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Methodology to Measure the Protective Areal Density of Ceramic Tiles Against Projectile Impact

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ABSTRACT

The protective areal density of any armour material is the important property required for armour design. In this study, ballistic performance of hot pressed boron carbide tiles, with a tile thickness of 12.2 mm, was evaluated using the protective areal density (PAD) test method, against hard steel 12.7 mm armour piercing (AP) projectiles. The binary response data on complete penetration/ partial penetration obtained from PAD testing was fitted with the standard logistic regression model. A detailed discussion on statistical procedure has been presented. The $PAD_{(pp = 0.5)}$ was estimated to be 82.5 kg/m^2 and the lower and upper bounds of 95 per cent confidence interval for $(PAD)_{(pp = 0.5)}$ was found to lie between 79.5 kg/m^2 and 85.0 kg/m^2.

Keywords: Ballistic testing; Protective areal density; Armour ceramic; Logistic regression analysis; Binomial data analysis

1. INTRODUCTION

Bulk ceramic materials have been in use for armour applications at least since 1950[1]. There have been many attempts to predict the ballistic performance of ceramic materials from physical and mechanical properties[2-5]. But so far, ballistic performance of ceramic materials has not been successfully predicted from any physical or engineering material properties. Hence, even today the direct ballistic test method is a necessary one to determine ballistic performance of ceramic materials. Moreover, ballistic performance determined from these experiments for ceramic materials are very much influenced by the test method, type of projectile used, and with geometry of the test. There are many direct ballistic test methods described in literature for evaluation of ballistic performance of ceramic materials[6-7]. The protective areal density (PAD) test is one of the ballistic performance evaluation test method for ceramic materials that permits testing amour in a more realistic configuration. The PAD ballistic test procedure has been elaborately described by Mark Adams[8]. In essence, the PAD test involves determination of target areal density which provides 50 per cent protection against a projectile, with a fixed projectile velocity. This test is similar to the ballistic limit test, described by Crouch[9], *et al.* where areal density of the target is kept constant but the projectile velocity is varied to determine the 50 per cent protection velocity (V_{50}). (i.e., there is a 0.5 probability that the target will be completely penetrated). The design of PAD ballistic test method and the analysis of test data are shown in Fig. 1.

As shown in Fig. 1, it is possible to conduct PAD tests along any constant backing areal density test line or constant ceramic areal density test line. But generally these tests are conducted along constant ceramic areal density test line, by varying backing areal density. In PAD test, ballistic data on complete penetration/partial penetration is generated as a function of armour thickness or areal density for the armour system being studied. The binary data of complete penetration / partial penetration from PAD test are statistically analysed as per procedures described in literature[10-12]. The binary response data can be fitted with any one binomial regression model. The binomial regression model is a special case of an important family of statistical models, namely generalised linear models[13,14]. The Binomial family is associated with several link functions and out of which the most common functions are probit, logistic (logit), and complementary log-log functions[11]. In recent times, the logistic regression model has become the standard method of analysis for binary response data to

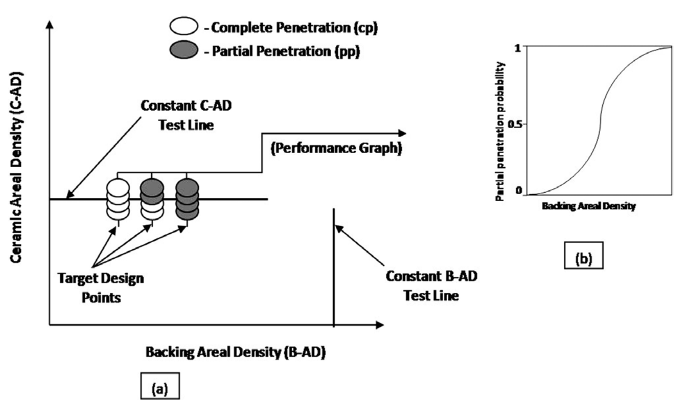

Figure 1. (a) Design of experiments in protective areal density (PAD) test configuration and (b) fitting of binomial ballistic test data.

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model the relationship between the binary outcomes and the independent variable (like areal density in this case) in many fields[11]. The statistical analysis procedure using the logistic regression model can be found elsewhere[15,16].

