Beyond V_{50}: A More Comprehensive and Efficient Methodology for Assessing Armour Performance

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Abstract. Assessing personal armour protection involves repeated destructive testing to infer ballistic resistance; for example, ballistic limit (V_{50}) evaluations determine the velocity-dependent perforation risk. Many common ballistic standards rely on firing procedures and analysis methods developed before the widespread integration of computer systems in ballistics testing (e.g., the up/down firing method, arithmetic V_{50}). These aspects of ballistic testing, including data acquisition and analysis can now be modernized and automated using commercially available ballistics measurement hardware and software. The new methodology benefits from modern real-time computation capabilities and reduces the cost of ballistics testing by requiring fewer shots to obtain more information, especially for hard armour systems having limited multi-hit capacity. A common objective of ballistics testing is comparing two or more armour systems to determine which is better suited for a given application. The present study proposes a framework to compare armour systems with similar ballistic limits (V_{50}) by leveraging data collected during standard testing to describe the undermatched (V_{05}) and overmatched (up two times the V_{50}, but for practical reasons, it is often limited to $1.5 \cdot V_{50}$) velocity regimes. The analysis introduces two novel data presentation tools, Yawgit, which proposes a mixed velocity-yaw perforation probability, and Ballistic Triple Plots, which fully describe the ballistic resistance characteristic in the three velocity regimes. The discussion also includes implementing and interpreting confidence intervals to differentiate the performance of two armour systems. V_{50} Assist™, a commercially available ballistic testing software that guides users through all aspects of testing described in common ballistic standards, was used in the present study for data collection, firing procedure, and analysis.

1. CURRENT STATE OF BALLISTIC TESTING STANDARDS ANALYSES

Common ballistic test standards for personal body armour systems outline the methodologies, threats, parameters, and analyses required for certification. These standards typically assume that the ballistic limits (V_{50}) metric fully describes the ballistic resistance of armour. Armour systems with a higher V_{50} do tend to provide more protection than systems with a higher V_{50}, but this conclusion only extends to the velocities near the ballistic limit. Common test standards do not attempt to quantify the relative performance of perforating and non-perforating events across the full range of feasible threat velocities. The ballistic limit is not a flawed metric but should be augmented with information obtained across a broader range of velocities. This data is critical for manufacturers to improve products, for researchers trying to understand what affects armour performance, and for acquisition officers specifying performance criteria.

The firing methods specified in standards repeatedly test armour over a range of velocities that elicit both non-perforations (partial penetrations, PPs) and perforations (complete penetrations, CPs). With sufficient tests producing velocity-outcome data, it is possible to perform statistical analyses to ascertain the V_{50} ballistic limit. Standard procedures include traditional up-and-down methods in AEP 2920 [1], NIJ 0101.06 [2], and MIL-STD-662F [3], and the Modified Langlie from [4] although more involved methods, such as three-phase optimal design (3PoD) [5] have been proposed but are not referenced yet in ballistic standards.

Efforts to assess the ballistic resistance properties are complicated by data censoring, which describes the incomplete information gained during testing. Ideally, each shot would produce a single value – the exact outcome transition velocity (V_{OT}) at which a non-perforation (PP) becomes a perforation (CP). Instead, the velocity-outcome information of every shot can only be used to reach one of the two following conclusions: the outcome was a PP; therefore, the velocity did not reach the PP/CP transition, or the outcome was a CP; therefore, the velocity was above the PP/CP transition. Unfortunately, due to variability in the armour and projectile manufacturing/composition (i.e., defects) and test conditions (i.e., projectile yaw), V_{OT} is not identical for every shot. The V_{50} metric approximates the average V_{OT} value.

Trivial metrics such as the average of the *k* highest PP velocities and *k* lowest CP velocities, seen in MIL-STD-662F [3] and Section H.1 of AEP 2920 [1], provide very little information and require several caveats regarding the overlapping and grouping of results. To reduce bias when using this method, the maximum velocity spread may be constrained [1]. Consequently, advanced statistics such as logistic regression are required to approximate the distribution of the outcome transition velocity (i.e., $V_{OT} \sim N(\mu,\sigma)$). A "link function" such as Logit, Probit, or complementary Log-Log (Gompit) relates strike velocity to outcome probability [6]. Despite weighing velocity-outcome data when solving logistic regression parameters, common testing standards do not sufficiently consider the nuanced differences between two PPs (or two CPs) at different velocities. The definition of an outcome transition velocity may become less clear in specific applications, such as hard armour systems with a known shatter-gap or blunting-gap effect. Using different witness materials to assess perforation (i.e., Army vs Navy vs Protection) also influences the transition velocity. Nonetheless, the fundamental concept of censored outcome transition velocity is transferable. It illustrates the need for a more descriptive assessment of the differences between shots with the same outcome and distinct velocities. Alternate methods to logistic regression that reduce the dependency on normality assumptions and simultaneously describe the physical behaviour and statistics have also been proposed [7]. Logit is the recommended method for NIJ 0101.06 [2], with minimal information provided in the standard regarding the method of interpretation [2]. AEP 2920 (Section H.3) [1] requires a Probit analysis to compute both the mean and standard deviation of the perforation probability distribution; it also mentions leveraging the logistic regression best-fit parameters to approximate the limit velocities (V_{01} and V_{99}) and describes a method of computing confidence intervals on the two regression parameters (V_{50} and σ). The concept of confidence intervals need not be limited to just the V_{50} value but can be plotted over the full range of test velocities and can be used to assess the confidence level at any perforation probability (i.e., V_{05}) [6], [8]. However, no commonly referenced ballistic test standards for personal armour provide a framework for the computation or interpretation of the full confidence interval width at a value other than the V_{50}.

