

THE EFFECT OF LARGE AIR GAPS ON THE PENETRATION OF
12.7 MM ARMOUR PIERCING ROUNDS DUE TO INDUCED YAW

by

Lieutenant James Robertson, RAN

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Abstract

Perforation of targets by spin stabilised projectiles is known to induce yaw. A study has been conducted to investigate how this induced yaw, affects penetration of a second target at distances up to 3 m. Reductions in penetration due to this effect has potential applications in maritime platforms which commonly have structures of this type.

The study used 12.7 x 108 mm Armour Piercing rounds and low carbon steel targets of either 10 or 12 mm thickness. In the study two targets were separated by gaps of either 2 or 3 meters. The study observed that significant yaw is consistently induced in the projectile by perforation of the first target. The study has demonstrated that this induced yaw causes a significant increase in ballistic limit velocity against a second target. This results in a model of penetration for the second target which is highly dependent on induced yaw. Numerical modelling has also been conducted in order to characterise the penetration mechanism presented by the experimental data.

1. Introduction

When considering the perforation of targets by small arms rounds, obliquity has been extensively studied in order to determine its mitigating effect[1–5]. The effect of yaw on a round striking a target has been investigated to a lesser extent. Obliquity describes the angle between a projectile and target when its axis of symmetry and direction of travel are aligned. Yaw describes the angle between a projectile's direction of travel and its axis of symmetry. The difference between oblique and yawed impact are illustrated in Figure 1. The focus on obliquity is understandable as rounds are much more likely to impact a target in this manner. Any difference in aspect between an effector system and its target results in oblique impact. Additionally, many armour systems deliberately exploit the mitigating effect of oblique impact. An example of this is frontal armour in tanks. Conversely, yaw requires a disturbing moment to move a projectile's axis of symmetry away from its direction of travel. Prior to striking a target, this disturbing moment may be caused by factors such as barrel whip and wind. However, these factors usually only results in small magnitudes of induced yaw.

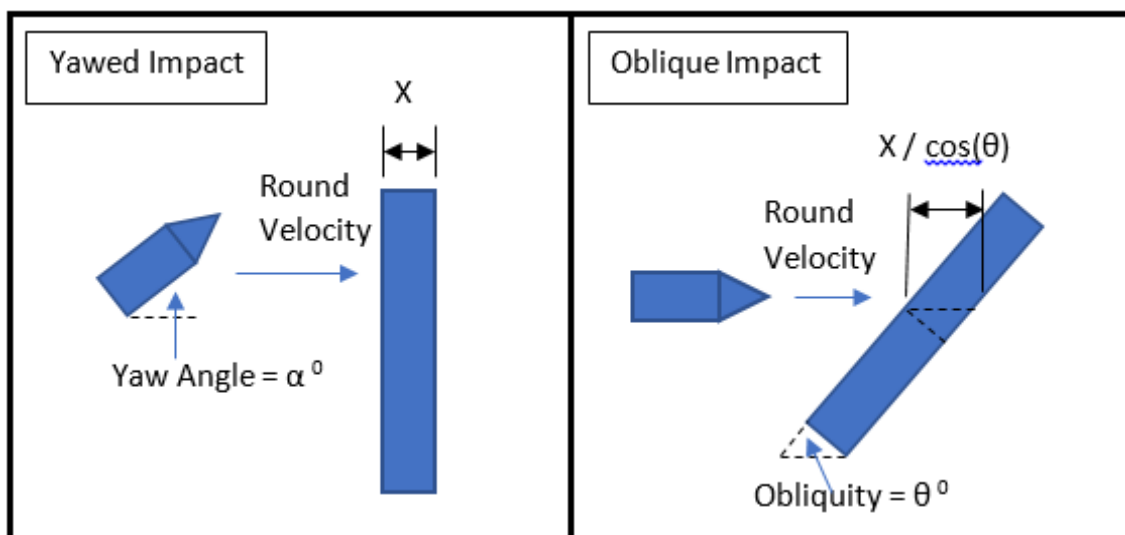


Figure 1 - Diagrammatic Representation of Yaw and Obliquity

However, another mechanism which induces yaw on a round is penetration. Oliver and Whitty observed this effect and documented large magnitudes of yaw from relatively thin penetrations [6]. This induced yaw has the potential to significantly reduce the penetrative capacity of the round for subsequent layers of protection. This is particularly true for hard penetrators against relatively ductile

targets where ductile hole enlargement is the primary method of penetration. However, the disturbing moment induced by the first penetration requires time to significantly change the aspect of the round. This required time for yawing of the round typically translates to round displacements in the order of metres. Due to volumetric restrictions in air and land platforms, secondary protection structures are not commonly found at these distances. However, maritime platforms often have compartment structures separated by distances in this range.

In this study, 12.7 mm Armour Piercing (AP) rounds have been fired against pairs of targets separated by gaps of either 2 or 3 metres. The targets were made of low carbon steel with a thickness of either 10 or 12 mm. The study has quantified the frequency and magnitude of induced yaw caused by penetration of the first target. Significant yawing of the rounds has been observed. This induced yaw has been observed to significantly affect the round's capacity to perforate the second target. Numerical modelling has been conducted in order to further understand the relationship between yaw and penetration. This has allowed the development of ballistic limit curves based on the yaw of the impacting penetrator. Using these curves and the statistical distribution of yaw we have developed a rudimentary model for predicting the probability of penetration. The veracity of the model is limited by the scope of the current study and further data to validate and expand the model will increase its usefulness. A fully validated model would have practical applications in predicting the threat levels for platforms with structures containing large air gaps.

2. Definition of Terms

For clarity and consistency, the following terms are defined for use in this study:

Velocity	
V_0	Projectile Initial Velocity
V_{bl}	Ballistic Limit Velocity
V_r	Projectile Residual Velocity
Dimensional Measurement	
H	Target Thickness
D	Projectile Diameter
L	Projectile Length
L_{eff}	Projectile Effective Length
Mass and Density	
m_p	Mass of Projectile
m_{pl}	Mass of Plug (plugging failure mechanism)
ρ_p	Projectile Density
Material Properties	
Y_t	Yield Strength
σ_r	Effective Resistive Strength
Pitch and Yaw	
α	Total Projectile Yaw
α'	Projectile Horizontal Yaw
α''	Projectile Pitch
Johnson-Cook Model Parameters	
Y	Johnson Cook Yield Strength
A	Yield Stress at Low Strains
B	Strain Hardening Constant
ϵ_p	Effective Plastic Strain
n	Strain Hardening Exponent
C	Strain Rate Constant

ϵ_p^*	Normalised Effective Plastic Strain Rate
T_H	Homologous Temperature
m	Thermal Softening Exponent

3. Literature Review

A literature review has been conducted to understand the current level of knowledge within the study's area of interest. The primary focus of the literature review was to identify current understanding regarding the effect of yaw on small arms projectiles. The review will focus on AP projectiles with ogive nose shapes as commonly found in small arms ammunition.

3.1 Ballistic Impact Review

3.1.1 Terminology

For the purposes of the current study it is important to define important terms related to the interaction of the projectile and target. Zukus [7] has previously provided the following definitions.

Penetration refers to a projectile entering a target.

Perforation refers to the projectile penetrating the target and passing completely through.

Embedment refers to the projectile penetrating the target and remaining within it.

These definitions are useful in defining the important concept of Ballistic Limit (BL) velocity. This concept is used to define the minimum velocity at which the projectile defeats the target. Three widely used definitions for this are the Army, Protection and Navy BL definitions [8–10]. Figure 2 details each of these requirements. The Navy BL has been used as the current study has potential applications in this domain. This definition of BL is regarded as the most difficult to achieve armour defeat. This definition accounts for the fact that Navy personnel and equipment are often not in close proximity to the armour (as accounted for by the witness plate in the Protection BL definition). The ductile targets and hard projectiles used in the current study mean minimal breakup of the armour will occur on the back face. This should result in similar values for both the Navy and Protection BL.

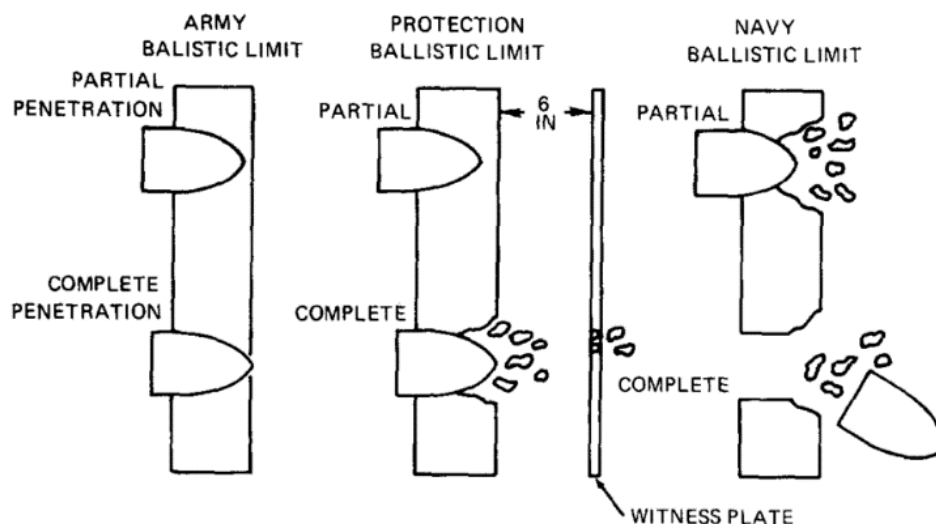


Figure 2 - Ballistic Limit Definitions [9, p.10]

3.1.2 Mechanisms of Target Failure

Figure 3 illustrates the most common failure mechanisms experienced by targets. When rigid projectiles penetrate ductile plates with a H/D ratio close to unity we expect the primary failure mechanism to be ductile hole growth. With respect to our 12.7 mm projectiles, the 10 and 12 mm targets have H/D ratios of 0.93 and 1.11 respectively¹. The mechanism of ductile hole growth has been described in detail by Woodward [11]. Backman and Goldsmith [9] also examined this mechanism and came to similar conclusions. Recent work by Rosenberg and Dekel [12] has further validated this model.

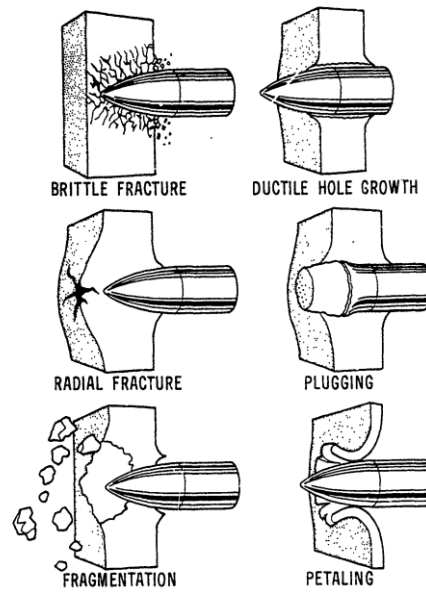


Figure 3 - Common Target Failure Mechanisms [7, p.11]

3.2 Analytical Models of Ballistic Limit

For our study, it is useful to examine analytical equations for the penetration of ogive nosed projectiles. Previous work conducted by Recht and Ipson [13] provided a useful analytical equation for calculating residual and BL velocities in projectile/target pairs. Lambert and Jonas further extended this work to define of a more general form of their equation which could be used to account for factors such as projectile deformation [14]. The form of the equation presented by Lambert and Jonas is shown in eq. (1). The validity of this equation to calculate residual velocities is substantiated by work conducted in a number of studies [15–17].

$$V_r = a(V_0^p - V_{bl}^p)^{\frac{1}{p}} \quad (1)$$

In this equation p is used to account for factors such as projectile deformation. A value of $p = 2$ indicates minimal deformation of the projectile. Due to the hardness of the AP penetrator, a value of $p = 2$ is reasonable for our model. The value of a in eq. (1) is determined by the size of the plug produced during the perforation process and takes the form shown in eq. (2).

$$a = \frac{m_p}{m_p + m_{pl}} \quad (2)$$

¹ Based on penetrator diameter of 10.8 mm, See Figure 13. (assumes projectile jacket and fill have been stripped by initial yaw inducing penetration)

The ogive nosed projectiles and ductile plates used in the current study will produce failure by ductile hole growth as previously discussed. This penetration mechanism will produce minimal plugging. With this in mind, it is reasonable to assume a value of unity for α . This gives the simplified form of eq. (1) shown in eq. (3).

$$V_r = (V_0^2 - V_{bl}^2)^{\frac{1}{2}} \quad (3)$$

In order to calculate V_r we require values for V_0 and V_{bl} . Expected V_0 values for the ammunition under consideration are $820 \pm 20 \text{ m.s}^{-1}$. V_{bl} can be calculated from material properties using eq. (4) as documented by Rosenberg and Dekel [12,18].

$$V_{bl} = \sqrt{\frac{2 \cdot H \cdot \sigma_r}{\rho_p \cdot L_{eff}}} \quad (4)$$

In our study, the value of V_r after penetrating the front plate will need to exceed V_{bl} of the second plate in order to cause a perforation of the second plate. As an example, consider two 12 mm target plates of the type used in our study being penetrated a 12.7 mm AP round. The following parameters can be used with eq. (4) in order to calculate V_{bl} of the projectile/target pair.

