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Ballistic Limit of Laminated Panels with Different Joining Materials Subjected to Steel-Hardened Core Projectile

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Abstract: This paper presents the computational-based ballistic limit of laminated metal panels comprised of high-strength steel and aluminium alloy Al7075-T6 plates to necessitate a weight reduction of 25% in the existing armour steel plate using three different joining materials. Numerical models of the triple-layered panels were developed using the commercial Explicit Finite Element code and were impacted by a 7.62-mm armour-piercing projectile at velocities ranging from 400 m/s to 1000 m/s. The ballistic performance of each configuration plate in terms of the ballistic limit velocity, depth of penetration and end of penetration, was quantified and considered. It was found that the panels with joining materials exhibited a better ballistic limit on an average of 1.5% than that of the panel without a joining material. The penetration depth of the panel joined by polyurethane possessed the lowest depth of 22 mm with a higher contact duration compared to the panel without a joining material. This happened because the polyurethane adhesive was better able to absorb energy at a high strain rate impact than the other joining materials. Thus, based on the investigation that was carried out, polyurethane seems to be the most interesting option for joining different metals of Ar500 and Al7075-T6 as a laminated panel for armoured vehicle applications.

Keywords: Lightweight material, metal laminate, polyurethane, epoxy, filler metal, ballistic impact

1. Introduction

Steel has been widely utilised in armour applications due to its high strength and cheaper cost of production [1]. Steel has a relatively high density, which restricts the mobility of armoured vehicles. This characteristic, which has become a major disadvantage of armour steel, has motivated researchers to find lighter materials to integrate with the existing armour steel to obtain the same level of protection [2]. In order to reduce the weight of the vehicle so as to lower fuel consumption and to improve the manoeuvrability of the vehicle, the current trend in the military industry is to integrate lightweight materials [3]. One of the ways of doing this is by laminating the existing steel with lightweight materials such as composites, aluminium alloys and magnesium alloys. Aluminium alloys have the potential to reduce the weight of existing armoured vehicle bodies due to their high stiffness-to-weight ratio. Several investigations have been carried out to reveal the ballistic resistance of different aluminium alloys. It has been observed that aluminium has some weaknesses compared to high-strength steel when dealing with a ballistic impact. Since aluminium alloys have a poor ballistic performance, they are often utilised in multi-layered or spaced structures in combination with other materials, especially high-strength steel [4].

The main criterion for the performance of an armoured vehicle is its capability to resist a ballistic impact from a high-velocity low-mass projectile. The materials used to join the layered plates in a laminated panel should also not compromise the stiffness and strength of the panel of the vehicle during a high-velocity impact because the structural resistance to a severe impact is directly related to the structural integrity [5]. The structural performance involves the transmission of forces between the layers in the laminated panels, which are closely related to the deformation and energy absorption capabilities of the panels [6]. Thus, it is essential to better understand the local strength and energy-absorption characteristics of the layered panels with the joining materials in order to determine the behaviour and properties of the laminated panels developed for use in these vehicles in terms of their strength during a high-velocity impact such as a ballistic

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impact. There are various methods for joining the plates, such as welding, riveting, brazing, and adhesive bonding. The adhesive and brazing mechanisms significantly yield more advantages than the other methods due to their uniform stress distribution on a surface, resulting in a large stress-bearing area. Both methods allow bonding among a wide range of laminated materials, and excellent damping and shock-absorbing properties as well as impact resistance.

The types of joining materials dominate the failure mode of joints. When a joining material, such as urethane or toughened epoxy, exhibits a tendency to deform, a plastic zone is initiated at the end of the adhesion joint, creating a white band as the damage zone [7]. An experiment was carried out to correlate the measured strength with the theoretical work of adhesion [8]. Therefore, the balancing strength in the joints was contributed by the plastic or viscoelastic dissipation of the adhesive layer or substrates, as highlighted by Morinière et al. [9]. Although the joining process, like the adhesion and brazing techniques, has been widely utilised, there are still issues with regard to producing a consistent strength under a low-velocity impact and understanding its fracture because each bond with the joining material has a unique characteristic in terms of the joining process, types of plates and joining materials.