Given the high cost of ballistics testing due in part to the destructive testing of many samples and limited information gained with every shot, full use of all available data should be prioritized. Not all ballistic tests are the same – there are fundamental differences in the testing of soft armour systems compared to ballistic-resistant hard armour plates, from the mounting fixture to the type of backing/recovery media (e.g., clay, foam packs, air). Standard analyses use the velocity-outcome data with little consideration for the many other aspects of ballistic testing that can provide insight into the armour performance. For example, there is little or no consideration for the undermatched (V_{05}) or overmatched (up to $1.5 \cdot V_{50}$), where the results are predominantly PPs or CPs, respectively, but other properties that are not typically measured can vary significantly within each range. Overmatch is more often relevant to fragment-simulating projectiles (i.e., blast simulants) than bullets with velocities constrained by casing size. It is feasible to perform these additional measurements on every shot at minimal cost to quantify the ballistic performance across the three velocity regimes (undermatched, limit, and overmatched) without requiring additional testing. For example, to evaluate the undermatched velocity regime, when testing on a clay block, the backface deformation for PPs may be measured for NIJ 0101.06, or the number of plies perforated in a multi-layer soft armour can be counted. The overmatched performance can be evaluated by measuring the residual velocity (V_r) of armour in an air-backed fixture [9] or the depth of penetration into a recovery media such as multi-layered foam packs. V_r-V_s overmatch data are especially important for fragmentation-resistant armour since used in vulnerability/lethality codes for conducting casualty reduction analysis. Ballistic standards also consider projectile yaw, but only to the extent of assessing shot fairness by limiting to 5° in MIL-STD-662F [3] and NIJ 0101.06 [2], and 3° or 5° in AEP 2920 [1]. To be fully compliant with the testing requirements of these standards, yaw must be measured for every shot; therefore, the data is being recorded but is not used to its full potential.

Notably, the test standards all aim to provide a repeatable framework for assessing ballistic resistance of personal body armour. In this context, the results are taken to indicate a pass or fail at the specified certification level. However, this approach does not provide sufficient context for a researcher or purchaser to understand the difference in performance between two sample types tested according to the same methodology. Therefore, there is currently no guidance on the quantitative comparison of the two armour systems. Single-purpose tools (spreadsheets or code) designed to perform partial analyses (DRDC Ballistic Limit Calculator (BLC) [10]) or guide the user through firing procedures (GoNoGo [5]) have been developed, but no fully integrated software exists. V_{50} Assist™ (Biokinetics and Associates Ltd., Ottawa, Canada), which was used to produce all results in this paper, is a commercial-off-the-shelf (COTS) ballistics software package that walks the user through firing procedures, data collection, and analyses as described in common ballistic standards and literature.

2. METHODOLOGY

For the present study, two multi-layered soft armour systems were tested according to procedures outlined in AEP 2920. Testing was performed on a soft armour clamping fixture with force and tensions described in the DRDC-V frag vest method [9]. Witness paper positioned approximately 150 mm down range of the samples was used to assess the outcome of each shot (i.e., protection criterion) as a CP or a PP. The standard test methodologies were modified slightly with additional data collection not typically performed in ballistic testing to increase the value and knowledge gained for every shot. For each shot, the strike velocity, projectile yaw, and residual velocity (for CPs only) were measured, and the number of perforated plies was counted. Both materials were tested using the 1.1g (17 gr.) chisel nose cylinder Fragment Simulating Projectile (FSP) defined in [1].

2.1 Sample Preparation

Two materials were included in the present study. The focus of the present study is on the comparative analysis and not the relative performance of two materials with similar ballistic limits. Material A had an assembled sample areal density of 3 kg/m^2). Preliminary testing was conducted on the Material B packs to determine the ply count required to have a comparable V_{50} to Material A. Material B had an assembled sample areal density of 2.6 kg/m^2. Samples were assembled in 400mm x 400mm layers for use in the DND clamping fixture [9]. Each sample was clamped to the required 2-30 N before testing. The samples were partially stitched along the upper corners and in a U-shape along the lower perimeter to facilitate the capture of the projectiles that did not fully perforate the samples. The stitching pattern and nine-shot firing pattern are shown in Figure 1.

