EFFECT OF THE BONDING LAYER ON BALLISTIC PERFORMANCE OF PERSONAL PROTECTIVE PLATE ARMOR

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Abstract
Wave propagation phenomena produced during a high velocity impact plays a fundamental role for designing personal protective armor. State of the art ballistic plates used in personal vests are composed of a hard ceramic surface bonded to a high strength ductile polymer layer. Typical bonding agents include either high performance adhesives or synthetic resins that, depending on the ceramic – polymer composition, have a particular thickness. Recent scientific literature has shown that there exists a markedly influence of both the type of bonding agent, and its thickness, on the ballistic performance of hybrid armors, which may be explained by the acoustic impedance mismatch between plate materials. This paper reports on a novel simulation parametric study, validated by ballistic experiments, which shows that it is possible to tune appropriately both the acoustic impedance and thickness of a bonding agent in order to increase the level or protection of personal protective armor against multiple impacts. The parametric study took into account the effect of three types of bonding agent (epoxy, polyurethane and EVA-polyethylene) in different thicknesses (0.1mm to 1mm), on the ballistic performance of a silicon carbide (SiC)-aramid armored plate against a 7.62mm AP ammunition projectile. Simulations were performed in ANSYS AUTODYN 2D, using a finite element (FE) – smoothed particle hydrodynamics (SPH) coupling approach. This study was successfully compared against ballistic experiments on armored plates using EVA-polyethylene bases coupling agent (thicknesses of 01mm, 0.5mm and 1mm).

1. Introduction
Personal protective armors are used to provide protection against penetrating projectiles and fragments from blast waves. Armor inserts are designed according to the body part to be protected in order to offer the best ballistic protection. For the upper torso, multiple layers of woven fibers with high tensile strength are commonly used. For example, para-aramids (Kevlar and Twaron) or ultra high molecular weight polyethylenes UHMWPE (Dyneema and Spectra) [1]. However, projectiles composed by a hard core, as AP ammunitions, are unlikely to be defeated by textile armor; thus, a hard strike face is necessary to break up or distort the projectile. Additionally, it is essential reach a low weight in the armor to obtain portability and comply with ergonomic aspects. Then, advanced ceramics have been selected for designing these kind of armors as they offers hardness and low weight; for example, alumina, silicon carbide (SiC) and boron carbide (B_4C). The material combination of these armors is known as ceramic composite material [2,3].

When a high-energy AP ammunition impacts a ceramic composite armor, the layer erodes and breaks the projectile; furthermore, the shock pressure of the impact fractures the ceramic with a conical pattern distributing the residual energy over a much larger area on the backing composite; thus, the composite backing plate deforms to absorb the remaining kinetic energy of the projectile, stopping fragments and the projectile itself. The composite backing, which is composed of layers of ballistic fibers, has a high specific strength and a high modulus making the material difficult to break and allowing a high dissipation of energy as a longitudinal stress wave.

Through the ceramic, the impact produces a compressive stress shock wave that reflects back as tensile wave when reaches the interface. The amplitude of the reflected tensile wave depends on the impedance mismatch (*I*) between the ceramic and the backing material [4,5]; however, the adhesive material between the ceramic and backing plate changes *I* at the interface; moreover, *I* can change with the thickness of the adhesive. The impedance mismatch between two materials is defined by Eq.(1), where Z is the acoustic impedance of the material defined by Ec.(2), and ρ and c are the density and sound speed of the material, respectively.