- $H = 0.012 \text{ m}$
- $\sigma_r = 650.3 \text{ MPa}$
- $\rho_p = 7850 \text{ kg.m}^{-3}$
- $L_{eff} = 0.0104 \text{ m}$
- $m_p = 0.030 \text{ kg}$
- $D = 0.0108 \text{ m}$
- $Y_t = 312 \text{ MPa}$

Projectile Effective Length and Effective Resistive Strength are calculated using equations (5) and (6) which are also provided by Rosenberg et al [18]. Using these values, we can calculate the V_{bl} of the 12 mm plates to be 437 m.s^{-1} .

$$L_{eff} = \frac{m_p}{\pi \cdot \left(\frac{D}{2}\right)^2 \cdot \rho_p} \quad (5)$$

$$\sigma_r = \left(2 + 0.8 \cdot \ln\left(\frac{H}{D}\right)\right) \cdot Y_t \quad (6)$$

Having calculated the ballistic limit of the 12 mm targets, we can now calculate the residual velocity of the round after penetrating the first plate. V_0 is assumed to be 820 m.s^{-1} . Using eq. (3), V_r is calculated as 694 m.s^{-1} . This value significantly exceeds the previously calculated V_{bl} of 437 m.s^{-1} for a second 12 mm target. It would therefore be expected that a projectile striking at normal incidence

would easily exceed the V_{bl} of a second 12 mm target and perforate it. If yawed rounds fail to achieve perforation, this will provide evidence that yawing of rounds increases the V_{bl} of the projectile/target pair.

3.3 Numerical Models of Ballistic Limit

During our study, numerical modelling and simulation were used to expand understanding of the mechanisms at work during yawed penetration. To achieve this, numerical models were developed which were then used for simulation. The development of these models required an understanding of the phenomenon at work and how they might be simulated.

3.3.1 Computational Method

Before conducting numerical analysis, a suitable computational method must be selected. The most common processors are Lagrangian, Eulerian, Arbitrary Lagrange-Euler (ALE) and Smooth Particle Hydrodynamics (SPH).

In the Lagrangian model, elements within the model move with the velocity of the material in the model. The mass within each element is maintained when using this processor and mass is not able to migrate from one element to another. This processor is less computationally intensive than the other processors. Maintaining mass within elements also makes tracking material interfaces and material behaviour simpler. Additionally, plasticity and damage are easily modelled and tracked with this processor. These properties of the processor make it one of the most popular for conducting simulations of ballistic impact scenarios. However, the model has shortcomings when dealing with large material deformations. These deformations can lead to the model mesh becoming highly distorted. These distortions may affect the accuracy of the solution and the efficiency of the processor. These distortion effects need to be managed within the processor using methods such as erosion or remapping.

In the Eulerian model, a fixed volume is used to evaluate equations which govern conservation of mass, momentum and energy. In the model mass is allowed to flow from one cell to another. This allows the processor to handle large material deformations more efficiently. The processor method also makes it ideally suited to handling fluid flows. However, tracking material interfaces and behaviour is more difficult than with the Lagrangian method. The processor is also more computationally intensive than the Lagrangian processor due to the requirement to include empty space in the solution. Figure 4 provides a visual representation of the difference between the Lagrangian and Eulerian processors.

The ALE processor is an extension of the Lagrangian model. ALE extends the Lagrangian processor by allowing the element mesh to move and deform independently of the material. However, the mesh generally follows a Lagrangian deformation pattern. The advantage of this method is that it allows the distorted element meshes to be smoothed without requiring a complete re-mesh. The major disadvantage of this method is that it is more computationally expensive than both Lagrangian and Eulerian methods. Another feature of this processor is that the relative motion of the element mesh and materials must be accounted for in the constitutive equations of the materials.

SPH is a Lagrangian processor which does not employ a grid [19]. SPH is a computationally intensive processor due to the nature of its algorithms and the associated requirements for neighbour searching. SPH was not considered for the simulations as its high computational requirements are out of proportion to improvements in the solution for our particular problem. It is also known that SPH is not well suited to modelling ballistic penetration of ductile materials.

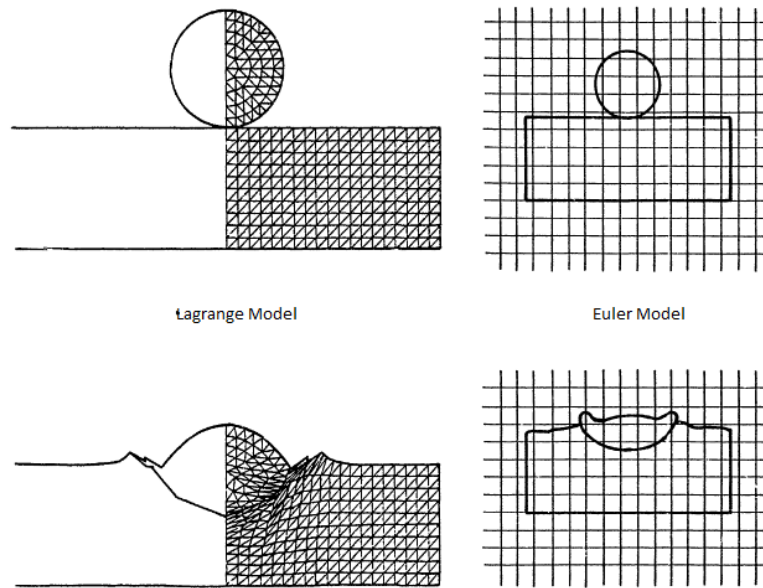


Figure 4 - Visual Representation of Lagrange and Euler Model [7, p.11]

Based on the assessment of various numerical processors, the Lagrangian processor was chosen to conduct the numerical simulations. As previously discussed, this processor has been extensively and successfully employed for ballistic simulations. Computational requirements of this processor for ballistic simulations are reasonable when implemented with well-designed models. The characteristics of well-designed models include appropriately sized element meshes and careful parameterisation of characteristics such as erosion.

Ansys Explicit Dynamics [20] software has been used to implement the Lagrangian numerical modelling. A diagrammatic description of the Lagrangian processor implemented in the software is provided in Figure 5.

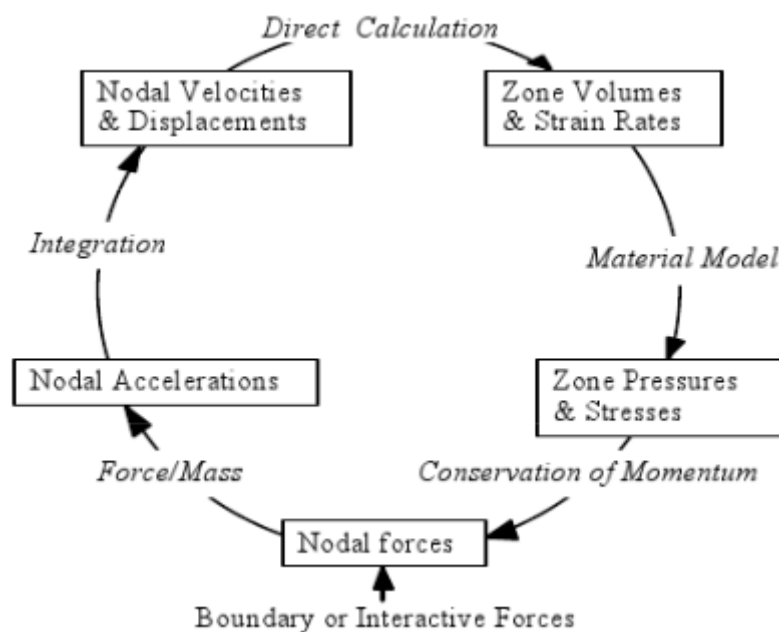


Figure 5 - Lagrangian Processor Used in Ansys Explicit Dynamics [21, p.30]

3.3.2 Strength Model

The strength of the both the target and projectile materials are affected by the penetration scenarios under consideration in the study. A useful model for representing these changes in strength is the Johnson-Cook (JC) constitutive model. This model was first described by Johnson and Cook in 1983 [22]. The model describes the strength behaviour of materials subjected to high strains, strain rates and temperatures. These characteristics are typical of those found in ballistic impact scenarios. There are numerous examples of the JC model being effectively utilised in studies of ballistic impact scenarios [15,23–25]. The model is defined as shown in eq. (7).

$$Y = (A + B\varepsilon_p^n)(1 + C\log\varepsilon_p^*)(1 - T_H^m) \quad (7)$$

The three bracketed sections of eq. (7) represent the three elements which affect material strength. The first bracketed section represents strain hardening. The constant A represents the yield stress of the material at low stress rates. The combination of the constant B and the exponent n are used to define strain hardening of the material. The second bracketed section represents the change in strength characteristics due to high strain rates and is characterised through the constant C . The final bracketed section represents thermal softening of the material in these scenarios and is characterised through the exponent m . During our study, the JC model will be used in modelling both projectile and target materials.

3.3.3 Equations Of State

An Equation Of State (EOS) defines the relationship between pressure, density and temperature for a given material. In the ballistic impact scenarios under consideration, the Shock EOS was utilised for both the target and penetrator. The use of this model allows the effective modelling of material interactions at the high pressures and strains rates involved in ballistic scenarios.

3.4 Penetration Induced Yaw

Thus far the literature review has concerned itself with penetration mechanics in order to identify methods to assess the impact of yawing on penetration. Another important aspect to be understood is the mechanism of inducing yaw. In our study, we are concerned with how yaw is induced into the round after penetrating an initial target. The phenomenon of penetration induced yaw has been investigated by Oliver and Whitty [6]. In their study, 5 sheets of 13 mm caneite³ spaced 250 mm apart were penetrated. The aspect of rounds was recorded following penetration. The results of their study showed significant yaw induced in the rounds.

This yawing causes precession and nutation of projectiles due to their gyroscopic stabilisation. This behaviour within axial symmetric projectiles is well understood and was described as early as 1920 by Fowler et al [26]. Numerous authors have expanded and refined this work in order to better define the motion of projectiles [27–29]. This has led to a well-defined model for spin stabilised projectile motion based on velocity and angular momentum. This model defines differential equations for three degrees of freedom in the aforementioned properties. It is therefore commonly referred to as the Six Degrees Of Freedom model (6DOF). The text *Modern External Ballistics* by McCoy [30] provides the most recent and comprehensive treatment of this model. Output from the model has shown a high level of agreement with empirical data. Figure 6 shows a typical plot of a small calibre round's pitching and horizontal yawing motion during its first metres of flight after firing. This example shows the small magnitude of precession and nutation associated with this event. However, the 6DOF model has been

³ A common wall boarding material similar to fibreboard, material used had an areal density of 13.5 kg.m⁻²

shown to effectively characterise the precession and nutation of rounds subjected to large yawing forces.

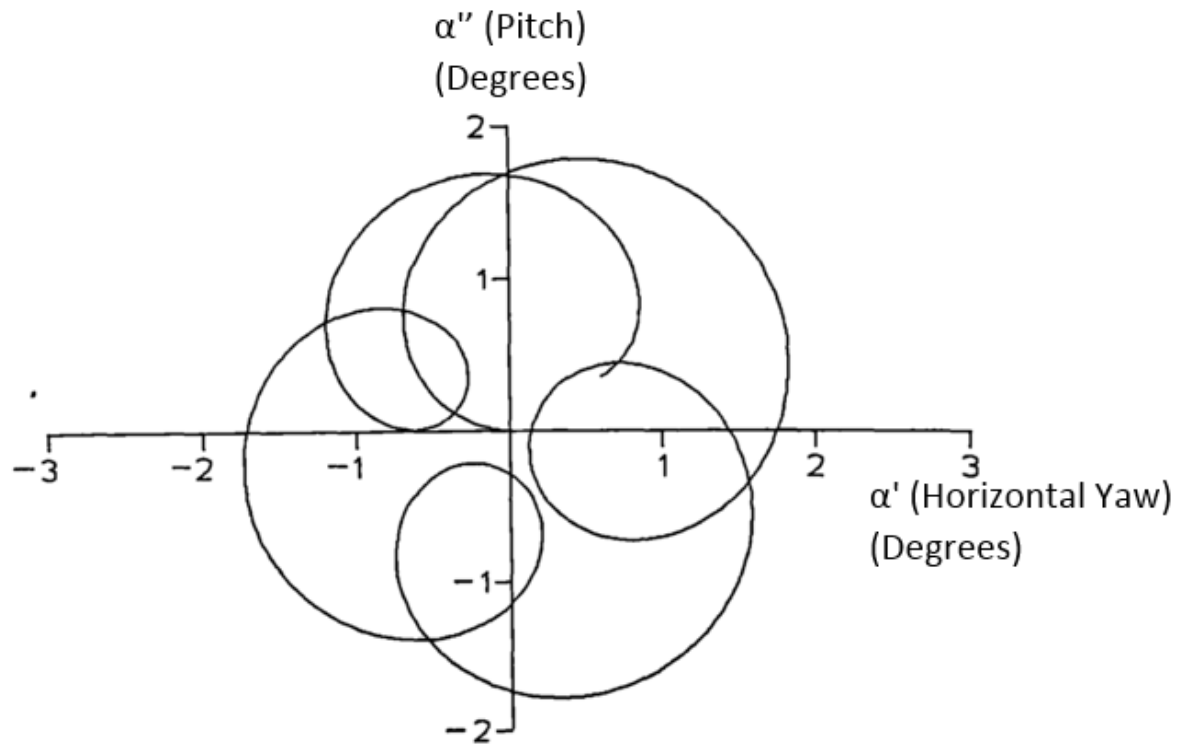


Figure 6 - Precession and Nutation of a Small Arms Round – Muzzle to 15 Yards Range [30]

Based on the gyroscopic and dynamic stability of the rounds used in the study, they would be expected to continue exhibiting precession and nutation after penetration of a target. After penetration, the precession and nutation magnitudes would be much greater than those shown in Figure 6. No open literature was found which documents the magnitude of induced yaw after penetration of metal plates, so this data will need to be collected experimentally.