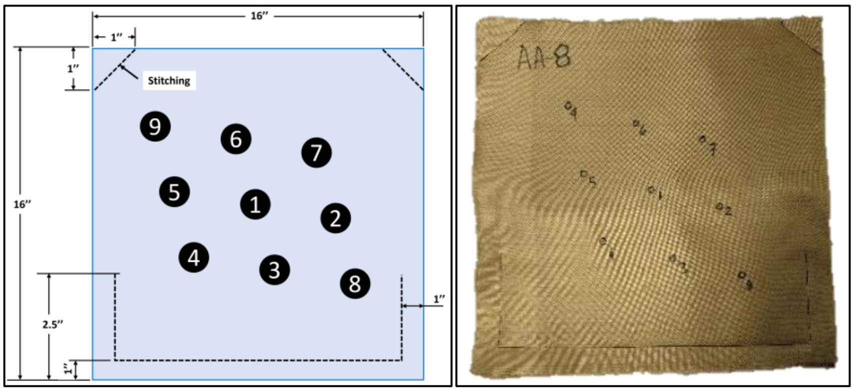


Figure 1: Proposed (left) and actual (right) stitching and shot pattern.

2.2 Firing Procedure

A total of 48 shots were conducted on each of the two materials. The shots were split into three series. First, 16 shots were performed using the AEP 2920 [1] up/down firing method with an initial velocity estimate of 520 m/s. The following series of 16 shots were conducted with a reinitialized up/down procedure where the initial velocity was the Probit V_{50} of the 16 shots from series 1. The initial velocity for the third series was determined using the combined 32-shot dataset (16 from each of series 1 and 2).

2.3 Measurement Devices

Data collection was performed using commercially available measurement devices. Projectile velocity was assessed using the SpeedTube^{TM} (Biokinetics and Associates Ltd., Ottawa, Canada), a ballistic chronograph with two pairs of light gates to redundantly measure the velocity of each shot at approximately 2.5 m before impact. The strike velocity was computed in the SpeedTube^{TM} (Biokinetics and Associates Ltd., Ottawa, Canada) software using the average drag coefficient method described in Eq II in Annex K of AEP 2920 [1]. Yaw was measured approximately 250 mm up-range of the sample using the YawBox^{TM}, which uses a single camera and mirrors to obtain two orthogonal views of the projectile. Both the YawBox^{TM} and SpeedTube^{TM} are shown in Figure 2. A Doppler radar (Infinition Inc., Trois-Rivières, Canada) was positioned to measure the residual velocity of projectiles that fully perforate the armour system. The Doppler radar was positioned at a 30° angle from the firing trajectory; therefore, a correction factor was applied to determine the residual velocity along the initial trajectory.

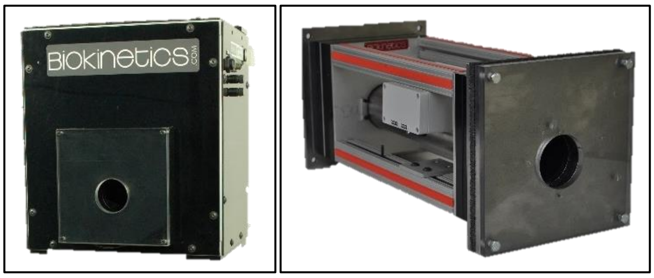


Figure 2: Pictures of the YawBox™ (left) and SpeedTube™ (right).

2.3.1 Measurement Uncertainty

All measurement devices in this study were analysed to quantify the expanded uncertainties according to the principles of the guide to the expression of uncertainty in measurement (GUM) and ISO 17025. The expanded uncertainty, reported with a coverage factor of 2 and a normally distributed coverage level of approximately 95% is ±0.12% for the SpeedTube™, ±0.46° for FSPs with the YawBox™, and ±1.1% for 17-grain FSPs with the Infinition doppler radar in its present configuration.

