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SIMULATION OF AN IMPACT ON AN ARAMID FABRIC PANEL BY A .357 PROJECTILE

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Abstract: *This paper presents a model for impact bullet – panel of woven aramid fabrics in order to use it for an initial assessment of similar panels to protect against bullets in a range of 100…800 m/s. Based on these initial simulations, the designer could select the number of layers for actual tests. The factors that could be varied in these simulations could be the shape and dimensions of the projectiles, their mass and impact velocity. It is presented only the case of impacting a panel with .357 Magnum, with an incidence velocity of 420 m/s. The panel is composed of 8 layers of plain woven fabrics (200 mm x 200 mm), with weft and warp yarns, the yarn geometry being close to Teijin CT736 phenolic fabric, with 1680 DTEX and 410 g/m^2. The simulation helps to identify the stages of panel failure and to evaluate qualitatively the similarity in panel failure with that of the actual panel, tested under the same conditions as the model.*

Keywords: aramid fabric panel, impact, .357 Magnum, simulation by FEM

1. Introduction

Today's modern military operations, technology-driven warfare tactics, street weapons and very different munitions require the development of advanced ballistic armour systems that are tough, flexible, lightweight and highly energy-absorbing features [1]. In the late 1960s, the evolution of the modern generation of ballistic vests emerged as a result of the development of new fibrous, synthetic materials, with anti-ballistic performance, leading to a new era of fabric-based protective systems for various types of ballistic threats [2], [3], [4].

The factors affecting the protective performances of an armor are many, depending on the threat, the target and the impact features [5]. For a protective panel, these include the fiber nature, the architecture of yarns and fabrics, the finishing materials (foils, yarns, gels etc.), the fixing of layers (sawing, stitching etc.).

Aramid fiber is, nowadays, one of the commonly used fibers in protective applications, a class of synthetic fibers, first introduced by DuPont in the early 1960s. These fibers are marketed under the names Kevlar [6] and Twaron [7]. Both have the following advantages: they are up to five times stronger than steel, but still flexible, heat resistant, cut resistant, chemical resistant and can withstand high ballistic impacts [8]. The new tendency is to design body armour that could withstand more than one type of threats, including different bullets, fragments, knifes, spikes and other weapon threats. New facilities for measuring impact parameters, failure mechanisms help to test rigorously

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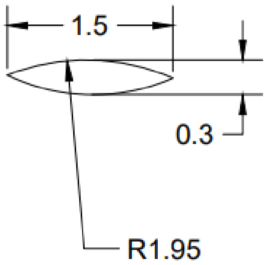
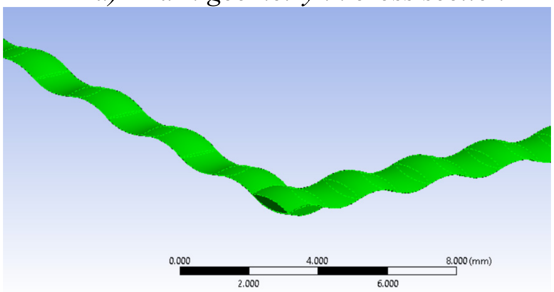
multi-threat vests that can stop both bullet and stab attacks [2].
Several methods are used to investigate the ballistic impact performance of a protection system, for a better and clearer understanding of different parameters, such as [9], [10]: experimental method, empirical method, numerical method, analytical method and combined method. The experimental tests on actual armors are mandatory for introducing a new design solution in use and the conditions to be fulfilled by such a product are included in national, international or military standards, as Ballistic Resistance of Body Armor NIJ Standard-0101.06 [11]. Standards approved by national or international organizations are the last to be conform with and tests are on more numerous samples and with tight conditions in order that these protection armors to face the high level of risk, with high degree of confidence [12].
But numerical methods have becoming a very proficient tool in designing an armor, reducing time to design the initial solutions and to optimize already existing solutions to be lighter, more secure or to face new threats.
An impact projectile – target could be simulated at different scale. For homogenous materials like steel or other metallic alloy, the macro scale, implying the entire shield with isotropic properties could give a response quite similar to the actual protective system. But relatively new materials, based on fibers and layered structures require models at different scale in order to simulate the impact, depending on the designer's skills, the actual system and its shape and dimensions.
The objective of this paper is to simulate, as close as possible, the behaviour of woven aramid fabrics under a bullet impact. Then, this model could be used in a preliminary selection of designs including aramid woven fabrics.