$$I = 1 - \frac{4Z_1Z_2}{\left(Z_1 + Z_2\right)^2} \qquad (1)$$

$$Z = \rho c \qquad (2)$$

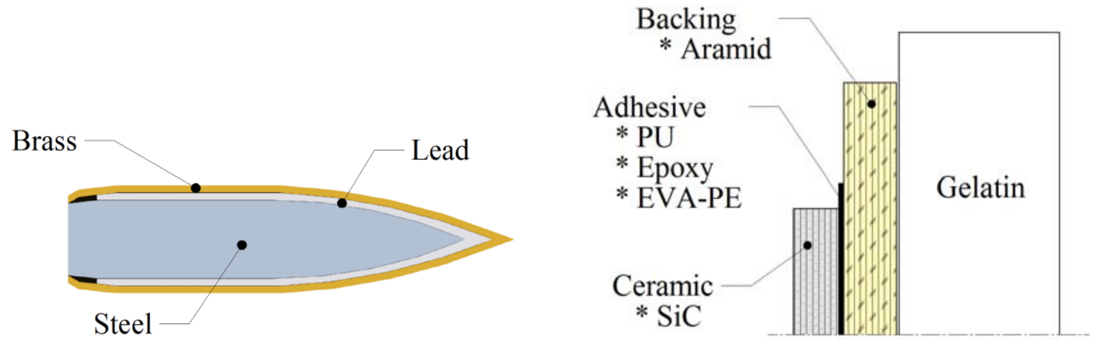
Most of the ceramic composite armor researchers have not taken into account the role of the adhesive layer because, experimentally, it is difficult to both control the adhesive thickness, and to measure the changes of stress waves inside the layer [6,7]. However, nowadays it is possible to use numerical modeling to understand the physical mechanism of ballistic events. Even though, there are many commercial software available to simulate ballistic events (AUTODYN, LS-Dyna, and others) all of them require the parameters of constitutive material relations in order to obtain an appropriate solution. Many researchers have focused in obtain a constitutive relations for different materials and also have proposed failure models; for example, the Jhonson-Holquist model [8] for ceramic materials and orthotropic model for fiber-reinforced composite materials [9].

The severe mesh tangling and distortions using grid based Lagrangian solvers is another problem associated to numerical modeling at large deformations and large strains. Sometimes, it involves energy problems in the simulations; therefore, it is necessary to use an erosion criterion in order to eliminate the distorted elements in the model. Nevertheless, an improper selection of an erosion criterion can change dramatically the results of a simulation. Thus, mesh-free computational methods have been used to avoid these issues in ballistic simulations; for example, smoothed-particle hydrodynamics (SPH) is one of these mesh-free methods.

In this paper a novel simulation parametric study was developed taking into account the effect of three types of bonding agent (epoxy, polyurethane and EVA-polyethylene), in different thicknesses, over a silicon carbide (SiC)-aramid plate, in order to assess the level or protection of a personal protective armor against multiple 7.62 AP ammunition impacts (Figure 1). In addition, ballistic experiments were carried out on armored plates using EVA-polyethylene based coupling agent (thicknesses of 0.1mm, 0.5mm and 1 mm).

2. Materials and computational models

Simulations were performed in ANSYS AUTODYN 2D, using a finite element (FE) – SPH coupling approach. Projectile and ceramic were modeled using SPH; whereas, adhesive and backing materials were modeled as lagrangian.



(a) (b)

Figure 1. (a) 7.62x51 AP projectile, and (b) SiC-Aramid armored plate.

Additionally, a representation of ballistic gelatin were located behind the armor in order to represent a typical ballistic test (0101.06 NIJ standard - Ballistic Resistance of Personal Body Armor- uses it to measure the level of trauma). According to the NIJ standard, the trauma must be less than 44mm in order to do not generate severe injuries to the torso. Material models used for simulations were taken of different references (see Table 1).
The 7.62mm AP ammunition modeled was the MKE reference at initial velocity of 845m/s. The projectile was composed of a hard steel core lead-filled body and a brass jacket (Figure 1a).
Ceramic composite armor consisted of a SiC layer of 9 mm and an aramid composite of 10.5 mm. A thin layer of adhesive agent was assembled between materials (see Figure 1b). Two types of bounding and a blended adhesive were used: epoxy, polyurethane (PU) and ethylene-vinyl-acetate and polyethylene (EVA-PE) blended adhesive. They were selected as they are commonly used in commercial armor applications. The thickness of adhesive layer was modified between 0.1mm and 1mm.
Comparisons between the different configurations were made using: (1) the projectiles´ desacceleration profiles, (2) the percentage of damage in the ceramic layer and (3) the reflected pressure waves at the interface. The percentage of damage in the ceramic layer was calculated comparing the initial and final area of the unbroken ceramic (see Figure 2). Pressure at the interface was measured placing gauges along the ceramic-adhesive interface. Values were averaged in order to obtain a single comparative value. Additionally, a gauge was positioned at the gelatin surface in order to measure the value of the pressure wave at this point.

