Influence of adhesive geometry and material property on the ballistic protection performance of ceramic composite armour panels

P. Tan

Land Division, Defence Science and Technology Group, 506 Lorimer Street, Fishermans Bend, Melbourne, Victoria 3207, Australia
Ping.tan@dst.defence.gov.au

Abstract. Ceramic composite body armour is generally a system composed of a ceramic strike face plate and fibre reinforced composite backing plate. It absorbs an impact by blunting and shattering hard projectiles, capturing the fragments, distributing and absorbing the kinetic energy across the armour panel. A technique to combine the ceramic and fibre reinforced composite plates is the use of adhesives. However, investigation of the adhesive geometry and material property on the damage/energy-absorbing mechanisms and ballistic protection performances of ceramic composite body armours is scanty. In this study, various finite element models were developed using the commercial finite element software ANSYS/AUTODYN to investigate the effects of adhesive interlayer thickness, number, shape, material type and the size of cohesion between adjacent ceramic tablets on the ballistic protection performances and damages of the selected ceramic composite armour panels, including ballistic limit velocity, maximum backface deformation, damage area and pattern. Two types of ceramic strike face plates were considered in this investigation; one was made of monolithic ceramic plate(s) and the other composed of different size ceramic tablets. The ceramic materials used in this preliminary study were chosen to be silicon carbide and alumina. The composite backing material was selected to be Kevlar fibre reinforced composite. Seven different types of resin materials were used as adhesives to bond the ceramic composite armour panels respectively. The ceramic strike face and fibre reinforced composite backing plates considered were assumed to be perfectly bonded by the adhesive at the interface without defects. The corresponding modelling methodology and techniques were validated by comparing the present predicted results with those previously reported. It was found from this numerical study that for the panels considered, the ballistic limit velocity and damage are generally affected by the key parameters of the adhesive, whereas the influence of the key parameters on the predicted value of maximum backface deformation is not significant. This information may offer advantages to meet the requirement for design of future body armours.

1. INTRODUCTION

Ceramic composite body armours are generally made of ceramic strike face plate and fibre reinforced composite backing plate. One of the most common methods for combining these materials is using the adhesive, which are crucial for their further development and improvement. Hence, it is necessary and required to understand the influences of adhesive geometry and material property on the behaviour of ceramic composite body armours under various impacts. In order to investigate the effects of adhesive layer type and thickness on the ballistic behaviour of ceramic/metal armours subjected to low calibre projectile impact, Zaera et al [1] conducted numerical and experimental studies. Both numerical and experimental results showed that the ceramic damage is greater in the armours bonded using polyurethane adhesive than that using epoxy resin. The numerical study also shows that the thicker the adhesive layer the greater the damage to the ceramic, whereas it was observed from a set of full-scale fire tests that fragmentation increases in inverse proportion to the thickness of the adhesive. Lo´pez-Puente [2] conducted experimental and numerical studies to investigate the influence of adhesive layer thickness on the ballistic limit of ceramic/metal armours, in which the toughened epoxy resin was used for the adhesive layer, of different thickness. It was noted that for alumina/aluminium configurations considered, a variation of the adhesive layer thickness affects the efficiency of the armour and a thickness value of 0.3mm was found optimum. Übeyli et al [3] experimentally investigated the effects of mechanical properties of backing material and laminating type as well as the adhesive type on the ballistic performance of Al_2O_3/Al2024 (alumina/aluminium) laminated composites armour against 7.62 × 51 mm armour piercing projectiles. It was noted that composites bonded with polyurethane exhibited more resistance to spalling of ceramic tiles than those bonded with epoxy. However adhesive type had no appreciable effect on the ballistic performance of the composites. Tasdemirci et al [4] experimentally and numerically investigated the effects of rubber, Teflon and aluminium foam interlayer materials on the ballistic performances of ceramic/composite armour targets. It was reported that the presence of interlayer altered the stress wave transmission

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between the ceramic and composite layers. Damage in the ceramic layer was highly localized around the projectile impact zone for without interlayer and rubber interlayer configuration, while aluminium foam and Teflon interlayer spread the damage zone in the radial direction. Grujicic et al [5] performed finite element analyses to investigate the role of adhesive layer in the ballistic/structural performance of ceramic/polymer–matrix composite hybrid armour. It was noted that significant improvements in the ballistic protection performance and durability of hybrid armour can be attained by proper modifications in the adhesive layer mechanical properties. Prakash et al [6] conducted a numerical study to investigate the influence of adhesive thickness on the dynamic responses of Al_2O_3/Al5083 H116 composite targets subjected to ogive nosed projectile impact. They pointed out that the impact responses of the ceramic/metal composite panels were influenced to different degree by the adhesive thickness. Seifert et al [7] carried out experimental study to understand the effect of adhesive stiffness on the failure of ceramic tiles adhered to metallic backings, in which four different types of adhesive were tested. It was found from testing results that the damage behaviour of the ceramic/metal composites can be controlled either by the adhesive thickness or stiffness. Jiusti et al [8] experimentally investigated the influence of filling materials on the ballistic performance of Al_2O_3 mosaic armours. They found that the epoxy-filled mosaics exhibited a significantly superior performance than the filling-free mosaics. Gao et al [9] conducted experimental and numerical investigations on the influence of adhesive layer on the high velocity impact performance of the ceramic/metal composite armour. It was reported that the size of fractured ceramic was decreased with the thickness of adhesive layer. Wang et al. [10] performed a drop weight test to investigate the effects of partitioned tile layer, impact location, stagger mode, tile shape and size, adhesive type, as well as fiberglass mesh on the low velocity impact resistance of a layered and staggered bio-inspired building ceramic composite. It was noted that the elastic adhesive interlayers had higher efficiency than the rigid ones in improving the fracture toughness of the composite.