2.4 Data Collection

Data collection and analyses were performed using the V_{50} Assist™ COTS software, an all-in-one package to walk a user through standard ballistic testing. The initial parameters of the selected firing procedure were input into the software, which provided the next velocity. For every shot, the powder load used by the technician, the strike velocity reported by the SpeedTube™ (Biokinetics and Associates Ltd., Ottawa, Canada), the projectile yaw measured by the YawBox™ (Biokinetics and Associates Ltd., Ottawa, Canada), and, if applicable, the residual velocity from the doppler radar system, outcome (PP/CP), and the time of the test, were input into V_{50} Assist. Preceding test velocities and outcomes were used to recommend the next velocity and load required to reach that velocity. The end of each test series is indicated by the software, and individual completion criteria (e.g., CI width less than 4% of V_{50} in [1]) are updated after every shot. Following the end of the test series, each sample was dissected to identify how many layers had been perforated for each PP. Any modification of test data prompted immediate recompilation of all analyses, including all parameters specified in MIL-STD-662F [3], NIJ 0101.06 [2], and AEP 2920 [1]. Charge calibration, chronological shot velocities, logistic regressions (Logit, Probit, Gompit, Scobit, Weibull, Yawgit), unperforated ply ratio, energy absorption ratio, and several other analysis types are plotted to illustrate the benefits of recording more data during ballistic testing.

3. ANALYSIS METHODOLOGY

The present study demonstrates a methodology that maximizes the information gained during ballistic testing. This is achieved using all available data points, including performing additional measurements to adequately quantify the ballistic resistance in the three velocity regimes (under-matched, V_{50}, and over-matched) without requiring additional shots or armour samples.

3.1 Ballistic Resistance Triple Plot

The ballistic resistance triple plots are a visual representation of the armour performance in the three velocity regimes overlayed on the same axis. Different curves may be selected for the three velocity regimes depending on the armour type and test configuration. To illustrate the potential of the triple plots, the following three curves were selected and plotted as protection curves (i.e., probability of 100% at 0 m/s): unperforated ply ratio (UPR) for under-matched velocities, logistic protection probability for ballistic limit velocities, and energy absorption ratio (EAR) for over-matched velocities. The UPR is defined as the fraction of layers that were not perforated during the test. For example, if a fragment perforated 10 plies in a 40-ply sample, the UPR is 0.75. The UPR quantifies the remaining protective margin and helps assess the safety margin (i.e., how close was the sample to failure?). As is common practice in ballistics testing, any non-perforating fragments would remain in the sample for subsequent shots and dissection is only performed after all shots are completed. The data is trivial to acquire following typical testing but is generally discarded. The effects of trapped projectiles on future shots are unknown; however, shot spacing is typically selected to ensure a suitable shot-to-shot spacing. The UPR definition presented here is a special case of the residual areal density ratio (RADR), where the test samples are composed of a single material. The more general RADR, which is the sum of the areal densities of all unperforated layers normalized by the areal density of the sample, can be used if materials with different areal densities are present in the sample. A logit-inspired continuous fit was then used to determine the expected UPR across the full range of velocities.

$$P_{surv-UPR} = 1 - \left(1 + e^{-(\beta_0 + \beta_1 UPR)}\right)^{-1} \tag{1}$$

The protection probability can use any logistic regression link function and is the complement of the perforation probability. The logit link function formulation was used in this study.

$$P_{surv-logit} = 1 - \left(1 + e^{-(\beta_0 + \beta_1 V_s)}\right)^{-1} \tag{2}$$

The over-matched component is based on the residual velocity model of Lambert-Jonas described in [11] based on an energy approach with three parameters describing the magnitude, asymptotic slope, and limit velocity. The Lambert-Jonas equation was previously shown to be adequate for computing the armour effective velocity [12] characterizing the overmatch regime. The energy absorption ratio, described in [13], is the difference between the incident projectile kinetic energy and the projectile's residual kinetic energy after passing through the armour. The EAR, which is the absorbed energy (incident-residual) normalized by the incident energy, assumes the energy used to deform the projectile is negligible and may not be valid for all projectiles. The EAR version presented here is derived by inserting the Lambert-Jonas residual velocity regression in the EAR definition. After the computation of the EAR over the full range of velocities, the Armour Performance Rating (APR) can be computed as the average EAR in a velocity range [13]. Here, it is computed between V_{50} and $1.5 \cdot V_{50}$.

$$EAR = \frac{V_s^2 - \left(\alpha\left(V_s^{\delta} - V_l^{\delta}\right)^{\frac{1}{\delta}}\right)^2}{V_s^2}, \; V_s > V_l \tag{3}$$

3.2 Yawgit

Many common ballistic testing standards call for projectile yaw to be measured shortly before impact to judge the fairness of the test. For example, if the yaw exceeds 3° or 5°, the test should be repeated according to [1] and [2]. Unfortunately, yaw cards, which are still commonly used in ballistics test facilities, provide cruder measurements than digital systems [14] and are likely less repeatable due to the potential for different measurements by different technicians. With COTS digital systems, yaw can be assessed with significantly higher certainty by eliminating user variability. Standards requiring yaw measurements as a go/no-go screening tool acknowledge that the yaw angle affects the outcome but assume that if it is close to a direct impact, the effect is small and thus negligible. To maximize the value of each test, the effects of projectile yaw can be quantified to provide meaningful information regarding the ballistic resistance, particularly when the value is already measured for fairness screening.