2. The Model

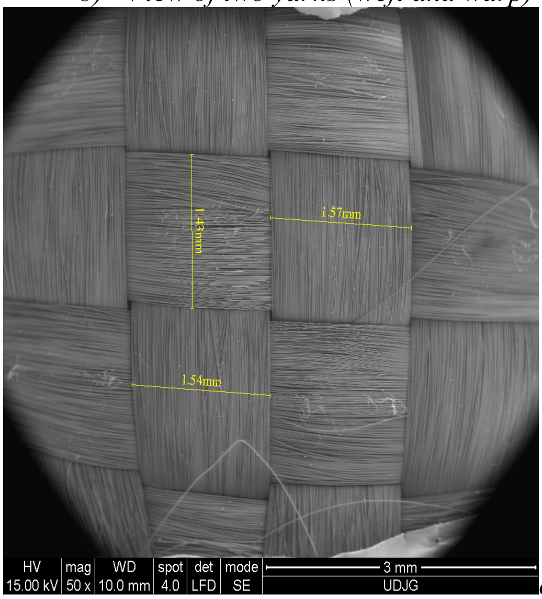
A very useful ranking of models used in simulation impact is given in [13], the author pointing out the advantages and limitations of each levels.
There has been an increasing emphasis in recent years to study the behavior of woven aramid fabrics at the filament scale to investigate the various deformation and energy dissipating mechanisms, at the micro scale [14]. A large gap still exists between the filament-to-yarn and fabric scales.
Nilakantan [15] reported a simulation of impact on a single yarn of Kevlar KM2, with 400 filaments, the material properties being assigned from experimental work. The issue of these models is that, being given the small dimensions of the fibers in cross section and the large number of fibers, the influence of the other yarns from the fabrics is difficult to assess. The researcher took into account effects of projectile-yarn and inter-filament friction, and filament response is simulated by considering two cases: the filaments are either constrained from spreading laterally during the impact event or are left unconstrained. The high degree of model resolution provides a logical insight for the yarn behavior and proves the influence filament friction, material properties and spreading and redistribution of the filaments during the impact.
The geometry of the model includes dimensions of the bullet and the fabrics. As the model level is meso, the geometry of the yarns is given in Figure 1, very close to the actual yarn. The cross section of the yarn has the shape of a double convex lens. with chords of R=1.95 mm and a lenght of 1.5 mm. The yarn thickness is 0.3 mm. The cross sections of both warp and weft yarns have the same section. This shape is close to lenticular shape as obtained by using generalised power-ellipse, with exponent n=2 [16], [17], the modeling of the yarn shape being important in obtaining a realistic woven fabric.
The lens model was proposed also by [18], but with lateral segments.



a) Yarn geometry in cross section



b) View of two yarns (weft and warp)



c) View of the actual fabric CT736

Figure 1: Geometry of the yarns

The geometry of the bullet is given in Figure 2 for .357 Magnum [19].

The initial conditions are:

- $v_0 = 420$ m/s, this a velocity characterizing level FB3,
- distance between the blunt surface of the bullet and the first yarn is 0.03 mm.