	Material	**EOS**	**Constitutive**	**Failure criteria**	**Reference**
	Brass	Johnson-Cook	Johnson-Cook	Johnson-Cook	[10–13]
Projectile	Lead	Shock	Steinberg-Guinan	Plastic deform.	[10,11,14]
	Steel	Johnson-Cook	Johnson-Cook	Johnson-Cook	[11–13]
Ceramic	SiC	Polynomial	Johnson Holmquist	Johnson Holmquist	[15]
Backing	Aramid	Orthotropic	Orthotropic softening	-	[9]
	Gelatin	Shock	Von Misses	-	[16]
	Epoxy	Shock	Copper-Symonds	-	[6]
Adhesive	PU	Shock	Visco-elastic	-	[6]
	EVA-PE	Shock	Elastic	-	Measured

Table 1. Material models used for EOS and constitutive equations used to simulate materials.

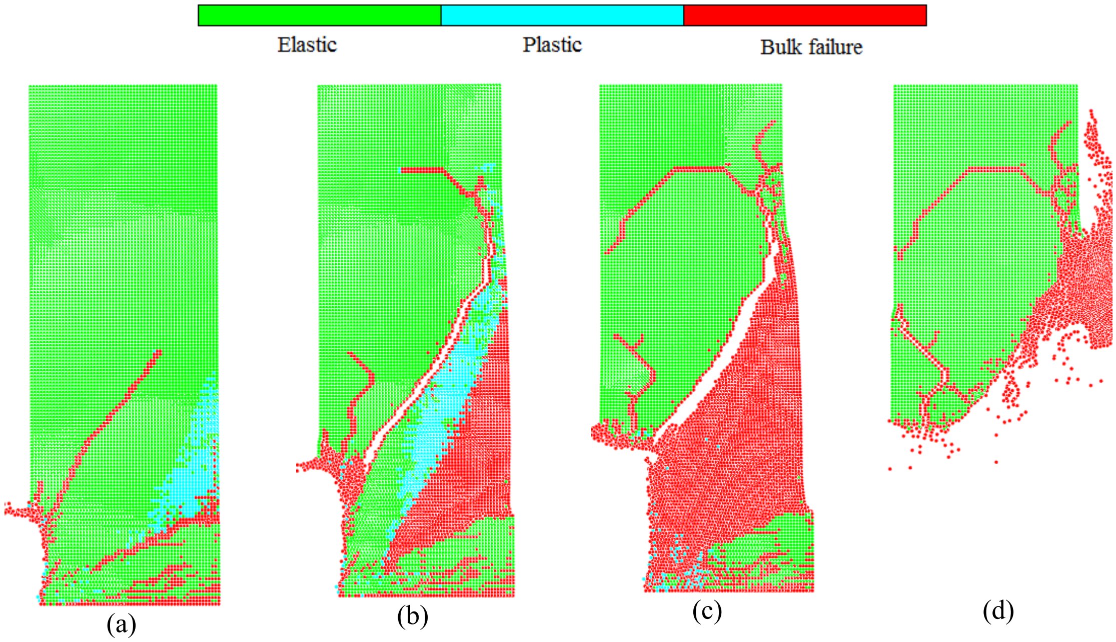


Figure 2. Evolution of damage on the ceramic during the impact penetration for armor using 0.5mm of PU adhesive: (a) 98.9µs, (b) 16.12µs, (c) 22.35µs, and (d) 100µs. Projectile and backing material are omitted.