R is an implementation of the object-oriented mathematical programming language S, which is a free software platform for statistical applications[17,18]. The R statistical software package can be used for many statistical analyses including fitting of various regression models to binary response data, estimating regression coefficients, and for plotting graphs from the data. Even though the PAD test is an important ballistic test procedure for the determination of ballistic performance of armour systems, only very few literatures are available and the details on analysis of ballistic test data is usually not found. In the present study, PAD testing was conducted on armour system that consisted of steel confined hot pressed boron carbide tiles backed by Al 2024-T351 backing against 12.7 mm AP projectile. A detailed discussion on logistic regression method and the procedure for determination of $(PAD)_{(pp\,=\,0.5)}$ has been described.

2. MATHEMATICAL MODEL

The results of PAD testing, like ballistic limit testing, are in the form of complete penetration / partial penetration which can be codified as 0 or 1. Such type of outcome data is called binary response data. One of the important binomial regression models which is extensively used for the analysis of binary response data is the logistic regression model. Mauchant[11], *et al.* have tested the goodness-of-fit for three binomial regression models such as probit, logistic, and complementary log-log functions for the ballistic limit test data and found that all three models yielded almost similar results. NIJ standard 0101.06 has also prescribed logistic regression method for the analysis of ballistic limit test data[19]. The central mathematical concept that underlies logistic regression is the logit- the natural logarithm of odds[15]. Generally, logistic regression is well suited for describing and testing hypotheses about relationships between a categorical outcome variable, and one or more categorical, or continuous predictor variables[15]. The method used in logistic regression is very similar to that of linear regression except with some differences. Once these differences are accounted for the method used for linear regression can be used for logistic regression also. The major difference between linear regression and logistic regression is that, in linear regression model outcome variable is assumed to be continuous, where as in logistic regression model outcome variable is binary or dichotomous[16]. Hence in logistic regression the curve is *Sigmoidal* or *S-shaped,* and resembles a cumulative distribution plot of random variable, where the extremes do not follow a linear trend. Also in logistic regression the errors are neither normally distributed nor constant, across the entire range of data[15]. The logistic regression method is explained follow:

Let us assume that X be the independent variable (thickness or areal density in this case) and Y be the outcome variable. The probability of occurrence of the outcome of interest π = Probability (Y = outcome of interest | $X = x$, a specific value of X), can be expressed as

$$\pi(x) = \frac{e^{\beta_0 + \beta_1 x}}{1 + e^{\beta_0 + \beta_1 x}} \tag{1}$$

In logistic regression a transformation called logit transformation, $g(x)$, is applied to the dependent variable $\pi(x)$ so that the desirable properties of a linear regression model are obtained[15,16]. The logit transformation *g(x) = logit (Y) = natural log (odds)* is defined as follows:

$$g(x) = \ln\left[\frac{\pi(x)}{1-\pi(x)}\right] = \beta_0 + \beta_1 x \tag{2}$$

where β_0 is the Y intercept, β_1 is the regression coefficient, and the logit g(x) is linear in its parameters.

The model parameters β_0 and β_1 are estimated using maximum likelihood method. The maximum likelihood method is a standard method which yields the unknown parameters of the model which maximise the probability of obtaining the observed data set[20]. To do this a function called the likelihood function is constructed which expresses the probability of the observed data as a function of unknown parameters. The maximum likelihood estimates for constant β_0 and for regression coefficient β_1 are derived from this likelihood function using the procedure described elsewhere[16,21]. The value of parameters β_0 and β_1 are estimated using R or any other MLE software. The quantities, $\hat{g}(x)$- maximum likelihood estimate of logit *g(x)*, and $\hat{\pi}(x)$ - maximum likelihood estimate of $\pi(x)$ are estimated by substituting the model parameter estimates $\hat{\beta}_0$ and $\hat{\beta}_1$ in the following equations.

$$\hat{g}(x) = \hat{\beta}_0 + \hat{\beta}_1 x \tag{3}$$

$$\hat{\pi}(x) = \frac{e^{\hat{\beta}_0 + \hat{\beta}_1 x}}{1 + e^{\hat{\beta}_0 + \hat{\beta}_1 x}} \tag{4}$$

Hence, the fitted values, $\hat{\pi}(x)$, is obtained as a function of independent variable x (thickness or areal density) using Eqn (4).

