Journal of Mechanical Engineering *Vol SI 4(3), 20-34, 2017*

Characterising Ballistic Limits of Lightweight Laminated-Structure as a Protective Panel for Armoured Vehicle

N.A. Rahman[1], *M.F. Abdullah, S. Abdullah*[2],
W.F.H. Zamri, M.Z. Omar, Z. Sajuri
Department of Mechanical & Materials Engineering, Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

[1]*najihah.ar@gmail.com*
[2]*shahrum@ukm.edu.my*

ABSTRACT

This study investigates the ballistic performance of aluminium alloy Al7075-T6 and magnesium alloy AZ31B served as the intermediate layer in triple-layered laminated panel using computational analysis. Aluminium and magnesium alloys offer a considerably potential for reducing the weight of an armoured vehicle body due to low densities and high energy absorption capabilities. The poor ballistic performance of these materials can be improved by layering with the high strength steel, Ar500. A commercial explicit finite element code was implemented to develop triple-layered panels impacted by a 7.62 mm armour piercing projectile at velocity range of 900 to 950 m/s. Two models were constructed where aluminium alloy and magnesium alloy served as intermediate layer in the first model and the second model respectively. The ballistic performance of each model in terms of ballistic limit velocity and depth of penetration was evaluated. Considering the 25% existing armour vehicle weight reduction, it was found that magnesium alloy has equivalent ballistic limit to that of aluminium alloy which is at 1020 m/s. At the standard projectile velocity, aluminium stopped the projectile at 24 mm depth and magnesium stopped at 25 mm. Thus, lightweight materials can be suitable combinations for designing lighter armoured vehicle panel without neglecting its ballistic performance.

ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2017-02-12
Accepted for publication: 2017-05-12
Published: 2017-10-15

Keywords: *Piercing Projectile; Ballistic Limit; Depth of Penetration; Finite Element; Laminated-Structure.*

Introduction

Steels have been generally preferred in armour applications for their high strength, ductility, hardness, good formability and cheaper production. The characteristics of high density steel has restricted the armour vehicle manoeuvrability which has directed the researchers to find lighter materials to be integrated with existing armour steel satisfying the same level of protection. The main criterion in designing of a protective structure is to be able to withstand the ballistic impact from the ammunitions. Ballistic impact resistance is usually denoted by ballistic limit. Ballistic limit of a target panel is defined as the maximum velocity of a projectile performed a complete perforation with zero exit velocity. Aluminium alloys and magnesium alloys are of current interest in military industry because of their high stiffness-to-weight ratio, good formability, good corrosion resistance, and recycling potential [1]. The density of magnesium is approximately 35% lower than aluminium and approximately 77% lower than steel [2]. Both aluminium alloys and magnesium alloys have the advantage in that their density is relatively low compared to other armour materials and subsequently reduction of overall armour vehicle weight can be achieved for a required level of protection [3].

Nevertheless, magnesium alloys has not been perceived to have properties suitable for armour vehicle body application. It has relatively lower impact toughness compared to steel and aluminium alloys as it possesses low elastic modulus and ductility [4]. Impact toughness is an important dynamic mechanical property affecting the performance of a structure under high velocity impact. However, magnesium alloys exhibits better energy absorption capability per areal density compared to steels and aluminium alloys under dynamic compression tests making it possible to be integrated with existing armour steels in designing a multi-layered protective structure [5]. It has been observed in several investigations that both aluminium and magnesium alloys have lower ballistic resistance compared to the armour steel [2, 6]. Previous studies have reported that layering aluminium alloys with high strength steel has become an interest in improving these alloys ballistic performance while achieving the reduction of the overall armour vehicle body weight [2]-[6].

The computational approach on the other hand has been proven to be a powerful and economical tool for penetration predictions of projectiles over all ranges of striking velocities [7]. Recently, researchers focused on implementing finite element method to study the behaviour of multi-layered panels consisting of aluminium alloys and steels under high velocity impact. Forrestal et al. reported the performance of laminated armour steel and aluminium alloys of Al7075-T6 and Al5083-H116 can be integrated with armour steel to serve as vehicle protective structures and demonstrated relatively good performance as existing material [8]. Flores-Johnson et al. performed finite element analysis of the impact of a 7.62 mm APM2 projectile on multi-layered armour plates to investigate the effect of different layer configurations, thicknesses and material properties on ballistic performance. Ubeyli et al. investigated the effect of laminate configuration on the behaviour of aluminium laminated composite against 7.62 AP projectiles and found that using hard material on the first layer and aluminium alloy on the back layer can improve the ballistic performance of an armour steel [9].