It is essential to understand the relationship between these properties and their response to the joining strength in order to produce a reliable joint for a metal laminate panel. The joining material is introduced into a metal laminate panel to improve its ballistic impact resistance. In order to enhance the attractiveness of the constructed laminated plate with the inclusion of the joining material through the adhesion and brazing techniques, it is essential to study the strength of the joints with different types of metals under a ballistic impact. Therefore, the aim of this study was to investigate, by means of a finite element analysis, the effect of different joining methods for different metals, namely, aluminium alloy and high-strength steel, that were subjected to a ballistic impact. Thus, this study analysed the effect of different joining materials on triple-layered laminated composites with regard to the ballistic limit velocity, penetration process and permanent deformation under a ballistic testing against a 7.62-mm APM2 projectile.

2. Methodology

The methodological framework used in this study is given in Figure 1. The combination of Ar500 steel and Al7075-T6 aluminium was an interesting option that led to weight-saving and an improvement in the ballistic performance of the original Al7075-T6 plate. Firstly, geometric modelling was performed using computer-aided design (CAD) software. Then, a finite element model was formed using a dynamic explicit FE code. Two types of FE models were constructed: a triple-layered panel without joining materials and a triple-layered panel with joining materials. For the latter panel, three types of joining materials were assigned: epoxy, polyurethane and Al-Si-Zn filler metal. Epoxy and polyurethane were conservatively applied using the adhesive bonding technique, while the filler metal was joined using the brazing technique. Next, an FE analysis was performed for each FE model at different impact velocities ranging between 400 m/s to 1000 m/s. This velocity range was chosen according to the standard for 7.62-mm APM2 projectile set by The North Atlantic Treaty Organization (NATO) [10]. Finally, the penetration behaviour was observed in terms of the depth of penetration and the end of penetration time, and a further analysis using the Recht-Ipson model was carried out to find the ballistic limit for each panel.

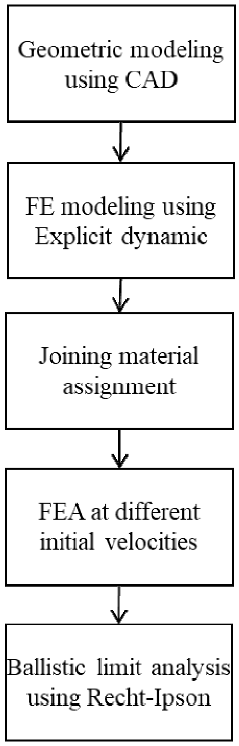


Fig. 1 Flow diagram of methodology used

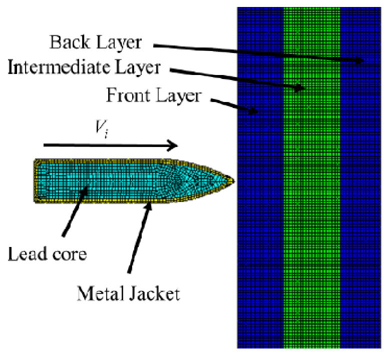


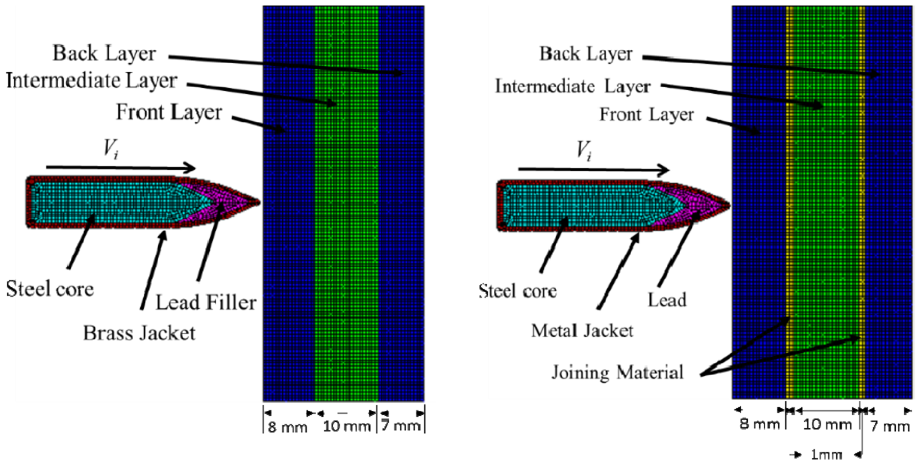
Fig. 2 FE model of panel subjected to 7.62-mm FMJ projectile for validation of FE model.