It is indicated from literature that the ballistic protection performance of armour plates are affected by the geometrical parameters and material property of adhesive interlayers used for bonding ceramic composite panels. Hence, testing and modelling of adhesive and cohesion in ceramic composite armour panels are crucial for identifying their behaviours under ballistic impact and for their further development and improvement. However, the research on the influence of adhesive and cohesion on the ballistic performance of armour panels composed of ceramic plate(s)/tablets as strike face and Kevlar fibre reinforce composite as backing plate is still scanty. This investigation aims at numerical study on the effects of adhesive/cohesion parameters, including adhesive interlayer thickness, number, material properties and shape, ceramic tablet pattern (or ceramic tablet size and location), size of cohesion between the adjacent tablets, on the ballistic protection performances and damages of the selected armour panels, including ballistic limit velocity (V_{bl}), maximum backface deformation (MAXBFD), damage area and pattern. Also, the effect of ceramic type on the sensitivity of ballistic protection performance of armour panels to the adhesive interlayer thickness is discussed. Comparisons of the ballistic performance and dynamic response for the ceramic composite armour panels with and without filling materials between the adjacent tablets are conducted. In this study, strike face plates are made of monolithic ceramic plate(s) or composed of different size of ceramic tablets, and the backing plates are made of Kevlar fibre reinforced composite (KFRC). Their corresponding finite element (FE) models were generated using the commercial FE software ANSYS/Autodyn [11].

2. NUMERICAL MODELLING

Figure 1 shows the FE models for three typical types of ceramic composite panels, which are named as SLMS-SiC for the panel having a strike face plate made of the single-layer monolithic silicon carbide (SiC) plate and a KFRC backing plate; TLMS-SiC for the panel having a strike face made of triple-layer monolithic SiC plates and a KFRC backing plate and TLST-SiC for the panel having a strike face composed of triple-layer SiC tablets/resin and a KFRC backing plate, respectively. The adhesive and cohesion materials used to bond the SiC plate(s)/tablets and KFRC plate are epoxy resin. All panels shown in Fig. 1 have the same panel thicknesses of 9.5 mm, same total thicknesses of 3mm SiC plate(s), 1 mm resin layer(s) and 5.5 mm KFRC plate. For the panel composed of ceramic tablets, the size of cohesion between two adjacent ceramic tablets (i.e., Tc in Fig. 1 (c)) was selected to be 0.5 mm.

The present FE models were developed using the commercial finite element software ANSYS/Autodyn [11], in which the zero x- and y-velocity boundary conditions were applied to the top edges of the panels as shown in Fig. 1(a). The panels are subjected to an impact from a 30 caliber fragment-simulating projectile (FSP). Only half of the panel and the 30 caliber FSP above the central line are shown in Fig. 1 due to the symmetry of the FE models. Gauge 1 in Fig. 1(c) located at the

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centre of the FSP for measuring the velocity of FSP was used to predict the value of the required ballistic limit velocity. In this study, the predicted value of V_{bl} was obtained by averaging the initial velocity of the projectile that led to a partial penetration (V_0^P) and the initial velocity that led to a complete penetration (V_0^c). The difference between V_0^P and V_0^c was chosen to be 20 m/s [12]. Gauge 2 in Fig. 1(c) measured the displacement of the selected point is located on the rear surface of the KFRC backing plate with the same vertical coordinate as Gauge 1. This measurement was used to obtain the predicted value of MAXBFD.

The KFRC material used for composite backing plate was considered to be homogeneous and orthotropic. It was modelled using the orthotropic equation of state (EOS), elastic strength model and material stress/strain failure model. The ceramic materials used for strike face plate, including SiC and alumina 99.7% (Al_2O_3-99.7) were considered to be homogeneous and isotropic. They were modelled by the polynomial EOS, Johnson–Holmquist strength model and failure model. The steel 4340 material used for the FSP was modelled using linear EOS, the Johnson–Cook strength and failure models. The adhesive and cohesive materials used to bond ceramic composite panels were considered as fluid resisting high pressure due to its low strength compared to those of other materials [2]. Hence, the adhesive and cohesive materials used in this study was modelled using the Mie Gruneisen EOS, in which the relationship between the shock velocity (U) and particle velocity (u_p) is expressed as

$$U = c_0 + su_p \tag{1}$$

where c_0 and s are parameters which are generally determined by experiments.

All material models mentioned above are available in the Autodyn material library [11]. The mesh sizes for panels and FSP were selected to be less than 0.8 mm based on the sensitivity analysis results.

For validating the modelling capability, a comparison of the ballistic limit velocity between the FE and testing results was conducted for the selected Kevlar fibre reinforced composite panels under the 30 caliber FSP impact. The difference between them is 2.2%. The present modelling methods and techniques were also validated in author's previous paper for the selected armour components including armour hard panels and helmets subjected to FSP impacts [12-13].

