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Technical Report

Optimization of geometrical characteristics of perforated plates

Igor Radisavljevic [a,*], Sebastian Balos [b], Milutin Nikacevic [a], Leposava Sidjanin [b]

[a] *Military Technical Institute, Ratka Resanovica 1, 11132 Belgrade, Serbia*
[b] *University of Novi Sad, Faculty of Technical Sciences, Department of Production Engineering, Trg D. Obradovica 6, 21000 Novi Sad, Serbia*

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ABSTRACT

In this paper, an attempt was made to design effective non-homogenous armor in form of perforated plate mounted at close distance from basic armor plate. Perforated plate with three perforation diameters: 9, 10 and 11 mm, two ligaments length: 3.5 and 4.5 mm ligaments, set at 0° and 28° angles, were combined to 13 mm basic plate and tested against 12.7 mm API ammunition. It has been shown that larger perforations gave a more efficient core fragmentation, while angled specimens were the only ones that offer full protection against five API shots when the perforated plate was placed at 100 mm from the basic plate. Perforations that are similar in size to the penetrating core diameter offer a more efficient core fracture, leading to a faster fragment separation. This may enable a smaller distance between the add-on perforated and basic plate to be used. Scanning electron microscopy analysis has shown a ductile fracture mode at impact point, with hardness values on plate basic level. On the other hand, a brittle fracture mode with a rise in local hardness measured near impact point is a result of intensive high speed plastic deformation produced by bending stresses. A drop in local hardness measured near impact point, may be the result of intensive cracking that occur due to repeated projectile impact.

1. Introduction

Non-homogenous armor is a type of metallic armor in form of a fence or a plate with perforations, usually circular, but other forms may also be used. This type of armor, mostly used in form of add-on or appliqué armor operates in conjunction with the vehicle basic armor. Both fences and perforated plates utilize the so-called free edge effect. If this effect occurs on the homogenous armor, it causes a serious drop in armor effectiveness: ballistic protection of armor plate impacted by projectile at or near the edge of the plate is notably lower. This phenomenon has made an impact on military specifications. For example, US and Serbian military specifications for armor plate test acceptance criteria imply that impacts within two projectile diameters for projectiles of 7.62–20 mm should be ignored, or proclaimed unfair [1–3]. However, if this effect is utilized on a spaced element of the non-homogenous armor, such as fences and perforated plates, it provides a very effective way of overcoming the projectile's penetrating performance [4–7]. Generally, when the projectile or projectile's penetrating core impacts the free edge, it may yaw, or more critically, it may fracture, due to the induction of bending stresses, as shown in [8–10]. Projectile or penetrating core fractured greatly diminishes its penetration performance, since the weight as well as their kinetic energy of the fragments is obviously smaller that of the whole projectile or penetrating core. Furthermore, the fragments are both yawed and blunted, which makes an additional negative effect on their penetration.

Typically, non-homogenous add-on armor that rely on penetrating core fracture or yaw induction, are effective if placed at some distance from the basic plate. This distance or air gap is needed to allow a sufficient yaw to be achieved, or to allow a sufficient separation of fractured penetration core fragments to degrade penetration so that the basic plate offers full protection. However, this implies increasing vehicle dimensions, which could have an adverse effect on mobility [11–16]. Furthermore, air gap can have an adverse effect on ballistic windows (weakened spots) if firing ports are already present on an infantry fighting vehicle [17], making them theoretically less effective in urban environment. To overcome these problems, it would be desirable to decrease the air-gap between add-on armor and basic plate. This may demand some trade-offs that refer to the geometrical modeling of perforated plates, regarding hole diameter [18–22].

In this paper, experimental results of perforated plates, specially designed to be more effective when mounted in relative proximity to the basic armor, with perforations that are larger than used in perforated plates mounted at a more conventional 400 mm distance as shown in [12]. The other scope of this paper is to explore the influence of ligament length (distance between perforation edges). In our previous work [12], ligament length equal to the perforation radius was used, which in case of a sufficient plate thickness and perforation size, as well as adequate material, a required protection criteria was achieved. By decreasing ligament length, a larger number of perforations can be made on the plate

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* Corresponding author. Tel.: +381 112051199; fax: +381 112508474.
E-mail addresses: igra@sbb.rs, vti@vti.vs.rs (I. Radisavljevic).

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of the given size, which has an influence on the weight of the perforated plate, making it lighter and therefore, more mass efficient. Furthermore, a greater overall perforated area allows the application of a thicker and more efficient perforated plate.

The present work was carried out as a part of a continuing program at Military Technical Institute – Belgrade and University of Novi Sad to study and develop different types of ballistic protection systems for the defense industry.

2. Experimental details

2.1. Perforation diameter modeling

According to the results shown in [12], 9 mm perforations were more effective in fracturing penetrating core than the smaller 7 mm perforations, which led to their higher effectiveness in conjunction with the basic plate in achieving ballistic protection. The drawback of larger perforations than 9 mm for a perforated plate intended to be used against 12.7 mm M8 API ammunition (and similar) is that there is a higher probability of an insufficient overlap between the penetrating core radius and the plate edge of $h/R = 0.34$, as shown in [8]. According to [8], and modified to the circular perforation rather than straight edge, the overlap (h) between penetrating core and perforation diameter shown in Fig. 1 may be expressed as:

$$h = D - d \qquad (1)$$

where d is the perforation diameter and D is the penetrating core diameter.