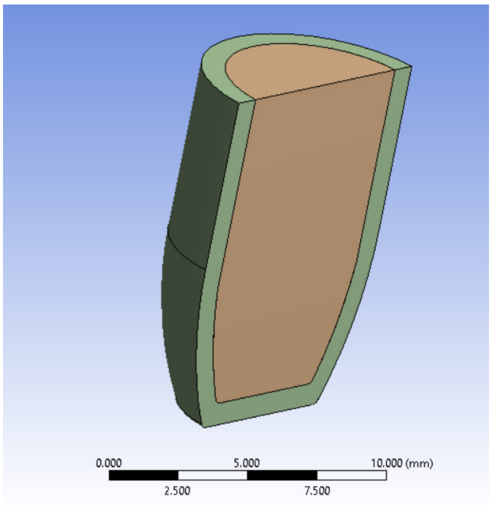


Figure 2: Geometry of the bullet .357 Magnum [19]

Boundary conditions imply that each yarn has the lateral cross sections fixed.

Contact conditions take into account friction:

- contact with friction:
  - for yarn-yarn contact, the friction coefficient COF=0.3 and it is considered constant,
  - for yarn-projectile contact, COF=0.3
  - for jacket-core contact, COF=0.5.

Constitutive models for the materials are different for core and jacket (Johnson-Cook models [20], [21], [22]) and for the yarn it was selected a biliniar hardening model (Table). For the failure of these materials, there were selected the following:

- for projectile core – EPS (see Table 1)
- for jacket it is applied Johnson-Cook failure criterion (Table 1)
- for the yarn EPS (Table 2).

The plastic strain at break is selected as failure criterion for the yarns and the core. For the jacket, it was kept a Johnson-Cook criterion.

These values are taken form literature [23], [24]. For each material model of the projectile, core and jacket, the reference strain rate is 1 s^{-1}.

Figure 3 presents half of the analyzed model.

Table 1. Characteristics of materials involved in the model of .357 Magnum [25]

Jacket (Copper alloy)	
Property	**Value**
Density [kg/m^3]	8300
Isotropic Elasticity	
Young modulus [Pa]	1.1e+11
Poisson ratio	0.34
Bulk modulus [Pa]	1.1458e+11
Shear modulus [Pa]	4.1045e+10
Specific heat [J/(kg·°C)]	385
Johnson Cook constitutive model of stress	
Initial yield stress [MPa]	90
Hardening constant [MPa]	292
Hardening exponent	0.31
Strain rate constant	0.025
Thermal softening exponent	1.09
Melting temperature [°C]	1082.8
Johnson Cook failure criterion	
Damage constant D1	0.54
Damage constant D2	4.89
Damage constant D3	-3.03
Damage constant D4	0.014
Damage constant D5	1.12
Melting temperature [°C]	1082.8
Core (lead alloy)C	
Density [kg/m^3]	11340
Isotropic Elasticity	
Young modulus [Pa]	1.6e+10
Poisson ratio	0.44
Bulk modulus [Pa]	4.4444e+10
Shear modulus [Pa]	5.5556e+09
Specific heat [J/(kg·°C)]	124
Johnson Cook Strength	
Initial yield stress [MPa]	24
Hardening constant [MPa]	300
Hardening exponent	1
Strain rate constant	0.1
Thermal softening exponent	1
Melting temperature [°C]	327.5
Reference strain rate (s^{-1})	1
Plastic Strain Failure	
Maximum equivalent plastic strain EPS	0.75

Table 2. Properties of yarns [26]

Property	**Value**
Density [kg/m^3]	1440
Isotropic bilinear model	
Young's Modulus [MPa]	83000
Poisson Ratio	0.35
Bulk modulus [Pa]	9.2222e+10
Shear modulus [Pa]	3.0741e+10
Bilinear Isotropic Hardening	
Yield limit [MPa]	2000
Tangent modulus [MPa]	1000
Plastic Strain Failure	
Maximum equivalent plastic strain, EPS	0.04