Confidence interval of any parameter is an interval which very likely contains the unknown value of the parameter for which the interval has been constructed[20]. In general, the confidence interval is estimated by inverting a test static[22]. Similarly, in logistic regression the confidence intervals for parameters are estimated from their respective Wald ratio (W) tests[16]. The Wald ratio test is based on comparing maximum likelihood estimate of a parameter to the estimate of its standard error. For example, the Wald ratio test for the maximum likelihood estimate of the slope parameter, $\hat{\beta}_1$, is given below,

$$W = \frac{\hat{\beta}_1}{\hat{SE}(\hat{\beta}_1)} \tag{5}$$

here the estimated standard error for the estimate of the slope parameter ($\hat{\beta}_1$) is calculated from the estimator of variance of $\hat{\beta}_1$, i.e,

$$\hat{SE}(\hat{\beta}_1) = \left[\hat{Var}(\hat{\beta}_1)\right]^{1/2} \tag{6}$$

Similarly, the estimator of the variance of the estimator of the logit is given by the following equation

$$\hat{Var}\left[\hat{g}(x)\right] = \hat{Var}\left(\hat{\beta}_0\right) + x^2\,\hat{Var}\left(\hat{\beta}_1\right) + 2x\,\hat{Cov}\left(\hat{\beta}_0,\hat{\beta}_1\right) \quad (7)$$

Hence, by estimating the variance of the estimator of logit the estimated standard error of the logit, $\hat{SE}\left[\hat{g}(x)\right]$, can be estimated. More detailed discussion on the variance and covariance of the estimated coefficients can be found elsewhere[16,21].

Generally, the end points of a 100 (1-α) per cent confidence interval for any arbitrary parameter θ is given by θ ± (Z or t) $s_{\hat{\theta}}$, where Z or t refers to normal distribution or t-distribution[20]. Similarly, the endpoints of a 100 (1-α) per cent Wald-based confidence interval for the logit can be given as[16] follows:

$$\hat{g}(x) \pm z_{1-\frac{\alpha}{2}}\,\hat{SE}\left[\hat{g}(x)\right] \quad (8)$$

where $z_{1-\alpha/2}$ is the $(1-\alpha/2)$ quantile of the standard normal distribution[23]. Hence, using Eqn (8) the endpoints (upper and the lower limit) of the 100(1-α) per cent Wald-based confidence interval for the fitted values are obtained as below,

$$\hat{\pi}(x) = \frac{e^{\hat{g}(x)\pm z_{1-\frac{\alpha}{2}}\hat{SE}\left[\hat{g}(x)\right]}}{1+e^{\hat{g}(x)\pm z_{1-\frac{\alpha}{2}}\hat{SE}\left[\hat{g}(x)\right]}} \quad (9)$$

Therefore, using Eqn (9) confidence interval of $\hat{\pi}(x)$ can be calculated as a function of independent variable *x* (thickness or areal density).

From Eqn (4) the probability for partial penetration as a function of protective backing thickness or areal density is determined. But, the upper and lower limit of the confidence interval for the partial penetration as a function of protective backing thickness or areal density is determined using Eqn (9).

3. EXPERIMENTAL

3.1 Materials

The 12.7 x 108 mm AP projectile used in these experiments consists of a hard steel core which is covered with copper jacket. The ceramic tiles used in these experiments were of 100 mm x 100 mm size hot pressed boron carbide with an average thickness of 12.2 ± 0.02 mm. The boron carbide tiles were manufactured by M/s Bhukhanvala Industries Pvt. Ltd, India. The microstructure of hot pressed boron carbide is shown in Fig. 2. The properties of boron carbide tiles are given in Table 1. The aluminium alloy 2024-T351 was used as backing material for the PAD test. The properties of aluminium alloy are given in Table 2. The thickness of the backing aluminium alloy was varied from 15 mm to 20 mm.

Table 1. Properties of hot pressed boron carbide tiles used in PAD experiments

Chemical composition	Average density (g/cc)	Average grain size (µm)	Hardness (HV0.5) (GPa)	Bend strength (MPa)
B_4C	2.527 ± 0.001	4 - 8	28 - 30	200 - 350

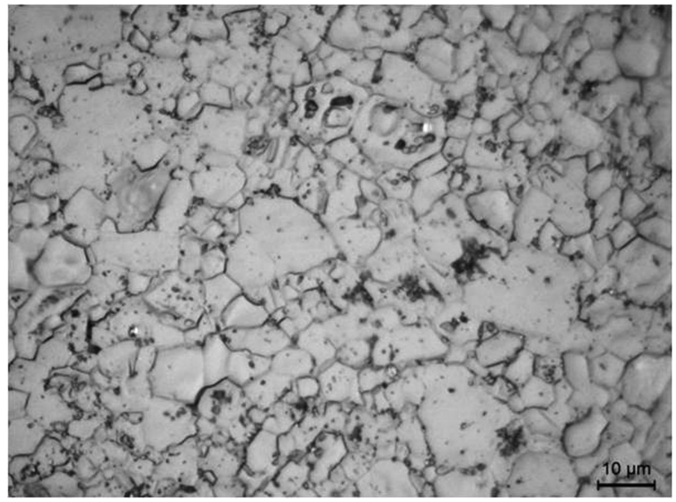

Figure 2. Microstructure of hot pressed boron carbide tile.

