International Journal of Impact Engineering 000 (2017) 1–10

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

An experimental and numerical investigation of the ballistic response of multi-level armour against armour piercing projectiles

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ARTICLE INFO

Article History:
Available online xxx

Keywords:
Armour piercing projectile
Perforated armour plate
High speed impact

ABSTRACT

This research deals with the experimental and numerical investigation of ballistic protection provided by a combination of perforated and base armour plates. A 7.62 mm armour piercing projectile was used during the experimentation to determine the ballistic response of an aluminum base armour plate and a combination of steel perforated and aluminum base armour plate. The armour piercing projectiles were able to penetrate the base armour plate while the combination of perforated and base armour plates was able to stop the penetration of the armour piercing projectile. A finite element method based numerical model was developed to investigate the defeating phenomenon of perforated and base armour plate combination. The brittle fracture caused by the bending of the projectile core due to the asymmetric impact was predicted and the resulting fragments of the projectile were unable to penetrate the base armour plate. Craters were formed on the surface of the base armour plate from the impact of the projectile fragments. The numerical model was able to predict the hole growth and penetration of projectile when only the base armour plate was impacted by the projectile.

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1. Introduction

Protection against projectiles of small calibre is a major concern for military and civilian structures. Metallic armour plates are commonly used on moving and static platforms to protect against multiple types of projectiles. The weight of the armour is a critical factor, especially when used on moving platforms. Thus, aluminum plates of high strength are a good choice for protection of moving platforms. However, armour piercing (AP) projectiles of even small calibre can penetrate the aluminum armour plates that provide protection against normal projectiles of the same calibre. The phenomenon of penetration of an AP projectile in an armour plate was explained by Woodward [1]. An initial increase in the hardness of the armour plate increases the penetration resistance because of the increased plastic flow resistance of the material. However, adiabatic shear becomes the dominant phenomenon after a threshold value of the armour plate hardness is achieved and the penetration resistance of an armour plate starts to decrease. If the hardness of an armour plate is further increased, fracture of the AP projectile core occurs because of the increased hardness. Brittle fracture of an armour plate may occur at very high hardness levels due to decreased toughness of the material. Steels of 500 HB hardness are considered to be in the transition region between the adiabatic shear and the projectile fracture [2].

To minimise the weight of the armour and improve the protection against AP projectiles, multiple armour plates where a perforated armour plate is placed at a distance in front of a base armour plate has been successfully used. Several types of perforation patterns may be used in the perforated plate. Balos et al. [3] experimentally determined the effect of geometric and material parameters, along with the method of mounting, on the ballistic response of perforated armour plates. The perforated armour plate induced bending stresses in the AP projectile core made from high hardness, low ductility steel. The AP projectile core fractured under the induced bending stress. It was observed that the perforated plates were not able to provide penetration protection if the bullet core remained intact after impact. Thus, the perforated armour plate should induce sufficient bending stresses for core fracture in order to provide ballistic protection against AP projectiles.

Projectile penetration in a metallic armour plate is a complex phenomenon that is difficult to predict completely using analytical relationships. Available analytical relationships also suffer from various limitations such as applicability under certain conditions [2]. In comparison, the finite element method can successfully predict the projectile penetration in metallic plates its underlying physics

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http://dx.doi.org/10.1016/j.ijimpeng.2017.04.028
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Please cite this article as: M.W. Ali et al., An experimental and numerical investigation of the ballistic response of multi-level armour against armour piercing projectiles, International Journal of Impact Engineering (2017), http://dx.doi.org/10.1016/j.ijimpeng.2017.04.028

[4–7]. One of the main considerations in a finite element based impact simulation is the material model of the projectile and the armour plate. The flow stress of the metallic materials is generally modelled using Johnson–Cook material model that provides a strain rate and temperature dependent material response. The Johnson–Cook material model has a number of parameters that need to be determined for a complete material definition. Paris et al. [4] studied the oblique impact of 14.5 mm AP projectiles on steel armour plates where experiments showed that the projectile core fractured into multiple fragments upon impact with the armour plate. An increase in the plate thickness increased the number of projectile fragments after impact. The oblique impact resulted in asymmetric loading on the projectile that led to the bending of the projectile and resulted in multiple brittle fractures in the core. The developed finite element model included Johnson–Cook based material definition for the armour plates and was able to predict the core fracture. Kılıç and Ekici [8] determined ballistic limit thickness of Secure 500 armour steel by numerical simulation using Lagrangian and smoothed particle hydrodynamics (SPH). The SPH method is a particle based representation of the partial differential equations of a continuum. The particles are not connected by edges as in a regular finite element mesh. The steel armour plate's material response was based on Johnson–Cook plasticity and Johnson–Cook damage and failure material model. The hydrodynamic material response was modelled by Mie–Gruneisen equation of state. The steel armour plate was modelled with an element erosion criterion that exhibited mesh dependence. Element erosion increased with increasing mesh density of the Lagrangian finite element models. Good correlation between the experimentally and numerically obtained results was reported. A modified form of Johnson–Cook material model was used by Tria and Trębiński [9] while developing finite element model of 7.62 mm AP projectile impacting 30 PM armour steel.

