POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Finite Element Analysis of Ballistic Resistance Performance Degradation in Damaged Small Arms Protective Inserts

Laurea Magistrale in Mechanical Engineering - Ingegneria Meccanica

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1. Introduction

Modern personal ballistic protection systems, particularly Small Arms Protective Inserts (SAPIs), are designed to defeat small and medium caliber threats while maintaining low weight and high mobility. Current advanced composite armors rely on a multi-layer architecture composed of a hard ceramic strike face backed by a ductile composite laminate. This configuration ensures high energy absorption efficiency and favorable strength-to-weight ratio.

Despite their excellent nominal ballistic resistance, SAPIs are vulnerable to multiple ballistic hits or off-design events. Low-velocity impacts and improper handling can generate barely visible or completely hidden damage within the ceramic tile or the composite backing. Because ceramic materials exhibit complex brittle fracture mechanisms and stochastic crack propagation, evaluating the residual ballistic performance of a damaged SAPI remains an open and critical problem.

Current inspection procedures (e.g., radiographic techniques) allow damage detection but provide only qualitative assessment of residual protective performance. As a consequence, decision-making regarding armor replacement is often conservative, statistically weak, and economically inefficient.

The primary objective of this work is to develop and validate a high-fidelity finite element (FE) modeling framework capable of:

- Accurately reproducing the ballistic response of an undamaged ceramic composite SAPI
- Quantifying performance degradation due to prior ballistic impact
- Assessing the influence of a pre-existing through-thickness crack in the ceramic layer

The final goal is to provide a predictive numerical methodology that supports quantitative prognosis of damaged ballistic protections.

2. Numerical model description

The main reference to validate the numerical model proposed in this work is *"Numerical investigation of the high-velocity impact performance of body armor panels"* by J. Lin et al. [1]. In this article the authors have discussed a numerical model of a composite SAPI subjected to the ballistic impact of a 7.62 APM2 projectile, validating it with experimental ballistic tests.

The investigated SAPI configuration (showed in figure 1) consists of:

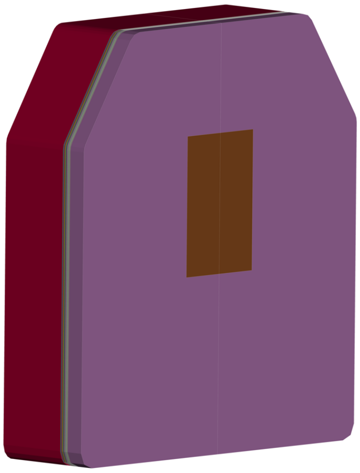

Figure 1: Finite element armor system model

- 12 mm Alumina (Al_2O_3) ceramic strike face
- 6.3 mm UHMWPE (Dyneema®) laminate backing
- 50 mm Roma Plastilina® No.1 clay block to evaluate Back Face Deformation (BFD), in compliance with NIJ Standard 0101.06 [2]

The assembly measures 250 mm in witdth and 300 mm in height. The 7.62 APM2 projectile (figure 2) is composed of an hardened steel core (red), a brass jacket (blue) and rear cap (yellow) and a lead filler (green).

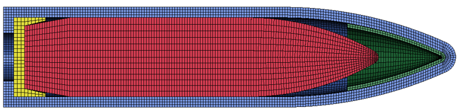

Figure 2: 7.62 APM2 projectile geometry and dimensions

The Alumina tile behavior is described using the Johnson–Holmquist II (JH-2) model [3], specifically developed for brittle materials under impact loading. This model is able to capture the characteristic damage phenomena in ceramics, such as shock wave propagation, radial cracking, conoid formation and comminution zone development.

The UHMWPE laminate is modeled using a global orthotropic formulation combined with the Tsai–Wu failure criterion to capture fiber tensile failure, matrix cracking and in-plane shear failure. Delamination is modeled with a layered strategy: the plies are meshed individually and bonded with a tiebreak contact.