Most of studies performed regarding multi-layered panels involve various types of aluminium alloys and steels. Currently, and to the best authors' knowledge, there are only a limited number of studies focused on the multi-layered panels consisting of magnesium alloys like AZ31B and steels. The aim of this study is to analyse the effect of different intermediate layer materials on the ballistic performance of triple-layered metal-laminate panel subjected to a 7.62 mm armour piercing projectile. Ballistic performance is evaluated based on the ballistic limit velocity and depth of penetration. A series of finite element analysis for different thickness of constituting materials at a range of striking velocities was conducted to analyse the effects.

Methodology

Computational Modelling

The geometrical model of 7.62-mm armour piercing ammunition projectile and the triple-layered target panel as in Figure 1 was modelled using a commercial finite element software package suitable for high velocity impact. The 7.62-mm armour piercing projectile was selected in order to satisfy the standard requirement of ballistic resistant for a protective structure panel [5]. The projectile used is made of a brass jacket, lead filler and ogive nose hardened steel core, and the total mass of projectile is 10.04 g with 7.7 mm diameter and 35 mm length. The target plate was modelled as 100 mm diameter circular plate and fully clamped at the edge boundaries. Two models of triple-layered configuration panels were constructed. First model consists of steel Ar500 as the front and back layer, and Aluminium alloy (Al7075-T6) as the intermediate layer. Second model is comprised of Ar500 as the front and back layer and the magnesium alloy (AZ31B) as the intermediate layer. For each model, two different layering configuration panels were chosen to study both lightweight materials behaviour under ballistic impact. Layering configuration differed in terms of thickness for each layer constituting the laminated panel. Ubeyli et al. has reported in their research that layering thickness serves important role in determining the ballistic resistant of laminated structure [9]. The layer thickness for each target panel was set according to Table 1. Each panel has a same total thickness of 25 mm considering the thickness of existing armour vehicle panel which is about 25 mm [10]. The target panels were subjected to an initial projectile velocity of 775-950 m/s which was chosen according to NATO STANAG 4569 ballistic protection level 3 (930±20 m/s) [11]. Decreasing and increasing the initial impact velocities were executed in order to obtain the ballistic limit of the target panels. Ballistic limit is an important parameter in determining the ability of a projectile to cause full penetration without any residual energy [6].

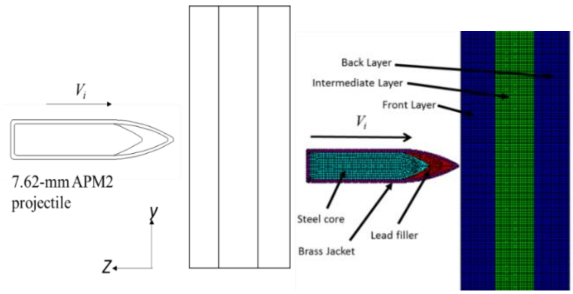

Figure 1: Geometric model of target plate and cross-section of Armour Piercing ammunition

Numerical simulation was carried out using an explicit nonlinear finite element code. The problem was simplified as axisymmetric model because the physical characteristics of the impact process such as bullet rotation are not considered for this study [12]. This work on the other hand only focused on the behaviour of impacted plate. The mesh comprised of four-node quad elements and the element size for both projectile and impact region is 0.5 x 0.5 x 0.5 mm3. Although it was demonstrated in previous work [11] that numerical simulations of penetration resistance of plates impacted with 7.62 mm projectile using very fine element size of 0.33 x 0.33 x 0.33 mm3 produced good result, computational effort has come into consideration for choosing coarser meshing elements. Node-to-node connectivity was applied using pure langrage algorithm with implementation of geometric erosion where geometric erosion strain of two was chosen for Ar500 steel to remove the elements experiencing large distortion and consequently, simulation failure can be avoided.

