Numerical simulation of the asymmetric bullet penetrating the perforated steel plate

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Abstract. In this study, the perforated steel plates were demonstrated to exhibit high efficiency in protecting against small-caliber armor-piercing projectiles. The oblique hipped armor plates combined with the perforated steel plates acted as an armored vehicle exhaust vent protect against 7.62mm bullet. To enhance the efficiency of the vehicle exhaust, the numerical model was built, consisting of the hipped armor plate, the perforated steel plate and the bullet core. By performing a simple test, the efficiency of the model was verified. After the bullet penetrates the hipped armor plate, the shape of its core changed to be asymmetric. The sizes of the perforated steel plate were preliminarily designed in accordance with the statistical results of numerical simulation. Effects of the perforated steel thickness and the impacting positions on the residual bullet were ascertained. The results of this study were conducive to designing exhaust vents.

1. Introduction

The perforated steel plate has been proved exhibiting high efficiency in strengthening ballistic performance against small-caliber armor-piercing projectiles by reducing their perforation capability [1, 2] When impacting positions of the projectiles are at the sides of the hole, bending stress will be exerted in the projectile core [3,4], thereby breaking the core or at least diverted from its incident trajectory [1]. The perforated steel plate has already been employed as the add-on armor, whereas experimental and numerical studies have been rarely conducted on this topic. Borvik et al. [2] considered ballistic penetration performance of five different high-hardness steel alloys. The effects of geometry, mounting of perforated plates as well as mechanical properties of the materials adopted for such application have been extensively ascertained. Burian W et al. [5] analyzed the ballistic impact of the AP projectiles on the perforated plates made of high-strength bainitic steel; they reported that holes pattern designed appropriately could reduce the weight of the armor by approximately 40% compared with the monolithic plates exhibiting the identical protection capability. Fras T et al. [6] delved into the impacting process of Mars 300, a type of high-strength armor steel; they also identified three different failure mechanisms. Radisavljevic I et al. [7] ascertained the performance of perforated plates outfitted with 13 mm basic plates against 12.7 mm API ammunition at a range of angles. In the test, three perforation diameters and two ligaments length were applied. They reported that larger perforations could lead to a more efficient core fragmentation, while angled specimens were the only ones ensuring full protection against five API shots the basic plate.

This study primarily aimed to design a novel armored vehicles exhaust vent, combined by the oblique hipped armor plates as well as the perforated steel plates. The exhaust vent was adopted to protect against 7.62mm bullet shooting at a fixing angle. The numerical model, of which the efficiency was verified by a simple test, was established to analyze the interacting process. Furthermore, the
effects of the perforated steel thickness and the impacting positions on the residual bullet were ascertained.

2. Numerical models

2.1. Modeling

7.62mm bullet is composed of the jacket, the bullet core, as well as other components. The bullet core is critical to penetrate the target. The jacket and other components will depart from the bullet core and slightly impact the perforating process. Børvik T et al. also demonstrated the crucial role of the bullet core [8]. Thus, in this study, the bullet core was considered when modelling the bullet. The geometric model of the simulation is illustrated in figure 1, covering the bullet core of 7.62 mm bullet, the hipped plate, as well as the perforated steel plate.

The mesh model was prepared with the use of the commercial code Hypermesh. By Ls-Dyna, numerical simulations were conducted. In this study, the bullet core, the hipped plate and the perforated steel plate were respectively meshed with hexagonal eight node solid elements. The mesh size in the bullet core ranged from 0.05 to 0.42 mm. The mesh sizes in the hipped plate were nearly 0.5mm on the plate planes; the size was down-regulated in the fillet to allow for the mesh smooth transition, while the mesh size in the thickness direction reached 1 mm. The perforated steel plates exhibited three thicknesses. On the planes, the mesh sizes were approximately 0.4mm, which were identical in the thickness direction, respectively. Nevertheless, the sizes ranged from 0.375 to 0.5 mm in different perforated steel plates. Figure 2 illustrates the finite element model of the bullet core. The two ends of the hipped plate were fixed, as well as the sides of the perforated steel plate. Contact-eroding-surface-to-surface was defined among the bullet core, the hipped plate, as well as the perforated steel. The bullet core had an initial impact velocity of 760 m/s. The bullet core mass was 4.84g, and the kinetic energy reached 1397.79J. The effect of gravity and air resistance were not considered in the finite element model.

