EPJ Web of Conferences **250**, 04001 (2021) https://doi.org/10.1051/epjconf/202125004001
DYMAT 2021

Optimisation of ballistic protection systems based on impact test/simulation correlation

Yohan Cosquer[1,3*], *Patrice* Longère[1], *Olivier* Pantalé[2], and *Claude* Gailhac[3]

[1]Institut Clément Ader, Université de Toulouse, ISAE-SUPAERO, MINES ALBI, UPS, INSA, CNRS, Toulouse, France.
[2]Laboratoire Génie de Production, Ecole Nationale d'Ingénieurs de Tarbes, Tarbes, France.
[3]CNIM Systèmes Industriels, La Seyne-sur-Mer, France.

Abstract. The complexity of ballistic protections increases with their efficiency. On this basis, an exclusively empirical approach is not adapted to optimise complex protection systems and the resort to numerical simulations is preferred if not mandatory. The present study proposes a methodology aiming at optimising complex multi-layer ballistic armours based on an experimental-numerical correlation. A multi-layer system is taken as example. A numerical model is first calibrated according to impact-on-monolithic-target test results. Once the model is validated, an optimisation process considering multi-layer configurations involving a sharp-nosed threat modifies the plates' thicknesses in order to minimise the total mass while ensuring the system's protective capacity in terms of residual velocity. The optimisation process shows that a single layer system is more efficient than a multi-layer one in the studied case.

1 Introduction

The design of ballistic protection systems for ground vehicles has long been an iterative process based on empirical approaches. With the emergence of new conflict zones, threats and groups, the vehicles protection level increases, and so as their mass. In order to improve their specific performance, these systems are often composed by several layers made up of different materials [1]. This complex composition brings many design parameters, for example material type, plate number and thickness, layering order. There exist analytical models aiming at determining one or several of these parameters, while generally applying to very specific situations. For example, Florence's model [2] makes it possible to identify the optimal thickness of each layer of a two-layered armour consisting in a ceramic front face and a ductile material back face, impacted by a flat-nosed projectile. Yet, changing the layer material type or/and projectile shape implies changing the model.

With more complex configurations, the analytical determination of an optimal set of parameters according to a fully experimental approach is not realistic, and the resort to numerical simulations is necessary. Protection systems optimisations based on a numerical approach have successfully been performed by several authors. For example, Park et al. [3]

* Corresponding author: yohan.cosquer@isae-supaero.fr

optimised thicknesses of a steel-aluminium two-layered armour impacted by a steel sphere based on finite element calculations; Paman et al. [4] went further by numerically optimising a multi-layered armoured (steel, titanium, aluminium) based on layering order and layers thicknesses. However, these works are mostly limited to metallic materials or/and by initial assumptions, viz. number of layers, materials, type of projectile.

The aim of this study is to propose a methodology that allows more diverse optimisations. It is based on the Verification & Validation procedure and relies on a correlation between experimental and numerical results. As an example, this methodology is applied to a multi-layered armour composed by an aluminium plate as front and rear layers, and air as intermediate layer.

2 Experiment

2.1 Experimental procedure

Impact tests were carried out using the 40mm-diameter gas gun of the STIMPACT facility at Institut Clément Ader lab. Targets are made of 150×150×6 mm^3 aluminium plates. The multi-layered protection system is composed by two plates as front and rear layers, plus a 10 mm air gap as intermediate layer. This spacing is assured by steel struts, bolts and nuts tightened with a controlled torque. The sub-calibrated projectile consists in a hard steel, 20mm-diameter 60g, sharp-nosed cylinder. Impact initial velocities range between 140 m/s and 230 m/s and the projectile hits the protection systems with a normal incidence. Two Photron SA5 fast cameras were used to record the plate/projectile interaction and to determine the initial and residual projectile velocities. For that purpose, space and time resolutions of 320×192 pixel^2 and 10^5 fps, respectively, were chosen.

2.2 Experimental results

Residual vs. incident velocities are plotted in the case of impact-on-single-plate tests (later used in the calibration and verification stage) in Fig. 1a. According to Fig.1a, the ballistic limit velocity is close to 210 m/s. The impacted plate shows a petaling failure mode, as seen in Fig.1b. Fig. 2 shows the damaged area of the multi-layered protection system (later used in the validation stage) after an impact test at 225 m/s, i.e. near the ballistic limit. The start of petaling is again clearly visible on the front plate, but its complete formation has been prevented by the rear plate. A small crack can be seen at the back of the rear plate.