Table 2. Properties of backing aluminium alloy 2024-T351

Density (g/cc)	Hardness (VHN)	Proof Stress (MPa)	UTS (MPa)	Elongation (Per cent)
2.78	130	310	457	14-16

3.2 Ballistic Test Procedure

The boron carbide tiles were tightly fitted in a steel lateral confinement by inserting a thin brass shim in between the ceramic tile and steel plate. The lateral confined ceramic tile was then placed over aluminium alloy 2024-T351 backing without application of any bonding material. In this study the bonding material has been avoided in order to eliminate the influence of adhesives on the ballistic performance of ceramic material. The target configuration for the PAD test is as shown in Fig. 3.

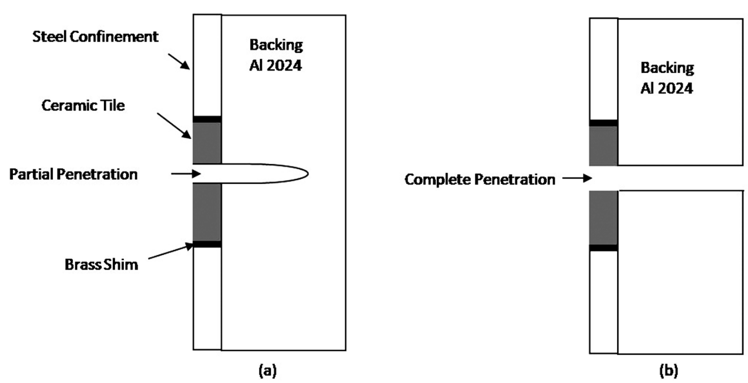

Figure 3. Schematic diagram of the PAD test target configuration (a) Partial Penetration (pp), and (b) Complete Penetration (cp).

A schematic of the ballistic test setup is as shown in Fig. 4. The projectiles were fired through a 12.7 mm calibre heavy machine gun (NSV/Russian HCB) placed over a stand at a distance of 10 m from the target. The angle of attack of projectile was normal to the target. The projectile velocity was measured using infrared light emitting diode-photovoltaic cells placed 2 m apart. The actual velocity measurement instrument used was manufactured by MS instruments, UK, Type 814. The

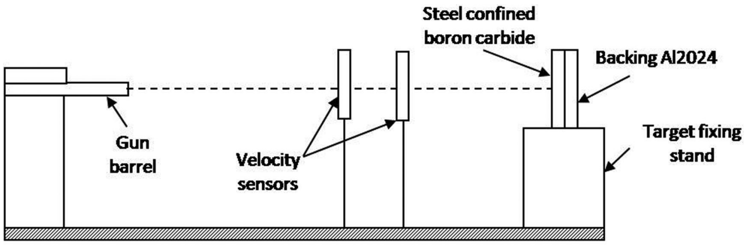

Figure 4. Schematic diagram of ballistic experimental set up for PAD test.

time interval between the interceptions caused by the projectile running across two transverse infrared beams was used to calculate the projectile velocity. The target of steel lateral confined boron carbide tile with aluminium alloy backing was fixed on a firing stand using C-clamps inside a firing bay for ballistic testing.

In PAD testing the target design points as shown in Fig. 1, are the points where actual ballistic experiments are carried out. The number of target design points along the test line was decided based on the availability of the target material, the degree of accuracy and the statistical confidence required for the determination of the partial penetration probability along the test line. In this study, tests were performed along a constant ceramic areal density test line where boron carbide tile thickness was maintained constant and backing Al 2024-T351 thickness was varied. During ballistic experiments, variation in projectile velocity was kept as minimum as possible. The average velocity of the projectile was found to be 829 ± 2 m/s. Post ballistic examination on the target was done, especially on the aluminium alloy backing, to assess the extent of damage imparted onto the backing aluminum alloy and also to obtain the complete penetration / partial penetration ballistic data. The penetration/ partial penetration criteria followed here is similar to the army ballistic limit criteria[9].

