Comparison of Polyurethane and Epoxy Adhesive High Strain Rate Performance Using Cohesive Zone Model

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1 Summary

It is known that the ballistic performance of ceramic composite personnel armour is highly dependent on the thickness of ceramic and backing material. Recent studies have begun focusing on the effect of adhesive bonding between the ceramic and the backing plate, because failure of the adhesive layer can cause separation between the ceramic and backing. This debonding between substrates causes the ceramic to underperform by shattering early due to an imperfect transmission of the stress wave to the backing material. Given that the adhesive plays such an important role in armour, it is important to better understand the underlying physics.

The authors at National Research Council Canada (NRC) have an ongoing simulation activity to investigate the behaviour of polyurethane and epoxy adhesives as a bonding material using cohesive zone elements (CZE). The objective is to assess the ability of CZE to replicate the adhesive's response and compare with experimental data. Polyurethane is known to have a high strain to failure ratio, ranging between 100-350%, however its tensile strength is approximately ~2.0-5.0MPa. Epoxy on the other hand while brittle in nature with a strain to failure ratio of 2%, has a high tensile strength of approximately 50MPa. There is concern that the ability of the adhesive layer to endure large amounts of strain and its stiffness would negatively impact the damage experienced by the ceramic. Another important factor is the acoustic impedance of the adhesive which determines the magnitude of the stress wave transmitted from the ceramic to the backing material. The larger the impedance difference between the ceramic and adhesive, the lower the magnitude of the stress wave transmitted into the backing and greater the stress wave transmitted back into the ceramic at the bond line interface. Given that ceramics fail in tension, a larger tensile wave is expected to cause more damage in the ceramic.

2 Introduction

Modern personnel armour system is complex in nature consisting of numerous sublayers of material each with a specific role in mitigating ballistic impacts (high strain rate ~10,000s^{-1}). Typically, at the component level, personnel armour system consists of the following subsections [1]:

i) A frabic material whose main role is to protect the underlying ceramic layer from incidental damage and/or environmental damage;
ii) A ceramic layer, whose primary function is to erode and/or break up the projectile upon impact;
iii) A thin adhesive layer which bonds the ceramic tiles to the underlying back-up armour plates. This component is the focus of the present study;
iv) A backing plate whose main role is to limit deflection and absorb the kinetic energy of the projectile.
v) A spall layer whose main function is to capture fragments/debris;
vi) Secondary adhesive's which bonds section i with ii, also, iv with v, will not be considered.

A schematic detailing the above components is shown in Figure 1. When armour-piercing projectiles impact onto the composite armour system, the projectiles are first shattered or blunted by the ceramic causing the load to spread over a larger ductile area. The backing metallic plate then absorbs the remaining kinetic energy of the projectile through structural deformation. It is known that the ballistic performance of ceramic composite armour is highly dependent on the thickness of ceramic and backing material, however recent studies have begun focusing on the effect of adhesive bonding between the ceramic and the backing plate. Failure of any layer in the armour system inherently causes a loss in performance of the overall component. In this case failure of the adhesive layer can cause separation between the ceramic and backing, such debonding between substrates cause the ceramic to underperform by shattering early due to an imperfect transmission of the stress wave to the backing material. [1-5]. Given that the adhesive plays such an important role in personnel armour system, it is important to understand better the underlying physics, this paper summarizes both experimental and modelling work in the area of ceramic-based armour.

