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Experimental investigation on the ballistic performance of double-layered plates subjected to impact by projectile of high strength

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ABSTRACT

In this paper, the ballistic performance of double-layered steel plates of different materials impacted by blunt- and ogival-nosed projectiles is experimentally investigated by a gas gun. The ballistic limit velocity for each configuration is obtained and compared on the investigation of the effect of the order of layers and the nose shape of projectiles on the ballistic resistance of targets. The experimental results showed that the ballistic limit velocities are higher for the double-layered plates of the upper layer of high strength and low ductility material and the lower layer of low strength and high ductility material than the configuration of the opposite layering order. Moreover, the ballistic limit velocities of ogival-nosed projectiles are significantly smaller than those of blunt-nosed projectiles. Furthermore, the keep integrity ability of ogival-projectiles is obvious stronger than that of blunt-nosed projectiles, and also the blunt-nosed projectiles lose some mass and their length shorten, but the loss of mass and length of ogival-nosed projectiles are tiny that can be neglected. 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

Optimization design of metal shields for protection against projectiles impact has long been of interest in military and civilian applications. As a potential improvement over monolithic plates, a multiple layer configuration that consists of several parallel plates has been proposed [1]. In fact, there are a great number of multi-layer plates used in engineering structure for design and manufacture intention. Although a lot of investigations have been done on the perforation resistance of monolithic plates experimentally, numerically, and theoretically, limited studies on multi-layered metal shields were reported in the open literature.

Zhang and Deng et al. [2–4] 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 steel plates. Deng and Zhang et al. [5] carried out an extensive experiments on the ballistic performance of monolithic, double- and three-layered steel plates impacted by blunt-nosed projectiles of different strength. The results showed that monolithic plates had lower ballistic limit velocities than multi-layered plates for projectiles of high strength, but monolithic plates given greater ballistic limit velocities than multi-layered plates for projectiles of low strength. Gupta et al. [6] 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 for monolithic plates of equivalent thicknesses. However, the monolithic plates offered more ballistic 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 analyses were compared with experiments and a good agreement was found. Radin and Goldsmith [7] compared the ballistic resistance of monolithic and multi-layered aluminum plates that impacted by blunt- and

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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. [8] conducted out an extensive experiments on mild steel plates struck by standard bullets 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 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 et al. [9] studied the ballistic 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 total thicknesses. Woodward and Cimpoeru [10] 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, and also the conclusions of blunt-nosed projectiles were the same to these of conical-nosed projectiles. Moreover, the monolithic plates were less effective than multi-layered plates for blunt-nosed projectiles, but the comparisons of the ballistic limit velocities between monolithic and multi-layered plates is not consistent for ogival-nosed projectiles. Marom and Bodner [11] 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 of equal weight, starting with maximum, was multi-layered flat beams in contact, uniform beams and separated flat beams. Corran et al. [12] carried out a series of experiments on the performance of multi-layered mild steel plates under the 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. [1,13] 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, the advantage seemed to disappear when ogival-nosed projectiles were used. Moreover, Teng et al. [14] evaluated the ballistic resistance of double-layered steel shields against projectile impact at the sub-ordnance velocity by using finite element simulations. It was shown that a double-layered shield of the same metal was able to improve the ballistic limit by 7.0–25.0% under impact by a flat-nose projectile, compared to a monolithic plate of the same weight. However, the double-layered shield was almost as capable as a monolithic plate under impact by a conical-nose projectile. Furthermore, it revealed that the best configuration was the upper layer of high ductility and low strength material and the lower layer of low ductility and high strength material. Dey et al. [15] revealed the effect of the layering order of plates on the ballistic resistance of double-layered plates by numerical study. They replaced one or both of the 6 mm thick Weldox 700E steel plates (soft) in the double-layered plates by 6 mm thick Armox 560T steel plates (hard), while keeping the protection weight and thickness the same. When one or both plates in the target were replaced with a stronger plate, the ballistic limit increased for both nose shapes. The double-layered plates of Weldox 700E + 6 mm Armox 560T had the highest ballistic limit velocity followed by 2 × 6 mm Armox 560T, 6 mm Armox 560T + Weldox 700E, Weldox 700E + Weldox 700E for blunt-nosed projectiles. The layering order had great influence on the ballistic limit velocity of plates, and also the increase was significantly higher if the softer Weldox 700E plate was placed in front of the hard Armox 560T plate. Moreover, the double-layered plates of 2 × 6 mm Armox 560T had the highest ballistic limit velocity, while Weldox 700E + Weldox 700E had the lowest ballistic limit velocity, and also layering order on the influence on the ballistic limit velocity of plates can be neglected for ogival-nosed projectiles. Furthermore, the experimental results were opposite to the numerical results given above for the blunt-nosed projectiles, while the results for the ogival-nosed projectiles were rather close. Ben-Dor et al. [16] found that a parameter determined the order of the plates in the multi-layered armor targets that provided the maximum ballistic limit velocity for rigid sharp impactor, namely, the plates must be placed in the order of increasing this parameter, regardless of their thicknesses. The right order of plates can be of prime importance if the values of this parameter vary strongly for different plates. Flores-Johnson et al. [17] presented a numerical investigation of the ballistic performance of monolithic, double- andtriple-layered metallic plates made of either steel or aluminum or a combination of these materials impacted by a 7.62-mm APM2 projectile. It was found that monolithic plates have a better ballistic performance than that of multi-layered plates made of the same material, and the double-layered plates with a thin front plate of aluminum and thick back steel plate exhibit greater resistance than multi-layered steel plates with similar areal density. Ben-Dor et al. [18] conducted analytical, numerical and experimental investigations on the effect of layering, spacing and change of the order of the plates on the ballistic performance of shields. It indicated that the order of plates of different materials in multi-layer shields may strongly affect the ballistic performance of the shield. Ben-Dor et al. [19] analyzed the effect of re-arranging plates in the shield against non-conical rigid impactors by approximate model for ductile layered shields.

Besides the studies of rigid projectiles, the deformable projectiles were also used for the ballistic tests of monolithic plates. Dongquan Liu and Stronge [20] examined the effect of various parameters on the extent of global deformation and localized failure mechanisms of plates that as a function of the relative size of plate and projectile, flow stress and fracture strain of the plate, projectiles mass and deformability at impact velocity close to the ballistic limit velocity. Chen et al. [21] 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. [22] described experimental and numerical studies on the impact of blunt-nosed steel projectiles against harder steel plates at impact velocity between 200 and 800 m/s. Tang [23] 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 also to increase the time duration of perforation. Similarly, Kim et al. [24] indicated that the soft nose acts as an energy absorber to be beneficial for the integrity of projectile structure in the perforation by numerical simulations and experiments.

The above literature indicate that the protection effectiveness of multi-layered plates remains a subject of debate. Moreover, the assumption of non-deformable projectiles was usually employed in the analysis of terminal ballistic resistance of targets in most investigations. In other words, the investigations on the projectile deformation and fracture behavior in the impact tests were limited and patchy. Especially, reports regarding multi-layered plates