Also, an experimental setup was performed using the same configuration of the simulation using the EVA-PE adhesive. SiC ceramic tiles of 50mm x 50mm x 9mm (provided by CeramTec) were used over 26 layers of hot pressed BK520 Twaron. The adhesive was provided as individual layers of 0.05mm (by Nolax) - making controllable its thickness. It was cured at 60ºC at low pressure. The ballistic tests were performed according to the NIJ 0101.06 Standard using the 7.62x51 AP ammunition fired at 857±18m/s.

3. Results and discussion

Figure 3 shows the total time required to stop the projectile for the different configurations (between 75µs and 82µs). There is not an evident pattern to relate the total time with the type of adhesive or the thickness.

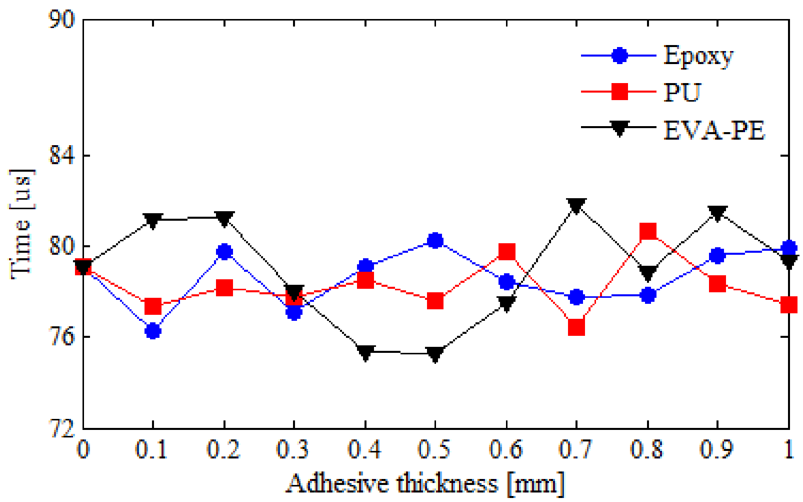


Figure 3. Comparison of the total time required to completely stop the projectile. Different types of adhesives and different thicknesses are compared.