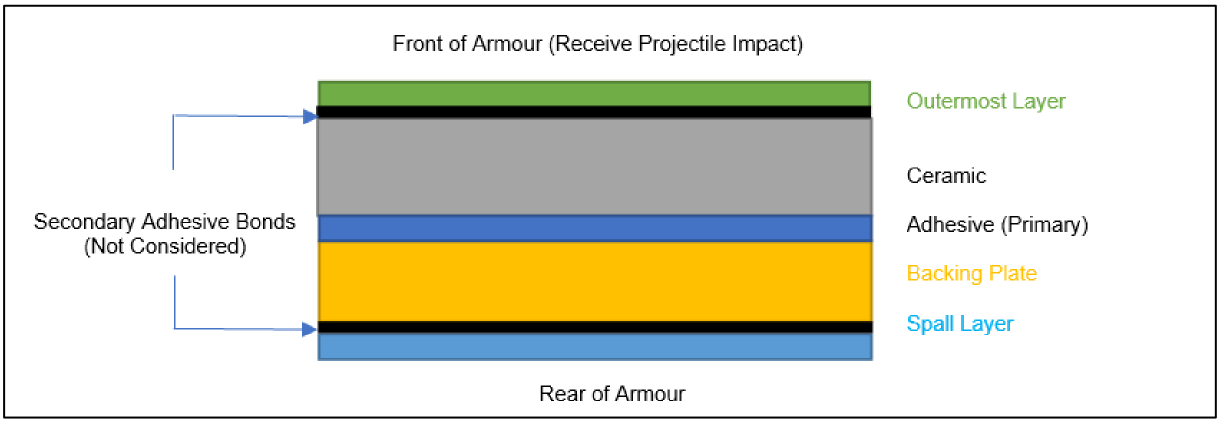


Fig.1: Schematic of Modern Personnel Armour System [1]

3 Experimental

Two classes of commonly used adhesive systems were considered: an epoxy exhibiting high stiffness but low strain to failure and a polyurethane with low stiffness but high strain to failure. This study focuses on the influence of two key adhesive properties, stiffness and elongation to failure, on overall ballistic performance.

The material properties of the two adhesives are listed in Table 1. The tensile strengths of the epoxy and TPU are relatively similar. However, as compared to TPU, the epoxy has much higher Young's modulus, but much reduced fracture strain. If the epoxy represents one end of the spectrum of adhesives, with high stiffness and low elongation at failure (or fracture strain), the TPU represents the other end of adhesives, with low stiffness and superb elongation at failure.

Adhesive	Modulus (MPa)	Tensile Strength (MPa)	Fracture Strain (%)	Sound Velocity (mm/µs)	Density (g/cm^3)
Epoxy EA9460	2758.0	30.3	3.5	2.56	1.33
Thermoplastic Polyurethane (TPU)	10.9	37.9	500	1.82	1.07

Table 1: Properties of Adhesives for Ballistic Panels

A surrogate target was built with ceramic tiles adhesively bonded onto a (or 12”x12”) Kevlar backing as shown in Figure 2 [6]. Ballistic test panels, each consisting of five to six panels, were bonded with the adhesives, namely epoxy and TPU. The bondline for all ballistic panels bonded with epoxy and TPU was maintained in the range of 0.5 to 1 mm. Ballistic tests were performed to evaluate and select the most promising adhesion methods, with a custom developed multi-hit method The bonded panel assemblies were clamped to a steel backing plate to resemble typical add-on armour that is bolted on the steel hull of a vehicle. Each armour panel was impacted three times with a 0.30 caliber bullet at projectile velocity above 900 m/s, within a range of ± 15 m/s. Each panel were subjected to three shots, the first two shots were located at the center of specific tiles, and the third shot was located at specific triple point. All tests were conducted at the room temperature ambient condition.