Both projectile and target plates utilised the Johnson-Cook (JC) material constitutive model which has been frequently used for ballistic impact simulation [12, 13]. The JC model was chosen for its ability to determine the strain rate for temperature dependence material models. This ability is important in order to avoid the stresses transmitted to the steel core were limited by the flow stress of the lead and brass jacket material. At a ballistic impact, the flow of stress is affected by the temperature. The JC material constitutive model is expressed as in Equation 1 [14].

$$\sigma_{eq} = \left(A + B\varepsilon_{eq}^{n}\right)\left(1 + \dot{\varepsilon}_{eq}^{*}\right)^{C}\left(1 - T^{*m}\right) \tag{1}$$

$$\dot{\varepsilon}_{eq}^{*} = \dot{\varepsilon}_{eq}/\dot{\varepsilon}_{0} \tag{2}$$

$$T^{*m} = (T - T_r)(T_m - T_r) \tag{3}$$

where σ_{eq} is the equivalent stress, ε_{eq} is the equivalent plastic strain, A, B, n, C and m are the material constants and $\dot{\varepsilon}_{eq}^{*}$ is the dimensionless strain rate where it is a ratio of the strain rate and a user-defined strain rate as in Equation 2. The T^{*m} is the homologous temperature and is defined in Equation 3, where T_r and T_m represent the room temperature and the melting temperature, respectively. This JC material model has been successfully implemented to model impact on steel [15] and aluminium targets [6]. The JC parameters used in this study are shown in Table 2.

Table 1: Target plate configuration

Target Plate	Material	Mass Reduction (%)	Front Layer (mm)	Intermediate layer (mm)	Back layer (mm)	Initial velocity, V_i (m/s)
Plate A	Ar500 + Al7075-T6 + Ar500	20	9	8	8	400-950
Plate B		25	8	10	7	
Plate C	Ar500 + AZ31B + Ar500	45	8	10	7	
Plate D		25	9	8	8	

Table 2: Material Properties and Modified Johnson-Cook model parameters

Material Properties	Ar500 [16]	Al7075 [6]	AZ31B [17]
Density, ρ (kg/m3)	7860	2804	1770
Poisson's ratio, v	0.33	0.3	0.3
Yield Strength, A (MPa)	1250	480	100
Strain Hardening, B (MPa)	362	477	380
Strain Hardening exponent, n	1	0.52	0.28
Strain rate constant, c	0.0108	0.001	0.04
Thermal softening constant, m	1	1	1.04

Ballistic Limit Analysis

The ballistic limit is defined as the highest possible impact velocity to cause perforation. When the projectile residual velocity is zero, then the initial velocity of the projectile that causes the perforation is the ballistic limit of the target panel. It can be determined experimentally or calculated analytically. Ballistic limit determined through experiment normally utilises the V_{50} method while analytically calculated using the Recht-Ipson Model. V_{50} is defined as the velocity at which the plate are penetrated by the projectile at the estimated probability of penetration is 0.5. V_{50} gives a single velocity value and can be recognised as the ballistic limit for a panel. Recht-Ipson Model on the other hand determines the ballistic limit using the conservation of energy principle. For validation purpose, V_{50} was used to validate the ballistic limit of 1 x 12 mm of Ar500, 1 x 20 mm Al7075-T651 and 1 x 31.5 mm AZ31B. However, Recht-Ipson Model was used to study the effect of different configuration panels on the ballistic impact.

The solid lines represent the Recht-Ipson model used to predict the residual velocity, V_r as in Equation 4 [18].

$$V_r = a\left(V_i^P - V_{bl}^P\right)^{1/P} \tag{4}$$

Where a and P are empirical constants which best fit the data and V_{bl} is the ballistic limit. The original Recht-Ipson model indicates that $a = m_p/\left(m_p - m_{pl}\right)$ and P = 2, where m_p and m_{pl} denote the mass of the projectile and plug, respectively, and is applicable only if the plastic deformation of the projectile is negligible. Observations of experimental data from the literatures show that the penetration process of 7.62-mm APM2 projectile does not involve any significant plugging. Therefore, a was set as 1 and P was fitted to the data trend line. The method of least squares was used to obtain the best fit for P and V_{bl}.