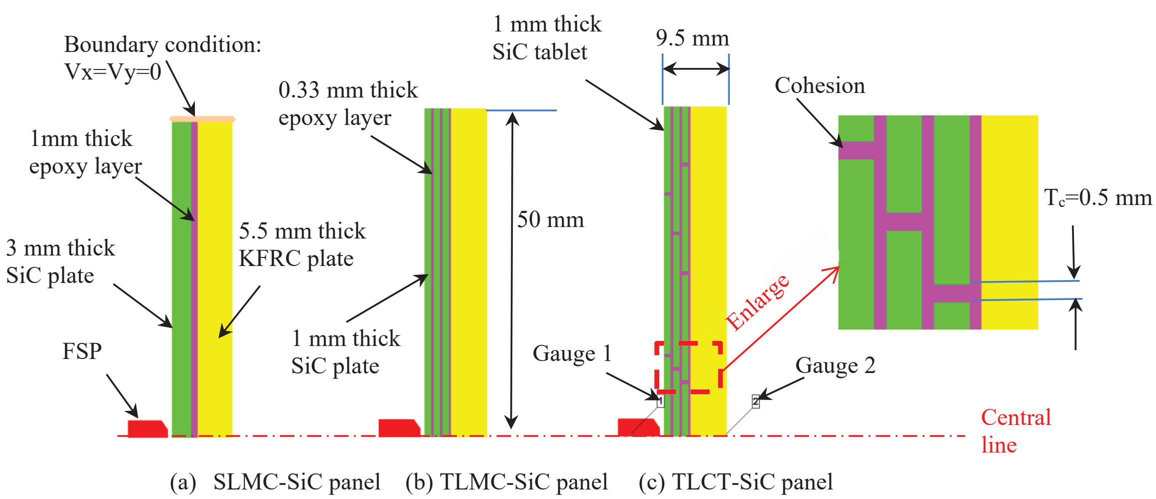

Figure 1. Schematics of the finite element models for the selected ceramic composite panels under a 30 caliber FSP impact

3. NUMERICAL RESULTS AND DISCUSSIONS

In order to understand the correlations between the ballistic protection performances (e.g., V_{bl} and MAXBFD) and the key parameters of the adhesive and cohesion, including adhesive interlayer thickness, number, material property and shape, ceramic tablet pattern, size of cohesion between the adjacent tablets, an extensive numerical study was conducted using the present FE models. The influence of the ceramic type on the sensitivity of ballistic protection performance of armour panels to

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the adhesive interlayer thickness was also investigated. The key parameters considered were varied in individual simulations: adhesive layer thicknesses of 0.5, 1 and 2 mm; adhesive layer number of 1 and 3; adhesive types of EPOXY RES1, EPOXY RES2, POLYETHYL, POLYRUBBER, POLYSTYREN and POLYURETH available in Autodyn material library [11] and EPOXY RES3 in [2]. It is worth to mentioning that for the adhesive materials considered in this study, only the EPOXY RES3 is modelled using the Von Mises strength model and Hydro (Pmin) failure model in addition to the Mie Gruneisen EOS; five different adhesive interlayer shapes shown in Fig.2 below, in which the triple-layer SiC panels are bonded with the same type of adhesive but with different adhesive interlayer shapes, and the thickness of ceramic layer bonded with wavy adhesive layer is not constant at 1mm; six different tablet patterns shown in Fig.3 below, in which the triple-layer SiC tablets having different size and location are bonded using the same type of adhesive; size of cohesion between two adjacent ceramic tablets (i.e., Tc in Figure 1 (c)) of 0.5, 1 and 1.5 mm, and ceramic type of SiC and Alumina (Al_2O_3-99.7) available in Autodyn material library [11]. A comparison of the ballistic protection performances and damages between the panels composed of SiC tablets filled with and without epoxy resin is also discussed.

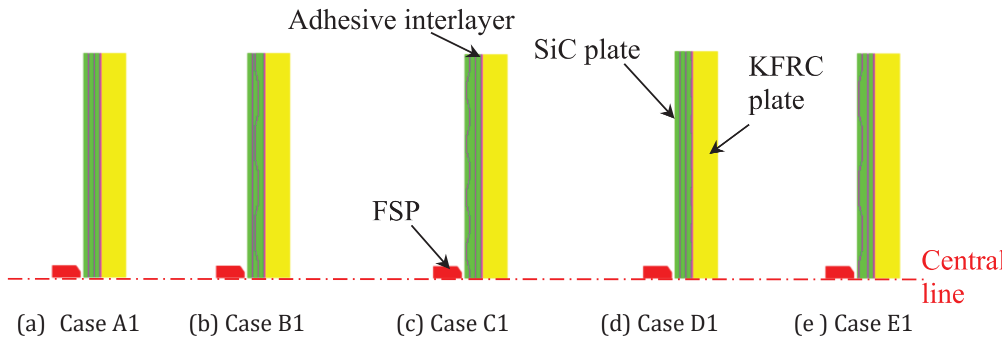

Figure 2. Schematics for the selected panels made of triple-layer monolithic SiC and KFRC plates having different adhesive interlayer shapes

