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The ballistic performance of metal plates subjected to impact by projectiles of different strength

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ABSTRACT

In this paper, the ballistic performance of monolithic, double- and three-layered steel plates impacted by projectiles of different strength is experimentally investigated by a gas gun. The ballistic limit velocity for each configuration target is obtained and compared based on the investigation of the effect of the number of layers and the strength of projectiles on the ballistic resistance. The results showed that monolithic plates had higher ballistic limit velocities than multi-layered plates for projectiles of low strength regardless their nose shape, and also the ballistic limit velocities of plates decreased with the increase of the number of layers. Moreover, monolithic plates showed greater ballistic limit velocities than multi-layered plates for ogival-nosed projectiles of high strength, and also the ballistic limit velocities of plates decreased with the increase of the number of layers. However, monolithic plates had lower ballistic limit velocities than multi-layered plates for blunt-nosed projectiles of high strength, and also the ballistic limit velocities of plates increased with the increase of the number of layers. The differences in the ballistic limit velocities between various impact conditions can be related to the transitions of perforation mechanisms and failure models of plates and projectiles.

1. Introduction

When a single plate is replaced by several layered plates, the number, thicknesses and order of layers, the air gap between layers, the nose shape and strength of projectiles affect the failure models of plates that lead to the differences of ballistic performance between different impact conditions. A lot of investigations have been conducted on the study of the ballistic resistance of monolithic and multi-layered plates experimentally, numerically, and theoretically.

Zhang and Deng et al. [1–3] carried out an extensive experiments on the monolithic and multi-layered steel plates struck by blunt-, ogvial- and hemispherical-nosed projectiles of high strength in order to investigate the effect of the air gap between layers, the number, order and thickness of layers on the on the ballistic performance of plates.

Gupta et al. [4] investigated the ballistic performance of multi-layered aluminum plates under the impact of flat-, ogival- and hemispherical-nosed steel projectiles. It was observed that the residual velocities of the projectiles for double-layered plates were comparable to those of the single plates of equivalent thicknesses. However, the single plates offered more resistance against perforation when the number of layers was increased. Ogival-nosed projectiles were found to be the most efficient penetrator, but hemispherical-nosed projectiles required maximum energy for perforation. Moreover, results of the finite element analysis were compared with experiments and a good agreement was found. Radin and Goldsmith [5] compared the ballistic resistance of monolithic and multi-layered aluminum plates that impacted by blunt- and conical-nosed projectiles. It was found that the ballistic resistance of in-contact multi-layered plates was inferior to that of monolithic plates of equal thickness, and also spaced multi-layered plates were less effective than in-contact multi-layered plates. Almohandes et al. [6] conducted an extensive experiments on mild steel plates struck by standard bullet to investigate the effect of target configuration on the ballistic performance. They concluded that monolithic plates were more effective than multi-layered plates of equal thickness. Moreover, the ballistic resistance of multi-layered plates decreased with the increase of the number of the layers. The ballistic performance of double-layered plates can be enhanced by using a thicker back plate, and also in-contact multi-layered plates had higher ballistic resistance than spaced multi-layered plates. Nurick and Walter [7] studied the ballistic

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resistance of multi-layered steel plates using conical- and flat-nosed projectiles. It was revealed that the ballistic limit velocities of monolithic plates were 4–8% higher than those of the in-contact multi-layered plates of equivalent thickness. Woodward and Cimpoeru [8] carried out experimental studies on multi-layered aluminum alloy plates of the same total thickness that perforated by blunt- and conical-nosed projectiles. It revealed that multi-layered plates of two equal plates presented the best performance followed by multi-layered plates of a thicker front plate and a thinner back plate, multi-layered plates of a thinner front plate and a thicker back plate. The monolithic plates were more effective than multi-layered plates, and also these conclusions of blunt-nosed projectiles were the same to those of conical projectiles. Marom and Bodner [9] carried out experimental and theoretical studies on the perforation behavior of multi-layered thin aluminum beams under impact by spherical-nosed bullet projectiles. They concluded that the general order of the ballistic resistance of the beam targets, starting with maximum, was multi-layered flat beams in contact, an equivalent weight uniform beam, and separated flat beams of equal weight. Corran et al. [10] carried out a series of experiments on the performance of multi-layered mild steel plates under impact of flat projectiles. They found that the in-contact layered plates were superior to the monolithic plates whose energy absorption dominated by membrane stretching. Teng and Dey et al. [11–13] recently reported comprehensive experimental and numerical studies on the perforation resistance of double-layered steel armor plates. They found that the ballistic limit velocity of a double-layered shield was 30% higher than that of the monolithic case in the case of a blunt-nosed projectile. However, these advantages seemed to disappear when ogival-nosed projectiles were used.