3.3 Calculations on Ballistic Test Data

The statistical analysis of ballistic test data, for the determination of $(PAD)_{(pp=0.5)}$ and the 95 per cent confidence interval for $(PAD)_{(pp = 0.5)}$, was done using R Version 3.0.1 statistical software[17]. The syntax of program code on various functions which were used in R software for fitting logistic regression model can be found elsewhere[18]. Using S language functions a program code was written in R with features for accepting input data from a file, for fitting binomial data, for determination of confidence interval, for plotting graphs and also for writing output data in a file.

4. RESULTS AND DISCUSSION

The protective areal density (PAD) test along the constant thickness (constant ceramic areal density) line of boron carbide tiles produced complete penetration/ partial penetration ballistic results. The damage produced on the front and rear side of the backing Al 2024-T351 plates due to projectile impact after defeating boron carbide tile were examined and are shown in Fig. 5. The extent of damage imparted on the backing aluminum alloy plate can be inferred from the different type of damage patterns observed on the rear side of the backing plate such as no bulge, smooth bulge, small cracks and through hole as shown in the Fig. 5. The binary response data (complete penetration/ partial penetration) from the ballistic tests were extracted using the following procedure. Among various types of damages, the presence of no bulge, smooth bulge and minor cracks which does not pass the kerosene through it in the backing aluminum alloy were considered as partial penetration. And the presence of through hole, cracks which passes light or cracks which allow kerosene to pass through were considered as complete penetration. The partial penetrations were coded with 1 and the complete penetrations were coded with 0. In order to decrease the uncertainty in PAD determination, as per the established procedure[8], the highest protective backing

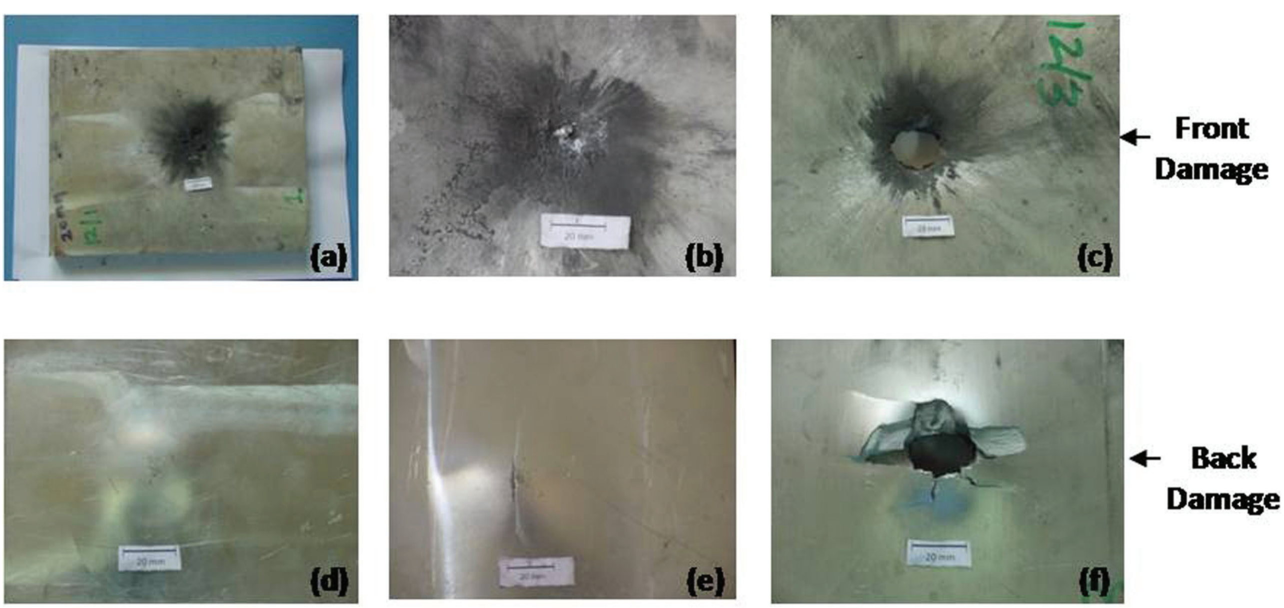

Figure 5. Different types of front and rear side damages observed on the backing Al 2024-T351 plate used in PAD test of steel confined born carbide tiles against 12.7 mm AP ammunition. ((a) and (d)) smooth bulge, ((d) and (e)) smooth bulge with crack, and ((c) and (f)) complete penetration.

thickness (PBT) targets which produced at least one complete penetration and PBT targets which produced at least one partial penetration were repeated as many times as possible within the constrain of available material at hand. It was found that at backing thickness of 17 mm there was a partial penetration observed (i.e, lowest PBT with partial penetration) hence, ballistic test with this backing thickness was repeated as many times as possible. Similarly, at backing thickness of 20 mm there was one complete penetrations observed (highest PBT with complete penetration) and hence at this backing thickness also ballistic tests were repeated for several times. In addition, the target design point in-between these two thicknesses (i.e., 19 mm backing thickness) was also got repeated as many times as possible. The binary response data (complete penetration/ partial penetration) obtained from PAD test along with test conditions are given in Table 3.