The current study will collect data on yaw, pitch and velocity for rounds using High Speed Video (HSV) and Doppler radar. Using empirical data from the study, a statistical model will be derived which describes the distribution of the round's yaw and velocity after penetration of an initial target.

Having established a statistical model which describes yaw and velocity following penetration of the first plate, it is then necessary to understand how these factors will impact on the round's ability to penetrate the second target plate. While the effect of obliquity on projectile penetration has been widely studied, the effects of yaw have been much less widely investigated. A review by Goldsmith in 1999 provided a summary of research into impacts by oblique and yawed projectiles [31]. Goldsmith et al also conducted experiments with flat nosed projectiles which identified the different mechanisms at work during penetration of a yawed projectile versus penetration by a purely oblique projectile [32]. A representation of the penetration mechanism for yawed rounds identified by Goldsmith et al can be seen in Figure 7. It can be seen in the figure that the penetration mechanism described involves plug shearing. However, the current study is using ogive nose shapes against ductile, intermediate thickness targets. As previously discussed, ductile hole growth will be the dominant penetration mechanism for this configuration. Numerous studies provide evidence of this penetration mechanism for the described configuration [11,12,18,33,34].

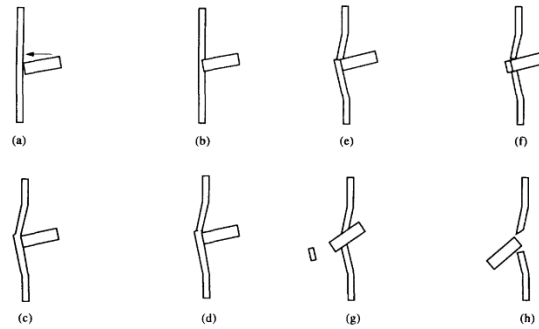


Figure 7 - Penetration Mechanism of Yawed Flat Nosed Projectiles [32, p.484]

Extensive review of the literature has found no research describing analytical equations for estimating penetration depth based on yawed, small L/D (<5) ogive nosed projectiles. As discussed by Walker and Anderson, comprehensive analytical equations for yawed projectile-target interaction are intractable [35, p.31]. Some work has been conducted to gather empirical data on yawing of rod penetrators. Anderson et al summarised the empirical data collected by various studies up to 1992 in *A Penetration Mechanics Database* [36]. The work detailed in the database is mostly concerned with rods of large L/D ratios against high hardness targets. The limited information in the database on small L/D ratio projectiles against ductile targets does not contain data on yaw. It will therefore be necessary to gather experimental data on the penetration mechanics of yawed ogive nosed projectiles. This experimental data can then be used to evaluate the penetration mechanisms involved and explore their relationship to currently understood mechanisms.

Another important aspect of yawed penetration is damage to the round caused by penetration. No literature was found for yawed rounds, although some literature exists on the effect of obliquity. Primary among these sources is the work conducted by Recht and Ipsen [8] to generate phase diagrams to represent different damage mechanisms related to the obliquity angle. An example of this type diagrams is provided in Figure 8. Generating diagrams such as these requires large amounts of detailed experimental data. Recent advances in the use of numerical models has proved useful in generating these types of models with smaller quantities of experimental data. Despite this, the open literature does not contain significant documentation of these types of models. A review of the literature was not able to identify a specific model for 12.7 mm rounds against low carbon steel plates. However, it is reasonable to assume that a phase diagram for a yawed 12.7 mm round might have a similar form to Figure 8.

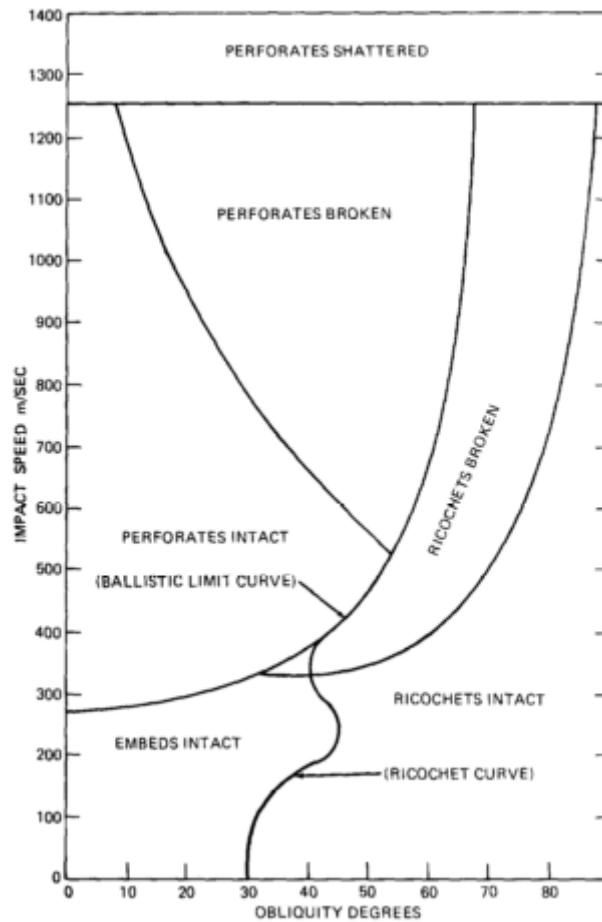


Figure 8 - Phase Diagram of 6.35-mm Diameter Ogive-nosed Projectile Penetrating 6.35-mm Aluminium Alloy Target [9, p.10]

4. Experimental

4.1 Experimental Setup

The experimental part of the study was designed to collect data on the mechanisms of yaw and penetration for two plates separated by a large air gap. This data is used to develop a statistical model for penetration under these conditions. The data will be further used to analyse the mechanism of penetration in the large air gap scenario. The data items and method of collection are detailed in Table 1.

Data Item	Collection Method
Initial projectile velocity (prior to penetrating first target)	Doppler radar
Projectile pitch	HSV
Projectile length in z-y plane	HSV
Projectile residual velocity (after penetrating first target)	HSV
Impact effects	Still imagery

Table 1 - Data Items and Method of Collection

The experimental setup is shown in Figure 9.

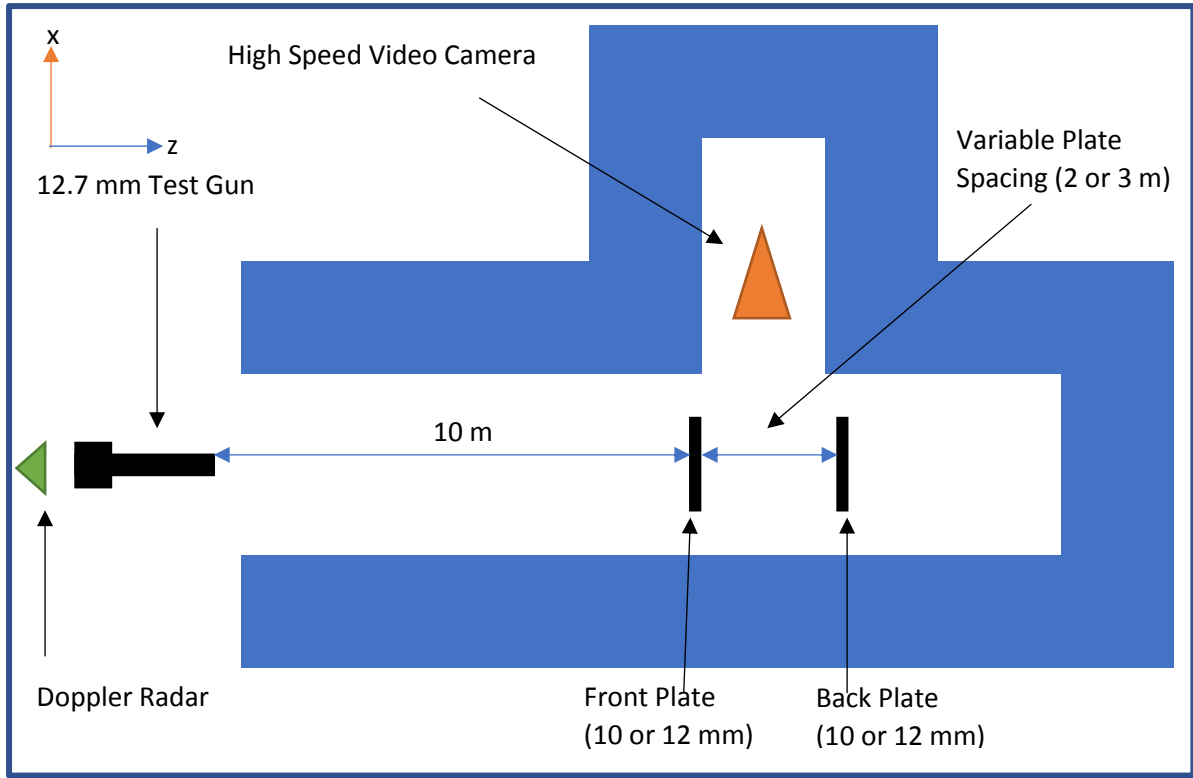


Figure 9 - Experimental Setup

4.2 Measurement Methods

In order to measure yaw, we must first define it in terms of a coordinate system. In our system, projectiles are assumed to travel along the z-axis in a positive direction. The x and y axis represent movement in the horizontal and vertical direction respectively when looking down range. Positive direction of the x-axis is to the left. Positive direction of the y-axis is up. In our study, total yaw refers to the angle made by the projectile's axis of symmetry with the z-axis and is notated as α . Total yaw consists of the two components α' and α'' , also referred to as horizontal yaw and pitch respectively. The components α' and α'' represent the orthogonal angles made by the projectile's axis of symmetry with the z-y and z-x planes respectively. A visual representation of these two elements is shown in Figure 10. Total yaw can be calculated from these two quantities using the simple trigonometric relationship in eq. (8).

$$\alpha = \tan^{-1} \left(\sqrt{\tan^2 \alpha' + \tan^2 \alpha''} \right) \quad (8)$$

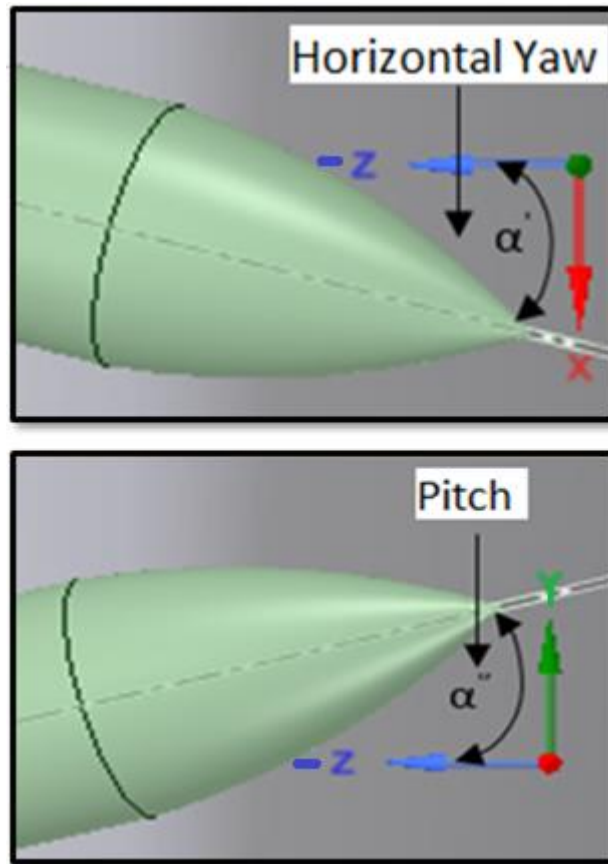


Figure 10 - Visual Representation of Pitch and Yaw

In the experimental setup, HSV is only collected in the z-y plane. This imagery allows simple measurement of α'' (pitch) from the imagery. As total length of the penetrator has been measured at 51 mm, α' (horizontal yaw) can be calculated from the imagery using the trigonometric relationship shown in eq. (9). Measurement of pitch angles, projectile length and residual velocity was done using inbuilt measurement tools in the HSV camera software.

$$\alpha' = \cos^{-1}(l/51), \quad l = \text{length of projectile (mm) in } z - y \text{ plane} \quad (9)$$

Still imagery and Doppler radar velocities were also collected. The Doppler radar provided data on initial projectile velocity prior to penetration of the first target plate. Still imagery was used to document penetration results on target plates.