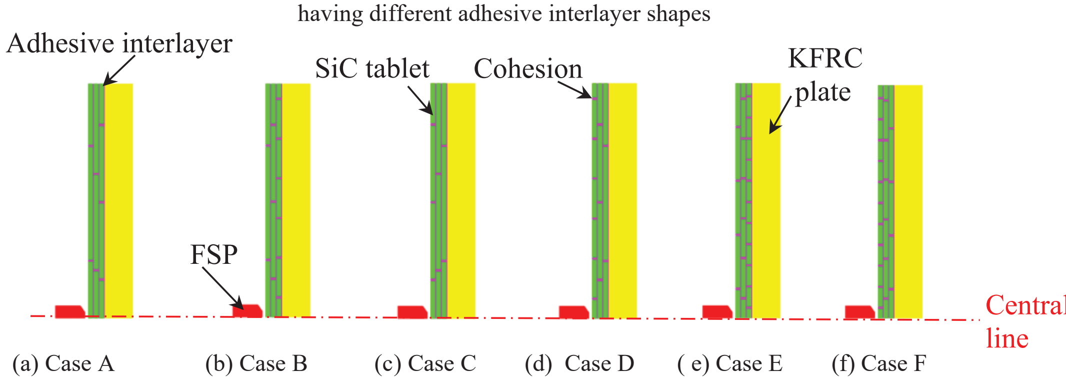

Figure 3. Schematics for the panels composed of KFRC backing plate and triple-layer SiC tablets having different sizes and locations

Figure 4(a) plots the variations of the predicted V_{bl} with the total adhesive layer thickness (T_{ad}) for the armour panels having a strike face made of single-layer monolithic SiC plate (Fig.1(a)), triple-layer monolithic SiC plates (Fig.1(b)), and triple-layer SiC tablets/resin (Fig.1(c)), respectively. It is noted from Fig. 4(a) that for the selected panels, the predicted V_{bl} reduces with an increase in T_{ad}. The predicted V_{bl} for the single-layer monolithic SiC plate is more sensitive to the change in T_{ad} than others. Figure 4(a) also indicates that for the selected panels made of monolithic SiC plate(s) and having the same areal density, an increase in the adhesive layer number from one to three results in a reduction of predicted V_{bl} ranging from 33 to 39%. To investigate the effect of ceramic type on the sensitivity of predicted V_{bl} to T_{ad}, the ceramic material of Al_2O_3 is used to replace the SiC in the panels made of triple-layer monolithic ceramic plates and those composed of triple-layer ceramic tablets/resin, respectively. Their corresponding variations of the predicted V_{bl} with T_{ad} were plotted in

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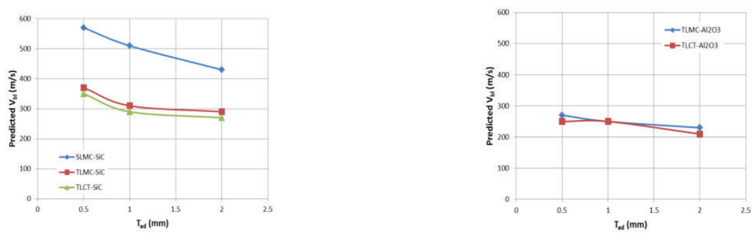
Fig. 4(b). It is noted that for the Al_2O_3 panels considered, an increase in T_{ad} results in a slight reduction or remain unchanged in the predicted V_{bl}. A comparison of the variations between Fig. 4(a) and (b) indicates that for the cases considered, the predicted V_{bl} for the panels made of SiC is more sensitive to the change in T_{ad} compared to those made of Al_2O_3. In addition, it was found in Fig. 4 that for the panels having strike face made of SiC or Al_2O_3, replacement of strike face made of triple-layer monolithic ceramic plates with that composed of triple-layer ceramic tablets/resin leads to a slight decrease or remain unchanged in the predicted V_{bl}. This implies that for the strike face plate considered, replacement of the multi-layer monolithic ceramic plates with multi-layer ceramic tablets could improve flexibility of armour panels without significant reduction in V_{bl}. Under an impact of a 30 caliber FSP having an initial velocity of 200 m/s, the predicted MAXBFD between the panels is slightly affected by the T_{ad} and adhesive interlayer number. For example, the different between the selected panels having T_{ad}=0.5 mm and T_{ad}=2 mm ranges from 0.12 mm to 0.35mm, and those between the selected panels having adhesive interlayer number of 1 and 3 ranges from 0.42 mm to 1.12mm.



(a) For the case of SiC (b) For the case of Al_2O_3

Figure 4. Variations of predicted V_{bl} vs T_{ad} for the selected panels having strike face plates made of SiC or Al_2O_3

Figure 5 illustrates the damage patterns and areas at the time of 0.2 ms for the selected SLMC-SiC, TLMC-SiC and TLCT-SiC having T_{ad} of 0.5 mm or 2 mm respectively. The initial impact velocity of the FSP was chosen to be 200 m/s. It is noted that for the panels considered, damages in the ceramic strike face plates are localized around the projectile impact zone. This is consistent with the results obtained by Tasdemirci et al [4] (i.e., damage in the ceramic layer was highly localized around the projectile impact zone for without interlayer and rubber interlayer configuration). Figure 5 also indicates that the damages in the ceramic strike plates are greater in the panels having T_{ad} of 2 mm compared to those having T_{ad} of 0.5 mm. This finding is similar to that reported by Seifert et al [7] (i.e., the damage behaviour of the ceramic/metal composites can be controlled by the adhesive thickness.) and the numerical result from Zaera et al [1] (i.e., the thicker the adhesive layer the greater the damage to the ceramic).