Results and discussion

Validation of Finite Element Model

Finite element models were validated against the experiment data of Weldox 700E [16], Al7075-T651 [6] and AZ31B [2]. Weldox 700E was chosen to be compared with Ar500 used in this study because of their equivalent material properties in terms of density, the Young's modulus and Poisson's ratio. The ballistic limits of Ar500, Al7075-T6 and AZ31B were numerically obtained and compared to the ballistic limits obtained from the related literatures. The simulation data established overestimation of ballistic limit with percentage differences about 0.3%, 3.5% and 7.6% for Ar500, Al7075-T6 and AZ31B, respectively. The overestimation of ballistic limit from numerical results as in Table 3 is attributed by the absence of dislocation effect in JC constitutive model because at high velocity, during the deformation process, the dislocations interaction becomes intense and large amount of energy rises up, generating the strain hardening effect as the mechanical response [19]. However, the differences between ballistic limit of simulation and experimental result are acceptable considering the complexity of the problem and the limitation of the material constitutive model criterion and also the meshing size [20-21].

Table 3: Percentage difference of residual velocity between simulation results and experimental results from literature

Material	Plate Thickness (mm)	Ballistic limit		Percentage difference (%)
		Experimental from literatures (m/s)	Numerical (m/s)	
Ar500	12	798	800	0.3
Al7075-T6	20	628	650	3.5
AZ31B	31.5	511	550	7.6

Effects of Lightweight Materials on Ballistic Limits

In order to assess the performance of the different configurations, further simulations were carried out for a wider range of velocities. The trend of ballistic performances for each target plate configuration set in Table 1 can be observed in Figure 2. The solid lines of Recht-Ipson model as in Equation 2 are fitted to the at least six numerical data from finite element analysis. The ballistic limit and Recht-Ipson parameters of Equation 2 for all panels obtained using the least square method were tabulated in Table 4. Statistically, the ballistic limit of Recht-Ipson model obtained are very convincing with R2 value of 0.96 to 0.98. The Recht-Ipson equation obtained for each laminated panel seems to have a very high relation with the simulation data and thus, the equation can be used to predict the residual velocity of projectile at different initial velocity. The strength of projectile greatly influences the ballistic limit velocity of a plate [22]. Meanwhile, the initial velocity of a projectile directly affects the residual velocity of the projectile as it surpasses the ballistic limit. Plate A with 8-mm Al7075-T6 as the intermediate layer holds the highest ballistic limit which is 1.9% higher than Plate D with 8-mm AZ31B. However, Plate D attains higher weight reduction. Change in AZ31B thickness gave marginal change about 0.9% in ballistic limit but change in Al7075-T6 thickness offered 2.8% increment in ballistic limit which is quite high considering high velocity range.

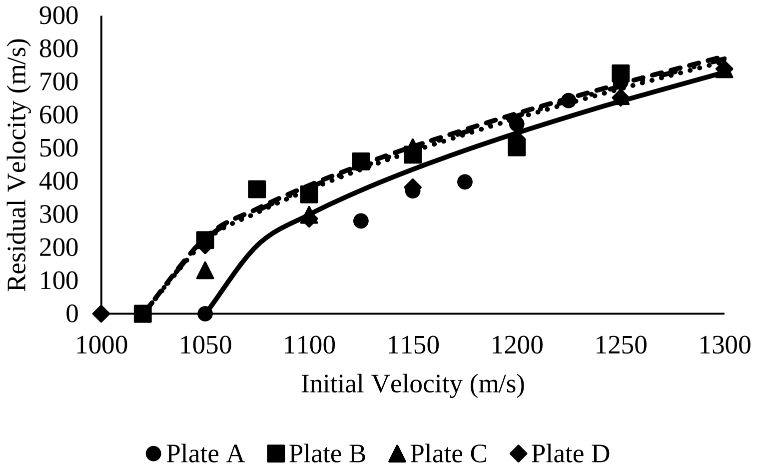

Figure 2: Predicted residual velocity using Recht-Ipson model

Table 4: Ballistic limit and Recht-Ipson parameters for each plate

Recht-Ipson Parameters	Plate A	Plate B	Plate C	Plate D
a	1	1	1	1
V_{bl}	1050	1020	1020	1030
P	2.2	1.92	1.88	1.9