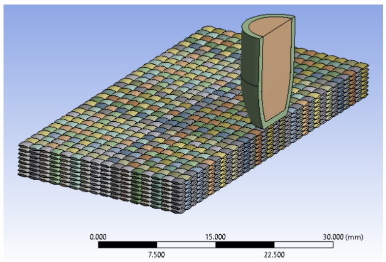
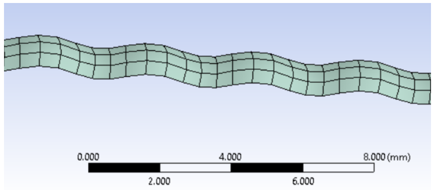
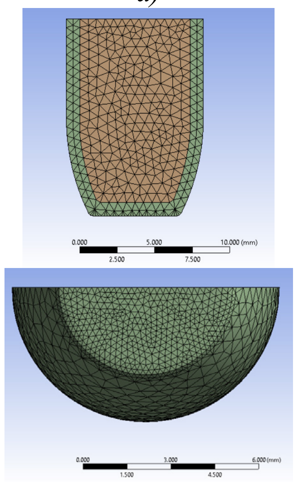


Figure 3: View of the half-model



a)



b)

Figure 4: The mesh network of the yarn and the bullet

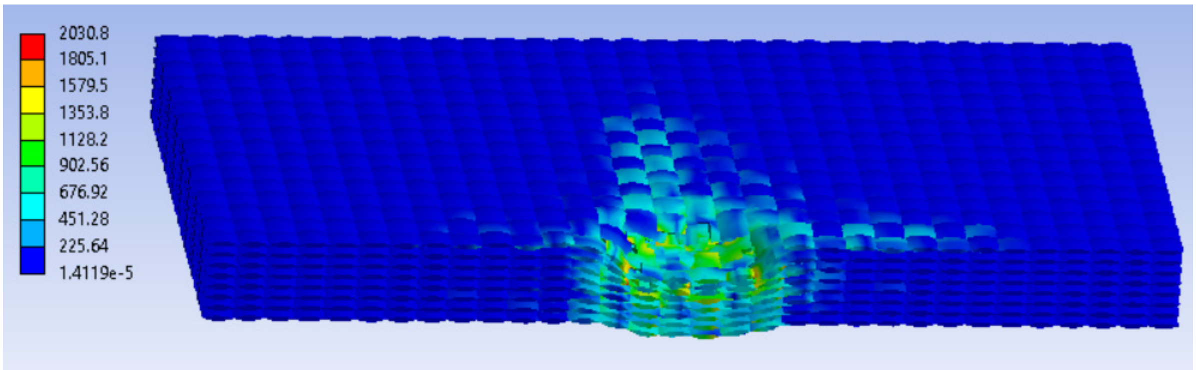
The mesh network is ordered automatically, but still having 2 elements at least on the jacket thickness, see Figure 4.

3. Simulation results

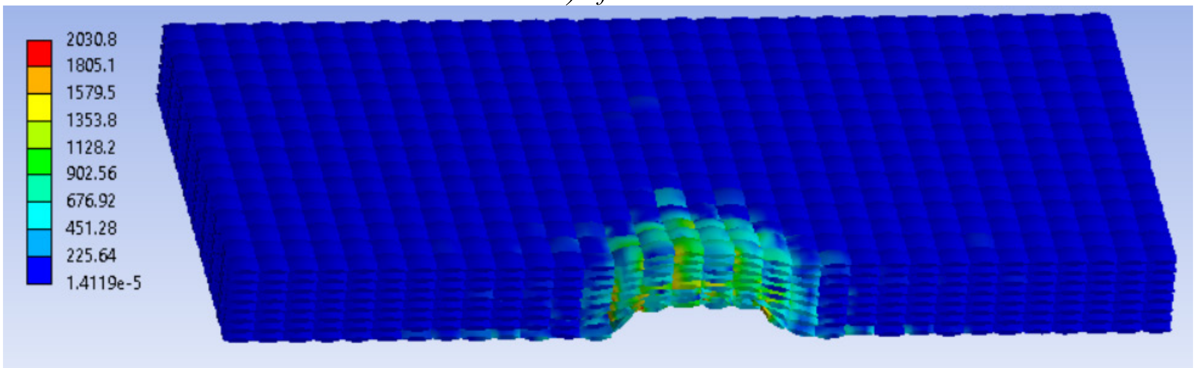
The simulation helps us assessing the progress of the deterioration and identifying the failure mechanisms that are difficult to be "seen" during the actual contact. Usually, the failure mechanisms are identified by comparing the initial panel and projectile with the tested (distroyed) panel and the deformed or fragmentated bullet [26]. Based on succesive images, the stages of the impact.