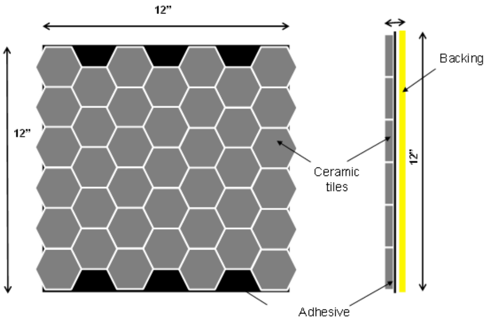
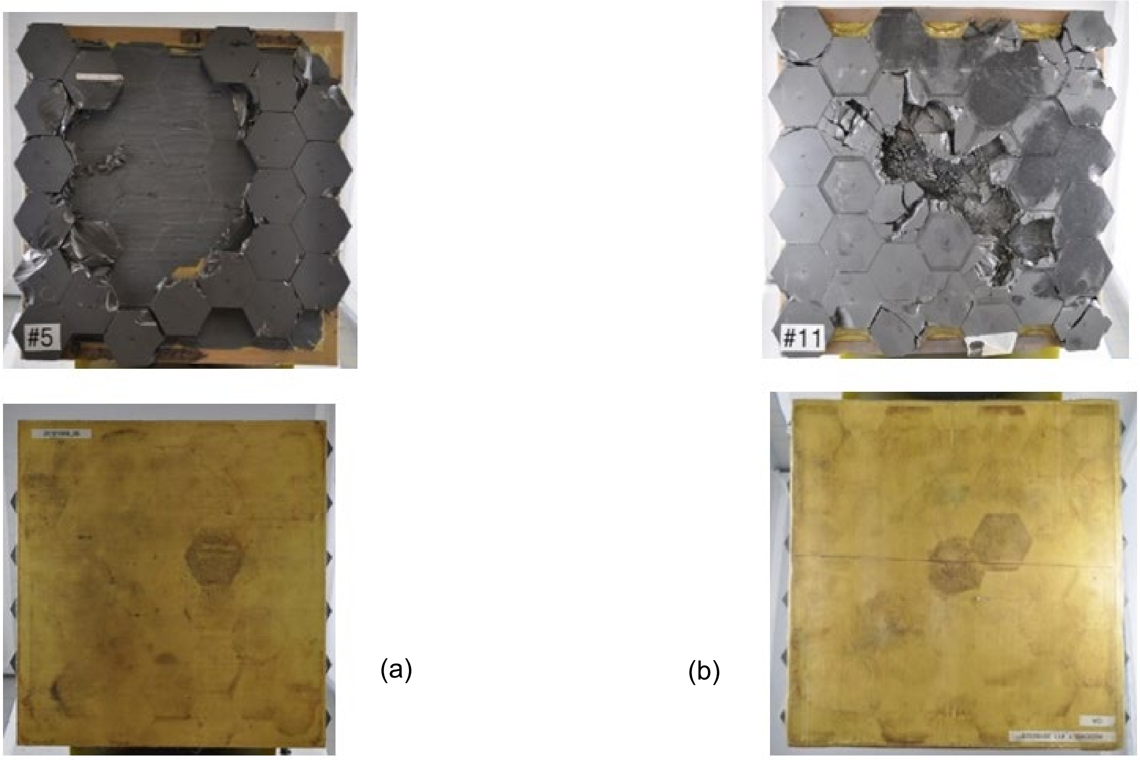


Fig.2: Ceramic-Kevlar Composite Panel Clamped with a Steel Backing Showing the Three Impact Locations for Multi-hit Ballistic Response Testing

The panels bonded with the stiff epoxy (3.5% elongation at break) showed poor multi-hit ballistic response. As shown in Figure 3a, after the first shot the damage area of the ceramic was so extensive that there were no ceramic tiles left in the shooting zone. The same extensive damage from the first shot was observed on all other panels bonded with epoxy. Due to the missing ceramic tiles in the second and third shot locations, no further impacts were carried out on this group of panels. Any further impact on shot two and three locations would have led to penetration through the Kevlar backing due to missing ceramic tiles.

In comparison, the ballistic panels with the TPU adhesive with high elongation at break showed a marked enhancement of multi-hit capability. At the first and second shots, where the centres of the tiles were impacted, the damage was contained within these tiles themselves and the area away from the impact sites remained intact (see Figure 3b). The ballistic test results show that no penetration was found on any of the test panels

This testing showed that, in spite of the high stiffness of the epoxy, the observed large area of disbonded tiles was attributed to low strain to failure of the adhesive. This suggests that, among the adhesive properties, elongation of an adhesive plays a more important role to multi-hit capability than stiffness when it is used to bond rigid ceramic tiles to flexible backing Kevlar as in this study. TPU bonded ceramic/Al samples also exhibited better peel strength than the samples bonded with stiffer but more brittle epoxy adhesive.



