Ballistic Performance Evaluation of Aluminium Plate Impact by Fragment Simulating Projectile

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Abstract. The ballistic performance has drawn attention to researchers from a military background. They intend to provide solutions to ensure the soldiers in the front line of war do not kill in action. A casualty in war can lead to depression among soldiers and not to mention to their family as well. The aim of this work is to provide preliminary data for the ballistic limit velocity, VBL of the hydrodynamic ram study. The test was conducted at Science and Technology Research Institute (STRIDE), Batu Arang, Selangor which is under the Ministry of Defence (MINDEF) Malaysia. The gas gun and fragment simulating projectiles (FSP) were employed in this test. There were about 16 rounds of fire were shot with different velocities from 246 up to 373 m/s. The ballistic limit velocity was calculated by taking the average of an equal number of highest partial perforation and the lowest perforation velocities. It was found that the VBL was equal to 275.8 m/s. On top of that, there were two main failure modes observed i.e. partial penetration and complete penetration.

1. Introduction

Generally, the ballistic study involves a projectile and a target. The projectile's velocity and the type of target's materials play a major role in the ballistic performance. It is because these two parameters influenced the ballistic limit velocity, VBL. Researchers, especially from the military background, are keen to determine VBL because they intend to ensure the safety of the soldiers on the battlefield.

Aluminum is well known as a light material with the capability of good energy absorption. Soldiers need armor with these characteristics to move faster to survive in any combat situation [1]. Steel on the hand is heavier compared to aluminum even though has a higher capability of energy absorption. Thus, aluminum is a better choice to be used an armor.

Many types of researches have been conducted in the ballistic limit study. There were researches employed fragment simulating projectile (FSP), live bullets either 7.62 mm or 5.56 mm, hemispherical and sphere projectile as their striking impactor. Meanwhile among the type of targets were a single plate, double plates, laminated plate, composite plate, and heat-treated plate [2]. However, there was less attention given towards target in hydrodynamic ram (HRAM) scenario. HRAM is an event occurred when a high velocity of projectile perforates a fluid-filled container. The projectile converted its momentum and kinetic energy to the container via a fluid. This leads to damage to container structure and consequently the failure of the container [3]. Concorde's tragedy on 25 July 2000 happened due to this HRAM events.

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The aim of the present work is to provide preliminary data for the ballistic limit velocity, $V_{BL}$ of the hydrodynamic ram study.

2. Test Set-up

FSP was employed as the projectile and a single plate of aluminum was used as the target. There were 16 rounds of shots fired. This test was conducted at Science and Technology Research Institute (STRIDE), Batu Arang, Selangor. STRIDE is one of the institutes under Ministry of Defence (MINDEF) Malaysia. From the test conducted, $V_{BL}$ was successfully determined and main failure modes were observed. Figure 1 shows the schematic layout of the test. The gas gun was employed to launch fragment simulating projectile (FSP). The velocity of FSP before and after the impact was recorded by using chronograph 1 and 2, respectively. Figure 2 shows chronograph employed to record the velocity of the FSP. The velocity of FSP launched from the gas gun was controlled by charge weights inside the bullet’s jacket. When charge weights increased, the velocity of FSP increased too. The image of the FSP in the aluminum plate was taken by using a digital single-lens reflex camera. The image was taken after the fire shot took place. The FSP was fixed into the 7.62 mm bullet’s jacket with a sabot as shown in Figure 3. The most left figure shows a completed projectile which consisted of FSP, sabot and bullet’s jacket. Sabot was used to ensure the FSP snuggly fit into the bullet’s jacket. Then, bullet’s jacket was filled with charge weight. The middle and right picture show the sabot and FSP, respectively. In this study, only FSP was used a projectile to impact the aluminum plate. After the gas gun fired, FSP impacted the aluminum plate. Meanwhile, sabot and bullet’s jacket were scattered.

![Figure 1](image1.png)

**Figure 1.** The schematic layout of the test.
3. Result and Discussion

3.1. Ballistic Limit Velocity, $V_{BL}$

Table 1 tabulates the velocity of the FSP before impacted and after impacted the aluminum plate. Bear in mind, the readings were re-arranged by ascending the velocity to ease the analysis. The velocity before the FSP impacted the aluminum plate was termed as impact velocity, $V_{imp}$. Then, the velocity after the FSP impacted the aluminum plate was termed as residue velocity, $V_{res}$. There were two modes of penetration observed, which were partial penetration and complete penetration. Partial penetration
means the FSP failed to penetrate the aluminum plate and created bulge. Furthermore, complete penetration means the FSP successfully penetrated the aluminum plate and created petals. Thus, there was residue velocity recorded. It can be seen clearly that from an impact velocity of 246 m/s until 270 m/s, the FSP able to penetrate the aluminum plate partially. Thus, there was no residue velocity recorded for this case. However, from the impact velocity of 277 m/s until 373 m/s, the FSP able to penetrate the aluminum plate completely.