A general cross section view of the panel is given in Figure 5. The bullet is made invisible, helping to assess the damage in the panel. There are pointed out the following failure mechanisms: breakage of yarns, the pull-out of the yarns in the weft and warp directions of the fabrics, the compression of first yarns under the projectile and the large deformations of the yarns in the last layers. Analysis of equivalent stress distribution shows high stress values in the volume under the projectile and near it, in an almost cylindrical shape, and the highest values are concentrated in points where the yarns will be broken in the following moments.

First moment solved by the simulation reveals that the impact is very intense till $t = 5 \times 10^{-6} s$, because there have been already damaged three layers, meaning the breakage of 4 main yarns (in Figure 6 there are visible only two main yarns in both directions of the plain fabric because the model is run for its half).

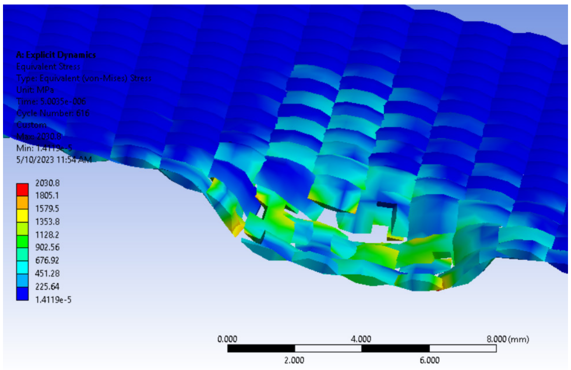


a) face view

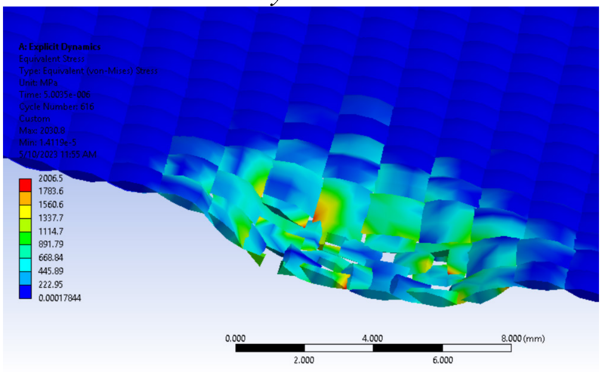


b) back view

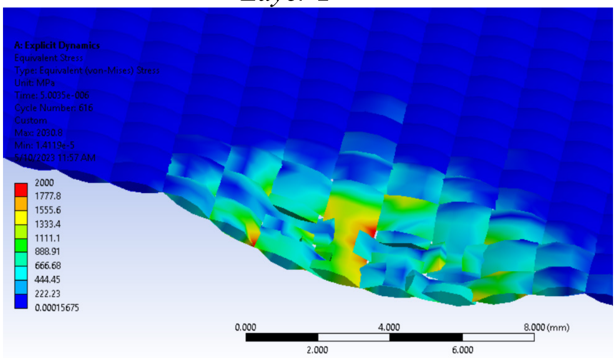
Figure 5: Equivalent stress distributions for the layered panel, at first moment of the simulation, $t = 5 \times 10^{-6}$ (each image has its own color and value scale, in MPa)