The metallic projectile components and the plastilina block are modeled using the Johnson–Cook constitutive law [4]:

$$\sigma_{VM} = \left(A + B\,\bar{\varepsilon}_p^n\right)\left(1 + C\ln\frac{\dot{\bar{\varepsilon}}_p}{\dot{\bar{\varepsilon}}_0}\right)\left[1 - (T^*)^m\right] \tag{1}$$

that allows to capture the effects of strain hardening, strain-rate sensitivity and erosion. Coupled with fracture criteria and equation of state it's able to accurately reproduce projectile erosion and plastic flow during impact.

The simulations are performed using the LS-Dyna explicit dynamic finite element solver.

3. Model Validation

The model was validated against numerical results reported in Lin's paper considering two different impact scenarios.

3.1. Soft Armor Validation

The UHMWPE laminate model was validated independently against ballistic test results involving a 7.62×25 mm projectile.

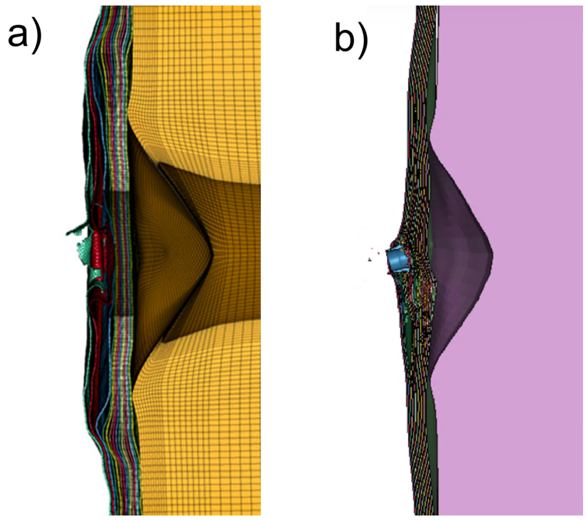

Figure 3: Comparison of the impact on the soft body armor at 300 μs: a) the original work by Lin et al. [1] and b) current work.

The model correctly reproduced deformation patterns and back-face deformation.

4. Composite SAPI Validation

The full alumina/UHMWPE system was validated under impact of a 7.62 APM2 projectile (as shown in figure 4).

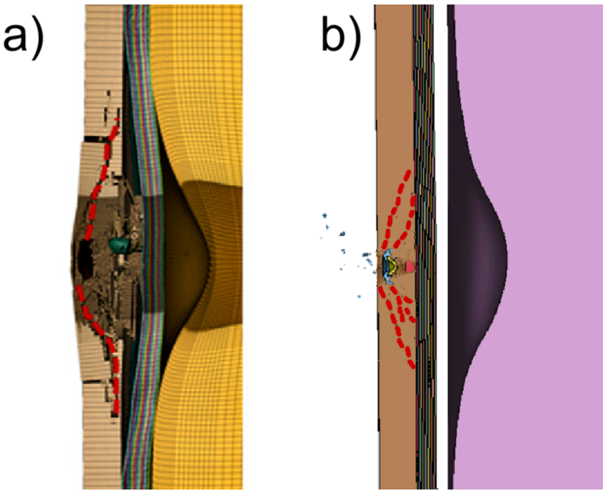

Figure 4: Comparison of the impact on the ceramic composite SAPI at 800 μs: a) the original work by Lin et al. [1] and b) current work.

The model results accurately matched the reference in ceramic fragmentation morphology (including conoid formation), projectile core erosion and back-face deformation (both final value and dynamic history).
This validation confirms that the proposed numerical framework is physically reliable and suitable for damage studies.

5. Results

The two prior damage scenarios (namely multiple ballistic hits and ballistic impact on the cracked ceramic SAPI) are here presented.