In addition, a ballistic test was carried out to validate the FE model of the laminated panel without joining materials, as shown in Figure 2. The triple-layered panel consisted of an 8-mm thick Ar500 steel as the front layer, a 10-mm thick Al7075-T6 aluminium as the intermediate layer and a 7-mm thick Ar500 steel as the back layer, thereby achieving a weight reduction of 25% from the existing ballistic resistant panel. Johnson-Cook material constitutive models were used to represent the materials involved in this FE analysis, and this is discussed further in the section on Finite Element Modelling.

The ballistic tests were performed using the NATO Stanag 4569 standard, which specifies the protection levels for armoured vehicles in five categories [10]. The threat, subject to this study, was denoted by level 2, which was one level lower than the practice standard that an armoured vehicle should surpass to protect its occupants [1]. The experimental result was then compared with the finite element result, and the study was then extended to a higher level of threat, which was the NATO Stanag 4569 protection level 3. The experiment was conducted for the laminated panel without joining materials for the validation of the finite element model only. The effect on the laminated panel with joining materials under a ballistic impact was investigated through finite element analysis. The experimental approach can provide good penetration results, but it is very expensive. The finite element approach, on the other hand, has been proven to be a reliable and economical tool for the penetration predictions of projectiles over all ranges of striking velocities [11].

2.1 Finite element modeling

Geometrical models of a 7.62-mm armour piercing ammunition projectile and the triple-layered target panel, as in Figure 3, were developed for a high-velocity impact using a software package. The projectile that was used was made of a brass jacket, lead filler and ogive nose hardened steel core, and the total mass of the projectile was 10.04 g with a diameter of 7.7 mm and length of 35 mm. The target plate was modelled as a 100-mm diameter circular plate and it was fully fixed at the edge boundaries. Four models of the triple-layered configuration panels, as in Table 1, were constructed, where Al7075-T6 was placed in the intermediate layer and Ar500 was placed in the front and back layers. One model (Plate A) was developed without joining material as the reference panel. The other three models (Plates B, C, and D) were constructed such that each layer was joined using three types of joining materials: epoxy, polyurethane and Al-Si-Zn filler metal.



(a) (b)

Fig. 3 Finite element model of projectile and laminated plate for: (a) Laminated panel without joining material, (b) Laminated panel with joining materials.

Table 1 Laminated panel configuration

Plate	Layer thickness	Type of Joining Material
A	1x8mm Ar500, 1x10mm AL7075-T6, 1x7mm Ar500	None
B		Epoxy
C		Polyurethane
D		Al-Zn-Si Filler

The Johnson-Cook (JC) model has been utilised widely to describe the behaviour of materials that are subjected to large strains, high strain rates and high temperatures [3, 10]. It combines the strain hardening, strain rate and thermal softening effects, and has been used extensively to describe the behaviour of materials that are subjected to a high-velocity impact. It is in the form of Equation 2 [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 $\dot{\varepsilon}_{eq}^{*} = \dot{\varepsilon}_{eq}/\dot{\varepsilon}_{0}$ is the dimensionless strain rate, i.e. the ratio of the strain rate to the user-defined strain rate. T^{*m} represents the homologous temperature, and is given by the equation, $T^{*m} = (T - T_r)(T_m - T_r)$, where T_r and T_m represent the room temperature and the melting temperature, respectively.