In case of 12.7 mm M8 API projectile, penetrating core diameter (D) is 10.9 mm [8]. For $d = 9$ and $D = 10.9$ mm, according to Eq. (2), h equals 1.9 mm. If h/R ratio is calculated, where R is $D/2$, the following equation may be obtained:

$$h/R = 0.35 \qquad (2)$$

This is in full accordance with the results obtained by Chochron et al. [8], who experimentally found that $h/R \geqslant 0.34$. This means that against 12.7 mm M8 API, the perforation diameter should not be larger than 9 or 9.05 mm. If the smaller, 7 mm perforation is considered, an insufficient bending stress is induced, influencing the diminishing of the free edge effect [12]. If the larger perforation would have been used, the h/R ratio would be lower than the proposed 0.35 or 0.34, which could cause the induction of insufficient bending stress. This drawback is minimized by the vehicle orientation towards the shooter, where when in the move, the vehicle exposes its additionally protected side for only brief time. Such a plate, with larger holes than 9 mm may represent an interesting trade-off between the worst-case scenario (an impact with $h/R < 0.34$ and projectile trajectory normal to the perforated plate) and achieving vehicle compact dimensions due to a relatively small distance between the add-on perforated plate and basic plate.

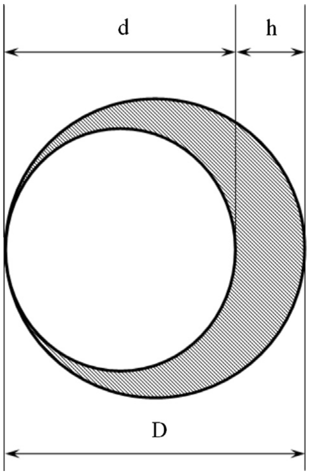

Fig. 1. Penetrating core diameter (D), perforation diameter (d) and overlap (h).

2.2. Materials characterization

Perforated plates were made of Hardox-450 steel [23] in as - received condition, and according to [24] they are classified as Class 1b armor. Its chemical composition (Table 1) was determined by an optical emission spectrometer ARL-3460, while for determining non metallic elements, an IR spectrometer LECO CS-244 were used, according to ASTM E415-08 and ASTM A751-11.

Mechanical properties of Hardox-450 steel were tested at room temperature, on the basis of five samples in case of tensile and Charpy V-notch specimens and five Brinell hardness indentations (Table 2) according to ASTM E8/E8M-11, ASTM E23-07ae1 and ASTM E10-12, respectively.

Hardox-450 microstructure was determined by a conventional optical microscopy (OM) and scanning electron microscopy (SEM). Its microstructure consists from tempered lath martensite, which closely corresponds to carbon content of Hardox-450 steel (Fig. 2).

2.3. Perforated plate samples

The dimensions of tested plates were 700 × 400 or 500 × 400 mm. The thickness of the plates was 6 mm. Perforations were machined by water–jet machine (Water Jet Sweden 2100), operating at 4100 bar pressure, with an abrasive flow of 140 g/min and by using ∅0.76 mm jewel. Perforated plates with two perforation diameters were tested (10 and 11 mm) and the results were compared to the results of perforated plate with 9 mm perforations obtained in [12]. The ligament length of perforated plates with 9 mm perforation was 4.5 mm; with 10 mm perforation was 3.5 mm, while for 11 mm perforation the ligament was 3.5 and 4.5 mm (Table 3). Furthermore, in Table 3, distance to basic plate, inclination and normalized weight (area density) of various perforated plates is given. In Table 4, perforated plate weight saving due to material removal and number of drilled perforations is shown in relation to perforation diameter and ligament length. All given value are calculated for the plate dimension 700 × 400 mm.

Perforated plates were firmly mounted by means of bolts, using two steel frames at 400 mm and 100 mm distance from the basic 13 mm RHA plate (Fig. 3). According to [2], basic 13 mm RHA plate at vertical position (°), also as 10 mm angled at 28°, offer protections against 7.9 mm SmK projectile with hardened steel core from 100 m. Perforated plates were mounted at 0° and at an angle of 28° between projectile trajectory and plate surface, Fig. 4. Damage area was calculated by using the same methodology described in [12].

2.4. Ballistic testing

Ballistic testing was performed using 12.7 mm M8 API ammunition, in accordance with the procedures described in the Technical regulations for RHA plate acceptance [2]. According to these regulations, muzzle velocity of M-8 API round is 910 ± 15 m/s, or

Table 1
Hardox-450 chemical composition.

C	Si	Mn	Cr	Ni	P	S	V	Fe
0.22	0.69	1.62	0.80	0.36	0.020	0.005	0.02	Balance