In ballistic testing, the Logit perforation probability depends on an expression containing a linear combination of a constant and the strike velocity (V) as the argument. Other logistic regressions (e.g., Probit, Gompit) are similarly constructed. Expanding the Logit argument to include a contribution from precise digital yaw angle measurements is now possible. The proposed modification can be applied to any logistic link function (e.g., Logit).

$$P_{yawgit} = \left(1 + e^{-(\beta_0 + \beta_1 V + \beta_2 \theta)}\right)^{-1} \tag{4}$$

The new perforation probability (Yawgit) adds a linear combination of the yaw (θ) to the original formulation. Significant insight into the validity of the small-yaw screening assumption can be gained from this logistic regression. For example, the magnitude and sign of β_2 may help determine if small yaw angles are more or less likely to perforate the armour. An analysis of the sensitivity to outliers was not performed in this study. For data representation of Yawgit, it is recommended to solve for the coefficients using maximum likelihood, then plotting the perforation probability across a range of velocities for several fixed yaw angles (isolines) at 0°, 1°, 2°, 3°, 4°, and 5° (isolines). The isolines will have the same slope but will be translated along the velocity axis. Similarly, the isolines can be defined at fixed velocities while varying the yaw (i.e., V_{50}, V_{50}+50m/s)

3.3 Confidence intervals

A comparison of the perforation probability versus velocity curves of two materials cannot be performed without confidence intervals (CIs). AEP 2920 [1], which provides the most thorough description of confidence intervals in common ballistic standards, only provides a method of assessing the confidence intervals for the Probit fit coefficients (V_{50} and σ). Proper confidence intervals on probability for the full velocity range in logistic regression are constructed using Wald's test. These confidence intervals can be interpreted around the central portion of the curve (e.g., V_{25}-V_{75}). Unfortunately, they may become difficult to interpret in small series with few shots due to divergence at the upper and lower tails. The probability confidence intervals determined using Wald's test (vertical) can be transformed into confidence intervals on velocity (horizontal), which have much better convergence characteristics [15]. The interpretation of these confidence intervals is different and depends on the formulation of the research question [15]. For example, if the focus is on the range of velocities that contain the V_{50}, the horizontal formulation is suitable. Otherwise, the vertical formulation, which is used in AEP 2920 [1], must be used if the focus is on the range of perforation probabilities at a given velocity.

The selection of the coverage level of the confidence intervals is critical to the interpretation of the results. When considering a single test series, a 95% confidence level is suitable and reflects the confidence level required by AEP 2920 [1] on logistic coefficients. If two logistic regressions are being compared, the confidence interval width must be adjusted. The null hypothesis being posed is effectively the following: what is the probability of observing non-overlapping V_{50} confidence intervals for independent series if $V_{50A}=V_{50B}$? The answer is $p<0.006$ if using 95% confidence intervals. Instead, statistical significance (i.e., $p<0.05$) is reached when the confidence level is reduced to 83.4% [16]. Note, 83.4% confidence intervals are narrower than 95% confidence intervals. Both types of confidence intervals are implemented in V_{50} Assist™ where the confidence level can be customized to any value.

4. RESULTS AND DISCUSSION

The present analysis first computed the ballistic limit and associated parameters as specified in common personal ballistic armour standards (MIL-STD-662F [3], NIJ 0101.06 [2], and AEP 2920 [1]) using V_{50} Assist™ (Table 1). Series 1 of the Material B testing had a large zone of mixed results (ZMR) and thus failed to quantify a valid arithmetic V_{50} according to the H1 method of AEP 2920. The metrics computed according to common ballistics standards are primarily focused only on the V_{50} value. However, NIJ 0101.06 [2] discusses how to compute the velocity corresponding to any perforation probability, and AEP 2920 [1] shows equations for V_{05} and V_{95}. The benefit of many of these approaches is their simplicity and ease with which the performance can be measured. The alternative is that every test facility and research lab must apply its own statistical analyses to achieve maximum benefit in ballistics testing. Therefore, relying on fully validated and verified COTS analysis packages to walk a user through ballistics testing would provide a standardized series of traceable tools for any test facility.