![Figure 1. Geometric model.](image1)

![Figure 2. Bullet core finite element model.](image2)

Johnson-Cook model was employed for the bullet core, the hipped plate and the perforated steel plate. The bullet core was made of hot rolled low carbon steel, and the material parameters are listed in table 1. G denotes shear modules, A indicates the yield stress, B and n refer to the constants of strain hardening, C represents the constant of strain rate, and M denotes the parameter of thermal softening. Tr and Tm respectively refer to the specific heat capacity and the melting point. D1, D2, D3, D4 and D5 are the constants related to failure strain. The hipped plate and the perforated steel plate were made of a type of armor steel. By the material mechanical properties test, the material properties of the armor steel were characterized.

Table 1. The material and Johnson-Cook model of the bullet core.

| Density | G (GPa) | A (MPa) | B (MPa) | n | c | m | Tr (K) | Tm (°C) | D1 | D2 | D3 | D4 | D5 |
|---------|---------|---------|---------|----|---|---|-------|--------|----|----|----|----|----|
| 7850kg/m³ | 70 | 200 | 700 | 0.4 | 0.05 | 0.9 | 477 | 1793 | 3.0 | 0 | 0 | 0 | 0 |
2.2. numerical simulation model Verification
A simple exhaust vent without the perforated steel plate was adopted to verify the numerical simulation model. The residual bullet core harvested after the ballistic performance test is presented in figure 3, and the mass of the residual bullet core was 3.75g. The simulated residual bullet core after the bullet penetrated the simple exhaust vent is illustrated in figure 4. The mass of the residual bullet ranged between 3.85 and 3.94g after the bullet impacted different positions of the simple vent’s hipped plate. Moreover, the shapes of the residual bullet core achieved by simulation were nearly identical to the collected ones after the test. The error between the simulation result and the test result ranged from 2.6% to 4.8%. Furthermore, the simulation results were well consistent with the test results, revealing that the numerical simulation model could be used to simulate the interacting process.

![Figure 3. Residual bullet after test.](image)

![Figure 4. Residual bullet obtained by simulation.](image)

3. Statistics of the bullet project size
The shape and movement direction of the bullet varied after the bullet penetrated the hipped steel plate. The interacting process between the bullet and the hipped plate is demonstrated in figure 5. Given the results of numerical simulation, the residual bullet core, penetrating the hipped steel plate and projected in its initial direction, is presented in figure 6.

![Figure 5. Interacting process between the bullet and the hipped steel plate.](image)

![Figure 6. Residual bullet core sizes after penetrating the hipped steel plate.](image)
The positions of the bullet impacting the hipped steel plate were altered, and the shape and size of the residual bullet were studied statistically. As revealed from the statistical results, the shapes of the residual bullet were noticeably similar. The sizes of the residual bullet in the transverse direction were from 24.0 to 25.3mm and 9.3 to 9.4mm in the transverse direction and the longitudinal direction, respectively.

The hole of the perforated steel plate is supposed to be narrower than the projected size of the residual bullet. Given the convenience of processing and manufacturing, by minimizing the effect of the perforated steel plate on the exhaust resistance, the holes of the perforated steel were developed to be rhombus. Referencing the minimal projected sizes of the residual bullet core, and using a safety factor of 0.8, the final size of the rhombic hole was 19mm and 7mm in the transverse and the longitudinal directions, respectively. Moreover, the stem width of the perforated steel plate was 2.5mm as suggested from the processing test. The thickness of the perforated steel plate reached 2mm. The major structural dimensions of the perforated steel plate are shown in figure 7.

![Figure 7. Structure sizes of the perforated steel plate.](image)

### 4. Simulation results and discussions

#### 4.1. Effect of impacting positions on the residual bullet

To ascertain the effect of the impacting position of the perforated steel plate on the residual bullet, the position of the perforated steel plate was regulated to ensure that the bullet could exactly impact the various positions, as shown in figure 8.