4.3 Test Equipment

4.3.1 Firing Apparatus

Firing of the rounds was conducted using a 12.7 mm DShK machine gun barrel mounted in a specialised test mount located at the Bashforth experimental range at Cranfield University in the United Kingdom. An image of the test mount can be seen in Figure 11. The barrel had a length of 1070 mm with a 381 mm (1 in 15) twist rate. The mount was also fitted with a laser target designator to allow aiming of rounds on the target plate.

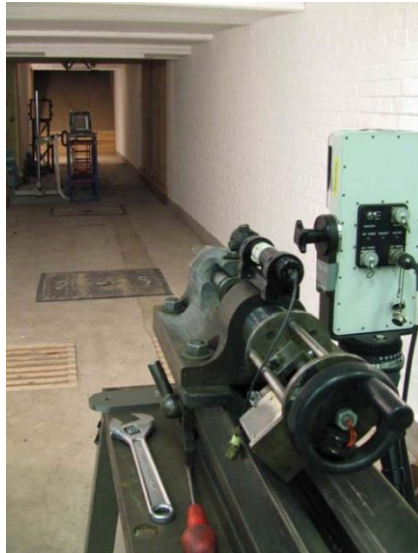


Figure 11 - Gun Test Mount

4.3.2 Doppler Radar

A Doppler radar was used to gather data on initial velocity prior to penetration of the first target plate. The Doppler radar used was a Weibul model W-700.

4.3.3 High Speed Video Camera

A Phantom High Speed Camera, model V-1212, was used to gather data on yaw, projectile length and residual velocity after penetration of the front plate. The camera utilised Phantom Camera Control software, version 2.6.279.0 (64 bit).

4.3.4 Ammunition

Ammunition used in the tests was 12.7 x 108 mm AP. The ammunition was of Chinese manufacture and the head stamp indicated date of manufacture as 1967. Average round mass was 125 g. The mass of each round was weighed prior to firing and this data can be found in Annex B of [37]. Projectile mass of the rounds was measured at 48 g. Penetrator mass was measured at 30 g. An image of the ammunition is provided at Figure 12. Dimensions of the projectile and penetrator can be seen in the drawing at Figure 13. Based on its dimensions and mass, penetrator density (ρ_p) was calculated to be 7850 kg.m^{-3} .



Figure 12 - 12.7 x 108 mm AP Ammunition

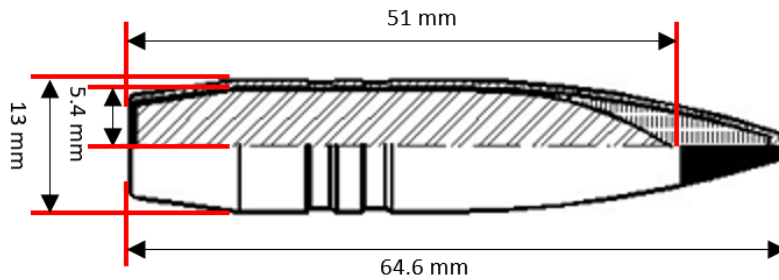


Figure 13 – Projectile Dimensions, 12.7 x 108 mm AP Round

4.3.5 Target Plates

Target plates used for the study were 300 x 300 mm S275 steel plates supplied by Tata Steel. Plate thickness used were 10 and 12 mm. Plates were manufactured in accordance with standard BSEN-10025-2:2004 [38] and were grade S275JR+AR. Test certificates for target steel are available at [39]. Details of target steel material properties are provided in Table 2.

Thickness (mm)	Yield Stress (MPa)	Tensile Strength (MPa)	Elongation A80 (%)
10	311.2	482.7	28
12	312.0	471.0	27

Table 2- Target Material Properties

4.4 Experimental Procedure

A total of 39 experimental firings were conducted. Comprehensive details of all firings are available in the experimental notes for the study [37]. The following sections describe the method and purpose of each group of firings.

4.4.1 Proof Firings

Five proof firings were conducted. The purpose of these firings was to

- Confirm round that round velocity was within $820 \pm 20 \text{ m.s}^{-1}$.
- Confirm the round did not have significant yaw prior to penetrating the first target plate.

4.4.2 Yaw Firings

The purpose of the yaw firings was to establish a plate/air gap combination which would exhibit penetration and non-penetration events in the back plate. This would allow statistical and phenomenological analysis to be conducted on a sample firing set.

To establish this combination, the thickest plates were used first with a separation of 2 m. Four rounds were fired at this combination. All rounds perforated the back plate and observation of exit holes on the back plate suggested that this combination had a low probability of yielding non-perforation events. A typical exit hole from the back plate of this combination is shown in Figure 14. All collected imagery of these penetrations is available at [37], rounds R06-R09.



Figure 14- Exit Hole, Back Plate (12 mm plates separated by 2m)

In order to achieve non-perforation events for analysis, the air gap was increased to 3 m with 12 mm front and back plates. This produced a number of non-perforation events within the first few firings, so a larger set of experimental firings was conducted. A total of 19 rounds was fired at this configuration. A typical non-perforation event for this configuration is shown in Figure 15. This image shows the front side of the second target plate when the round has been stopped.



Figure 15 - Non-perforation, Front of Back Plate (12 mm plates separated by 3m)

Having established that increasing the air gap reduced the penetrative effect of the round, a further series of firings was conducted using a 3 m air gap with two 10 mm target plates. A series of eight firings was conducted using this combination. No non-perforation events were observed during this firing series. However, the profiles of the penetrations on the second target plate suggested that a wide variety of yaw angles had been induced in projectiles by penetration of the first plate. The failure of the second target to stop the round suggests the BL velocity of the second 10 mm plate was too low even when modified by the yawing of the round.

To investigate this further, a firing serial of four rounds was conducted with a front plate thickness of 10 mm and second target plate thickness of 12 mm. These firings produced three perforations and one non-perforation event. The penetration profiles suggested a wide range of induced yaw.

5. Results

5.1 Proof Firings

Proof firings yielded velocities within the expected range as shown in Table 3. Examination of the HSV indicated that no significant yaw was introduced into the round prior to penetration of the first target.

Round	Weight (g)	Velocity (m/s)	Description
R01	124	829	Proof round 1
R02	126	829	Proof round 2
R03	125	824	Proof round 3
R04	124	834	Proof round 4
R05	125	810	Proof round 5

Table 3 - Proof Round Weights and Initial Velocities

5.2 Yaw Firings

5.2.1 Two 12 mm Plates Separated by 2 m Air Gap

The first set of firings against 12 mm plates separated by a 2 m air gap yielded no non-perforation results on the second target plate. Based on the generally clean entry and exit damage to the back plate, it was determined that non-perforation events were unlikely in this configuration. Unfortunately, due to failure of HSV equipment, no useful pitch and yaw data was able to be obtained from these firings. Table 4 provides the results of these firings.

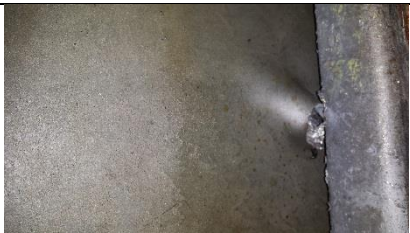
Round Reference Number (from [37])	Initial Velocity (Doppler Radar)	Result	Imagery (Exit from back plate)
R06	810	Perforation	
R07	Doppler Radar Failure	Perforation	
R08	Doppler Radar Failure	Perforation	No image available
R09	804	Perforation	

Table 4 - Firing Results, Two 12 mm Plates Separated by 2 m Air Gap

5.2.2 Two 12 mm Plates Separated by 3 m Air Gap

The second set of firings against two 12 mm plates separated by a 3 m air gap yielded 13 perforations, 4 non-perforations and 2 null results. Null results were due to impact with test apparatus items. HSV was recorded for the firings and is available at [40] in Phantom Camera Control file format.

Doppler radar provided initial round velocities. Yaw angles were calculated from HSV of the firings. Results of these firings are presented in Table 5. If null results are discarded from the result set, rounds were prevented from perforating the back plate in 23.5 percent of firings.

Round Reference Number (from [37])	Initial Velocity (before front plate penetration)	Residual Velocity (after front plate penetration)	Average Total Yaw (calculated)	Impact Result	Impact Imagery (impact on front of back plate)
R10	805	643.0	46.0	Non-perforation – target frame, null result	
R11	815	667.5	22.4	Perforation	
R12	824	672.7	50.2	Non-perforation	
R13	824	680.9	44.3	Non-perforation – hit target frame, null result	
R14	820	672.4	28.7	Perforation – steep angle of exit	

R15	839	695.1	39.9	Non-perforation – round flat against back plate	
R16	825	678.2	18.4	Perforation	
R22	811	678.8	25.1	Perforation	
R23	809	670.9	39.9	Non-perforation	
R24	806	680.7	15.9	Perforation	
R25	809	677.0	44.5	Non-perforation	
R26	803	664.9	15.9	Perforation	
R27	810	668.9	23.6	Perforation	

R28	814	678.6	16.1	Perforation	
R29	815	663.4	34.1	Perforation – very steep angle of exit	
R30	807	659.0	22.6	Perforation	
R31	823	682.8	27.8	Perforation	
R32	811	658.5	27.3	Perforation	
R33	804	659.0	23.1	Perforation	

Table 5 - Firing Results, Two 12 mm Plates Separated by 3 m Air Gap

5.2.3 Two 10 mm Plates Separated by 3 m Air Gap

The third set of firings consisted of 8 rounds against two 10 mm plates separated by a 3 m air gap. All these firings resulted in perforation events. HSV was recorded for the firings and is available at [40] in Phantom Camera Control file format. Doppler radar provided initial round velocities. Yaw angle was calculated from HSV of the firings. Results of these firings are presented in Table 6.

Round Reference Number (from [37])	Initial Velocity (before front plate penetration)	Residual Velocity (after front plate penetration)	Average Total Yaw (calculated)	Impact Result	Impact Imagery (impact on front of back plate)
R18	824	710.3	47.2	Perforation	
R19	815	700.5	27.7	Perforation	No Imagery available
R20	814	HSV Failure		Perforation	
R21	816	702.9	31.4	Perforation	
R34	809	689.8	27.8	Perforation	
R35	811	700.5	34.7	Perforation	
R36	822	705.4	16.0	Perforation	

R37	829	723.0	35.6	Perforation	
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Table 6 - Firing Results, Two 10 mm Plates Separated by 3 m Air Gap

5.2.4 Front Plate - 10 mm, Back Plate – 12 mm, Separated by 3 m Air Gap

The final set of firings consisted of four rounds against an initial 10 mm target plate separated from a second 12 mm target plate by a 3 m air gap. These firings resulted in one non-perforation event. HSV was recorded for the firings and is available at [40] in Phantom Camera Control file format. Doppler radar provided initial round velocities. Yaw angle was calculated from HSV of the firings. Results of these firings are presented in Table 7.

Round Reference Number (from [37])	Initial Velocity (before front plate)	Residual Velocity (after front plate penetration)	Average Total Yaw (calculated)	Impact Result	Impact Imagery (impact on front of back plate)
R38	820	700.5	27.7	Perforation	
R39	809	695.5	28.0	Perforation	
R40	810	690.6	44.9	Non-perforation	
R41	805	699.1	2.2	Perforation	

Table 7 - Firing Results, 10 mm Front Plate, 12 mm Back Plate, Separated by 3 m Air Gap

6. Analysis

6.1 Effect of Yaw on Penetration

6.1.1 Experimental Results

The firings conducted against two 12 mm plates separated by a 3 m gap provided interesting results with respect to the effect of induced yaw. These results, as shown in Table 5, provide evidence that penetration of an initial target affects the ability of the round to perforate a second target. Figure 16 shows the distribution of total yaw and penetration for these rounds. From the figure, it can be seen that rounds above a certain value of yaw are prevented from perforating the second target independent of their residual velocity. Since BL is normally fixed for a given projectile/target pair, this suggests the BL is increasing with yaw.