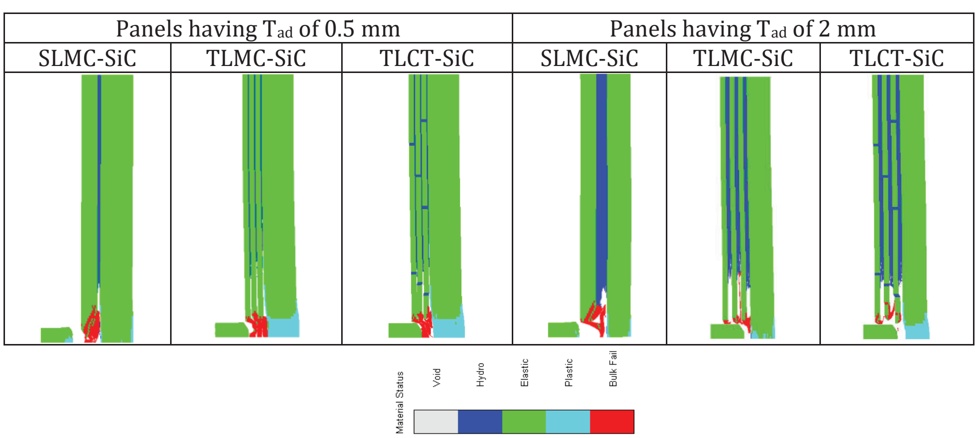


Figure 5. Damage patterns and areas for the selected panels having different adhesive interlayer thickness/number under an impact of 30 caliber having the initial velocity of 200 m/s (at t = 0.2 ms)

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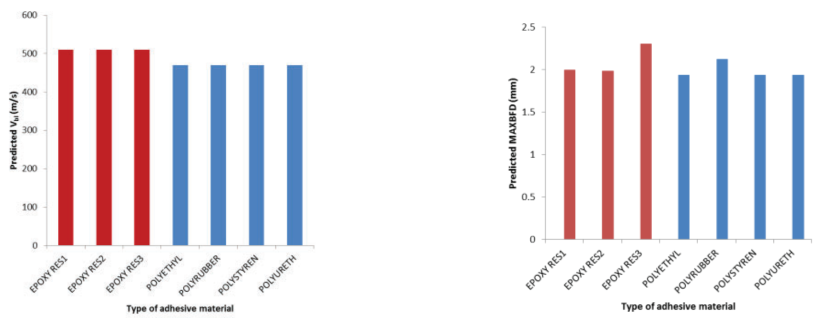
Figure 6 illustrates a comparison of the predicted V_{bl} and MAXBFD for the panels, which were made of single-layer monolithic SiC plate and KFRC backing plate as shown in Fig. 1(a), but bonded with seven different types of adhesive materials respectively, including EPOXY RES1, EPOXY RES2, EPOXY RES3, POLYETHYL, POLYRUBBER, POLYSTYREN and POLYURETH. It is noted from Fig.6(a) that for the epoxy resins considered, changes in parameters c_0 and s required using the Mie Gruneisen EOS or changes in the values of shear modulus, Yield Stress and Hydro tensile limit do not affect the predicted V_{bl}. The predicted values of V_{bl} for panels bonded with POLYETHYL, POLYRUBBER, POLYSTYREN and POLYURETH are the same. However, the predicted V_{bl} for the panels bonded with epoxy resin is 8.51% higher than those bonded with POLYETHYL, POLYRUBBER, POLYSTYREN and POLYURETH, respectively. The predicted values of MAXBFD for the selected panels, which are subjected to an impact from a FSP having initial velocity of 300 m/s, are shown in Figure 6(b). It is interesting to note that the predicted MAXBFD for the panel bonded with EPOXY RES3 is higher than others. However, for the panels considered, the difference of the predicted MAXBFD between them ranges from 0.003 mm to 0.37 mm, which are not significant and can be ignored.



(a) Predicted V_{bl} (b) Predicted MAXBFD

Figure 6. Predicted values of V_{bl} and MAXBFD for the selected SLMC-SiC bonded with different types of adhesive materials

Figure 7 demonstrates the damage patterns and areas for the selected SLMC-SiC bonded with different types of adhesive materials and subjected to an impact of a FSP having initial velocity of 300 m/s. It is found that the debonding damage between the ceramic strike face plate and KFRC backing plate, which could result in the degradation in overall strength of the panel, is significant for the panels except for that bonded with EPOXY RES3. This implies that changes in the values of shear modulus, Yield Stress and Hydro tensile limit may significantly affect the debonding damage between the ceramic strike face plate and Kevlar composite backing plate.