3 Numerical simulations

3.1 Numerical procedure

Numerical simulations are conducted using the commercial finite element code ABAQUS/Explicit running on the supercomputers CalMiP and PANDO. Calibrations and optimisations are achieved using the commercial software ISIGHT. The plates are discretized using C3D8R (3D hexahedron reduced integration) finite elements while the projectile is modelled using a rigid body (no damage was observed on the projectiles after the tests). Aluminium behaviour is reproduced using the rate- and temperature-dependent Johnson-Cook model [5] for its deviatoric part, and Mie-Grüneisen type equation of state for its hydrodynamic part (adapted from [6]). Damage initiation follows Johnson-Cook damage law [7], and damage evolution until fracture is assumed to obey Hillerborg approach [8]. Coefficients, mostly taken from the literature [9, 10], are reported in Table 1. The value of the energy G_f dissipated during the damage evolution stage serves as a correlation variable between experimental and numerical results.

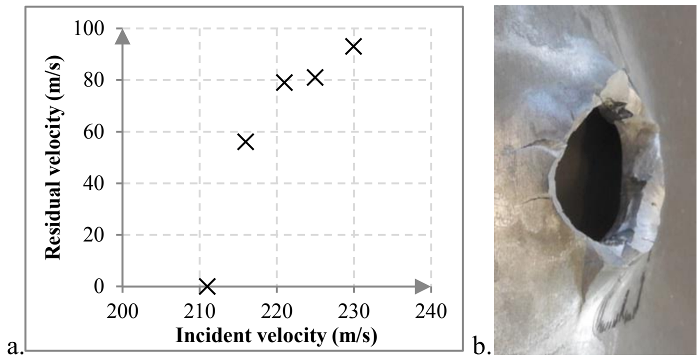

Fig. 1. Tests on single aluminium plate a. Residual vs. incident velocity. b. Rear side of the plate after impact at 230 m/s.

Fig. 2. Test on a multi-layered protection system at 226 m/s. From left to right: front face of the front plate, rear face of the front plate, front face of the rear plate, rear face of the rear plate.

3.2 Calibration and verification

This first step consists in calibrating the coefficient G_f in Table 1 from impact tests carried out on a single plate by minimizing the difference between experimental and numerical residual velocities. ISIGHT is used for that purpose with Downhill Simplex (or Nelder-Mead) method. Only the test with the highest incident velocity is considered, as it is less dependent on the boundary conditions. 393,409 elements and 426,867 nodes compose this model. The calculation typically lasts 12 minutes on 36 cores. After twenty iterations, the algorithm converges to a $G_{f,0}$ value. The same procedure with a flat-nosed projectile leads to a different $G_{f,0}$, as failure mechanisms are very different between flat- and sharp-nosed projectiles. A common $G_{f,1}$ value is tentatively chosen to minimize the deviation between experimental and numerical results, see Table 2. The resulting numerical simulation for sharp-nosed projectile is shown in Fig.3, to be compared with Fig.1a.

3.3 Validation

The validation step aims at verifying the robustness of the model by comparing experimental and numerical results not used in the calibration and verification steps. For that purpose, the protection system evolves from a single plate to a multi-layer armour:

aluminium plates as front and rear layers, and air as intermediate layer. This model contains 771,169 elements, 841,926 nodes and requires 45 minutes of calculation on 36 cores. According to Figs.4-5, the numerical results are in a good agreement with the experimental observations: the front plate fails by petaling and the rear plate is slightly damaged. The main difference lies in the back face of the rear plate, with a more important deterioration in the numerical case than in the experimental one (Fig.2). As the numerical model is conservative, it is considered as validated.