(a) (b)

Fig.3: Images of the Front and Back Faces of Bonded Panel Assemblies after Ballistic Impacts

4 Cohesive Zone Model

This section details the material properties and parameters required to represent the epoxy adhesive numerically. The cohesive mixed mode elastoplastic was chosen as for this simulation, considering only peel tension, as a result it is not needed to derive the properties for the shear tension or the rate dependency of the material. In these conditions, only six parameters are needed in order to characterize the response of the adhesive material, see Table 2.

Parameter	Description	Unit	Value
Density	Density	kg/m^3	1078
EMOD	Elastic Modulus	MPa	823
GMOD	Shear Modulus	MPa	823
GIC_0	Energy Release Rate Tension	Pa × m	3334.08
T0	Yield Stress, Tension	MPa	41.00
FGI	Ratio of Plastic Energy to Total Energy	[-]	0.16

Table 2: Parameters needed for material cohesive mixed mode elastoplastic

Except from the density, which is obtain from the material data sheet provided by the manufacturer, all parameters are derived from the Force-Displacement (F-D) curve obtained from a tension test using the Rigid Double Cantilever Beam (RDCB) method set-up described by Cronin *et al* [7] Figure 4a. This set-up consists of two steel adherends bonded together by a layer of adhesive. The two adherends are pulled apart in tension while the F-D curve is extracted Figure 4b. From the results, the authors then derived the Traction Separation Law (TSL) for use in the cohesive mixed mode elastoplastic, Figure 4c.