Table 1. Initial velocity and residue velocity.

| Test | Impact velocity, $V_{imp}$ (m/s) | Residue velocity, $V_{res}$ (m/s) | Penetration |
|------|---------------------------------|----------------------------------|-------------|
| 1    | 246                             | -                                | Partial     |
| 2    | 247                             | -                                | Partial     |
| 3    | 248                             | -                                | Partial     |
| 4    | 250                             | -                                | Partial     |
| 5    | 253                             | -                                | Partial     |
| 6    | 261                             | -                                | Partial     |
| 7    | 267                             | -                                | Partial     |
| 8    | 270                             | 128                              | Complete    |
| 9    | 277                             | 145                              | Complete    |
| 10   | 285                             | 168                              | Complete    |
| 11   | 295                             | 179                              | Complete    |
| 12   | 311                             | 254                              | Complete    |
| 13   | 356                             | 259                              | Complete    |
| 14   | 359                             | 264                              | Complete    |
| 15   | 362                             | 282                              | Complete    |
| 16   | 373                             | -                                | Complete    |

The ballistic limit calculated by taking the average of an equal number of the highest partial penetration and the lowest complete penetration velocities [4]. When all the 16 data were taken into consideration, the ballistic limit velocity, $V_{BL}$, was equal to 291.3 m/s. By looking back at Table 1, this value was not acceptable. The value must be in between 270 m/s and 277 m/s. Table 2 tabulates the value of ballistic limit velocity, $V_{BL}$, by reducing the number of tests. It was reduced by deducting the highest the partial penetration and the lowest complete penetration velocities. When test 6 until 11 were taken into consideration, the value of ballistic limit velocity, $V_{BL}$, was 275.8 m/s. This value was valid since it represented the velocity of the FSP which had 50% to penetrate the aluminum plate.

Table 2. Ballistic limit velocity, $V_{BL}$.

| The test has taken into consideration | Ballistic limit velocity, $V_{BL}$ (m/s) |
|--------------------------------------|----------------------------------------|
| 1-16                                 | 291.3                                  |
| 2-14                                 | 288.6                                  |
| 3-14                                 | 286.0                                  |
| 4-13                                 | 282.5                                  |
| 5-12                                 | 277.4                                  |
| 6-11                                 | 275.8                                  |

The ballistic limit velocity, $V_{BL}$ also can be determined by using Recht and Ipson equation as shown in the equation (1) [1]. It was employed by researchers to determine the velocity ballistic limit,
If the impact velocity, $v_{imp}$ and residue velocity, $v_{res}$ were known. Meanwhile, $a$ and $p$ are the coefficient of the equation. Commonly the value of $a$ and $p$ are 1 and 2 [5], respectively.

$$v_{res} = a(v_{imp}^p - v_{bl}^p)^{1/p}$$  \hspace{1cm} (1)

Table 3 tabulates the value of ballistic limit velocity, $V_{BL}$ by using equation (1). In this case, tests from 9 until 16 were considered because residue velocities occurred only for these tests. By comparing the $V_{BL}$ obtained from the average method and equation method, the discrepancies were ranges from 7.8% until 13%. The average of the discrepancy was about to 11%. Therefore, a new equation was proposed as stated in the equation (2). When equation (2) was employed to determine the new value of $V_{BL}$, the discrepancies were reduced significantly as tabulated in Table 3. The average of the new discrepancy was 1.2%. Thus, in this study, equation (2) was suitable to be employed compared with the equation (1). This equation (2) represented a new Recht and Ipson equation which based on results obtained in this study.

4. Modes of Failure

In this study, two main modes of failures were observed as tabulated in Table 1. They were partial penetration and complete penetration. Partial penetration occurred when the impact velocity was less than ballistic limit velocity, $V_{BL}$. Thus, the FSP was able to penetrate the aluminum plate partially. However, when the impact velocity bigger than the $V_{BL}$, complete penetration was observed. Figure 4(a) and 4(b) show these two modes of failure. In Figure 4(a), the FSP failed to penetrate the plate. The FSP was only able to create a crater at the front plate and a small bulge at the rear plate. The impact velocity was 246 m/s. Meanwhile in Figure 4(b), the FSP successfully penetrated the plate. Petals were developed at the rear plate. Petals were created due to high radial and circumferential stresses [2]. The impact velocity was 277 m/s. Y. Shin et al (2018) observed the same phenomenon in their experiment [6].
Figure 4. Modes of failure.

Figure 5 shows the residue velocity versus impact velocity graph. The data was taken from Table 1 but considered the complete penetration only because in that specific case, residue velocity was observed. It shows clearly that it is best described as a linear correlation between these two velocities as represented by equation (3). This equation was linear because as the residue velocity increased, the impact velocity increased too. Equation (3) does not relate with equation (1) and equation (2) since the equation (3) was developed based on result tabulated in Table 1. Therefore, equation (3) is not a new Recht and Ipson equation since the ballistic limit velocity as in equation (1) and equation (2) is not included. This observation exhibited the same trend with previous researchers [1][7][8].

\[ v_{imp} = 1.56v_{res} - 299 \]  

(3)
5. Conclusions
The ballistic limit velocity was found equal to 275.8 m/s. From the data obtained, a new Recht and Ipson equation proposed as stated in equation (2). It suited well with the experiment conducted. There were two modes of failure observed which were partial and complete penetration. The impact velocity played a major role in determining the mode of failure.

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