Table 1. Summary of representative ballistic results as per common ballistic standards

	Material A Results (m/s)				**Material B Results (m/s)**			
Series	1	2	3	1-3	4	5	6	4-6
MIL-STD-662F								
6 Shot V_{50}	496.2	501.4	495.0	497.8	517.3	512.2	504.2	510.3
NIJ 0101.06								
Logit V_{50}	496.9	501.1	494.4	497.0	512.8	511.8	503.8	509.6
Logit Std. Dev.	7.3	12.2	5.6	9.0	30.7	17	23.5	23.8
AEP 2920 §H.1								
Arithmetic V_{50}	493.1	498.0	497.5	493.1	*	512.5	522.2	*
AEP 2920 §H.3								
Probit V_{50}	497.4	500.7	494.1	497.0	513.1	510.9	503.6	509.6
Probit Std. Dev.	12.5	20.7	9.3	15.7	51.6	28.7	38.5	40.0
V_{50} Lower 95% CI	484.8	485.7	486.7	489.9	479.7	490.5	478.1	494.2
V_{50} Upper 95% CI	508.9	515.2	501.5	504.0	545.6	531.2	529.1	524.9

*Convergence criteria not met

4.1 Ballistic Resistance Triple Plot

The fundamental objective of a ballistic resistance triple plot is to simultaneously present protection outcomes in the three velocity regimes (undermatched, limit, and overmatched). In the present study, the three representative curves selected to represent the velocity regimes were: the Unperforated Ply Ratio (UPR), protection probability logit, and Energy Absorption Ratio (EAR). The average EAR over the range of V_{50} to $1.5\cdot V_{50}$ is shown as well. This can be particularly beneficial in cases where it is impossible to differentiate the performance of two armour systems using computations outlined in ballistic standards (Table 1). The triple plot with fit coefficients (Figure 3), constructed using the combined 48-shot dataset for each material, illustrates the relative ballistic performance of Material A and Material B across the three velocity regimes further supporting the assertion that Material B may have outperformed the Material A samples in this series of tests.

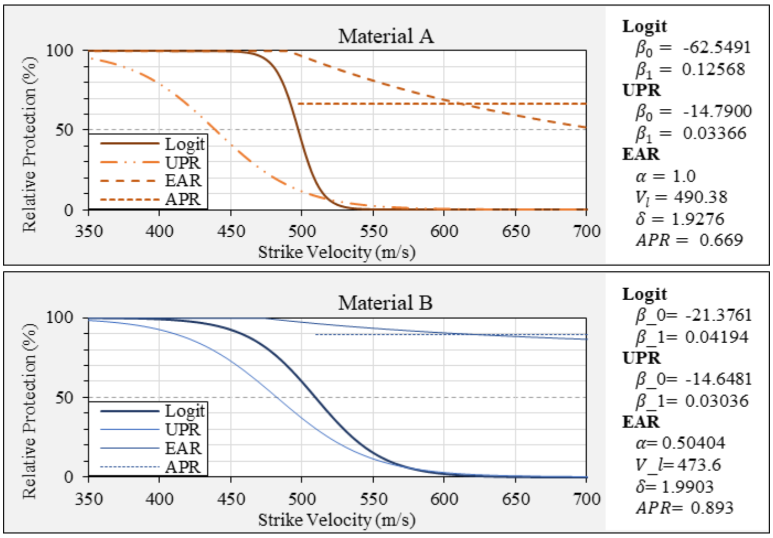
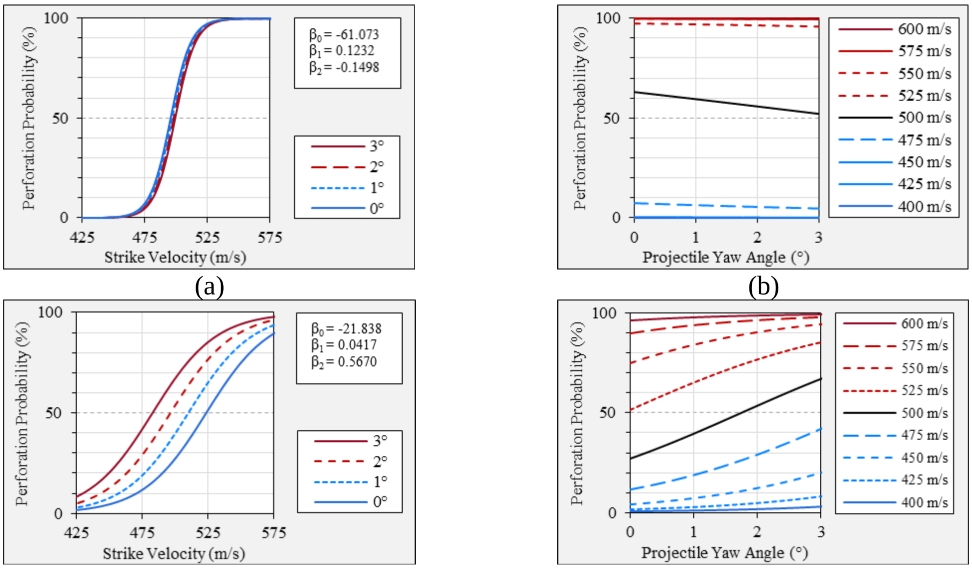


Figure 3: Ballistic resistance triple plots illustrating the unperforated ply ratio (UPR), logit protection probability, energy absorption ratio (EAR), and armour protection rating (APR) for two materials.