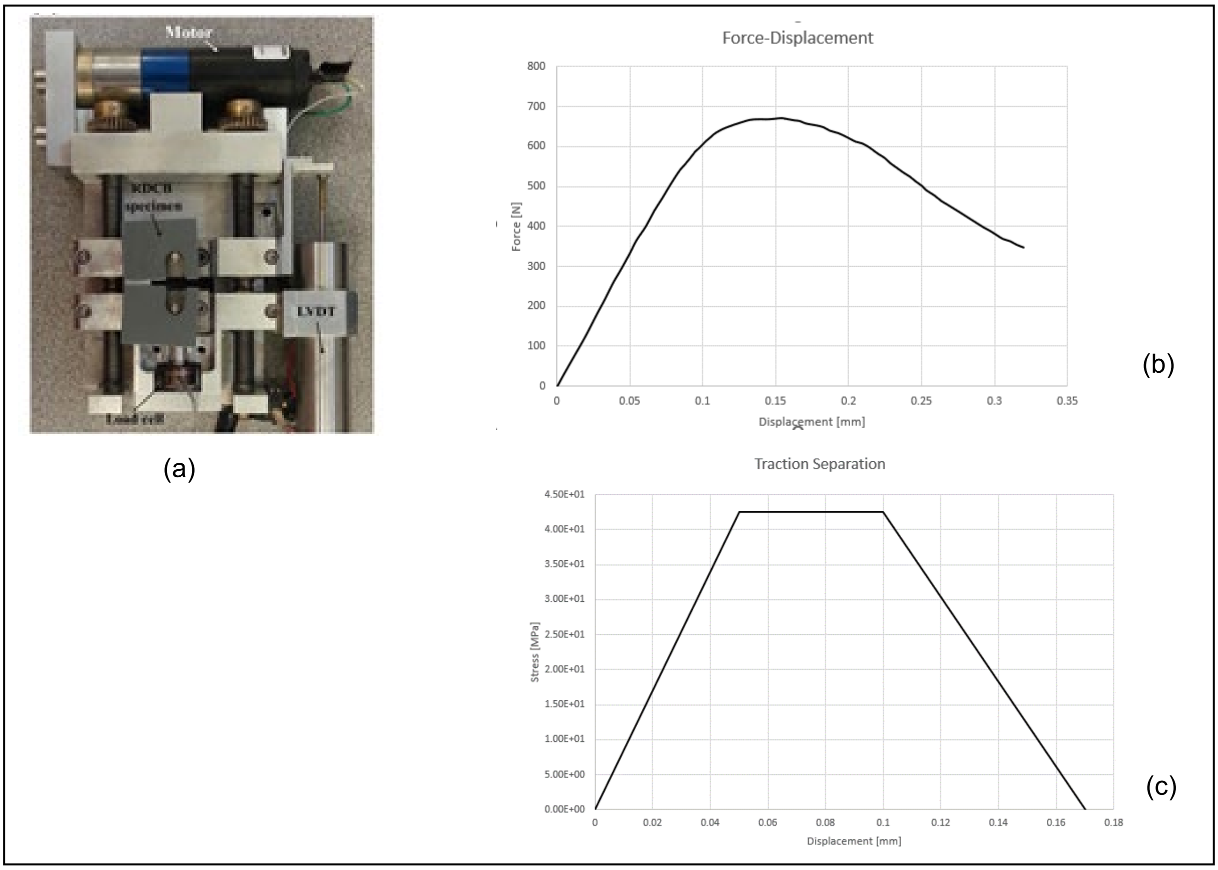


Fig.4: Description of the Rigid Double Cantilever Beam (RDCB) setup [6]

In this section, the parameters found in the Table 2 are applied to a numerical model to determine their accuracy by comparing the simulation F-D curve results with experimental F-D curve. For this simulation, the Rigid Double Cantilever Beam was recreated in LS-Dyna. The steel adherends, adhesive bond and pins have been created using the dimensions provided in the study. The numerical setup used for the simulation is shown on Figure 5.

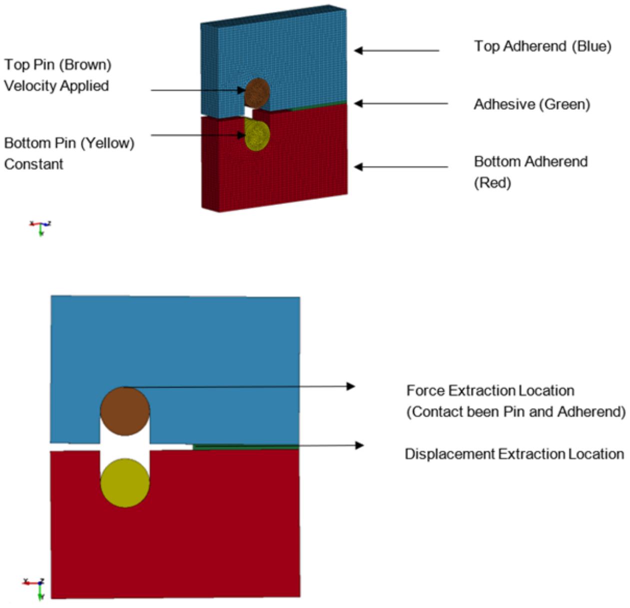


Fig.5: Rigid Double Cantilever Beam Simulation

The comparison of the F-D curve derived from the simulation is shown in Figure 6, where the comparison of results show a good agreement for the elastic portion between the simulation and experimental. The peak Force obtained from simulation is 11% higher than experimental one. This difference is attributed to the conversion formulas used to convert the F-D to the T-S graph. Some refinement is needed regarding deviation value for T10 and FG1 ratio which defines the yield stress and total energy.