All plates experienced decrement in ballistic limits as the thickness of intermediate layer was decreased. The effect of the lightweight material is not significant in determining the ballistic limit. However, its capability of absorbing the kinetic energy and prevent further projectile penetration can be seen in Figure 3. Figure 3 shows the perforation and interaction of triple-layered panels at initial velocity of 950 m/s at t = 70 μs. It can be seen that Plate A with Al7075-T6 as the intermediate layer and attributing 20% weight reduction exhibit the best ballistic resistance in terms of penetration depth. At the maximum standard velocity of 7.62-mm APM2 projectile, increasing the thickness of AZ31B as in Plate C seems to stop the projectile better than that in Plate D. AZ31B has a relatively low Young's modulus, compared to Al7075-T6, which translates into a relatively high specific stiffness. Higher stiffness typically contributes to higher energy absorption capability upon ballistic impact [23]. Different energy absorption patterns for the lightweight materials of Al7075-T6 and AZ31B serving as the intermediate layer can be observed in Figure 4 and Figure 5 for projectile initial velocity of 400 m/s and 900 m/s, respectively. The intermediate layer is still having the ability to absorb energy at lower impact velocity of 400 m/s, reflecting such behaviour through fluctuating energy that is being absorbed. Whilst at higher velocity of 900 m/s, the energy has been absorbed completely and stalling behaviour is reflected through constant energy after 0.05-0.07 ms. However, these triple-layered plates penetration depth are still 22-38% larger than that of existing armour steel [7].

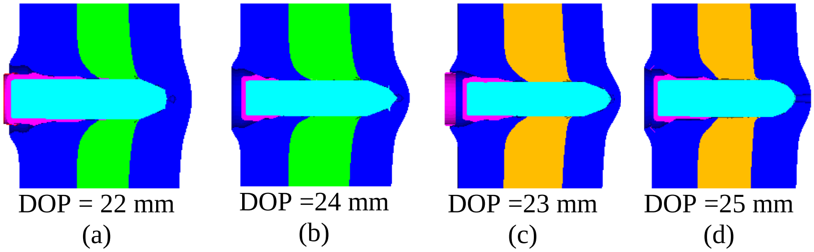

Figure 3: Depth of penetration at initial velocity of 950 m/s for: (a) Plate A, (b) Pate B, (c) Plate C, and (d) Plate D.

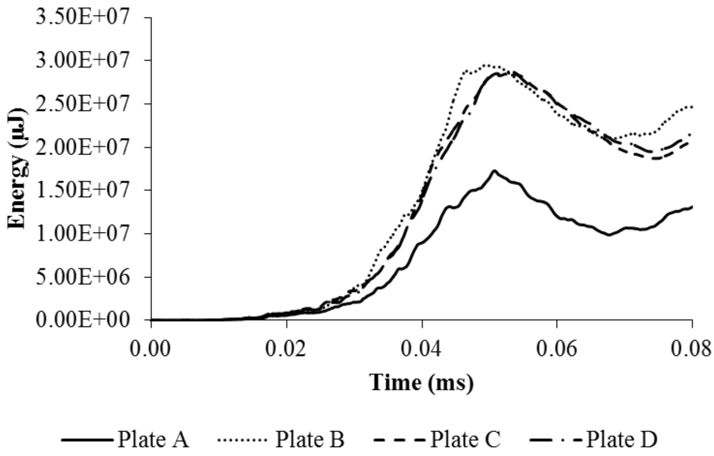

Figure 4: Energy absorbed by intermediate layer for each plate at initial velocity of 400 m/s.

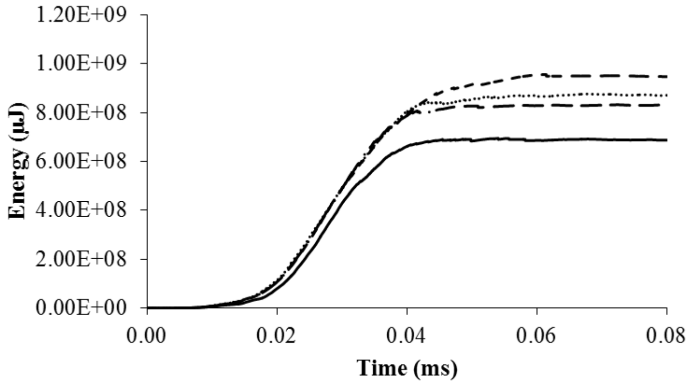

Figure 5: Energy absorbed by intermediate layer for each plate at initial velocity of 900 m/s.