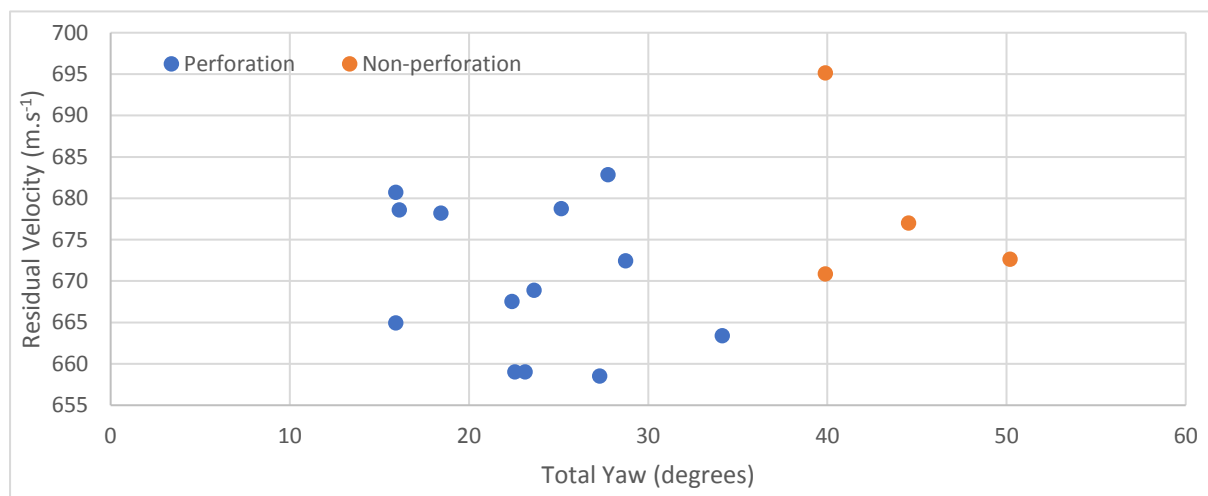


Figure 16 – Distribution of Total Yaw Indicating Perforation of Second Target for Two 12 mm Plates Separated by 3 m Gap

To demonstrate this, it is useful to consider the BL velocity of the 12 mm target plates. Using equations (4), (5) and (6) from the work of Rosenberg and Dekel [12,18], BL velocity can be calculated from the projectiles material properties and the target's yield strength. The calculated BL velocity for the 12 mm targets using this method is 437 m.s^{-1} . We can subsequently use eq. (1), which is based on the Recht and Ipson model [13], to calculate the residual velocity for each round after penetrating the first target. These calculated values are shown along with experimental values in Figure 17. The similarity between calculated and experimental values for residual velocity indicates that the calculated value of 437 m.s^{-1} for BL is close to the actual value. Since both calculated and experimental values of residual velocity are greater than 600 m.s^{-1} , all rounds should penetrate the second target plate if yaw is not a factor for penetration.

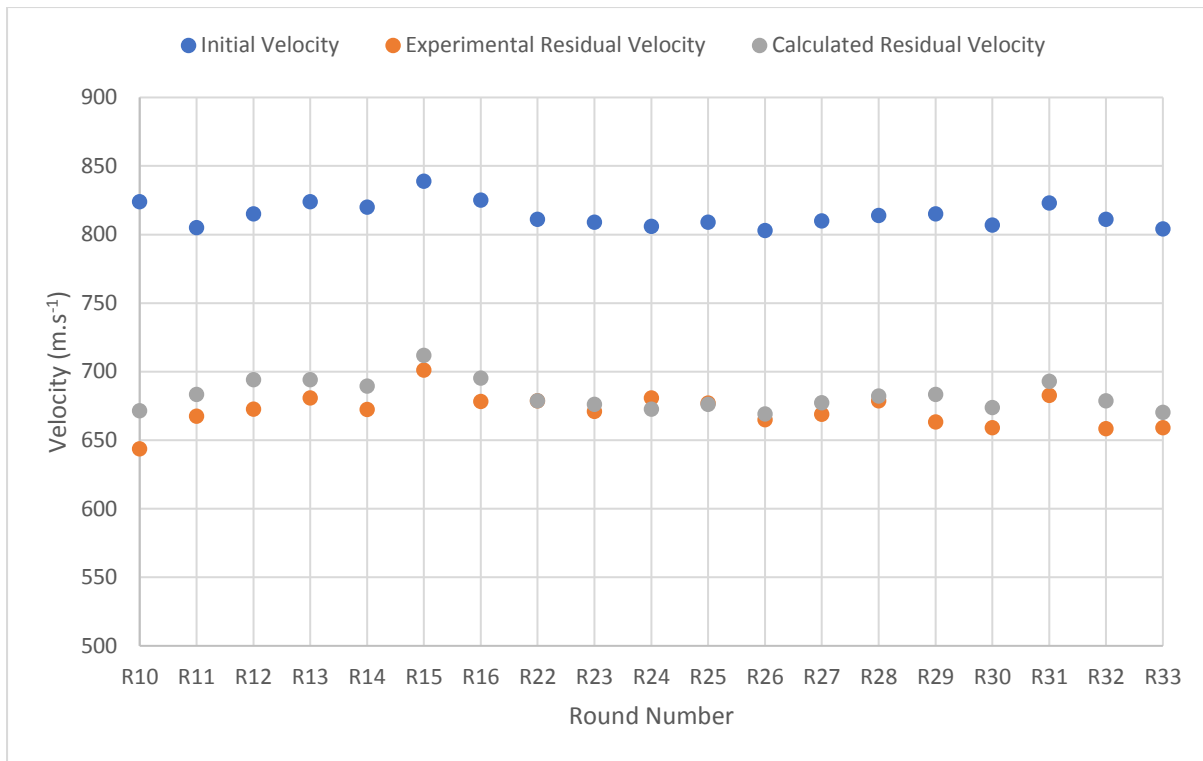


Figure 17 - Calculated and Experimental Residual Velocities after Penetration of 12 mm Target

However, as suggested by the data presented in Figure 16 and in various other sources [31,32,41], it is known that yaw does affect penetration. Knowing that yaw is affecting penetration, it is now important to understand the relationship between yaw and BL velocity for the projectiles/target pairs under consideration. The problem of projectile/target interactions is difficult to quantify analytically for a yawed projectile. It is therefore useful to conduct a numerical analysis for comparison to the empirical results.

6.1.2 Numerical Simulation

In order to better understand how yaw is reducing the BL velocity of the projectile/target pair, a numerical model was constructed. The numerical model was developed using ANSYS Explicit Dynamics software [20]. The model consisted of a penetrator element and a 0.08 x 0.08 m test plate element. The geometry of the projectile was constructed from the dimensions of Figure 13. A visual representation of the numerical model for the 12 mm thickness target is provided at Figure 18. Material properties of the penetrator and target not related to the JC and EOS properties were based on generic properties for steel.

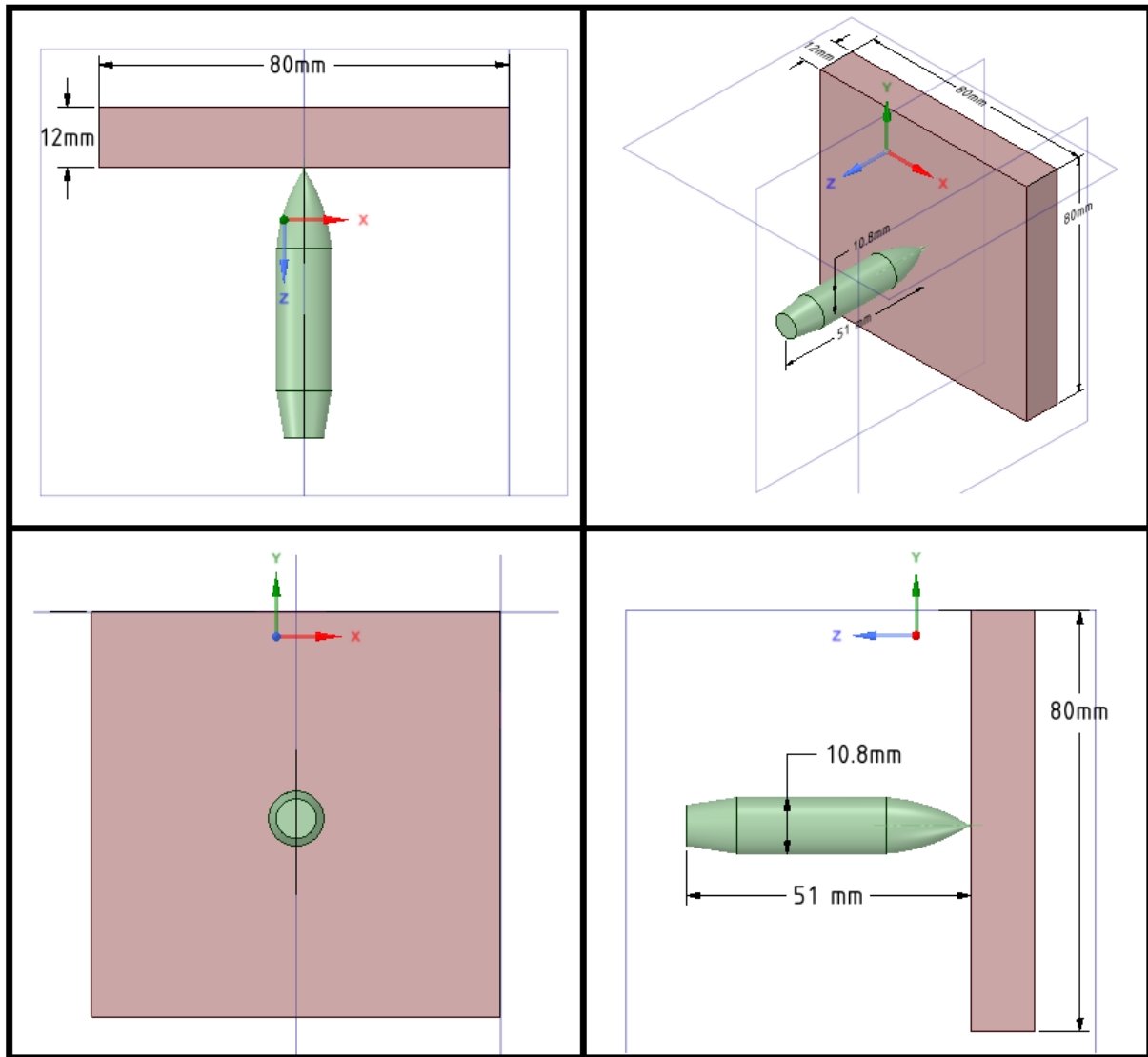


Figure 18 - Visual Representation, Numerical Model with 12 mm Target

6.1.2.1 Strength Models and Equations Of State

Model properties for the JC strength model were taken from the literature. The target and penetrator JC parameters were based on values provided by Senthil et al [42]. In their study Senthil et al used a hardened steel penetrator and low carbon steel targets of a similar composition to ours. A comparison between the compositions of the two target steels is provided in Table 8. The Shock EOS used parameters provided in the ANSYS material library for steel. All material properties used in the numerical model are provided in Table 9.

	Element (percentage by mass)						
	C	Si	Mn	S	Cr	Ni	Al
Current Study	0.1610	0.0080	1.1900	0.0120	0.0170	0.0230	0.0360
Senthil et al	0.1880	0.1855	0.8375	0.0342	0.0213	0.0217	0.0762

Table 8 - Comparison of Target Material Composition, Current Study vs. Sethil et al [42]

Property	Value – S275JR + AR Steel Target	Value – Hardened Steel Penetrator
Density	7850 kg.m ⁻³	7850 kg.m ⁻³
Specific Heat	460 J.kg ⁻¹ .C ⁻¹	460 J.kg ⁻¹ .C ⁻¹
Johnson Cook Strength Model		
Strain Rate Correction	First-Order	First Order
Initial Yield Stress	312 MPa	2700 MPa
Hardening Constant	422 MPa	211 MPa
Hardening Exponent	0.345	0.065
Strain Rate Constant	0.0156	0.005
Thermal Softening Exponent	0.87	1.17
Melting Temperature	1800 C	1800
Reference Strain Rate (/sec)	0.0001	0.0001
Shear Modulus	80 GPa	80 GPa
Shock EOS Linear		
Gruneisen Coefficient	2.17	2.17
Parameter C1	4569	4569
Parameter S1	1.49	1.49
Parameter Quadratic S2	0	0

Table 9 - Material Properties Used in Numerical Model

6.1.2.2 Mesh Convergence Study

A mesh sensitivity study was conducted to ensure the mesh sizes used in the numerical studies were optimised for the solution. The study was conducted using the 12 mm thick target being impacted at normal incidence by the projectile traveling at 680 m.s⁻¹. The velocity represents a typical residual velocity after penetration of an initial 12 mm target, as taken from the experimental data in Table 4. The criteria for the mesh convergence was minimising the difference between the numerical model's residual velocity and an analytically calculated value. The analytical value was calculated at 518.9 m.s⁻¹ using eqs. (3) and. (4).