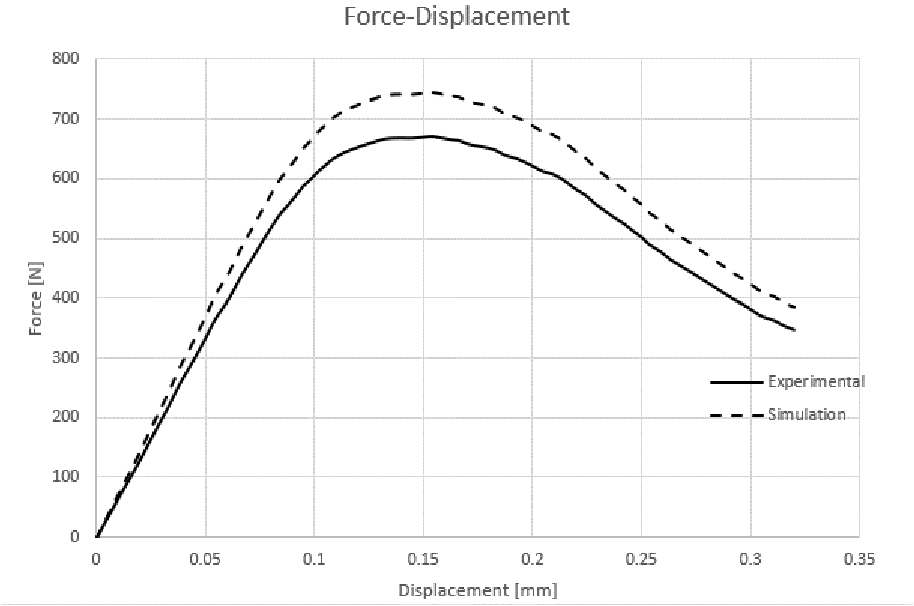


Fig.6: Comparison of Experimentl and Simulation Force - Displacement

5 Projectile

The projectile used in this simulation is 0.30 cal. 7.62mm APM2 with a tungenstun core. The dimensions of the projectile is taken from [8] and repeated in Table 3.

	Projectile			Core		
	Length (mm)	**Diameter(mm)**	**Weight (g)**	**Length (mm)**	**Diameter(mm)**	**Weight (g)**
0.30-Cal. APM2	35.3	7.85	10.8	27.4	0.24	5.3

Table 3: Dimensions of Bullet

The numerical bullet developed by the NRC is shown in Figure 7, with the shell and core modelled using tetra elements. The lead filler is ignored as it is only used as a stabilizer and does not impact penetration performance.

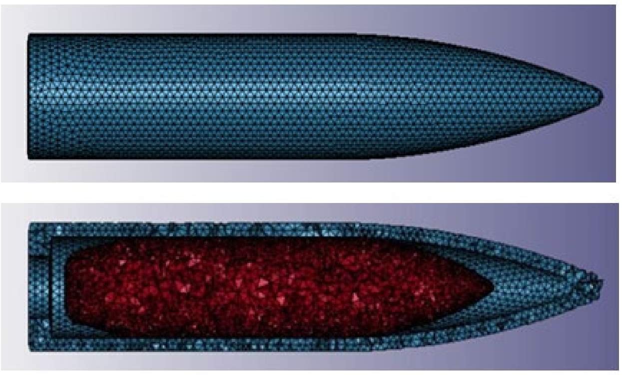
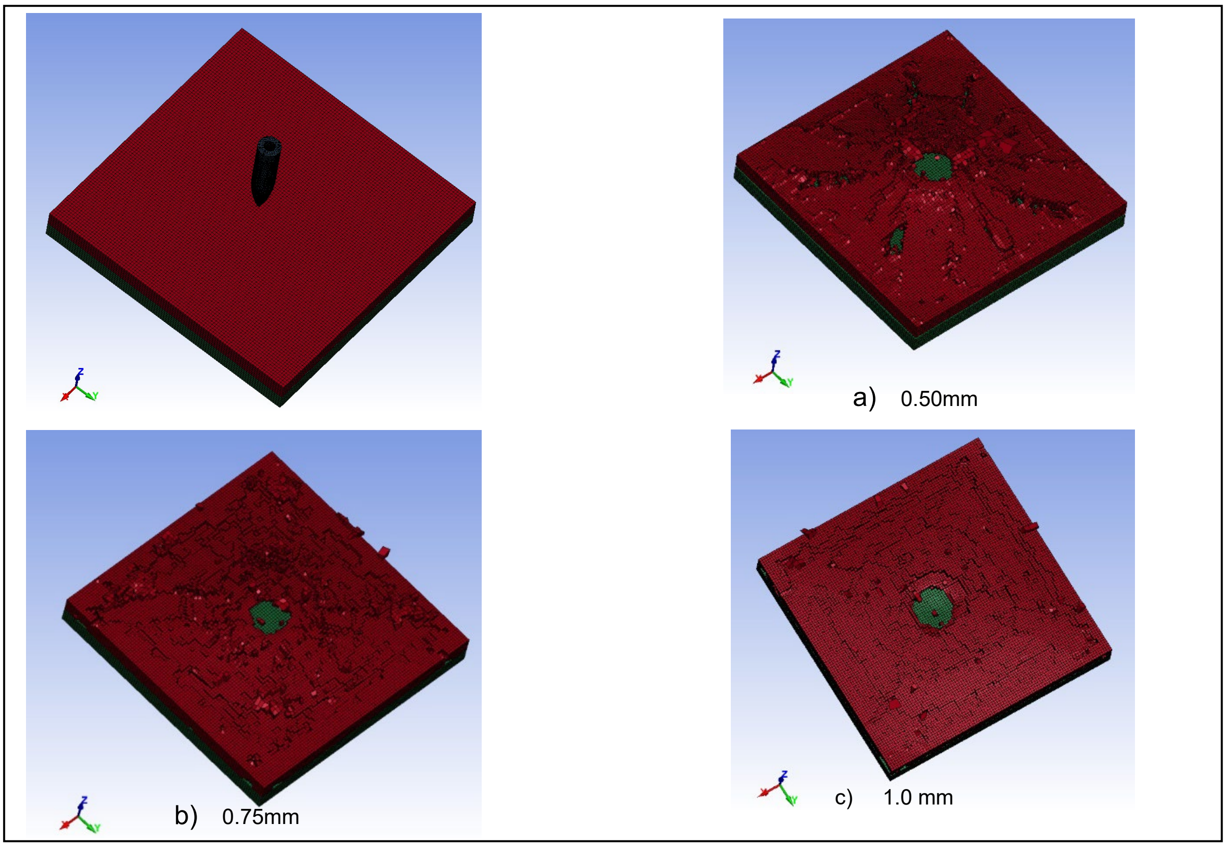