It appears from the above literature review that there have been many papers which examined the deformation and failure behavior of plates that most focus on the rigid projectiles impact tests. However, the effect of deformation and failure behavior of projectiles to the ballistic performance of steel plates is limited. It is poses an interesting question: Under what kind of projectile impact would a multi-layered shield be superior in the ballistic limit velocity than a monolithic plate of the same total thickness?

Besides the studies of rigid projectiles, the deformable projectiles were also used for the ballistic tests of monolithic plates. Dongquan and Stronge [14] examined the effect of various parameters on the extent of global deformation and localized failure mechanisms of the target plate that as a function of the relative size of plate and projectiles, flow stress and fracture strain of the plate, projectiles mass and deformability at impact velocities close to the ballistic limit velocities. Chen et al. [15] constructed a rigid-plastic model to assess the effect of a soft nose on the perforation of metallic plates struck by stubby projectiles. Effects of transverse shear, bending and membrane deformations on the perforation process were included in a rigid-plastic analysis. Chen et al. [16] described experimental and numerical studies concerning the impact of steel blunt-nosed projectiles against harder steel plates at impact velocities between 200 and 800 m/s. Tang [17] investigated the influence of soft nose of projectiles on the perforation of steel plates by experiments. The initiated ahead structural response of target plate was beneficial to decrease the relative impact velocity between projectile and target and to increase the time duration of perforation. Similarly, Kim et al. [18] carried out the numerical simulations and experiments that indicated that the soft nose acts as an energy absorber to be beneficial for the integrity of projectile structure in the perforation.

It is evident from the literature review, the assumption of non-deformable (rigid) projectiles is usually employed in the analysis of the ballistic resistance of monolithic and multi-layered plates, and also the experimental data for the ballistic limit velocity has been interpreted in relation to mass, radius, nose shape of projectile, plate thickness and number of layers but not in relation to the ductility of the projectile material. In other words, the investigation on the projectile deformation and fracture behavior in the impact test is limited and patchy. Especially, reports regarding the effect of projectile strength on the failure and ballistic limit velocities of multi-layered plates are few. In fact, the failure models of projectiles greatly affect the perforation efficiency of projectiles and the ballistic performance of plates. So, further detailed studies, especially experimental investigation is required. Thereby, this paper will concentrate on the ballistic capacity of monolithic and multi-layered plates, where the varying factors will be the number of layers in relation to the strength and nose shape of the projectiles. To do this, the ballistic resistance of monolithic and multi-layered plates of the same equivalent thickness against blunt- and ogival-nosed projectiles impact is studied.

2. Experimental details

2.1. Experimental setup

The impact tests were conducted in a one-stage gas gun at Hypervelocity Impact Research Center in Harbin Institute of Technology, where the impact velocity was controlled directly by the gas pressure, as depicted in Fig. 1. Square targets with a side of 230 mm were fixed to a thick armor plate by means of eight bolts arranged on a 170 mm diameter pitch circle in the target chamber, as shown in Fig. 2.

A Photron FASTCAM SA5 high speed camera was used to record the process of projectile penetrating target and the projectile motion. From the digital images, traveled distance, impact angle, velocity and acceleration as a function of penetration time for the projectiles during penetration were obtained. The selected frame rate was 50,000 per second, so that a frame was taken every

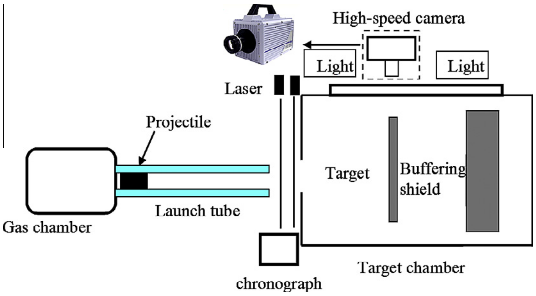

Fig. 1. Schematic of one-stage gas gun experimental system.

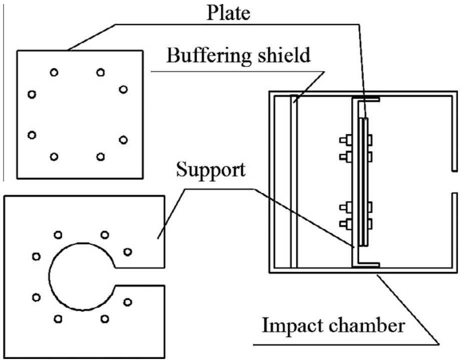

Fig. 2. Target supports.