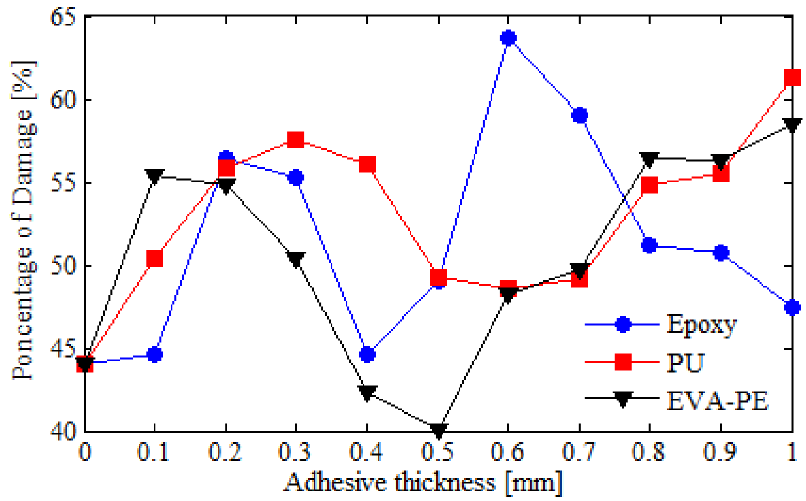


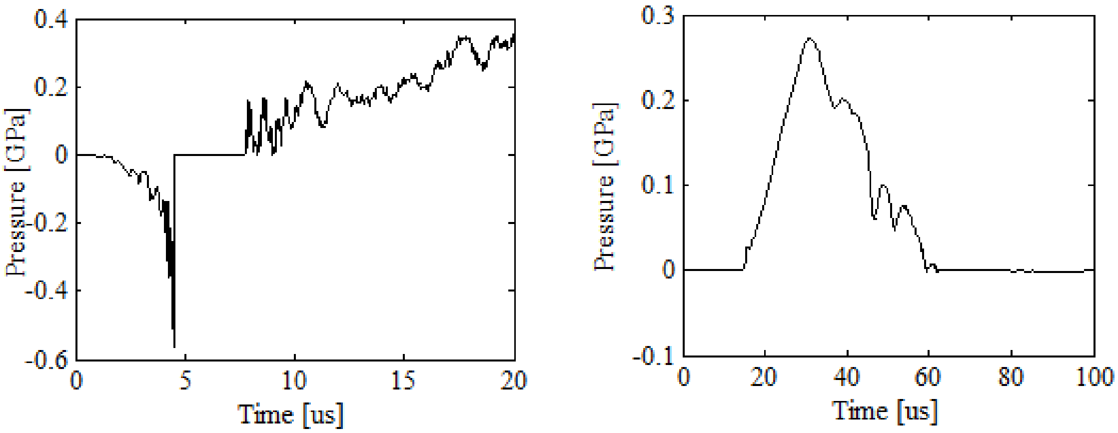
Figure 4. Comparison of percentage of damage on the ceramic at t= 100µs. Different types of adhesives and different thicknesses are compared.

Figure 4 shows the percentage of damage of the ceramic, measured at t = 100µs. After that time, ceramic does not suffer additional damage. This figure shows that the adhesive thickness influences the ceramic damage, and these results can be used to design ceramic composite armors for multi-impact applications because a lower damage on ceramic means a better protection for further impacts; for example, a adequate thickness of EVA-PE adhesive can reduce the damage on the ceramic of around 58% (1 mm) to 40% (0.5 mm).

Also, Figure 4 shows that ceramic with EVA-PE adhesive shows lower percentage of damage that others adhesives between 0.2 and 0.6 mm; whereas, ceramic with epoxy adhesive shows lower damage at thickness shorter than 0.2 mm and larger than 0.8 mm. In general, PU adhesive seems to show the worst behavior for multi-impact ballistic applications because it involves higher damage on the ceramic.

In order to understand damage on the ceramic, propagated tension waves were studied. Tension waves are important as ceramics are more susceptible to failure in tension. A common pressure profile at the ceramic-adhesive interface is shown in Figure 5a, where a high negative pressure (tension stress) is generated when the compression waves are reflected at the interface. The negative pressure was integrated until 2µs time in order to only take account the first reflected wave (after that time, the pressure is a mixture of different waves), and all integrated values along the ceramic-adhesive interface were averaged to obtain a single comparative value. These results are shown in the Figure 6 for the different configurations. This figure shows that the ceramic EVA-PE interface displays the lower negative pressure values; whereas, ceramic PU interface generates the higher ones. It means that PU adhesive generates higher tension waves on the ceramic; thus, a higher damage on it. However, due the initial part of the tension wave was only taken, the profile of the Figure 6 is not the same as the one shown in the Figure 4. For this reason, pressure at the backing gelatin was studied.

Figure 5b shows a common pressure profile on the front part of the gelatin material. This figure shows a pressure wave generated when the pressure waves of the impact reaches the backing material. The pressure profile was integrated until 30µs (results are shown in the Figure 7 for the different configurations). According to the impedance mismatch, it is better for the ceramic to transmit the pressure waves in order to not generate reflected tension stress; then, for a higher transmitted pressure, a lower reflected tension on the ceramic.



(a) (b)

Figure 5. Pressure profiles during the impact penetration for armor using 0.5 mm of EVA-PE adhesive: (a) gauge on the ceramic at the interface with adhesive, and (b) gauge on the gelatin at the interface with backing.