In evaluating ballistic performance of a panel, the most important result besides ballistic limit is the depth of penetration. Usually the depth of penetration depth which determines whether the plate is perforated or not, is taken as the main reference point in comparing the ballistic performance of various target plates. On an equivalent weight basis, triple-layered plate of aluminium alloy Al7075-T6 (Plate B) has allowed less penetration depth compared to the laminated plate of magnesium alloy AZ31B (Plate D) as shown in Figure 3. Nevertheless, the depth of penetration for each plate in Figure 6 exhibits a similar trend and trend line drawn is described as exponential function. The function described is quite similar to penetration depth model of Rosenberg and Dekel which has presented penetration depth, H as a function of initial velocity, v in Equation (5) where A, B, C and D are constants depending on the material properties and dimension [24].

$$H = Dv^{(A+B+C)} \tag{5}$$

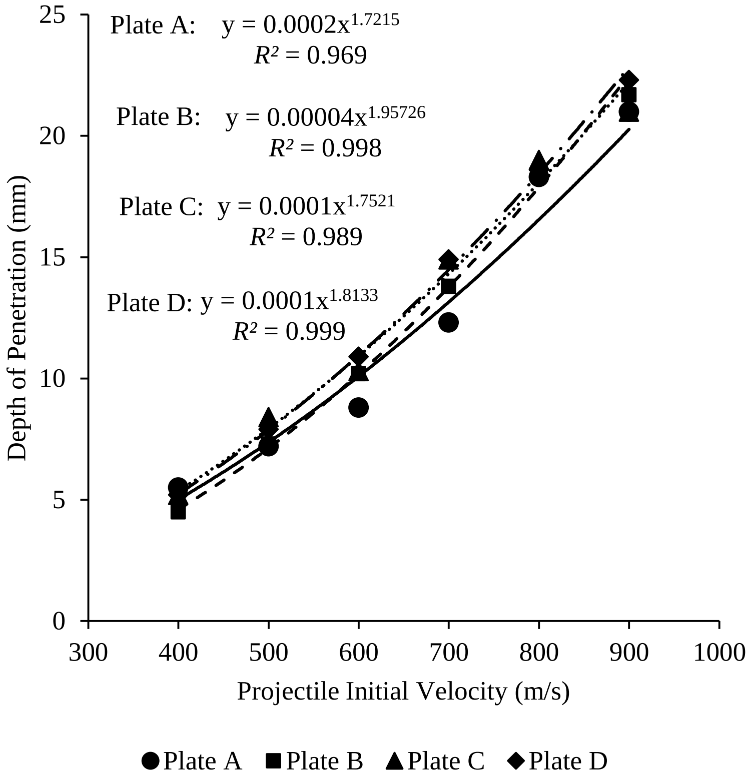

Figure 6: Depth of penetration of each plate at initial velocity ranging from 400 m/s to 900 m/s and its penetration prediction equation.

Figure 7 and 8 present the projectile velocity as a function of time for each plate for an initial velocity of 400 m/s and 900 m/s, respectively which indicates the decrement in projectile velocity until it stopped. The penetration process can be divided into three phases. Phase 1 indicated the phase which the kinetic energy is being absorbed to penetrate the first layer of the laminated panel. Penetration started to go deeper at phase 2 and the rate of energy absorbed increased as the projectile velocity was rapidly decreased. The projectile stopped the penetration process at phase 3 where the projectile was bounced backward at certain velocity. At lower velocity of 400 m/s, the trend of projectile velocity decrement is similar for each plate and the penetration process ended at a smaller range between 48 μs and 50μs which is about 5% maximum difference between each plate. Meanwhile, at a higher velocity of 900 m/s, the projectile penetration completed at a wider duration range which is between 62 µs to 72 µs. Plate A (Al7075-T6 as intermediate layer with 20% weight reduction) required the shortest time to stop the 900 m/s projectile at 62 µs and Plate B (Al7075-T6 as intermediate layer with 25% weight reduction) allowed penetration at the longest time for 72 µs. The variation of the penetration time can be explained with the depth of penetration trend for different projectile initial velocities as in Figure 6. As the projectile initial velocity increases, the variation of the penetration depth becomes more significant.

