minimum pressures, stresses or strains. Strain based element erosion criterion is the most popular [29–32]. However, there is no test procedure available to determine these failure criteria for an intended target material. It should be noted that the element erosion is a numerical consideration and not as same as the material failure. In this study, strain parameters are used as failure criteria. Since no direct method exists to determine these values, a calibration approach is used to establish suitable failure strain values while performing numerical simulations of blunt-nose steel projectile penetration into steel target.

In the present study, numerical simulations have been performed to predict the experimental results. The constitutive models do not contain erosion. Element erosion approach is a separate option where erosion criteria can be set independently. Cells are removed after their effective strain exceeds the adopted erosion strain value. There are three kinds of effective strain: effective plastic strain, effective incremental geometric strain and effective instantaneous geometric strain. The latter is used here. If deformed cells are removed, the influence of their mass in the Lagrange grid will not be taken into consideration and the compressive strength as well as the internal energy of the removed cell material are not being maintained and do not appear in the subsequent calculations.

The objective of the present study is twofold:

1. To produce a new range of experimental data that can be used as benchmark tests for analytical theories and finite element methods and for comparison with recent models and the possible development of new models.
2. To establish suitable failure strain values that can be used in numerical simulations of blunt-nose steel projectile penetration into mild steel target, using non-linear finite element program.

2. Experiments

In the present paper, experiments on hard (armor-piercing) projectiles penetrated into mild steel monolithic and multi-layered targets were performed. The projectiles were launched from a 23 mm powder gun that was mounted on a rigid mount. Projectiles were fired with velocities of about 970 m/s or less. To reduce the projectile impact velocity an amount of powder (explosive substance used to drive the projectile) was removed from the projectile cartridge.

The projectile impact velocity was measured with electro-optical velocity measurement device. The target-holding fixture was located at a distance of 50 m from the gun. The tests were conducted in the laboratory setup described in Fig. 1. The projectile was 23 mm in diameter, 64 mm long and weighed 175 g (Fig. 2). It was made of hard-steel alloy with a blunt-nose. The mechanical properties of the projectile are shown in Table 1.

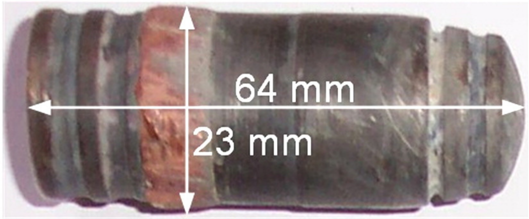

Fig. 2. Dimensions of the projectile.