First, by examining the logistic regression, the slope for Material A is steeper than for Material B, which indicates a more consistent performance for perforation probability (i.e., a smaller ZMR). The undermatched performance shows similar slopes (note: the number of plies for each material was different, but the ratio of unperforated plies provides a suitable basis for comparison). Typically, the V_{05}-perforation level (i.e., V_{95} for protection) would be used to differentiate the undermatched performance of two armour systems with a similar V_{50}; if additional data were not considered here, the Material A sample might have been considered superior. Another potentially interesting parameter when considering the undermatched velocity regime is the UPR at the V_{50} ballistic limit (approximately 10% for Material A and 35% for Material B). The significance of this result is unknown at this time; however, it may also be indicative of the ZMR width and consistency of results. The overmatch results interestingly converged on a similar limit velocity (from the Lambert-Jonas equation). The slope parameter indicates that Material B samples absorbed more energy than Material A. The EAR is averaged across the range of V_{50}-$1.5\cdot V_{50}$ to produce the APR. The steeper drop-off in the EAR for the Material A samples is reflected in the lower APR. The triple plot was constructed using data obtained in three series of 16 shots on each material. Significantly more information was gained by processing the results to query the performance in the three velocity regimes than if only the logistic regression of the perforation (or protection) probability was queried. If the test velocities did not have a suitable spread, a small number of additional shots could be conducted at undermatched and overmatched velocities to improve the confidence in the corresponding curves in the triple plot. Depending on the test, equivalent plots could be formulated to include backface deformation or recovery media depth, for example, if clay or foam packs were used. The focus of this paper is the comparative methodology when two materials have similar ballistic limits. Differences in areal density between Material A and Material B were therefore not considered (i.e., no normalisation was applied to the results).

4.2 Yawgit

The Yawgit curves (Figure 4) is a method of quantifying the perforation resistance of an armour system as a function of both velocity and yaw. Including isolines allows for a more intuitive interpretation of two-input regression (perforation probability as a function of yaw and velocity) than a heat map. The two types of isolines correspond to inputting a constant yaw or a constant velocity into the regression line. The interpretation of the isolines depends on the regression coefficients, which describe the slope, scale, and direction of isoline spacing. For example, Material A showed a very small positive correlation between perforation probability and yaw angle as shown in Figure 4 (a), where the isolines are very close together, and in Figure 4 (b), where the slopes are negative and shallow. Material B showed a negative relationship between perforation probability and yaw in Figure 4 (c), where the isolines for higher yaw angles are translated towards lower velocities, and in Figure 4 (d), where the slopes are positive.



(a) (b)

(c) (d)

Figure 4: Logistic (Yawgit) regression for perforation probability plotted with (a) Material A yaw isolines and (b) velocity isolines, and Material B (c) yaw isolines and (d) velocity isolines.

The interpretation of Yawgit isolines should normally be accompanied by a statistical analysis to assess the significance of the regression coefficients. The interpretation may be further limited by outliers. It may be prudent to verify the cross-correlation between velocity and yaw before performing a Yawgit analysis. When used carefully, the Yawgit analysis demonstrates that additional measurements performed during ballistic testing can better characterize armour performance across test conditions and velocities while providing an additional basis for comparing systems with similar V_{50} values.

4.3 Confidence Intervals

The use of confidence intervals is essential to fully understand the perforation probability of an armour sample and the expected variability of the results. In general, the width of the confidence intervals is expected to decrease as more shots are performed. The width of the ZMR will likely also affect the confidence intervals as a shallower slope in the logistic regression indicates a more variable outcome transition velocity. The standard up-and-down firing sequence, which focuses the shots on the V_{50} may not provide the true ZMR and the corresponding CI. Better-suited approaches such as 3PoD ensure that the actual extent/width of the ZMR is sufficiently explored, leading to more reliable CIs. The formulation of confidence intervals and the coverage level significantly affect the interpretation of the expected variability in results. When considering only a single test series, a 95% confidence level should be used to bound the expected results; however, the difference between ballistic limits may still achieve statistical significance if the 95% confidence intervals overlap. Given a null hypothesis $V_{50A}=V_{50B}$, the probability of the confidence intervals not overlapping reaches statistical significance (p-value <0.05) when the confidence intervals are narrowed to 83.4% [16]. Therefore, the probability of observing two non-overlapping 83.4% confidence intervals if the ballistic limit is the same is less than 5% (i.e., 95% confidence level). This approach provides an intuitive and visual methodology for assessing the <5% probability of two materials having the same ballistic limit if the pointwise +confidence intervals do not overlap. Figure 5 shows a case where the confidence level was reduced from 95% to 83.4%. This change resulted in a significantly different interpretation of the data beyond the 60% perforation probability. Therefore, inferences about the perforation probability above the V_{60} are only possible after reducing the coverage level, thereby eliminating any overlap.