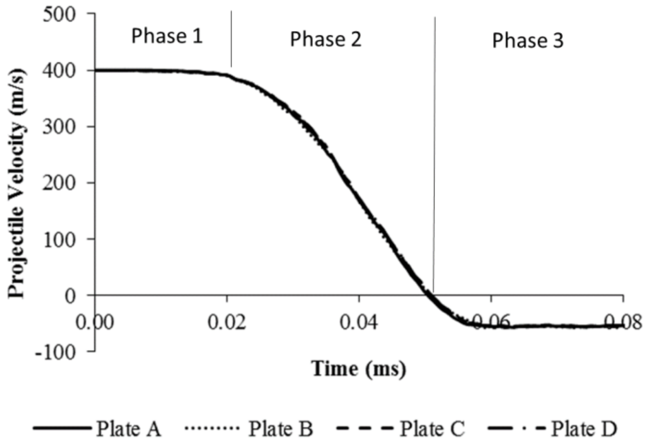

Figure 7: Projectile velocity as a function of time for each plate at initial velocity of 400 m/s.

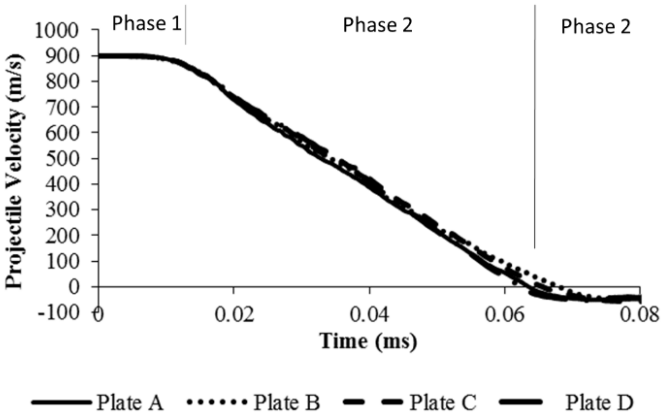

Figure 8: Projectile velocity as a function of time for each plate at initial velocity of 900 m/s.

Conclusion

The work demonstrated the capability of the FEA model developed to predict the ballistic behaviour of Ar500 and Al7075-T6, and Ar500 and AZ31B laminated panels which could be used for the design of experimental testing which might lead to reduction of the number of necessary tests needed for this study later on. The smallest depth of penetration was 22% higher than the existing armour steel material with ballistic limit of 1050 m/s. Considering the 20-45% of weight reduction held, it is observed that these triple-layered metal-laminate panels made of a combination of Ar500 and Al7075-T6, and Ar500 and AZ31B are interesting options for designing a protective structure as they potentially would lead to weight saving while improving the ballistic performance of the structure.

Acknowledgement

The authors would like to express their gratitude to Ministry of Higher Education Malaysia via Universiti Kebangsaan Malaysia and Universiti Pertahanan Nasional Malaysia under research funding LRGS/2013/UPNM-UKM/DS/04 for supporting this research project.

References

[1] A. Manes, F. Serpellini, M. Pagani, M. Saponara and M. Giglio, "Perforation and penetration of aluminium target plates by armour piercing bullets," International Journal of Impact Engineering 69, 39-54 (2014).
[2] T. L. Jones, R. D. DeLorme, M. S. Burkins and W. A. Gooch, "Ballistic evaluation of Magnesium Alloy AZ31B," ARL-TR-4077, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD (2007).
[3] T.L. Jones and R.D. DeLorme, "Development of a ballistic specification for Magnesium Alloy AZ31B. ARL-TR-4664, U.S. Army Research Laboratory: Aberdeen Proving Ground, MD (2008).
[4] A. Staroselsky and L.A. Anand, "Constitutive model for hcp materials deforming by slip and twinning: Application to Magnesium Alloy AZ31B," International Journal of Plasticity 19, 1843–1864 (2003).
[5] A. Srinivasan, U.T.S. Pillai and B.C. Pai, "Effect of Pb addition on ageing behavior of AZ91 Magnesium alloy," Material Science and Engineering A, 87-92 (2007).
[6] E.A. Flores-Johnson, M. Saleh and L. Edwards, "Ballistic performance of multi-layered metallic plates impacted by a 7.62-mm APM2 projectile," International Journal of Impact Engineering 38(12), 1022-1032 (2011).