$$\sigma = \left(A + B\varepsilon^{n}\right)\left(1 + C\ln\dot{\varepsilon}\right)\left(1 + T^{*m}\right) \quad (1)$$

The JC material constitutive model was used to represent the projectile and metal-laminated panel of Ar500 steel and Al7075-T6 aluminium, while the Cowper-Symonds material constitutive model was utilised to represent the joining materials in the finite element model. The JC parameters for the Ar500 steel, Al7075-T6 and projectile materials used in this study, as shown in Table 2, were adopted from the previous works of Forrestal et al. [10] and Manes et al. [3]. These parameters were chosen because the materials used in the previous works had almost similar material properties in terms of their density, Young's modulus and Poisson's ratio with those from this study.

Table 2 Parameters of Johnson-Cook model for target plates and projectile materials [10, 3]

Material Properties	Ar500	Al7075-T6	Steel	Lead	Brass	Copper
Yield Strength, A (MPa)	1250	480	1200	24	206	206
Strain Hardening, B (MPa)	362	520	1200	24	206	206
Strain Hardening exponent, n	1	477	50000	300	505	0.42
Strain rate constant, c	0.0108	0.001	0	0.1	0.1	0.01
Thermal softening constant, m	1	1	1	1	1.68	1
Melting temperature, T_m (K)	1800	893	1811	760	1189	1189

The Cowper-Symonds (CS) model, on the other hand, is an extension of the bilinear hardening model with some reinforcements, whereby the plasticity limit is calibrated by the coefficient determined from the formula, as in Equation 2, where $\dot{\varepsilon}$ is the strain rate, and C and q are the CS constants [9].

$$\sigma = 1 + \left(\dot{\varepsilon}/C\right)^{q} \quad (2)$$

However, the CS model was chosen over the JC model to represent the joining materials because of its simplicity. It was quite difficult to obtain the JC parameters for the joining materials, and it seemed unnecessary to use the JC model because the balance strength of the joints was contributed by the plastic joining material layer. Besides, the CS model was based solely on the conventional plasticity theory and the effect of the joining material on a ballistic impact was not as much as that of the Ar500 steel and Al7075-T6 aluminium [9]. The CS parameters for the joining materials were calculated from an experimental procedure that was conducted using static and semi-static loading tests and are tabulated in Table 3.

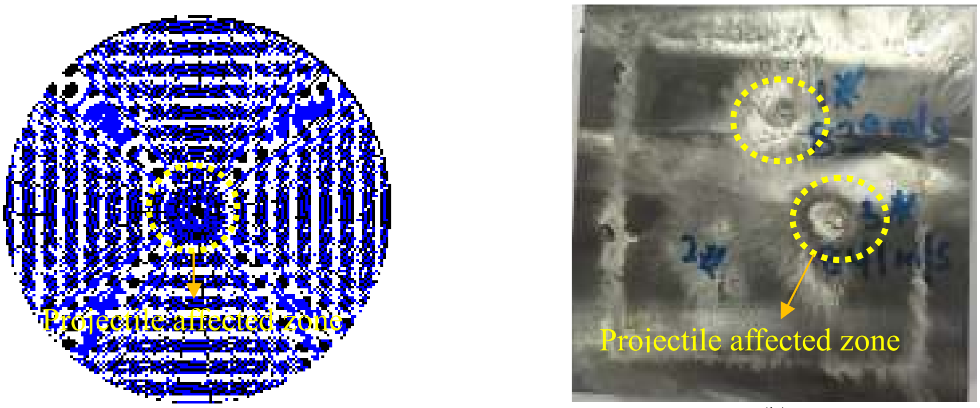
TABLE 3. Parameters of Cowper-Symonds model for joining materials

Cowper-Symonds Constant	Al-Si-Zn filler metal	Epoxy	Polyurethane
C	120	2188	50
q	5.0	5.5	4.0