5.1. Multiple hits

The investigation on the multiple hit ballistic resistance of the protection has been conducted simulating a first ballistic impact on a pristine SAPI and then doing a campaign of 4 second impact simulations, varying the distance from the first impact point, from 30 to 60 mm. In all the cases the projectile is able to defeat the armor, but as the spacing between the two hits increases, the residual kinetic energy of the projectile reduces, dropping to 0.03% of the initial projectile energy for a distance of 60 mm. The key ballistic performance indicators for the investigated scenarios are listed in table 1.
The ceramic conoid created in the first impact limits the alumina fragmentation in the second hit, and consequently the amount of energy the

	30 mm	40 mm	50 mm	60 mm
Resid. velocity [m/s]	545	490	505	83
Resid. mass [%]	23.1	27.3	15.6	3.4
Resid. kinetic en. [%]	6.23	6.67	2.97	0.03

Table 1: Residual core velocity, core mass and projectile kinetic energy

armor is able to absorb and dissipate. Figure 5 and 6 show how different impact distance affects the ceramic fracture morphology and UHMWPE failure mode (extensive tearing versus localized soft plugging).

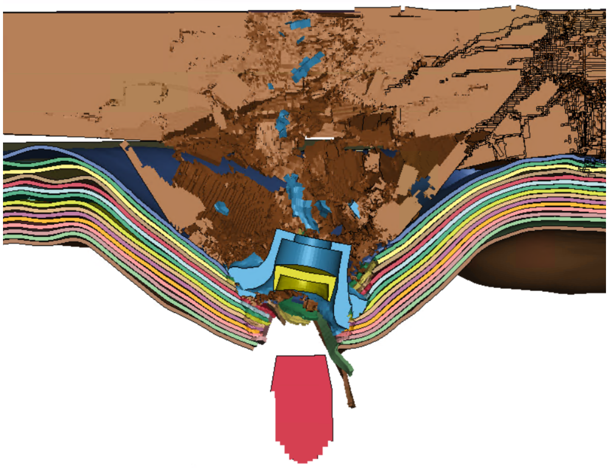

Figure 5: 30 mm spaced second impact simulation at 100 μs

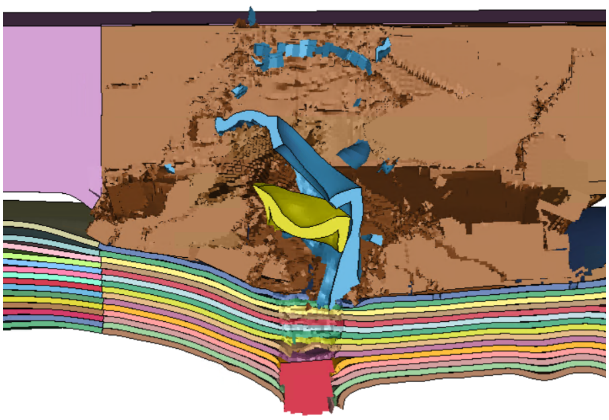

Figure 6: 60 mm spaced second impact simulation at 100 μs

5.2. Cracked ceramic tile

The effect of a crack through all the thickness and width of the alumina tile was studied simulating 6 impacts at increasing distances from the crack location, from 0 mm (projectile directly impacting the crack) to 20 mm. In all the simulated scenarios the armor is able to stop the threat, and the protective performance was evaluated measuring the back-face deformation with the back face signature with a plastilina backing. The results of this investigation (plotted in figure 7) highlight how increasing the distance from the crack results in a reduction of back face signature, with the exception of a local minimum in the near proximities of the crack, where the projectile is able to impact simultaneously both sides of the crack.

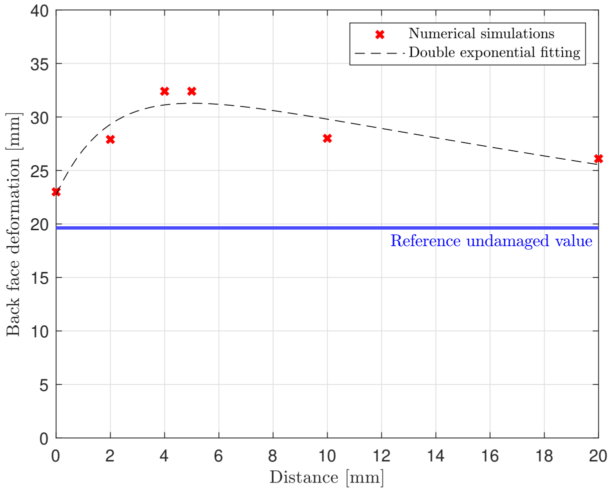

Figure 7: Back-face deformation in function of impact distance

The crack promotes shear sliding between the two sides of the ceramic tile and stops the shockwave propagation in the tile, preventing the formation of an extended conoid, that dissipates the projectile's energy, as shown in figure 8.