Layer 1



Layer 2



Layer 3

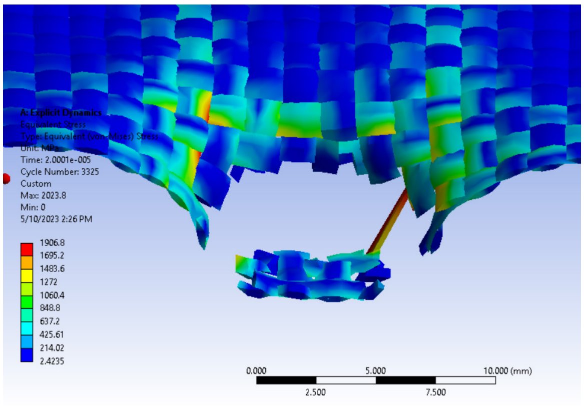
Figure 6: The aspect of first three layers of the panel at the moment $t = 5 \times 10^{-6} s$

At $t = 2 \times 10^{-5}$ s all the layers are broken (Figure 7) when making invisible all layers except layer 1 (Figure 7a) there may be noticed that a cap is cut from these layers hanug the surface almost had of the plane surface of the bullet had.

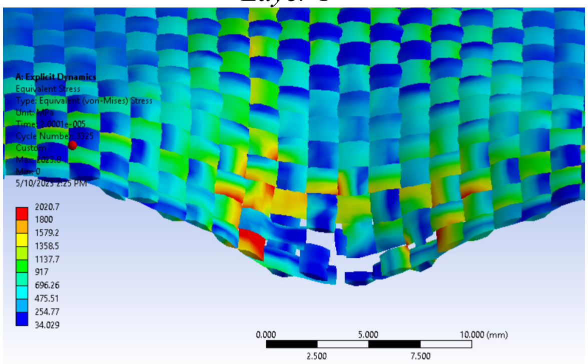
There were done hits on a panel made of 8 layers of CT 736 [7] and the images from actual tests and simulations were compared. The advantage of simulation, if realistic, is that it could “freeze’’ time and to follow the failure stages of the panel.

As the first numerical of simulation the yarns under the bullet are transversally broken.

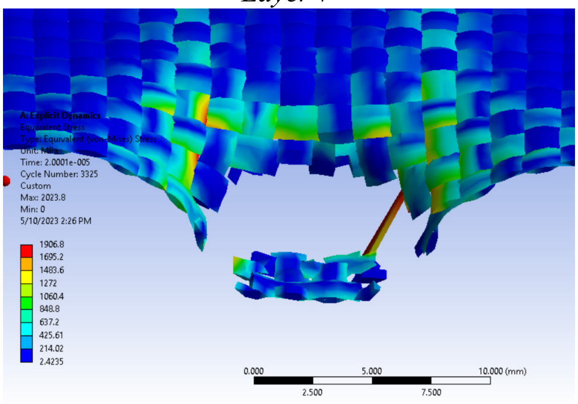
And the maximum values of equivalent stress is noteced to be than the yield limit of the yarn, meaning that break has occurred. This scenario is proved by Figure 7 for the first layers there are noticed broken yarns.