3. Results and Discussion

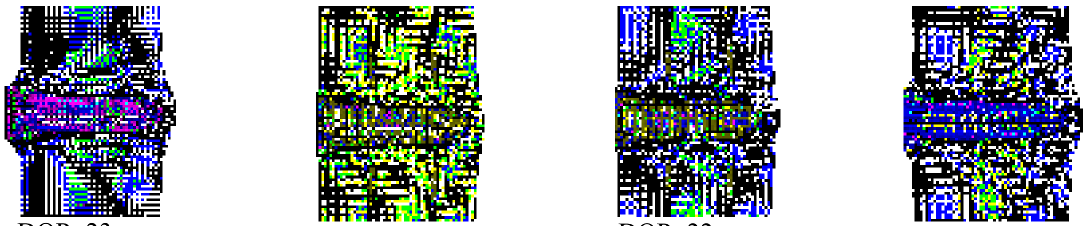
A ballistic test was carried out to validate the FE model of the laminated panel without the joining materials. The images of the front face of the triple-layered plate from the simulation and ballistic test are shown in Figure 4. The ballistic test results showed that the projectile partially penetrated both plates with a depth of penetration ranging between 1.5 mm to 1.9 mm. The average depth of penetration after three shots was calculated as 1.7 mm. Both the simulation and ballistic test showed that the projectile was completely shattered. This happened because the 7.62-mm FMJ projectile consisted of soft core lead, which was destroyed on the high-strength steel surface during the impact [1]. This result implied that the FE model of triple-layered metal laminated armour plates could be used effectively to study their behaviour subject to a higher level of threats with the inclusion of joining materials.

A ballistic test for a higher threat level was carried out using an FE analysis to study the effect of these three joining materials with Ar500 and Al7075-T6 for the triple-layered laminated panel configuration under a high-velocity impact. The final state of the laminated panel with the joining materials was compared to the laminated panel without joining materials, as in Figure 5, in terms of the depth of penetration (DOP). Based on the DOP results, it was noticed that the panels with the joining materials exhibited a better performance than the panel without joining material. The depth of penetration of the panel joined by polyurethane possessed the lowest depth of 22 mm. This was due to the ability of the polyurethane adhesive to absorb energy better during impact at a high strain rate. The polyurethane-joined metal laminates had a higher strength at high strain rates rather than low strain rates, according to Galliot et al. [12]. With regard to the elastic properties, when a load is applied to a polymeric material, the molecular chains will experience a phase of restructuring before plastic deformation because the adhesive bonding will increase in stiffness at a higher strain rate [13]. Under the static pressure of a partial load, the constituent molecular chains are relaxed and effectively facilitate the plastic deformation phase [14]. However, under the influence of an impact load at high strain rates, the molecular chains are not able to sort their positions and will then intersect with each other and be confined to their deformation slips [12, 15].



(a) (b)

Fig. 4 Comparison of triple-layered plate after the: (a) simulation, (b) ballistic test.



DOP=23 mm (a) DOP=22.5 mm (b) DOP=22 mm (c) DOP=22.5 mm (d)

Fig. 5 Penetration of 7.62-mm APM2 projectile at t = 0.07 ms at an initial velocity of 950 m/s for a laminated panel from the simulation results of: (a) Plate A, (b) Plate B, (c) Plate C, (d) Plate D

The time taken to stop the projectile, as shown in Figure 6, for the laminated panel without joining materials (Plate A), with epoxy bonding (Plate B), with polyurethane bonding (Plate C), and with an Al-Zn-Si filler bonding (Plate D) was 67 µs, 70 µs, 74 µs and 72 µs, respectively. The penetration depth of the panel joined by polyurethane, as in Figure 5(c), possessed the lowest depth of 22 mm with a higher contact duration compared to the panel without joining material. The increased ability of the joining materials to absorb the kinetic energy from the projectile helped to slow down the projectile during the penetration process [4]. This phenomenon increased the contact time of the projectile during the ballistic impact.