Types of adhesive materials						
EPOXY RES1	EPOXY RES2	EPOXY RES3	POLYETHYL	POLYRUBBER	POLYSTYREN	POLYURETH

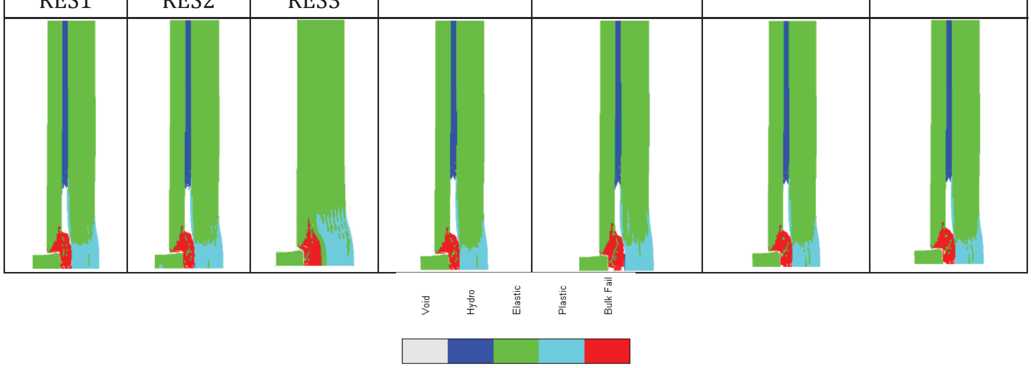


Figure 7. Damage patterns for the panels bonded with different types of adhesive materials under an impact of a 30 caliber FSP having initial velocity of 300 m/s (at t=0.2 ms)

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For the panels shown in Fig.2, it is noted from the numerical study that the predicted V_{bl} is not affected by the adhesive layer shapes, whereas the corresponding predicted values of MAXBFD, which are shown in Fig. 8, are slightly sensitive to the change in the adhesive interlayer shapes. The difference of the predicted MAXBFD between the panels ranges from 0.07 mm to 0.86 mm. A comparison of the damage patterns and areas for the panels is illustrated in Fig. 9. It is interesting to note that for the cases considered, the debonding damages generally occur in flat adhesive interlayers. There is almost not debonding damage in the waving adhesive interlayers. This implies that replacement of flat adhesive layer with waving layer in body armour may lead to improve the overall strength of the armour panels subjected to FSP impact.

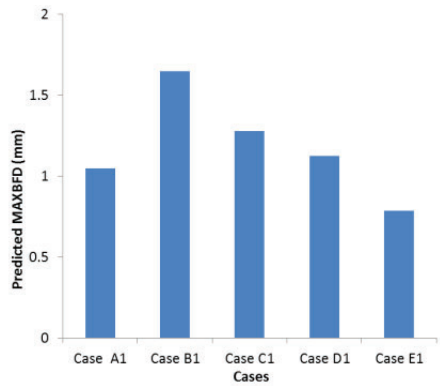

Figure 8. Predicted values of MAXBFD for the panels having different adhesive interlayer shapes under an impact of a 30 caliber FSP having initial velocity of 200 m/s. (at t = 0.2 ms)

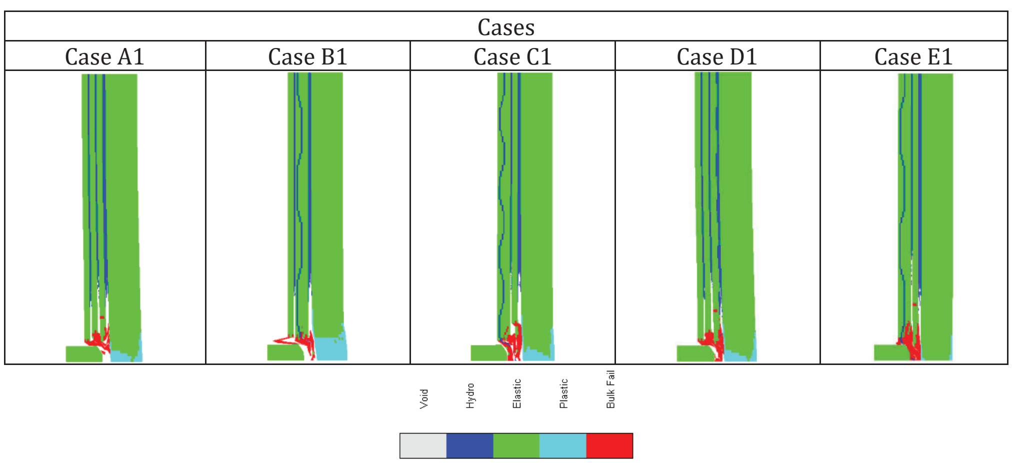

Figure 9. Damage patterns and areas for the selected TLMC-SiC having different adhesive interlayer shapes and under an impact of a 30 caliber FSP having initial velocity of 200 m/s (at t = 0.2 ms).

The predicted values of V_{bl} and MAXBFD for the selected panels, which have different SiC tablet patterns (i.e., different sizes and locations of SiC tablets) as shown in Fig. 3, are illustrated in Fig. 10. It is noted from Fig. 10(a) that for the panels considered, the percentage difference of the predicted V_{bl} between the panels ranges from 0 to 12.12%. This implies that optimal selection of the SiC tablet size and location may improve the ballistic performance of body armour composed of ceramic tablets. Figure 10(b) shows that the predicted values of MAXBFD for the panels considered, which are subjected to an impact of the FSP having initial velocity of 200 m/s, are slightly affected by the tablet pattern. The difference of the predicted MAXBFD between the selected panels ranges from 0.02 mm to 0.54 mm, which are not significant and can be ignored.