The target mesh was converged first, decreasing in increments of 0.2 mm, using a fixed mesh size of 1.4 mm for the projectile. At a mesh size of 1.0 mm, it was observed that the change in residual velocity from a size on 1.2 mm was just 1.4 %. This was regarded as adequate for the purposes of the study. The results of this portion of the convergence study are provided in Table 10.

Size (mm)	Residual Velocity (m.s ⁻¹)	Percentage Difference From Analytical Value (518.9 m.s ⁻¹)	Percentage Difference From Previous Value
1.4	475.2	-8.4	-
1.2	512.0	-1.3	7.1
1.0	519.5	0.1	1.4

Table 10 - Mesh Convergence –Target (1.4 mm projectile mesh, velocity 680 m.s-1)

The projectile mesh was then converged using the determined target mesh of 1.0 mm. This mesh was, decreased in increments of 0.2 mm. At a mesh size of 1.0 mm, it was observed that the change in residual velocity from a size on 1.2 mm was 2.3 %. While the mesh still appears to be diverging at this point, a 1 mm mesh was decided on due to computational resource limitations. The results of this portion of the convergence study are provided in Table 11.

Size (mm)	Residual Velocity (m.s ⁻¹)	Percentage Difference From Analytical Value (518.9 m.s ⁻¹)	Percentage Difference From Previous Value
1.4	519.5	0.1	-
1.2	525	1.2	1.1
1.0	536.9	3.5	2.3
0.8	549.0	5.8	2.3

Table 11 - Mesh Convergence - Projectile (1.0 mm target mesh, velocity 680 m.s⁻¹)

The result of the two sections of the convergence study was a mesh size of 1mm for both the target and the projectile. The percentage difference between the analytically calculated residual velocity and the numerical model output can be seen in Table 12. A comparison with calculated ballistic limit is also provided in this table.

Quantity	Numerical Result (m.s ⁻¹)	Analytical Result (m.s ⁻¹)	Analytical Difference (%)
Residual Velocity	536.9	518.9	3.5
Ballistic Limit	422.2	444.1	-4.9

Table 12 - Converged Numerical Model Mesh Comparison with Analytical Results for Normal Incidence

6.1.2.3 Results of Numerical Simulations

Using the developed numerical model, a number of simulations were conducted using five degree yaw increments. This allowed assessment of how the ballistic limit of the penetrator/target pair increased with yaw. These simulations were run for the experimental thickness of 10 and 12 mm. A projectile velocity was 680 m.s⁻¹ was used for simulation of the 12 mm thickness targets. A projectile velocity of 700 m.s⁻¹ was used for simulations of the 10 mm thickness targets. These values were representative of residual velocities obtained from analytical and experimental results. The simulations were conducted up to a maximum yaw of 30 degrees for the 12 mm thickness. The simulations were conducted up to a maximum of 35 degrees yaw for the 10 mm thickness. After these maximum yaw values., the round failed to penetrate the target in the numerical simulation.

An additional simulation was run against a 6 mm target as this allowed residual velocity values to be calculated across the entire range of induced yaw which was observed experimentally. A projectile velocity was 700 m.s⁻¹ was used and simulations were conducted up to a maximum yaw value of 60 degrees. The 6 mm simulation also provided a third set of data for investigating the shape of the BL curves. The residual velocities from these simulations are provided in Table 13.

Yaw	Residual Velocity – 6mm Target	Residual Velocity – 10 mm Target	Residual Velocity – 12 mm Target
0	630.4	582.0	535.1
5	611.8	568.3	517.7
10	585.1	511.2	469.0
15	555.5	445.7	361.6
20	521.2	380.0	285.7
25	501.8	328.3	227.3
30	457.4	266.3	164.1
35	425.6	198.5	
40	379.9		
45	315.5		
50	274.8		

55	236.5	
60	185.1	

Table 13- Residual Velocity From Numerical Simulations

The residual velocities from the simulations were used to calculate BL velocities for each increment yaw. These BL velocities have been plotted in Figure 19 along with experimental penetration data for comparison. The numerical model BL velocities can be seen to increase with yaw. These yaw varying values of BL will be hereafter be referred to as Yawed Ballistic Limit (YBL).

The results of the numerical simulations show BL increasing with yaw in a non-linear fashion up to an inflection point at around 15 degrees. After this inflection point, the increase in YBL with yaw can be seen to decay. Curve fitting was used to determine the shape of the YBL curves above this inflection point of 15 degrees. A software package called CurveExpert [43] was used to determine a suitable equation for the curve fit. The 6, 10 and 12 mm data were all found to have a reasonable fit to a logarithmic curve of the type shown in eq. (10). The software did identify other models such as vapour pressure and heat capacity as a better fit to the data. These equation forms were not used as they were not logical for the data set under consideration.

The work of Johnson and Geauque [44] provide some confidence that the form of the curve fitting is correct. Their work produced a number BL curves with a similar logarithmic shape after a critical yaw angle was reached. Some of their curves did showed decreasing BL velocity at very high yaw angles. However, as noted by the authors, this was likely due to brittle failure associated with shock at high yaw angles. The Bullet Proof Steel used in their work had a much higher hardness and yield stress than the ductile targets under consideration in the current study. We would therefore expect that these brittle failures would be much less likely with the current target material.

$$YBL = a.\ln(Yaw) + b \quad (10)$$

The coefficients for eq. (10) are provided in Table 14. YBL curves for yaw angles above 15 degrees are plotted in Figure 19 as dashed lines.

Plate Thickness	a	b
6 mm	-160.28	197.93
10 mm	81.86	159.94
12 mm	251.38	120.76

Table 14 - Extrapolation Curve Coefficients, $YBL = a + b.\ln(yaw)$

From Figure 18, it can be seen that the experimental data is consistent with the calculated YBL values. Experimental firings whose residual velocity exceeds the YBL were observed to penetrate the second target plate. Conversely, those not exceeding the calculated YBL were stopped. The exception to this was round R29 which perforated but had a residual velocity below the YBL for the 12 mm target. This round is highlighted in Figure 18. Review of the HSV for this round shows one of the clamps holding the back plate to its frame failing during impact. The round also appears to strike the target quite close to the edge. Either of these factors may have affected the BL velocity of the target producing a result not fitting the observed trend.

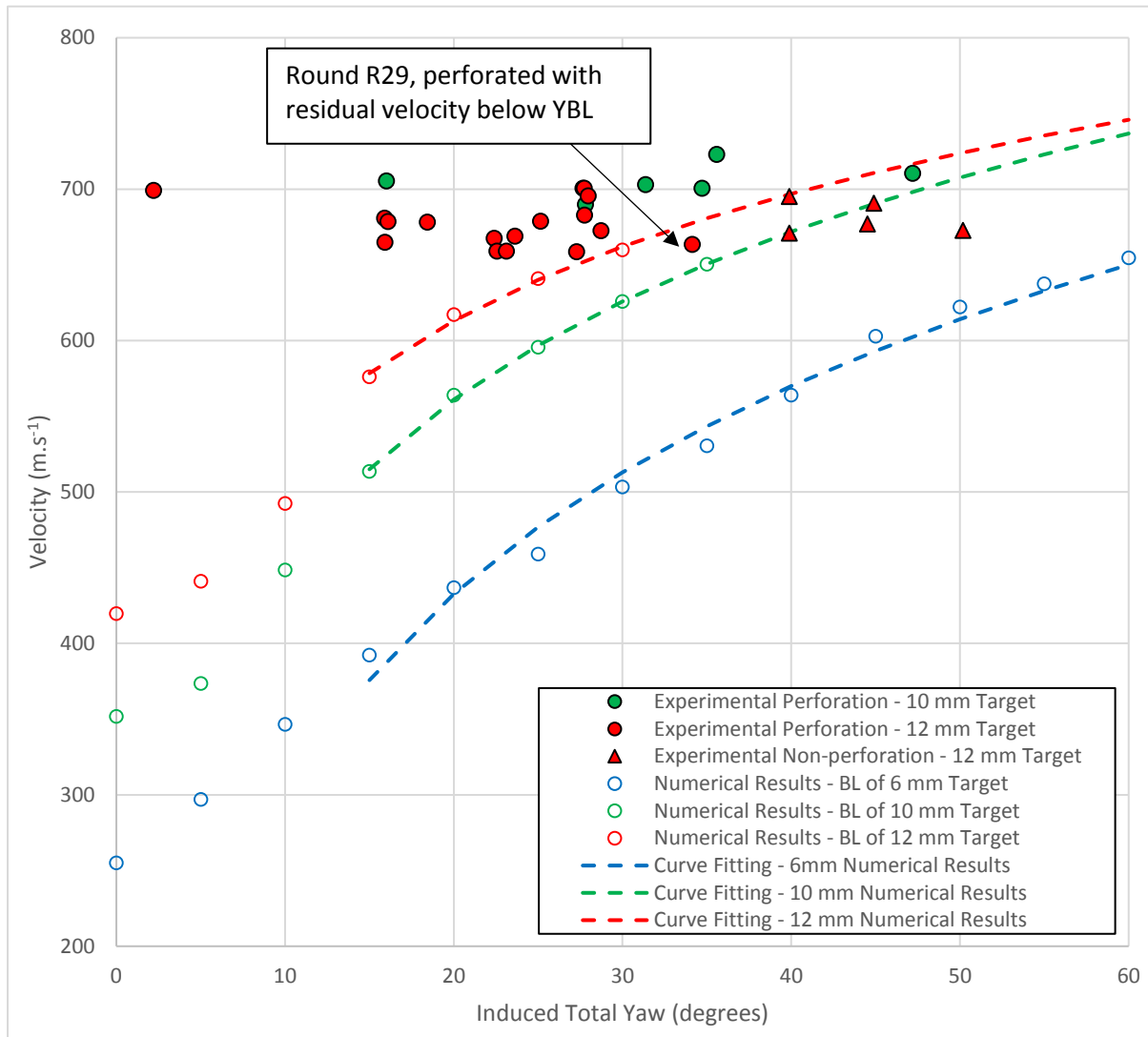


Figure 19- Result of Numerical Simulation and Experimental Penetration Data

It seems logical that the coefficients of eq. (10) could be related to target and projectile properties. However, the current numerical simulations conducted to establish residual velocities are not useful in establishing this relationship. The level of validation of the models is limited by the quantity of empirical data. There were 21 yaw/penetration events recorded against the 12 mm target and 7 events against the 10 mm target. Additionally, the coefficients calculated only relate to three thickness of one projectile/target type. The production of a large numbers validated numerical models would be required to confidently establish the relationship between the coefficients and projectile/target properties. Validation of such models would require large sets of empirical data over a wide range of configurations.

6.2 Distribution of Induced Yaw

The previous section has shown that yaw induced by an initial penetration reduces the BL when the projectile encounters a second target. This implies there is a level of yaw at which the YBL will prevent target penetration. With this in mind, it is useful to understand the statistical distribution of the yaw imposed on the round by the initial penetration. A review of induced yaw data from experimental results suggests a similar distribution of induced yaw for both 10 and 12 mm initial penetrations. This can be seen in Figure 20.