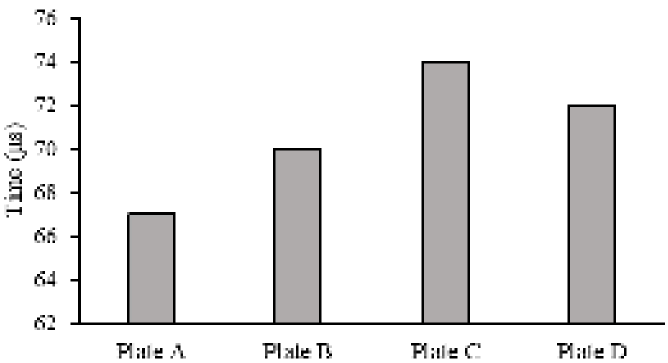


Fig. 6 Comparison of end of penetration for panels subjected to an impact velocity of 900 m/s.

A series of simulations of a 7.62-mm APM2 projectile at different velocities were conducted to evaluate the ballistic limits and depth of penetration at a standard projectile velocity. The ballistic limit was evaluated based on the lines representing the Recht-Ipson model that were used to predict the residual velocity, V_r.,

$$V_r = a\left(V_i^P - V_{bl}^P\right)^{1/P} \quad (3)$$

where a and P are the empirical constants that best fit the data, and V_{bl} is the ballistic limit. The original Recht-Ipson model indicated that $a=m_p/(m_p-m_{pl})$ 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 the experimental data from the literature showed that the penetration by the 7.62-mm APM2 projectile did 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}.

The trend of the ballistic performance for each target plate configuration set in Table 1 can be observed in Figure 7. The ballistic limit and Recht-Ipson parameters of Equation 3 for all the panels were tabulated in Table 4, where statistically, the ballistic limit of the Recht-Ipson model that was obtained was very convincing, with the coefficient of correlation, R^2 value being between 0.9601 to 0.9831. Plate C, with a polyurethane joint, had the highest ballistic limit, which was 1.9% higher than that of the other plates.

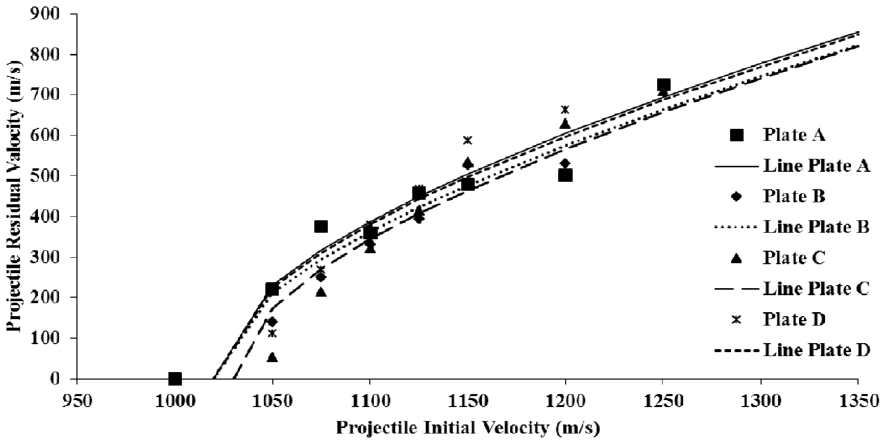


Fig. 7 Predicted residual velocity using the Recht-Ipson model.

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

	Plate A	Plate B	Plate C	Plate D
V_{bl}	1020	1020	1030	1020
P	1.92	1.84	1.86	1.9
R^2	0.9831	0.9605	0.9601	0.9635

4. Conclusion

This paper facilitated the selection of an appropriate joining material and process for laminated panels of Ar500 and Al7075-T6 to withstand ballistic impacts from a projectile threat. A triple-layer configuration panel was joined using two techniques: brazing and adhesion. From a finite element analysis of the ballistic test that was conducted, it was discovered that the polyurethane-joined laminated panel gave the best performance under a ballistic impact. The polyurethane-joined laminated panel surpassed the ballistic performance of the laminated panel without adhesive by 4.3%, and it took the laminated panel a time that was 10.4% longer to stop the projectile, while the ballistic limit improved by 1.9%. Thus, polyurethane seems to be the most suitable material for joining Ar500 and Al7075-T6 metals as laminated panels for armoured vehicle applications.

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