Table 3. Test details and the binomial response data of protective areal density test on steel confined hot pressed boron carbide tiles with Al 2024 -T351 backing against 12.7 mm AP

Backing thickness (mm)	Projectile velocity (m/s)	Partial penetration	Partial penetration code value
15	838	NO	0
15	835	NO	0
17	832	YES	1
17	830	NO	0
17	821	NO	0
17	822	NO	0
17	816	NO	0
17	834	NO	0
17	832	NO	0
17	838	NO	0
17	-	NO	0
17	829	NO	0
19	827	YES	1
19	828	NO	0
19	828	NO	0
19	825	YES	1
19	839	YES	1
19	833	NO	0
19	843	YES	1
19	816	YES	1
20	837	YES	1
20	827	YES	1
20	827	YES	1
20	820	NO	0
20	813	YES	1
20	838	YES	1
20	-	YES	1
20	-	YES	1

Fitting of the independent variable (backing thickness) and binary response data using logistic regression model was performed in R open software. Initially, Y intercept β_0 and regression coefficient β_1 were estimated from the PAD experimental data. The estimated value of parameters $\hat{\beta}_0$ and $\hat{\beta}_1$ were found to be -25.82 and 1.39, respectively. Further it is known from Eqn (2) that for a particular backing thickness (x) the ratio of odds becomes 1 which corresponds to the case of 50 per cent probability for partial penetration or complete penetration. Therefore, from the ratio of intercept β_0 and regression coefficient β_1 (i.e. - β_0 / β_1), the protective backing thickness corresponding to 50 per cent partial penetration probability (i.e., $(PBT)_{(pp = 0.5)}$) was calculated. The calculated $(PBT)_{(pp = 0.5)}$ was found to be 18.6 mm. From the estimated value of, $(PBT)_{(pp = 0.5)}$, protective backing areal density, $(PBAD_{(pp = 0.5)})$, was also calculated. The calculated $(PBAD_{(pp = 0.5)})$ was found to be 51.7 kg/m^2. Further the estimate of logit, $\hat{g}(x)$, as a function of independent variable (backing thickness) was determined by substituting the estimated parameter values of β_0 and β_1 in Eqn (3). Also using Eqn (4) the maximum likelihood estimate of the outcome variable, $\hat{\pi}(x)$, was determined as a function of independent variable x. Hence, the complete *S-shaped* binary response curve as a function of backing thickness was generated using R software which is shown in Fig. 6. Using the S-shaped binary response curve data the protective backing thickness corresponding to any probability (i.e, 0.1 - 0.99) of partial penetration (or protection) can be determined.

Similar to estimation of logit, $\hat{g}(x)$, the estimated standard error of logit, $\hat{SE}\left[\hat{g}(x)\right]$, as a function of independent variable (backing thickness), was also obtained using the estimated parameter values of Y intercept, β_0 , and regression