![Figure 8. Impacting positions on the perforated steel plate.](image)

The mass, velocity and kinetic energy of the residual bullet core are listed in table 2. According to the data in table 2, the minimal mass, velocity and kinetic energy of the residual bullet were achieved after WE point of the perforated steel plate was impacted. Besides, the maximal mass, speed and kinetic energy of the residual bullet core were achieved after WA point was impacted. As shown in figure 9, the damage and deformation of the perforated steel plate were promoted in turn after the WA,
WC, and WE points were impacted, respectively. Since the energy was conserved, the more serious the damage and deformation of the perforated steel plate, the more the energy would be consumed, and the less mass, velocity and kinetic energy the residual bullet core will exhibit. Once the structure and position of perforated steel plate were ascertained, the possible positions of the residual bullet impacting the perforated steel plate would be fixed. Accordingly, to stimulate the full working capacity of the perforated steel plate, the relative position of the perforated steel plate and the hipped steel plate should be designed reasonably. For this reason, the residual bullet core could impact the intersection area (WE point) of the perforated steel plate as close as possible.

Table 2. Residual bullet parameters VS impacting positions of 2mm perforated steel plate.

| Impacting position | Residual bullet parameters |  |
|-------------------|---------------------------|---------------------------|
|                   | mass | velocity | kinetic energy |
| WA                | 3.89 g | 449 m. s⁻¹ | 392.11 J |
| WB                | 3.87 g | 409 m. s⁻¹ | 323.69 J |
| WC                | 3.86 g | 429 m. s⁻¹ | 355.20 J |
| WD                | 3.88 g | 395 m. s⁻¹ | 302.69 J |
| WE                | 3.85 g | 392 m. s⁻¹ | 295.80 J |

Figure 9. Residual perforated steel plate.

4.2. Effect of the perforated steel plate thickness on the residual bullet
To ascertain the effects of the perforated steel plate thickness on the residual bullet, three different thicknesses of the perforated steel plate were studied. The penetrating processes of the perforated steel plates are depicted in figure 10, figure 11 and figure 12, respectively. According to figure 10 and figure 11, the bullet fully penetrated the perforated steel plate. Besides, only a small area around the contact zone failed, which would contribute to multi-hit. As suggested in table 3, the velocity and kinetic energy of the bullet core decreased noticeably after 3mm perforated steel plate was penetrated. As shown in figure 12, the bullet partially penetrated the perforated steel plate. For the springback of the perforated steel plate, the residual bullet exhibited a small velocity. Thus, 4mm perforated steel plate could avoid the facilities behind the perforated steel plate from being penetrated by the residual bullet core.

Figure 10. Interacting process between bullet and 2mm perforated steel plate.
Figure 11. Interacting process between bullet and 3mm perforated steel plate.

Figure 12. Interacting process between bullet and 4mm perforated steel plate.

Table 3. Residual bullet parameters after penetrating different thicknesses perforated steel plates.

| Perforated steel plate thickness | Residual bullet parameters |               |
|---------------------------------|-----------------------------|---------------|
|                                 | mass | velocity | kinetic energy |
| 2mm                             | 3.85g | 392 m. s\(^{-1}\) | 295.80 J      |
| 3mm                             | 3.74g | 52 m. s\(^{-1}\)  | 5.06 J        |
| 4mm                             | 3.50g | 11 m. s\(^{-1}\)  | 0.21 J        |

5. Conclusions
In the present study, the process of the asymmetric bullet penetrating the perforated steel plate was delved into by numerical simulation. The results revealed that the perforated steel plate with rhombic hole could effectively reduce the mass, velocity and kinetic energy of the bullet core, particularly impacting at the intersection area. Furthermore, 4mm perforated steel plate could avoid the facilities behind the perforated steel plate from being penetrated.

References
[1] Kiliç N, Bedir S, Erdik A, Ekici B, Taşdemirci A and Güden M 2014 Mater. Des. 63 427-38
[2] Børvik T, Dey S, Clausen A H 2009 Int. J. Impact. Eng. 36 948-64
[3] Mishra B, Ramakrishna B, Jena PK, Siva Kumar K, Madhu V and Gupta N K 2013 Mater. Des. 43 17-24
[4] Chocron S, Anderson Jr CE, Grosch DJ and Popelar CH 2001 Int. J. Impact. Eng. 25 423-37
[5] Burian W, Żochowski P, Gmitrzuk M, Marcisz J, Starczewski L, Juszczyk B and Magier M 2019 Int. J. Impact. Eng. 126 27-39
[6] Fras T, Roth C C and Mohr D 2018 Int. J. Impact. Eng. 111 147-64
[7] Radisavljevic I, Balos S, Nikacevic M and Siddian L 2013 Mater. Des. 49 81-89
[8] Børvik T, Forrestal M J and Warren T L 2010 Exp. Mech. 50 969-78