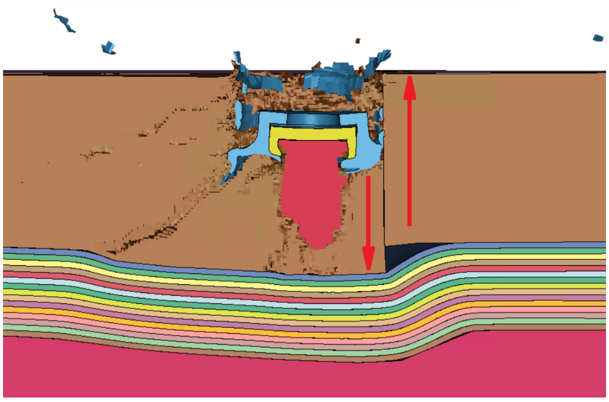

Figure 8: Projectile impact 5 mm from crack at 50 μs

When the distance of the impact point is increased, as in figure 9, the ceramic conoid can fully develop, and the protective performance approaches the nominal value of an intact armor.

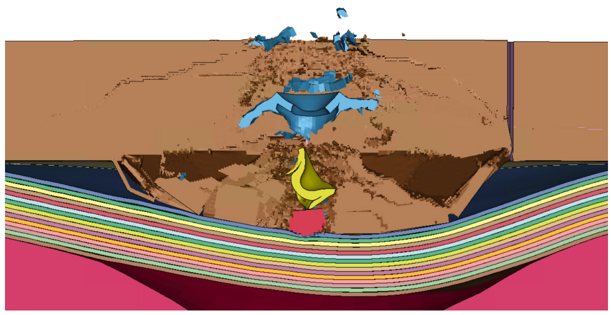

Figure 9: Projectile impact 20 mm from crack at 25 μs

6. Conclusions

The scope of this work is to build a validated numerical methodology capable of predicting ballistic resistance degradation in damaged SAPIs. This robust and sophisticated numerical tool can be used in synergy with conventional non-destructive inspection techniques (e.g. x-rays) integrating the numerical simulation results with the health insights that radiography imaging is able to provide.

The advantage of the proposed technique is that it provides quantitative key performance indicators, such as back face deformation or residual projectile velocity (instead of a qualitative prognosis estimation that conventional radiography screening is able to produce). Coupling this high-fidelity simulation framework with conventional radiographic screening can provide a more consistent acceptance/rejection criteria for decommissioning personal protection with variable amount of damage.

The drawbacks of this procedure are common in high-fidelity simulations: calibration and validation of the model (including the choice of material models) can be a cumbersome task, slowed down by the heavy computational burden of running these models.

The results of this work show a damage in the ceramic layer of a composite SAPI reduces the degree of protection because limits further fragmentation and development of ceramic conoid (mechanism that distributes the impact energy on a larger area of UHMWPE laminate). In-

creasing the distance from the damage results in increasing protective capability, allowing to define a safe radius outside of which the nominal protective capability is guaranteed.
To improve the readiness and response time of this health monitoring approach (with the goal to make it quasi real-time) future work will include training an artificial neural network on simulation results to predict projectile residual velocity or back-face deformation starting from x-ray data. Neural networks have been proven by other scholars to be a reliable and effective tool in surrogating traditional ballistic impact numerical models, with the drawback of needing a large training dataset to be consistent and robust.

References

[1] J. Lin et al. Numerical investigation of the high-velocity impact performance of body armor panels. *Thin Walled Structures, https://doi.org/10.1016/j.tws.2023.110909*, 2023.

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