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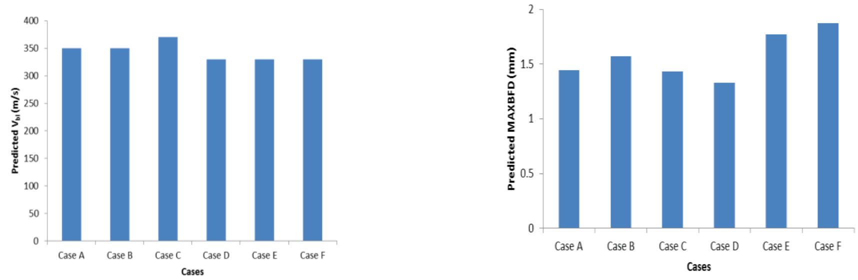

(a) Predicted V_{bl} (b) Predicted MAXBFD

Figure 10. Predicted values of V_{bl} and MAXBFD for the panels having different tablet patterns

Figure 11 illustrates the damage patterns and areas for the panels with different SiC tablet patterns shown in Fig.3. It is noted that for the cases considered, the damage patterns and areas are affected by the tablet pattern. Hence, optimal selected tablet size and location could improve the overall strength of the armour panels subjected to a FSP impact.

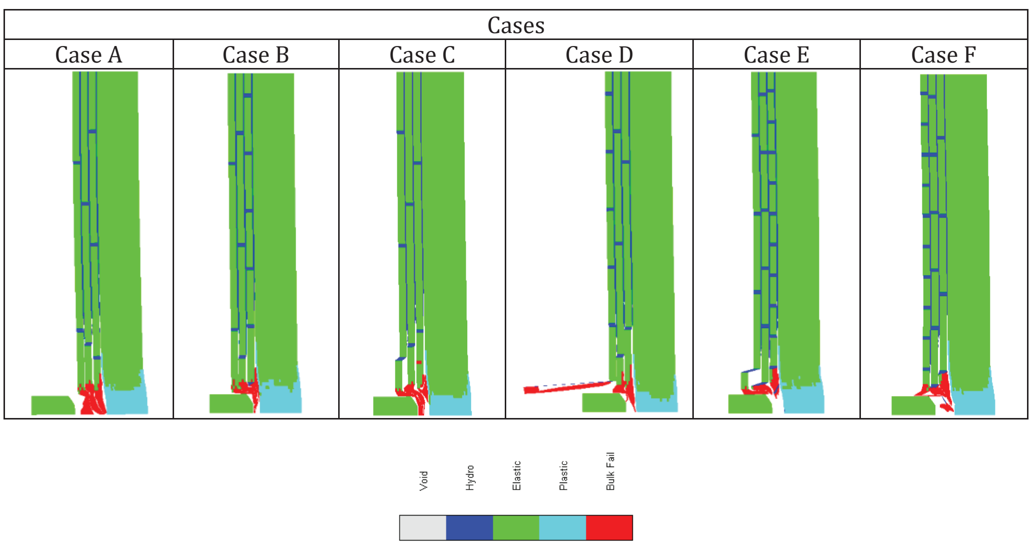

Figure 11. Damage patterns and areas for the panels having different tablet patterns and under an impact of a 30 caliber FSP having initial velocity of 200 m/s (at t=0.2 ms)

Figure 12 plots the variations of the predicted V_{bl} with the size of cohesion between the adjacent tables (i.e., T_c in Fig. 1(c)). It is noted that for the panels having T_{ad} of 0.5 mm, the predicted V_{bl} remains unchanged when T_c increases, whereas for those having T_{ad} of 2 mm, the predicted V_{bl} decreases slightly with an increase in T_c. This indicates that the predicted V_{bl} is more sensitive to T_c for the panels having higher values of T_{ad} compared to those having lower values of T_{ad}. For the panels impacted by a FSP having initial velocity of 200 m/s, the effect of T_c on the predicted MAXBFD is not significant. For example, for the panels having T_{ad} of 0.5 mm, the predicted MAXBFD is almost remain unchanged, while for those having T_{ad} of 2 mm, the predicted MAXBFD slightly increases as T_c increases. The difference of the predicted MAXBFD between panels is less than 0.45 mm, which is insignificant and can be ignored. A comparison of the damages between the panels having T_c=0.5 mm and T_c=1.5 mm for the case of T_{ad} = 0.5 mm or T_{ad} = 2 mm is illustrated in Fig. 13 for the epoxy-filled panels. It is noted that for the cases considered, the effect of T_c on the damage is not significant.

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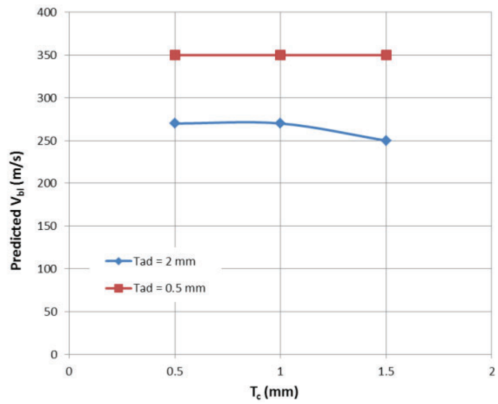