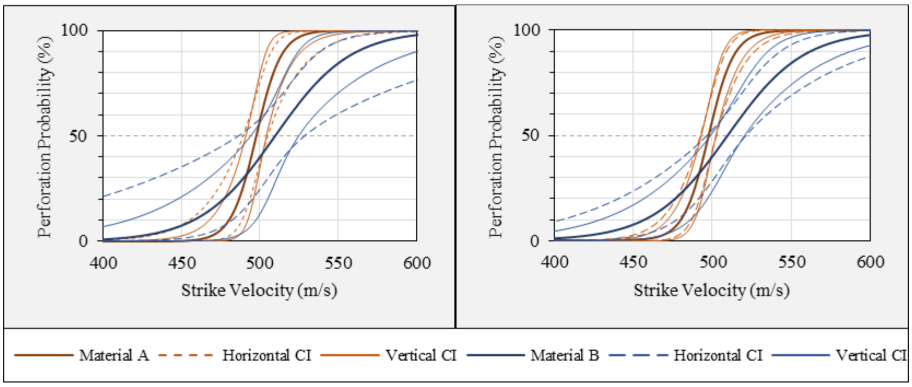


Figure 5: Logistic (Logit) regression for perforation probability for Material A and Material B test data plotted with 95% confidence intervals (left), and 83.4% confidence intervals (right).

Traditional confidence intervals computed using Wald's test typically show a much larger range of expected values towards the extremes (upper confidence bound for V_{01} and lower confidence bound for V_{99}) than at the ballistic limit (either bound for V_{50}). Transforming the confidence intervals from their original vertical formulation to the horizontal variant is a method that generally improves the convergence at the extremes of the curve. In all cases shown in Figure 5, the vertical formulation of the confidence intervals resulted in tighter confidence bands.

5. CONCLUSION AND RECOMMENDATIONS

The significant resources required to quantify the ballistic resistance of armour systems are the driving factor limiting the number of tests conducted. Existing ballistic test standards place the importance almost exclusively on velocity-perforation outcome data while focusing heavily on the V_{50} ballistic limit. There is limited emphasis on exploring other key metrics that describe the undermatched or overmatched ballistic resistance. The methodology described in this study provides the tools to quantify and interpret data that could be trivially acquired during testing with minimal additional effort yet further understanding of threat mitigation behaviour across a wide range of velocities and test conditions, which could significantly increase the value of every test.

This work introduced Yawgit, a bivariate logistic regression to quantify the perforation probability as a function of velocity and projectile yaw, leveraging yaw measurements that are already performed as a go/no-go screening tool. The proper use and interpretation of two types of confidence intervals on perforation curves (Logit) were also discussed, with a special focus on the coverage level being 95% for a single test series or 83.4% if two series are being compared with 95% confidence.

Ballistic resistance triple plots were created to describe armour performance across the three velocity ranges, providing a suitable basis for comparing two armour types. The ballistic resistance triple plots are flexible to different armour and threat types so long as the three velocity regimes are adequately represented. The tests described in this paper included an analysis of the unperforated ply ratio (UPR) for non-perforations of soft armour systems which quantifies the safety margin before failure. The energy absorption ratio (EAR) and the Armour Performance Rating (APR) were derived from the residual velocity to quantify the margin by which the armour was defeated. Examining metrics beyond the V_{50} is critical to comprehensively assessing the armour performance across all feasible velocities. These metrics, and others, can be used by manufacturers to design better armour systems or help scientists understand projectile/armour interactions and eventually could be integrated into test standards to ensure operators have the best possible protection.

The absence of computationally non-trivial metrics may be indicative that reliable, verified tools are not widely available to perform these analyses. The simplicity of concepts such as up/down firing procedures and arithmetic V_{50} does not justify their continued use when more advanced and descriptive alternatives exist. Implementing advanced ballistics analyses and statistics in test standards is long overdue. Many test facilities use various spreadsheets to track different aspects of ballistic testing, including firing procedures and analyses. V_{50} Assist™ is a fully validated and traceable COTS software package that walks technicians through ballistic testing, from firing procedures to analyses described in common ballistic standards. It was developed to provide ballistic test facilities (commercial and experimental) with a set of tools that provide consistent analyses independent of the statistical or analytical background of the technicians or researchers.

Disclosure Statement

The first author is a paid employee of Biokinetics and Associates Ltd., the developer of V50 Assist™, SpeedTube™ and YawBox™, for the duration of the present study. The methodology proposed in this study can be applied using software and hardware from other manufacturers.

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