When Figure 4 and Figure 7 are compared, indicates that a higher pressure on the gelatin resulted in a low ceramic damage (lower tension stress); for example, the maximum pressure for the EVA-PE adhesive is reached at a thickness of 0.5 mm where the lower ceramic damage occurs. The same relation it is found for the Epoxy adhesive, where at a thickness of 0.4mm. Therefore, a close relation was found between the damage on the ceramic and the transmitted pressure on the backing gelatin, which can be used for designing an optimum ceramic composite armor for multi-impact applications.

Figure 8 shows the results of ballistic tests on the SiC-Aramid armors using EVA-PE adhesive. Resulting back face signatures (BFS)were 28 mm, 37 mm, and 32 mm for 0.1 mm, 0.5 mm and 1 mm of adhesive thicknesses, respectively. BFS are similar to those obtained by simulations (Figure 9). Additionally, it is shown that the impact only damaged the first layers of the Aramid composite material; whereas, the ceramic is totally destroyed.

4. Conclusions

A novel simulation parametric study was developed to take into account the effect of three types of bonding agent (epoxy, polyurethane and EVA-polyethylene) in different thicknesses on a SiC-Aramid plate.

Ceramic with EVA-PE adhesive shows a lower percentage of damage that others adhesives between 0.2 and 0.6 mm; whereas, ceramic with epoxy adhesive shows lower damage at thickness shorter than 0.2 mm and larger than 0.8 mm. In general, PU adhesive seems to show the worst behavior for multi-impact ballistic applications because it involves a higher damage on ceramic.

Additionally, a close relation was found between the damage on the ceramic and the transmitted pressure on the backing gelatin, which can be used for designing an optimum ceramic composite armor for multi-impact applications.

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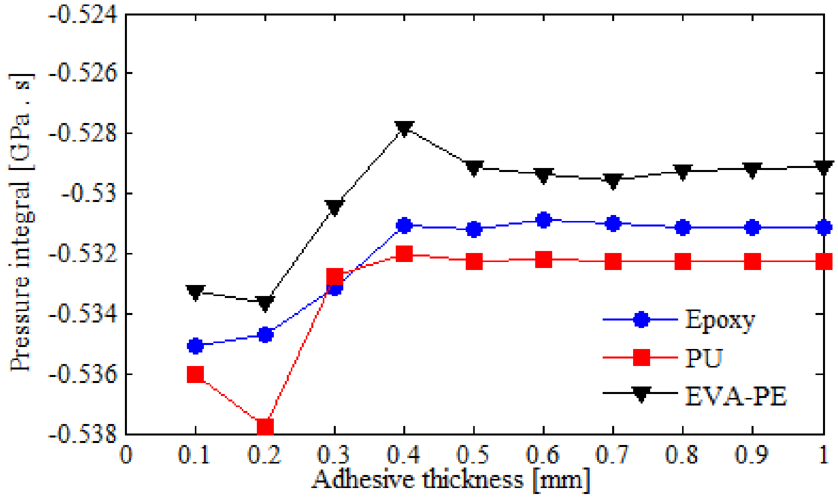


Figure 6. Integral of negative pressures until 2μs on the rear part of the ceramic. Different configurations are compared.