Table 1. Material coefficients for aluminium

ρ (kg/m^3)	**E (GPa)**	**ν**	**c_p (J/kg/K)**	**β**	**T_m (K)**
2700	74.66	0.3	875	1	775
A (MPa)	**B (MPa)**	**C**	**n**	**m**	**T_{ref} (K)**
352	440	0.0083	0.42	1	293
D1	**D2**	**D3**	**D4**	**D5**	**$\dot{\varepsilon}_0$**
0.13	0.13	-1.5	0.011	0	3.33E-4
Γ	**c_0 (m/s)**	**s**	**G_f**		
2.1	5380	1.337	-		

Table 2. Calibration of the plates material

	Flat nose	**Sharp nose**
Incident velocity (m/s)	224	230
Experimental residual velocity (m/s)	180	93
$G_{f,0}$ (normalised)	1.0	6.3
$G_{f,1}$ (normalised)	6.0	
New residual velocity (m/s)	174.5	95.0
Deviation	-3.06 %	+2.15 %

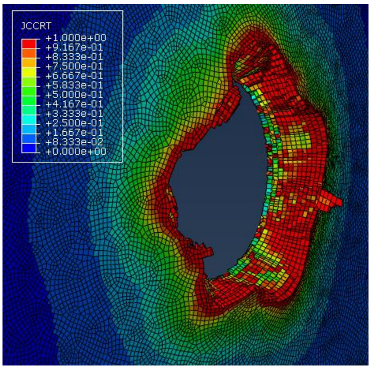

Fig. 3. Simulation on single aluminium plate at 230 m/s. Johnson-Cook damage initiation field.

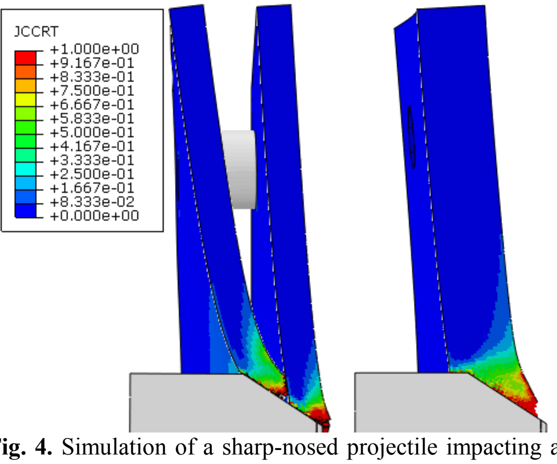

Fig. 4. Simulation of a sharp-nosed projectile impacting at 226 m/s a multi-layered protection system (2×6 mm), and a mono-layer version (1×12 mm). Johnson-Cook damage initiation field.

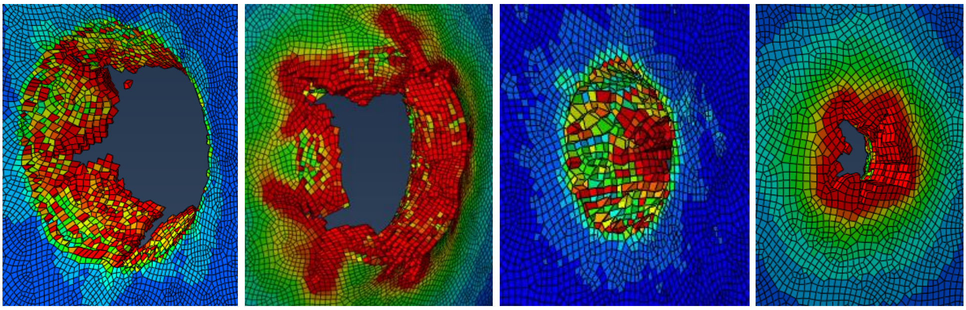

Fig. 5. Simulation of multi-layered protection system at 226 m/s. Johnson-Cook damage initiation field. From left to right: front face of the front plate, rear face of the front plate, front face of the rear plate, rear face of the rear plate.

3.4 Optimisation

The numerical model can now be used in the search for an optimal design of the multi-layered protection system. The objective is to minimise its mass while guaranteeing the absence of perforation by a projectile at 300 m/s. The width of the air gap is fixed and the plates' thicknesses can be modified independently. Moreover, a 1.0 minimal plate normalised thickness is set to guarantee the presence of several elements through the plates.

Fig.6 depicts the progression of the optimisation algorithm. 70 iterations, corresponding to about 70 hours, are necessary to converge to the final normalised thicknesses: 4.7 for the front plate and 1.0 for the rear plate (normalised mass per unit area: 1.0). It is noteworthy that the optimisation algorithm has reached the minimal admissible thickness value (1.0), meaning that the optimisation process is not completed and that this multi-layered design is accordingly not adapted to a sharp-nosed threat. As a comparison, according to a similar numerical model, a single-layer protection system would require a 5.2 normalised thickness (normalised mass per unit area: 0.91). Table 3 summarises these results.