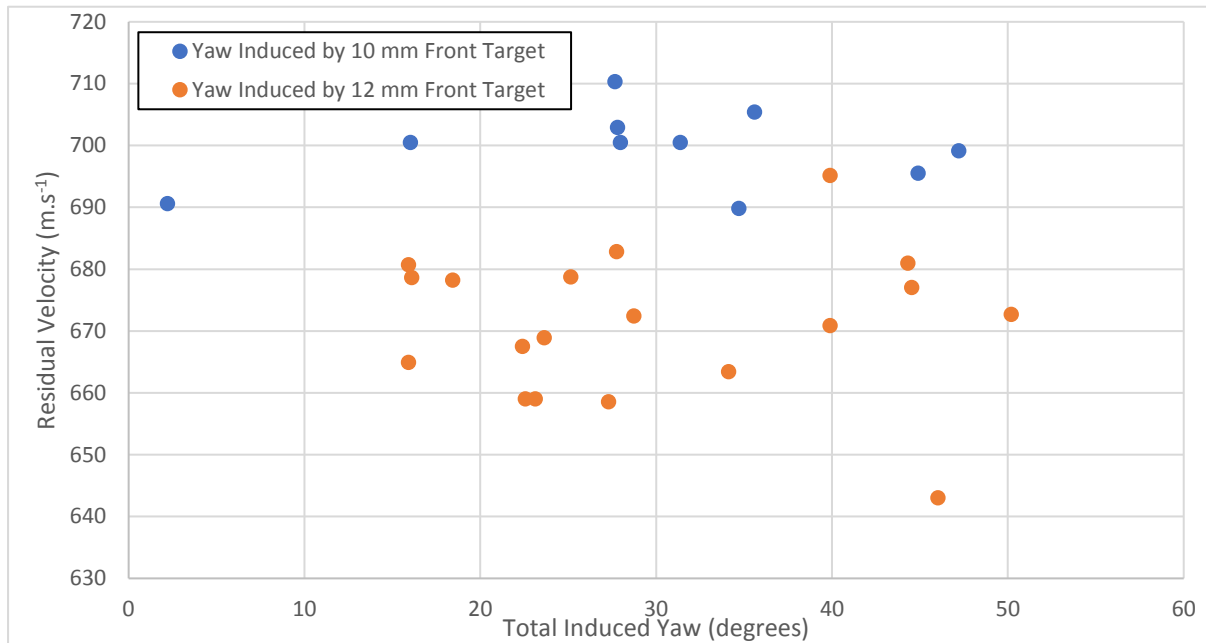


Figure 20 - Induced Yaw following Penetration of 10 and 12 mm Targets

In order to determine the statistical distribution of yaw, MiniTab [45] statistical software was used to perform a Goodness Of Fit (GOF) assessment. This assessment provides metrics of likely distributions for a provided data set. Based on the results of the GOF assessment, the yaw data was determined to best fit a normal distribution. The same process was conducted on the data for residual round velocities after penetration of the 10 and 12 mm targets. These were also found to best fit a normal distribution. The results of the assessment are provided in Table 15 along with the determined means and standard deviations.

Distribution	Anderson Darling Score	P Value	Mean	Standard Deviation
Yaw, 10 mm Plates	0.467	0.200	29.4	12.5
Yaw, 12 mm Plates	0.636	0.083	29.8	11.2
Residual Round Velocity, 10 mm	0.447	0.226	701.6	9.3
Residual Round Velocity, 12 mm	0.370	0.388	671.7	12.3

Table 15 - Goodness Of Fit Test Parameters and Assessed Normal Distribution Parameters

The distribution of yaw for the two plate thicknesses is similar. This is not unexpected as the two targets were made from the same material and had similar thicknesses. The choice of similar plate thicknesses was deliberate, as the study had a focus on how this phenomenon might be applied in maritime platforms and these thicknesses are representative of that application. It seems likely that the use of significantly different plate thickness for the first penetration event will produce different distributions of yaw. Due to the paucity of data in the current literature, characterising distributions for other configurations will require the collection of further data. Indeed, if enough data could be collected on varying configurations it may be possible to describe the relationship between material properties and yaw distribution analytically. Any analytical description is likely to relate variables such as projectile L/D ratio, nose shape, target thickness and target strength behaviour.

6.3 Probability of Penetration

Having determined an appropriate distribution for the yaw data, it is now possible to estimate the probability of penetration for a given configuration. Consider the experimental configuration with two 12 mm plates separated by a 3 m gap. Using the empirical data we could calculate the probability of penetration at 23.5 percent based on four penetrations out of seventeen fired rounds.

However, if we consider the previously described normal distribution for residual velocity, then 99.7 percent of rounds will lie within three standard deviations of the mean. It could therefore be assumed that three standard deviations above and below the mean would be reasonable maximum and minimum round velocities. This gives maximum and minimum round velocities of 708.6 and 634.8 m.s⁻¹ respectively. Using the previously described YBL curve (see eq. (10) and Table 14) for 12 mm thickness targets, we can transpose to give eq. (11). This equation allows calculation of the yaw value resulting in 100 percent stoppage of rounds.

$$Yaw = e^{\frac{V-251.38}{120.76}} \quad (11)$$

Solving eq. (11) for 708.6 m.s⁻¹ gives a minimum value of yaw to stop all rounds of 44.1 degrees. This is depicted visually in Figure 21 by the blue shaded area. When the same equation is used with the minimum round velocity, we can calculate a value of 23.9 degrees yaw, below which all rounds will perforate the target.

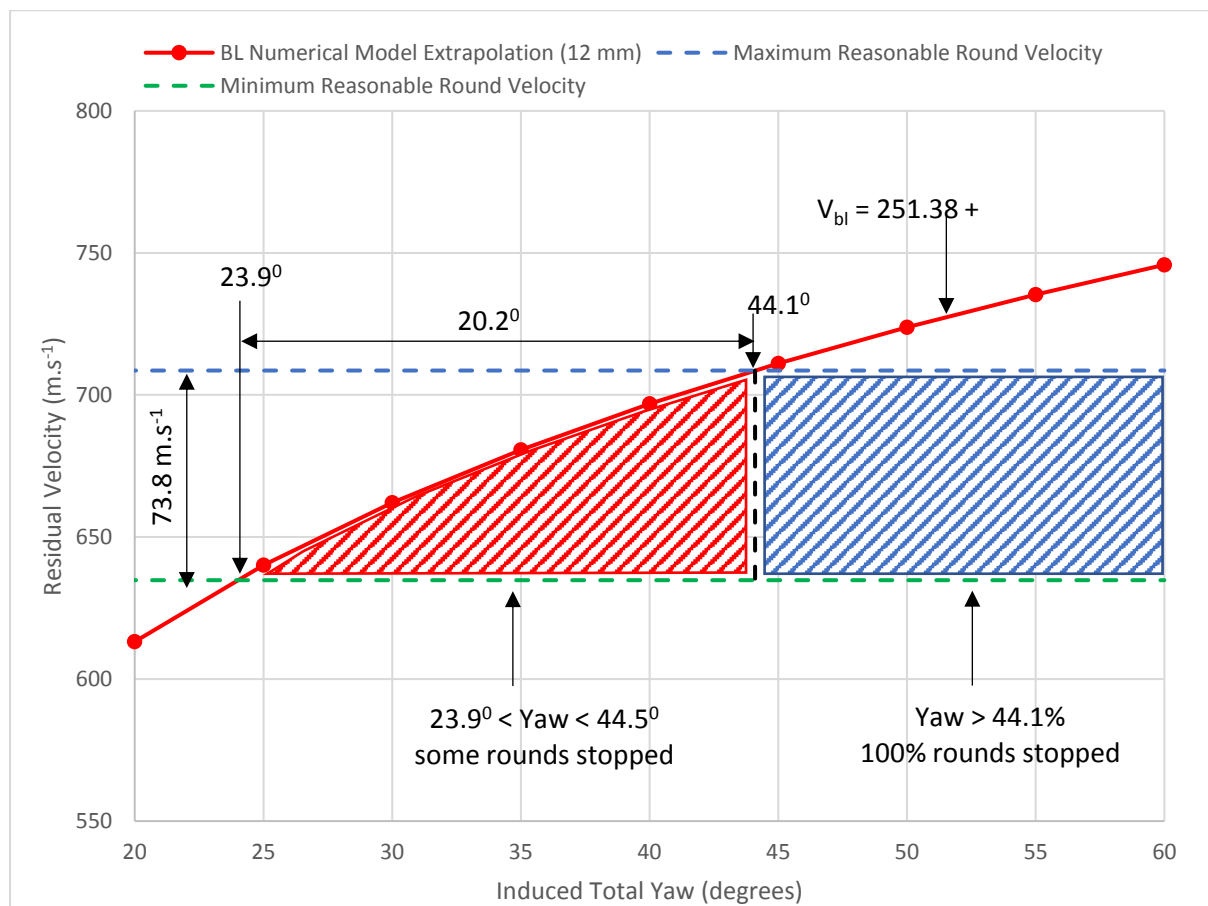


Figure 21 - Percentage of Rounds Below YBL

As depicted in Figure 22, based on the normal distribution of yaw, the percentage of rounds above 44.1 degrees yaw will be 10.1 percent.

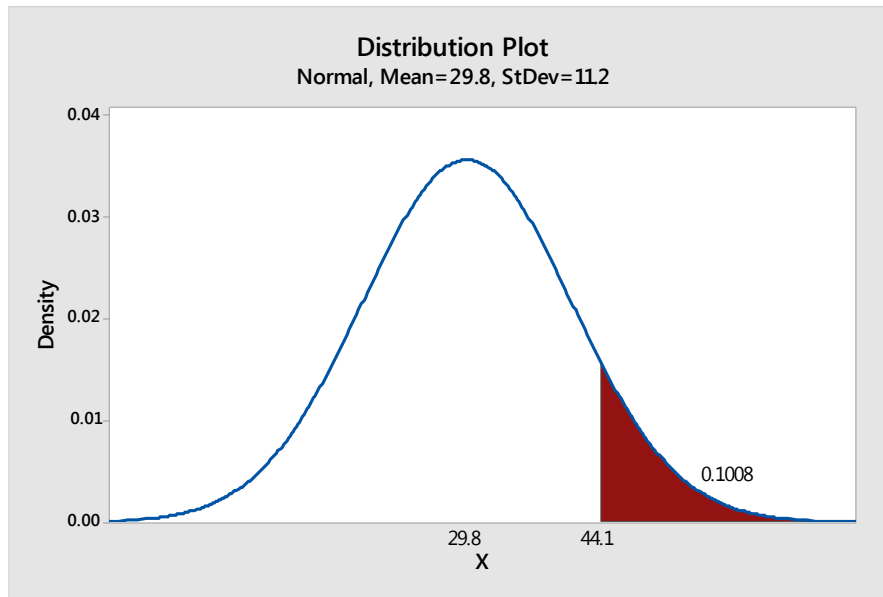


Figure 22 - Normal Distribution of Yaw Depicting Percentage of Rounds Always Stopped Due to Yaw

It can be seen in Figure 21 that rounds with yaw values between 23.4 and 44.5 will have a range of residual velocities both above and below the YBL. The red area on Figure 21 depicts the rounds in this area which would fail to perforate. This area is more difficult to calculate than the blue area as it contains two intersecting distributions. The area can be calculated using a method such as Monty Carlo evaluation. However, calculating the blue area, which gives a more conservative solution, would be acceptable for many applications.

This example demonstrates a statistical method for estimating the number of stopped rounds for a given configuration. Of course, the previous example is only valid for the targets and ammunition under consideration. Using this method requires an understanding of the distribution of the yaw, the variation of the targets BL with yaw and the projectiles likely maximum and minimum velocity. While values for the expected range of projectile velocity can be easily established, the other two require more effort. If this information is known, the method will be effective in understanding the protection offered by different configurations.

In the previously discussed example, we also have data for the distribution of yaw and residual velocity for 10 mm thickness targets. This allows consideration of different configurations. If the 12 mm front plate in the example were decreased to 10 mm we could calculate a new minimum value of yaw to stop all rounds. We start by calculating a new maximum reasonable velocity based on the 10 mm target's distribution of residual velocity. This gives a new maximum reasonable velocity of 729.5 m.s^{-1} . From the 12 mm back targets YBL curve, this translates to a minimum value of yaw to stop all rounds of 52.4 degrees. From the yaw distribution of the 10 mm plate, this equates to 3.3 percent of rounds. While this is a reduction in the number of rounds stopped of 6.8 percent, it would also represent an armour weight reduction of approximately 16.7 percent in the front plate.

The examples discussed are provided to illustrate how different armour configurations might be assessed using this methodology. Practical applications from the current study are limited by the small quantity of experimental data for validation of the distributions and YBL curves. However, the application of this methodology would be useful for specific applications if sufficient data was

collected to conduct this validation. The increased confidence in such models would also allow more detailed analyses to be conducted. Such validated models would allow the inclusion of the zone of mixed results as depicted by the red shaded area in Figure 21.

6.4 Effect of Plate Spacing

The bullet/target combination used in the study produced large amounts of flash when penetrating the plates. This flash made it difficult to collect HSV data related to induced yaw for the first meter after penetrating the initial target plate. However, review of the HSV after travelling one meter from the first penetration showed the round in its fully yawed state and travelling with precessional motion. Some of the video also suggests that significant yaw is occurring at half a meter or less, although this video was difficult to analyse due to the aforementioned flash. These results are somewhat consistent with those found by Oliver and Whitty [6] who documented full yaw 1.41 meters from the first penetration of a 13 mm Caneite sheet. However, it is difficult to make direct comparisons with this study as the round passed through five of these sheets prior to recording the yaw.

Despite extensive review of the literature, the authors were unable to find research pertaining to the yaw induced on spin stabilised rounds when penetrating metal plates. Changes in density during penetration are likely the dominant factor in inducing the yaw. These changes in density modify the drag coefficients of the round and induce yawing moments. After the round has penetrated the target, these moments cause the round to yaw. As the round travels towards the target, precessional motion occurs due to the spin stabilisation of the round. If these were the only forces acting on the round we would expect the same amount of induced yaw from each penetration. It is clear from the experimental data that this is not the case. It is therefore reasonable to assume that other factors also affect the yawing of the round and contribute to the distribution of yaw angles observed. In the HSV from experimental firings, it was observed that the jacket was stripped from the round during the penetration of the first target. It seems reasonable that variation in this stripping is a contributing factor to yawing of the round. Other contributing factors may be material inconsistencies and small amounts of pre-penetration yaw.