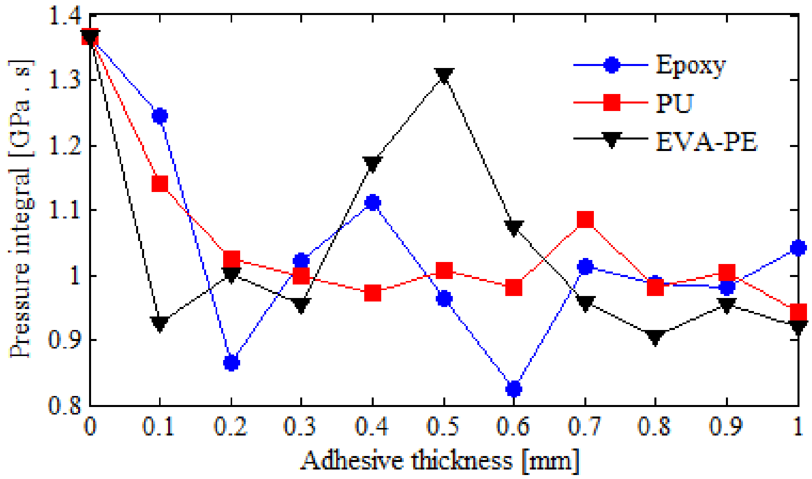
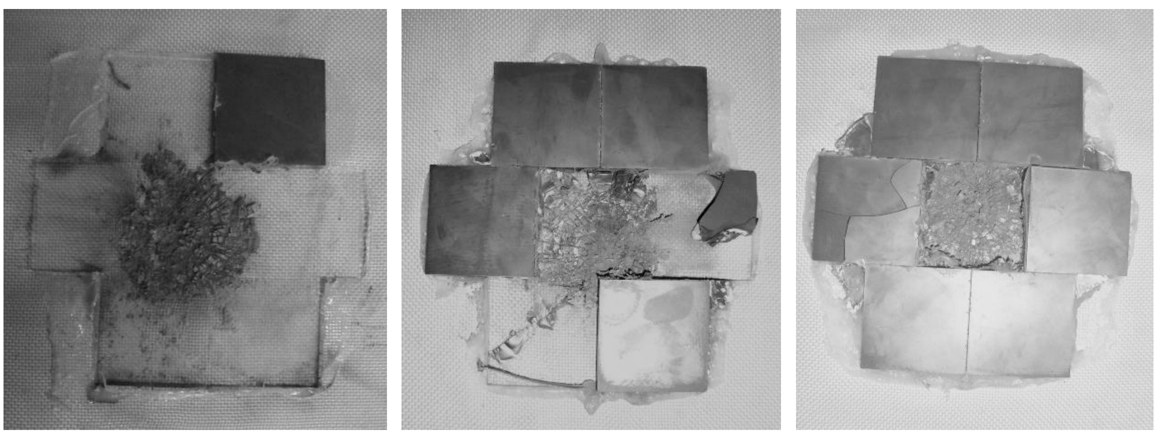


Figure 7. Integral of pressures until 30μs on the front part of the gelatin material. Different configurations are compared.



(a) (b) (c)

Figure 8. Result of ballistic test for the SiC-Aramid armors: (a) using 0.1mm EVA-PE adhesive, (b) using 0.5mm EVA-PE adhesive, and (c) using 1mm EVA-PE adhesive.

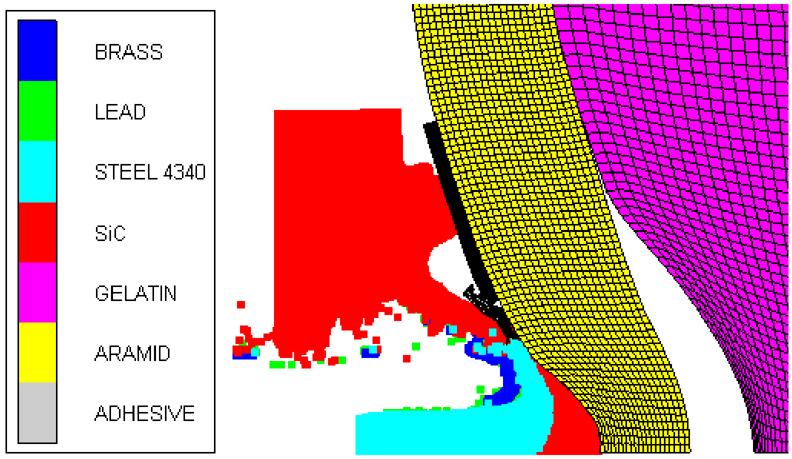


Figure 9. Final stage of simulation for SiC-Aramid armor with 1mm EVA-PE adhesive.

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