Fig.7: Numerical Model APM2 Projectile Bullet

6 Effect of Adhesive on Performance

An extension of the adhesive simulation detailed in section 3 & 4 was carried out by simulating three different adhesive bonding thickness (0.5, 0.75 and 1 mm). The object was to determine the effect if any of adhesive thickness on the transmission of the pressure wave through the ceramic, adhesive and backing. It is expected that a reduced, dispersed pressure wave, would result from a thicker adhesive along with a reduced deflection. Figure 8 shows the results, a varying degree of ceramic damage based on the adhesive thickness is noticeable. In the case of the 0.75 & 1.00 mm adhesive layer (Figure 8 b-c) the ceramic damage is diffused across over the ceramic spreading evenly across the face of the ceramic due to the pressure wave travelling into the steel plate and resulting in a lower stress wave being transmitted back into the ceramic. In the case of the 0.50 mm, Figure 8a the ceramic damage is localized to the center with radial damage lines reaching the plate edge, indicating am elevated level stress was transmitted back into the ceramic.


a) 0.50mm

b) 0.75mm

c) 1.0 mm

Fig.8: Comparison of Ceramic Damage between the Different Adhesive Thickness

7 Conclusion

Testing showed that, in spite of the high stiffness of the epoxy, the observed large area of disbonded tiles was attributed to low strain to failure of the adhesive. This suggests that among the adhesive properties, elongation of an adhesive plays a more important role to multi-hit capability than stiffness when it is used to bond rigid ceramic tiles.

To characterize the adhesive material properties used in the numerical simulation a Rigid Double Cantilever Beam (RDCB) method was used. This set-up consisted of two steel adherends bonded together by a layer of adhesive, the two adherends are pulled apart in tension while the Force-Displacement curve (F-D) is extracted. The F-D curve was then used to generate the Traction Separation Law, which detailed the adhesive material in the numerical simulation. The RDCB method was then used to regenerate the F-D curve, which showed an 11% difference between experimental and simulation.

A varying degree of ceramic damage based on the adhesive thickness was noticeable. In the case of the 0.75 & 1.00 mm adhesive layer the ceramic damage is diffused across over the ceramic spreading evenly across the face of the ceramic due to the pressure wave travelling into the steel plate and resulting in a lower stress wave being transmitted back into the ceramic. In the case of the 0.50 mm, Figure 8a the ceramic damage is localized to the center with radial damage lines reaching the plate edge, indicating am elevated level stress was transmitted back into the ceramic.

8 References

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