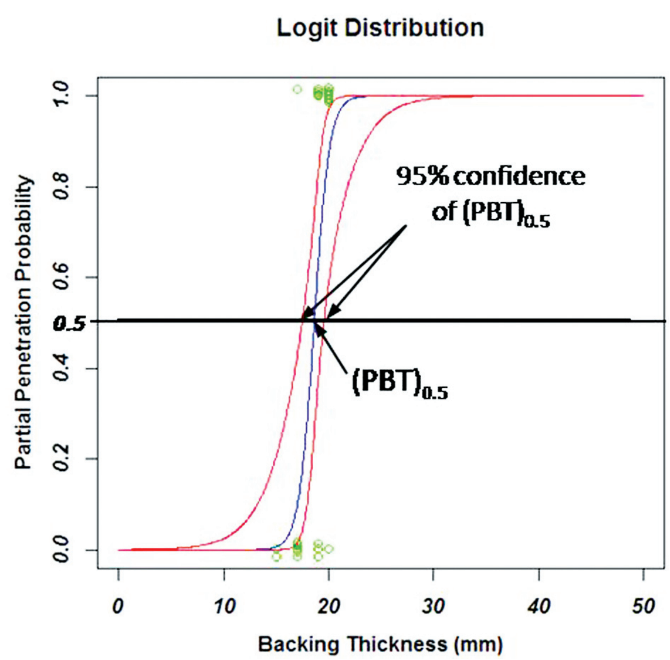

Figure 6. The complete S-shaped binary response curve for protective backing thickness of Al 2024-T351 backing, in a PAD test configuration with strike face of 12.2 mm thickness hot pressed boron carbide tiles confined in steel, against 12.7 mm AP ammunition.

coefficient, β_1, from Eqn (7). Further, by substituting the estimated values of $\hat{g}(x)$ and $\hat{SE}\left[\hat{g}(x)\right]$ in Eqns (8) and (9) the confidence interval of the estimate of logit, $\hat{g}(x)$, and the confidence interval of the fitted values, $\hat{\pi}(x)$, were determined respectively. It is known that for the 95 per cent confidence interval the value of α is equal to 0.05 and hence the value of $z_{1-\alpha/2}$ becomes $z_{0.975} \approx 1.96$[21,23]. Therefore, for determining 95 per cent confidence interval of the estimate of logit, equation (8) is modified as below

$$\hat{g}(x) \pm 1.96 * \hat{SE}\left[\hat{g}(x)\right] \tag{10}$$

Using Eqn (10) the lower and upper bounds of 95 per cent confidence interval of the estimate of logit was calculated. Further, by substituting the lower and the upper bound values of the estimate of logit (i.e, Eqn (10)) in Eqn (9) the upper and the lower bound of 95 per cent confidence interval for the fitted values , $\hat{\pi}(x)$, as a function of independent variable (backing thickness) was estimated. The estimated upper and the lower bounds, of the 95 per cent confidence interval for the binary response curve, are as shown in Fig. 6.

From Fig. 6, the 95 per cent confidence interval of the PBT corresponding to 50 per cent partial penetration, ($(PBT)_{(pp = 0.5)}$), was determined. The estimated lower and upper bounds of the 95 per cent confidence interval values of $(PBT)_{(pp = 0.5)}$ was found to lie between 17.5 mm and 19.5 mm, respectively. Therefore, the lower and upper bounds of 95 per cent confidence interval of the $(PBAD)_{(pp = 0.5)}$ was estimated to lie between 48.7 kg/m^2 and 54.2 kg/m^2. Using the estimated $(PBAD)_{(pp = 0.5)}$, the combined protective areal density (i.e, areal density of hot pressed boron carbide + Al 2024-T351 backing), otherwise simply called the protective areal density, $PAD_{(pp = 0.5)}$, of the armour system which provides 50 per cent protection against 12.7 mm AP was calculated. The boron carbide areal density corresponding to the constant ceramic areal density test line was 30.8 kg/m^2. Therefore, the calculated $PAD_{(pp = 0.5)}$ was found to be 82.5 kg/m^2. Also the lower and upper bounds of 95 per cent confidence interval for $(PAD)_{(pp = 0.5)}$ was found to lie between 79.5 kg/m^2 and 85.0 kg/m^2. Finally, in the present study even though experiments were performed with ceramic/ backing thickness ratio of 0.81 or less, as per Hetherington[24], the optimum ballistic performance is obtained for ratio greater than one.

5. CONCLUSIONS

- PAD evaluation was carried out on a ceramic armour system, consists of steel confined hot pressed boron carbide tile backed by Al 2024-T351 alloy without bonding, against 12.7 mm AP projectile.
- The ballistic test data on complete penetration/ partial penetration was collected on a constant ceramic areal density test line (i.e, with 12.2 mm thickness boron carbide tiles) by varying the backing plate thickness.
- The logistic regression statistical method was applied to model the binary ballistic test data using R open statistical software. The 50 per cent protective areal density, $PAD_{(pp = 0.5)}$, along with its lower and the upper bounds of 95 per cent confidence interval were extracted.
- The protective areal density, $PAD_{(pp = 0.5)}$, of the armour system (i.e, boron carbide + Al 2024-T351 backing) was estimated to be 82.5 kg/m^2 along with its lower and upper bounds of 95 per cent confidence interval between 79.5 kg/m^2 and 85.0 kg/m^2.