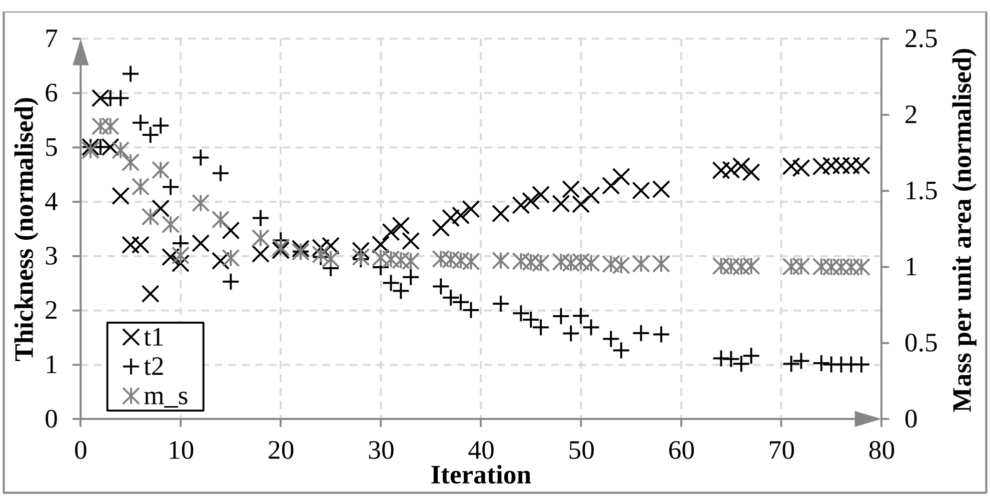

Fig. 6. Iterations leading to an optimised multi-layer protection system. Minimal thickness: 1.0. t1: front plate thickness ; t2: rear plate thickness ; m_s: mass per unit area (Normalised values)

4 Conclusion

A numerical model has been built to reproduce impact tests on aluminium plates. A first calibration step has been conducted following an experimental-numerical correlation in order to get identical residual velocities. Then, this model has been challenged to reproduce an impact on a multi-layered system, and showed a good agreement with the observed damaged areas. Finally, this multi-layered system has been automatically modified to minimise its mass while conserving its protective role. The optimisation process has shown that a single layer system is more efficient than a multi-layer one.

The application of the methodology to multi-material systems is in progress.

Table 3. Optimisation results (normalised values)

	Front plate thickness	**Rear plate thickness**	**Mass per unit area**
Optimised multi-layered system	4.7	1.0	1.0
Optimised single layer system	5.2		0.91

The authors acknowledge the financial support of French Agence Nationale Recherche Technologie (ANRT) and the high performance computing by CalMiP.

References

1. I. G. Crouch, *The Science of Armour Materials*, Woodhead Publishing (2017)
2. A. L. Florence, *Interaction of Projectiles and Composite Armor. Part II*. Stanford Research Inst. Menlo park CA (1969)
3. M. Park, J. Yoo, D.T. Chung, *An optimization of a multi-layered plate under ballistic impact*, Int. J. Solids Struct. **42**, 123–137 (2005)
4. A. Paman, G. Sukumar, B. Ramakrishna, V. Madhu, *An optimization scheme for a multilayer armour module against 7.62 mm armour piercing projectile*, Int. J. Prot. Struct. **11**, 185–208 (2019)
5. G.R. Johnson, W.H. Cook, *A constitutive model and data for metals subjected to large strains, heigh strain rates and high temperatures*, in Proceedings of the 7th Inf. Sympo. Ballistics (1983)
6. E. Grüneisen, *Theorie des festen Zustandes einatomiger Elemente*, Ann. Phys. (1912)
7. G.R. Johnson, W.H. Cook, *Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures*, Eng. Fract. Mech. **21**, 31–48 (1985)
8. A. Hillerborg, M. Modéer, P.E. Petersson, *Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements*, Cem. Concr. Res. **6**, 773–781 (1976)
9. X. Teng, T. Wierzbicki, *Effect of Fracture Criteria on High Velocity Perforation of Thin Beams*, Int. J. Comput. Methods **01**, 171–200 (2004)
10. S. Ryan, F. Schäfer, G. Spencer, S. Hiermaier, M. Guyot, M. Lambert, *An excitation function for hypervelocity impact-induced wave propagation in satellite structures*, AIAA 57th Int. Astronaut. Congr. IAC 2006, 3838–3846 (2006).