Due to the difficulty in determining yaw during the first meter after penetration, it is difficult to draw definitive conclusions about the minimum distance at which the full yaw effect is present. However, the HSV indicates that round yawing from initial penetration may be effective down to gaps as small as 0.5 m. Due to resource constraints, our study focused on quantifying the frequency and penetrative effect of the induced yaw. This meant the majority of firings were focused on varying plate thickness while keeping the gap fixed at 3 m. Further experimental firings with smaller air gaps would be useful in quantifying the minimum range at which the observed yawing effect is useful in preventing penetration.

7. Conclusions

The experimental work conducted as part of the study has observed that significant yaw is induced in 12.7 mm rounds by penetration of a ductile target. For the targets used in the study we have observed induced yaw values up to 50 degrees. The values of yaw after penetrating the first plate appear to be normally distributed. The study has observed that induced yaw significantly reduces a round's ability to penetrate targets. This has been demonstrated through both experimental results and numerical simulations.

The current study has been conducted using only one combination of target and projectile. This combination of intermediate thickness ($0.5 < L/D < 1.0$), ductile targets impacted by high hardness projectiles results in penetration by ductile hole growth. The combination also results in minimal

deformation of the projectile during the initial, yaw inducing penetration. The results of the study are therefore only useful when considering penetration schemes with these characteristics. However, within the stated scope of maritime platforms, this penetration scheme seems reasonable. Maritime platforms are generally constructed of reasonably ductile steels. Additionally, 12.7 mm AP rounds represent one of the highest ballistic threats for these platforms from small arms.

We have used numerical modelling to quantify the relationship between yaw and ballistic limit for the materials used in the study. The results of this modelling have been used to produce ballistic limit curves for yawed 12.7 mm AP rounds against these targets. These curves have been found to be consistent with experimental results, although the limitations of this modelling must be acknowledged. One of these limitations relates to the characterisation of the materials used in the study. Comprehensive characterisation of the materials with respect to strength behaviour in the ballistic regime would have increased confidence in the model. Another limitation was the relatively modest experimental result set available to validate the model.

It has been shown that the model can be used to predict probability of perforation using basic statistical methods. These techniques offer the advantage of allowing different armour configurations to be compared. For specific applications, properly characterised and validated models would allow the assessment of the yaw effect in different armour configurations.

The study has been restricted to consideration of a specific configuration, namely that related to maritime platforms. However, different physical and material characteristics will affect different configurations. High hardness targets are likely to cause perforation by other mechanisms such as shearing and plugging. Different thicknesses might produce perforation mechanisms such as petalling, cracking or spalling. This will yield different characteristics with respect to the change in ballistic limit as yaw is increased. A wide range of physical and material characteristics have not been investigated as part of this study. However, characterising this phenomenon with respect to a wide range of parameters suggests development of analytical or semi-analytical solutions may be possible.

8. Further Work

Further studies should be conducted to develop fully validated models for specific applications such as armour systems in maritime platforms. These models could enhance capability through weight saving in addition to the associated cost savings.

It would also be useful to further investigate how specific material and physical properties affect the penetration of yawed rounds. Examples of useful properties for investigation include material thickness, round velocity, material hardness and stress/strain parameters. Our numerical investigation suggests that analytical or semi-analytical equations may be possible if these properties could be adequately characterised with respect to yaw.

The current study has characterised yaw distribution for a specific target/projectile pair. Studies investigating the distribution of induced yaw with respect to specific material properties would be useful. The distribution of induced yaw also depends on the minimum distance required for maximum yaw to be induced and this should be a consideration in these types of studies.

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Annex A – High Speed Video Measurements and Calculations

The following table shows results of measurements and calculations from HSV data. Analysis for yaw and pitch began with the nearest clear frame to the back target. Subsequent frames for analysis were taken at intervals of five frames until flash from penetration of the front target prevented further measurement.

Round Identifier	Result on Back Plate	Initial Velocity (Doppler Radar)	Residual Velocity (measured from HSV)	HSV Frame Number (for Pitch and Yaw measurements)	Pitch (measured from HSV)	z-y Plane Length (measured from HSV)	Horizontal Yaw (calculated from z-y length measurement)	Total Yaw (calculated from Horizontal Yaw and Pitch)	Total Yaw - Average
SERIES 1 – 12 mm FRONT TARGET, 12 mm BACK TARGET, 2 m AIR GAP									
R06	Perforation	810	USEFUL ANALYSIS OF DATA NOT POSSIBLE DUE TO HIGH SPEED VIDEO FAILURE						
R07	Perforation	Doppler Radar Failure							
R08	Perforation	Doppler Radar Failure							
R09	Perforation	804							
SERIES 2 – 12 mm FRONT TARGET, 12 mm BACK TARGET, 3 m AIR GAP									
R10	Null Result	805	643.0	-12302	35.2	40.8	36.9	45.8	46.0
	Struck apparatus			-12307	35.2	40.8	36.9	45.8	
				-12312	32.9	39.7	38.9	46.0	
				-12317	32.9	39.7	38.9	46.0	
				-12322	27.9	37.7	42.3	46.5	
R11	Perforation	815	667.5	-10275	11.8	48.1	19.4	22.3	22.4
				-10280	11.8	48.1	19.4	22.3	
				-10285	9.5	47.7	20.7	22.5	

				-10290	9.5	47.7	20.7	22.5	
				-10295	9.5	47.7	20.7	22.5	
R12	No Perforation	824	672.7	-7410	7.6	29.7	54.4	54.5	50.2
				-7415	23.2	29.9	54.1	55.3	
				-7420	34.5	38.1	41.7	48.3	
				-7425	39.5	43.2	32.1	46.0	
				-7430	43.3	45.8	26.1	46.7	
R13	Null Result	824	680.9	-2649	41.6	47.5	21.4	44.1	44.3
	Struck apparatus			-2654	41.8	50.3	9.5	42.3	
				-2659	46.5	51.0	0.0	46.5	
R14	Perforation	820	672.4	-6167	28.6	49.5	13.9	30.9	28.7
				-6172	27.6	51.0	0.0	27.6	
				-6177	29.5	51.0	0.0	29.5	
				-6182	25.6	50.3	9.5	26.9	
R15	No Perforation	839	695.1	-9107	38.7	50.6	7.2	39.0	39.9
				-9112	40.4	51.0	0.0	40.4	
				-9177	38.7	50.6	7.2	39.0	
				-9122	34.4	45.4	27.1	40.5	
				-9127	27.8	42.4	33.8	40.4	
R16	Perforation	825	678.2	-2978	0.0	48.4	18.4	18.4	18.4

				-2983	0.0	48.4	18.4	18.4	
				-2988	0.0	48.4	18.4	18.4	
				-2993	2.3	48.4	18.4	18.5	
				-2998	2.3	48.4	18.4	18.5	
R22	Perforation	811	678.8	-2777	0.0	45.1	27.8	27.8	25.1
				-2783	5.0	45.3	27.3	27.7	
				-2787	7.1	47.4	21.7	22.6	
				-2792	9.5	47.7	20.7	22.5	
R23	No Perforation	809	670.9	-2863	32.3	44.1	30.2	40.6	39.9
				-2868	27.8	42.1	34.4	40.8	
				-2873	21.8	42.2	34.2	38.2	
R24	Perforation	806	680.7	-2543	6.8	49.4	14.4	15.8	15.9
				-2548	4.6	49.2	15.3	15.9	
				-2553	2.3	49.1	15.7	15.8	
				-2558	0.0	49.0	16.1	16.1	
R25	No Perforation	809	677.0	-2760	24.0	38.6	40.8	44.2	44.5
				-2766	32.9	39.7	38.9	46.0	
				-2770	37.9	44.7	28.8	43.6	
				-2775	41.6	47.2	22.3	44.4	
R26	Perforation	803	664.9	-2794	11.3	50.0	11.4	15.8	15.9
				-2799	13.5	50.4	8.8	15.9	
				-2804	15.6	50.9	3.6	16.0	
R27	Perforation	810	668.9	-3653	7.4	45.5	26.9	27.6	23.6

				-3658	11.8	48.1	19.4	22.3	
				-3663	14.0	48.5	18.0	22.3	
				-3668	16.3	49.0	16.1	22.3	
R28	Perforation	814	678.6	-3103	4.6	49.2	15.3	15.9	16.1
				-3108	0.0	49.0	16.1	16.1	
				-3113	9.1	49.6	13.5	16.1	
				-3118	14.0	50.4	8.8	16.4	
R29	Perforation	815	663.4	-3760	5.7	39.4	39.4	39.6	34.1
				-3765	0.0	41.2	36.1	36.1	
				-3770	8.1	41.6	35.3	35.9	
				-3375	12.8	44.2	29.9	31.8	
				-3380	17.0	47.1	22.6	27.3	
R30	Perforation	807	659.0	-3641	4.8	47.2	22.3	22.7	22.6
				-3646	7.1	47.4	21.7	22.6	
				-3651	9.5	47.7	20.7	22.5	
				-3656	9.5	47.7	20.7	22.5	
R31	Perforation	823	682.8	-2826	0.0	45.1	27.8	27.8	27.8
				-2831	2.5	45.1	27.8	27.9	
				-2836	5.0	45.3	27.3	27.7	
				-2841	7.4	45.5	26.9	27.6	
R32	Perforation	811	658.5	-2766	9.9	45.8	26.1	27.5	27.3
				-2771	14.6	46.6	24.0	27.3	
				-2776	19.2	47.7	20.7	27.2	
				-2781	21.4	48.4	18.4	27.2	

R33	Perforation	804	659.0	-4237	16.9	47.1	22.6	27.2	23.1
				-4242	16.3	49.0	16.1	22.3	
				-4247	18.4	49.6	13.5	22.3	
				-4252	18.4	49.9	11.9	21.5	
				-4257	16.2	49.0	16.1	22.3	
SERIES 3 – 10 mm FRONT TARGET, 10 mm BACK TARGET, 3 m AIR GAP									
R18	Perforation	824	710.3	-2154	32.3	44.1	30.2	40.6	47.2
				-2159	41.6	47.2	22.3	44.4	
				-2164	49.9	48.7	17.3	50.8	
				2169	51.7	47.5	21.4	53.0	
R19	Perforation	815	700.5	-1988	2.5	45.1	27.8	27.9	27.7
				-1993	7.4	45.5	26.9	27.6	
				-1998	9.9	45.8	26.1	27.5	
R20	Perforation	814	USEFUL ANALYSIS OF DATA NOT POSSIBLE DUE TO HIGH SPEED VIDEO FAILURE						
R21	Perforation	816	702.9	-3355	28.6	49.1	15.7	31.5	31.4
				-3360	28.6	49.1	15.7	31.5	
				-3365	26.6	48.2	19.1	31.3	
				-3370	24.4	47.4	21.7	31.1	
R34	Perforation	809	689.8	-3798	5.0	45.3	27.3	27.7	27.8
				-3803	2.5	45.1	27.8	27.9	
				-3808	0.0	45.1	27.8	27.8	
R35	Perforation	811	700.5	-3643	29.7	47.4	21.7	34.8	34.7

				-3648	27.6	46.5	24.2	34.6	
				-3653	23.2	44.8	28.5	34.7	
R36	Perforation	822	705.4	-2569	9.1	49.6	13.5	16.1	16.0
				-2574	4.6	49.2	15.3	15.9	
				-2579	0.0	49.0	16.1	16.1	
R37	Perforation	829	723.0	-2855	20.9	44.1	30.2	34.8	35.6
				-2860	13.4	42.3	34.0	35.5	
				-2865	0.0	41.2	36.1	36.1	
				-2870	8.1	41.6	35.3	35.9	
SERIES 4 – 10 mm FRONT TARGET, 12 mm BACK TARGET, 3 m AIR GAP									
R38	Perforation	820	700.5	-2518	9.9	45.8	26.1	27.5	27.7
				-2523	5.0	45.3	27.3	27.7	
				-2528	2.5	45.1	27.8	27.9	
				-2533	0.0	45.1	27.8	27.8	
R39	Perforation	809	695.5	-2891	9.9	46.1	25.3	26.8	28.0
				-2896	14.6	46.9	23.1	26.6	
				-2901	22.2	46.9	23.1	30.6	
R40	No Perforation	810	690.6	-2905	43.3	45.2	27.6	47.1	44.9
				-2910	41.4	43.9	30.6	46.7	
				-2915	37.9	44.1	30.2	44.2	
				-2920	29.1	39.9	38.5	44.2	
				3170	20.2	39.2	39.8	42.3	
R41	Perforation	805	699.1	-4367	2.2	51.0	0.0	2.2	2.2

				-4372	2.2	51.0	0.0	2.2	
				-4379	2.2	51.0	0.0	2.2	