Figure 12. Variations of predicted V_{bl} vs T_c for the selected panels

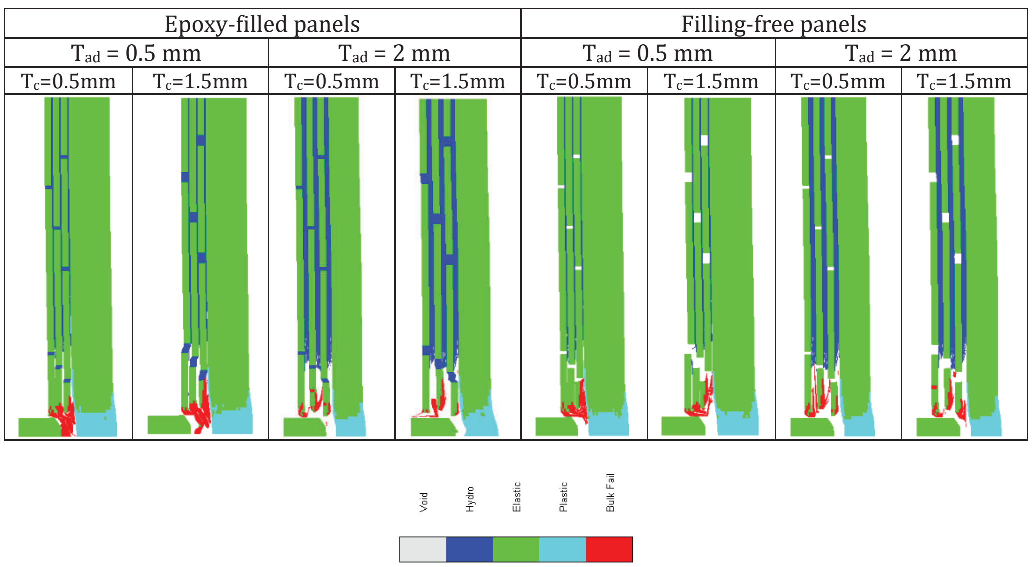

Figure 13. Damage patterns and areas for the selected panels filled with and without epoxy resin between the adjacent tablets under an impact of a FSP having initial velocity of 200 m/s (at t=0.2 ms).

In order to compare the ballistic protection performances and damages of ceramic composite armour panels with and without filling materials between the adjacent tablets, four typical TLST-SiC panels were considered and shown in Fig. 14 for the cases filled with or without epoxy resin, respectively. It is noted from the numerical results that for the cases considered, the difference of the predicted V_{bl} and MAXBFD between the panels filled with or without epoxy resin is not significant. For example, for the selected panels having T_{ad} of 0.5 mm, the differences of the predicted V_{bl} between the epoxy-filled and filling-free panels are zero, and those of the predicted MAXBFD between them range from 0 to 0.2 mm, which are not significant and can be ignored. However, the damage pattern and area in the panels are sensitive to the existence of cohesion, which are illustrated in Fig. 13. It is noted that the damage area in the filling-free panel is generally greater than that in the corresponding epoxy-filled panel.

Epoxy-filled panels	Filling-free panels

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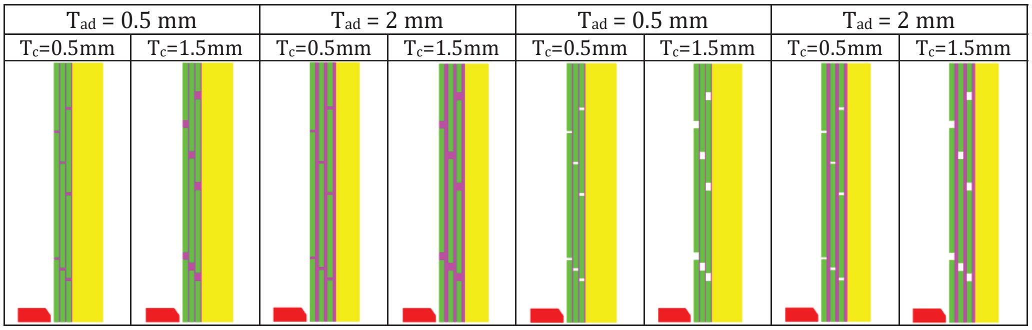

Figure 14. Schematics of the selected panels filled with and without epoxy resin

4. CONCLUSIONS

In this paper, the influences of adhesive geometry and material property on the ballistic protection performances and damages of the selected ceramic composite armour panels were studied by using the present finite element models, which were generated using the commercial finite element software ANSYS/AUTODYN. It was found from the corresponding numerical results that for the selected panels, an increase in total adhesive interlayer thickness (T_{ad}) or adhesive interlayer number results in a decrease in the predicted ballistic limit velocity (V_{bl}). The sensitivity of the predicted V_{bl} to T_{ad} is affected by the type of ceramic used for the strike face plate. The predicted V_{bl} for the panels bonded using epoxy resin is higher than those boned using POLYETHYL, POLYRUBBER, POLYSTYREN and POLYURETH. Also, the predicted V_{bl} is slightly affected by the change in the tablet pattern, but it is not highly sensitive to the change in the adhesive interlayer shape and the size of the cohesion between adjacent tablets. For the panels considered, the predicted MAXBFD is not significantly affected by the adhesive interlayer thickness, number, shape, material type and the size of cohesion between adjacent tablets. The numerical study also shows that for the cases considered, the difference of the predicted V_{bl} and MAXBFD between the panels filled with or without epoxy resin is not significant. However, the damage patterns and areas are generally affected by the adhesive interlayer thickness, number, shape, material type and the size of cohesion between adjacent tablets. The damage area in the filling-free panel is generally larger than that in the epoxy-filled panel. Also, it is interesting to note that replacement of flat adhesive layer with waving layer in body armour may lead to improve the overall strength of the armour panels subjected to FSP impact.

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