REFERENCES

1. Viechnicki, D.J.; Slavin, M.J. & Kliman, M.I. Development and current status of armor ceramics. *Ceramic Bulletin*, 1991, **70**(6), 1035-39.
2. LaSalvia, J.C.; Normandia, M.J. & Swab, J.J. A simple pre-ballistics evaluation methodology for ceramics. *In* Proceeding of 21st International Symposium on Ballistics, Adelaide, Australia, April 2004, 196-203.
3. James, B. The influence of the material properties of alumina on ballistic performance. *In* Proceeding of 15th International Symposium on Ballistics, Jerusalem, IsraeI, 1995, 3-10.
4. Lankford, J., Jr. The Role of dynamic material properties in the performance of ceramic armor. *Int. J. Appl. Ceram. Tec.,* 2004, **1**(3), 205-10.
   doi: 10.1111/j.1744-7402.2004.tb00171.x
5. Sternberg, J. Material properties determining the resistance of ceramics to high velocity penetration. *J. Appl. Phys.*, 1989, **65** (9), 3417-3424.
   doi: 10.1063/1.342659
6. Normandia, M.J. & Gooch, W.A. An overview of ballistic testing methods of ceramic materials, Ceramic armour materials by design, *Ceram. Trans.*, 2002, **134**, 113-138.
7. Savio, S.G.; Ramanjaneyulu, K.; Madhu, V. & Bhat, T.B. An experimental study on ballistic performance of boron carbide tiles. *Int. J. Impact Eng.*, 2011, **38** (7), 535-541.
   doi: 10.1016/j.ijimpeng.2011.01.006
8. Adams, M.A. Theory and experimental test methods for evaluating ceramic armor components, Ceramic armour materials by design. *Ceram. Trans.*, 2002, 134, 139-150.
9. Crouch, I.G. (Edit.), Chapter 7 & 11, The science of armour materials, Elsevier, 2016.
10. Fortier, C.; Bourget, D.; Pageau, G. & Beaubien, N. Comparative study of selected methods for estimating ballistic limit velocities of armour materials. *In* Proceeding of 17th International Symposium on Ballistics, Midrand, South Africa, 23-27 March 1998, 241-249.
11. Mauchant, D.; Rice, K.D.; Riley, M.A.; Leber, D.; Samarov, D. & Forster, A. L. Analysis of three different regression models to estimate the ballistic performance of new and environmentally conditioned body armour. NISTIR 7760, National Institute of Standards and Technology, 2011.
12. Ravid, M.; Shapira, N.; Galperin, S. & Medem, O. Armour performance analysis utilizing maximum likelihood ballistic limit calculation. *In* Proceeding of 27th International Symposium on Ballistics, Freiburg, Germany, 22-26 April 2013, 1379 - 1389.
13. McCullagh, P. & Nelder, J.A. Generalized linear models. Chapman & Hall, London, Ed. 2nd, 1989.
14. Gill, J. Generalized linear models: A unified approach. *In* Sage University Papers Series, **134**, Thousand Oaks, CA, 2001.
15. Peng, Chao-Ying J.; Lee, K.L. & Ingersoll, G.M. An

introduction to logistic regression analysis and reporting. *J. Educ. Res.,* 2002, **96**(1), 3-14. doi: 10.1080/00220670209598786
16. Hosmer, D.W. & Lemeshow, S. Applied logistic regression, John Wiley and Sons, 2000.
17. The R project for statistical computing. The R Foundation. http://www.R-project.org [Accessed on 03 Oct 2017]
18. Venables, W. N. & Ripley, B.D. Modern applied statistics with S. Springer, Ed. 4th, 2002. doi: 10.1007/978-0-387-21706-2
19. Ballistic resistance of body armor, NIJ Standard 0101.06, U.S. Department of Justice, July 2008.
20. Ryan, T.P. Modern engineering statistics, Wiley - Interscience, 2007, 128-142.
21. Wasserman, L.A. All of statistics: A concise course in statistical inference, Springer Science + Business Media, Inc., 2004, 152-153.
22. Casella, G. & Berger, R.L. Statistical inference, Duxbury, 2002, 419-440.
23. Millar, R.B. Maximum likelihood estimation and inference: with examples in R. SAS, and ADMB, John Wiley & Sons, 2011, 3-8.
24. Hetherington, J. G. The optimization of two component composite armour. *Int. J. Impact Eng.*, 1992, **12** (3), 409-414. doi: 10.1016/0734-743X(92)90145-J

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In the current study, he has contributed towards material selection and analysis of experimental data.