[7] N. Kiliç and B. Ekici, “Ballistic resistance of high hardness armor steels against 7.62 mm armor piercing ammunition,” Material and Design 44, 35-48 (2013).
[8] M.J. Forrestal, T. Børvik and T.L. Warren, “Perforation of 7075-T651 Aluminum Armor Plates with 7.62 mm APM2 Bullets,” Experimental Mechanics 50(8), 1245-1251 (2010).
[9] M. Übeyli, E. Balci, B. Sarikan et al., “The ballistic performance of SiC-AA7075 functionally graded composite produced by powder metallurgy,” Materials and Design 56, 31-36 (2014).
[10] Y. Wang, F. Wang, X. Yu, Z. Ma, J. Gao and X. Kang, “Effect of interlayer stress wave propagation in CMC/RHA multi-layered structure,” Composites Science and Technology 70, 1669-1673 (2010).
[11] N.A. Rahman, S. Abdullah, W.F.H. Zamri, M.F. Abdullah, M.Z. Omar and Z. Sajuri, “Ballistic limit of high-strength steel and Al7075-T6 multi-layered plates under 7.62-mm Armour Piercing Impact,” Latin American Journal of Solids and Structures 13, 1658-1676 (2016).
[12] H. Abdulhamid, A. Kolopp, C. Bouvet and S. Rivallant, “Experimental and numerical study of AA5086-H111 aluminum plates subjected to impact,” International Journal of Impact Engineering 51, 1-12 (2013).
[13] T. Børvik, M. Langseth, O.S. Hopperstad and K. Malo, “A perforation of 12mm thick steel plates by 20mm diameter projectiles with flat, hemispherical and conical noses - Part I: Experimental study,” International Journal of Impact Engineering 27(1), 19-35 (2001).
[14] G.R. Johnson and W.A. Cook, “A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures,” 7th International Symposium on Ballistic, 541-547 (1983).
[15] S. Dey, T. Børvik, O.S. Hopperstad, J.R. Leinum and M. Langseth, “The effect of target strength on the perforation of steel plates using three different projectile nose shapes,” International Journal of Impact Engineering 30(8-9), 1005-38 (2004).
[16] T. Børvik, M.J. Forrestal, O.S. Hopperstad, T.L. Warren and M. Langseth, “Perforation of AA5083-H116 aluminium plates with conical-nose steel projectiles – Calculations,” International Journal of Impact Engineering 36(2), 426-37 (2009).
[17] P.K. Jena, B. Mishra, K. Siva Kumar and T.B. Bhat, “An experimental study on the ballistic impact behavior of some metallic armour materials against 7.62mm deformable projectile,” Materials and Design 31(7), 3308–3316 (2010).
[18] R.F. Retch and T.W. Ipson, “Ballistic perforation dynamics,” Journal of Applied Mechanics 30, 384-390 (1963).
[19] Y.C. Lin and X.M. Chen, “A combined Johnson-Cook and Zerilli-Armstrong model for hot compressed typical high-strength alloy steel,” Computational Materials Science 49, 628-633 (2010).

[20] J. Hub, "Numerical estimation of ballistic resistance of armour materials against the bullet 7.62x54R," International Conference on Military Technology University of Defense, 817-824 (2013).
[21] W. R. Whittington, A. L. Oppedal, S. Turnage, Y. Hammi, H. Rhee, P.G. Allison, C.K. Crane and et al., "Capturing the effect of temperature, strain rate, and stress state on the plasticity and fracture of rolled homogeneous armor (RHA) steel 594," Materials Science & Engineering A, 82–88 (2014).
[22] X. Teng, S. Dey, T. Børvik and T. Wierzbicki, "Protection Performance of Double-layered Shields against Projectile Impact," Journal of Mechanics and Material Structures 2, 1309-1329 (2007)
[23] C.E. Anderson Jr and J.P. Riegel, "A penetration model for metallic targets based on experimental data," International Journal of Impact Engineering 80, 24-35 (2015).
[24] Z. Rosenberg and E. Dekel, "The deep penetration of concrete targets by rigid rods: Revisited," International Journal of Protective Structures 1(1), 125-144 (2010).