Layer 1



Layer 7



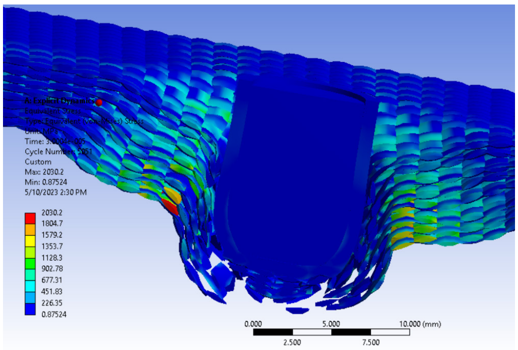
Layer 8

Figure 7: $t = 2 \times 10^{-5}$ *s*

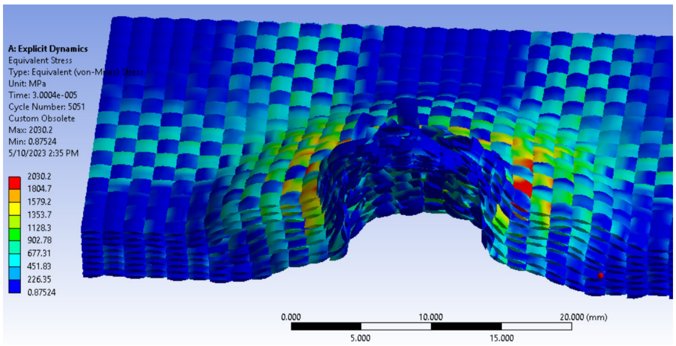
At $t = 3 \times 10^{-5}$ s (Figure 8 a) and b)) the cuts from each layers are tagged together with the bullet head and the bending caused by the passage of cylindrical body of the bullet is more intense on the last layers (see the red color on the main yarn in Figure 8 a) and b) a view from the back side of the panel in order to view stress concentrations on the yarns).

Color scale for stress values is given for each image.

At $t = 6 \times 10^{-5}$ s, Figure 9, the bullet is not anywere in contact with the panel. It is noticed yarns, that are pull-out from the fabrics as in actual impact progress. In Figure 9 b) the bullet is made invisible. At this moment, there could be breaks in yarns (red color, meaning 2001 MPa, close to strength limit of the yarn) because they are strongly bend.

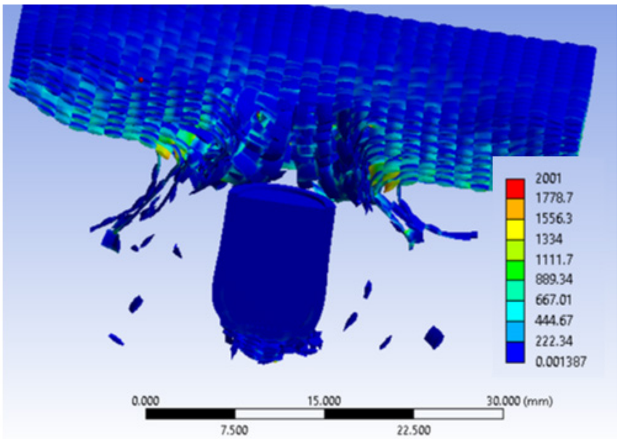


a)



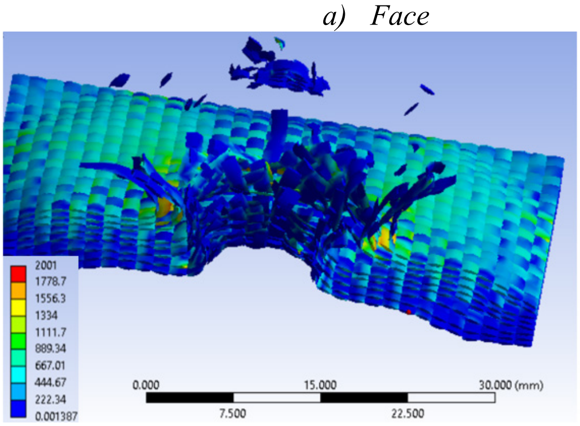
b)

Figure 8: $t = 3 \times 10^{-5}$ s



a) Face

b) Face from the real panel



c) Back

d) Back from the real panel

Figure 9: $t = 6 \times 10^{-5}$ s

Twaron® CT 736 is a well-proven fabric for the production of modern state-of-the-art ballistic helmets or hard-ballistic applications. This fabric style is available impregnated with PVB pure or with PVB phenolic [7]. In Figure 9, the fabrics have the phenolic coating.

4. Conclusions

The model using finite elements and designed by the authors proves to give similar failures and damages aspects and it could be recommended for initiating simulations with the same parameters (number of layers, impact velocity, similar projectiles etc.) in order to obtain a first virtual solution for a protective panel, from which the engineer could produce prototypes to be tested in actual conditions (actual ammunition, panels fabricated from aramid fabrics).

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