In addition to the Johnson–Cook plasticity and damage material models, a failure criterion is required to model the brittle fracture of the AP projectile core upon impact with a perforated armour plate. Paris [4] used a principal tensile stress spall failure criterion during the numerical modelling that was able to determine the brittle fracture of the projectile core, as was observed during the experimentation. Kılıç et al. [10] identified three underlying mechanisms for the added protection provided by the combination of perforated and monolithic plates. The first was the deviation of the bullet due to the asymmetric forces applied after impacting the perforation edge. The second mechanism was the breakage of the projectile because of the bending and the third mechanism was the erosion of the projectile nose. A tensile failure criterion with a critical tensile stress and an erosion criterion for the projectile nose were included in the material model. This resulted in good correlation between the bullet core fracture and the crater depths observed experimentally and predicted numerically.

In this research, an experimental and numerical investigation of the projectile penetration in a multi-layered armour was carried out. The multi-layer armour consisted of a perforated steel plate placed in front of an aluminum base armour plate. The setup may be used for the protection of vehicles carrying personal or static structures against AP projectiles of small calibre. Experiments were carried out to determine the ballistic response of the base armour plate and the combination of the base armour plate with the perforated armour plate placed in front of it. Numerical modelling based on finite element method was carried out to investigate the various underlying phenomena and develop a better understanding of the ballistic protection provided by the multi-layered armour.

2. Experimentation

Experimentation was performed to determine the ballistic response of single and multiple armour plates. The monolithic base armour plate was made of aluminum AA5083-H116 that is an aluminum-magnesium alloy with magnesium higher than 3 wt%. AA5083-H116 is among the highest strength aluminum-magnesium alloys. The alloy performs well under rolling and is suitable for making plates, thus, it is used in marine applications and protective structures. Mechanical properties of aluminum AA5083-H116 are given in Table 1. The monolithic base armour plate was 20 mm thick. The perforated armour plate was made of ballistic steel SECURE 500, which is a standard grade of steel for ballistic protection against hard-core projectiles. It has high hardness, good weldability and is cold formable. Mechanical properties of steel SECURE 500 are given in Table 2. The hardness of the perforated plate was HB 499 that was determined by Brinell Hardness Tester HB3000 and its stress vs. strain response is given in Fig. 1. Dimension of the perforated plate were 800 × 530 × 9 mm. The perforation pattern consisted of holes of 10 mm diameter, which were made to improve the ballistic protection again AP projectiles by inducing bending during impact. The perforated armour plate was fixed in front of the base armour plate at 110 mm. The two armour plates were securely bolted to each other and were separated by spacers.

The armour plates were impacted by 7.62 mm AP hard core bullet. The hard core bullets have an outer brass jacket with a hardened steel core [8]. The bullets were fired from a rifle placed at 10 m from the base / perforated plate. The projectile velocity was measured by Millennium 2 Chronograph System manufactured by Competitive Edge Dynamics, USA. The chronograph was placed 1 m away from the rifle towards the target plate. In each of the two experimental cases, five bullets were fired to determine the ballistic response of the armour plates. The bullet velocity was in the range of 710–725 m/s with an average velocity of 718 m/s. Schematic representation of the experimental setup is shown in Fig. 2 and the setup of perforated and base armour plates is shown in Fig. 3.

Table 1
Mechanical properties of aluminum AA5083-H116 [19].

Elastic modulus (GPa)	Shear modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)
70.3	26.4	320	315

Table 2
Mechanical properties of steel SECURE 500 [10].

Elastic modulus (GPa)	Shear modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)
206	80	1300	1600

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