A model for evaluating the ballistic resistance of stratified packs

C Pirvu¹, C Georgescu², S Badea³ and L Deleanu²

¹Incas Bucharest, Romania
²Faculty of Engineering, “Dunarea de Jos” University of Galati, Galati, Romania
³Scientific Research Center for CBRN Defense and Ecology, Bucharest, Romania

E-mail: constantin.georgescu@ugal.ro

Abstract. Models for evaluating the ballistic performance of stratified packs are useful in reducing the time for laboratory tests, understanding the failure process and identifying key factors to improve the architecture of the packs. The authors present the results of simulating the bullet impact on a packs made of 24 layers, taking into consideration the friction between layers (µ = 0.4) and the friction between bullet and layers (µ = 0.3). The aim of this study is to obtain a number of layers that allows for the bullet arrest in the packs and to have several layers undamaged in order to offer a high level of safety for this kind of packs that could be included in individual armors. The model takes into account the yield and fracture limits of the two materials the bullet is made of and those for one layer, here considered as an orthotropic material, having maximum equivalent plastic strain of 0.06. All materials are considered to have bilinear isotropic hardening behavior. After documentation, the model was designed as isothermal because thermal influence of the impact is considered low for these impact velocities. The model was developed with the help of Ansys 14.5. Each layer has 200 mm x 200 x 0.35 mm. The bullet velocity just before impact was 400 m/s, a velocity characterizing the average values obtained in close range with a ballistic barrel and the bullet model is following the shape and dimensions of the 9 mm FMJ (full metal jacket). The model and the results concerning the number of broken layers were validated by experiments, as the number of broken layers for the actual pack (made of 24 layers of LFT SB1) were also seven...eight.

1. Introduction

Models for evaluating the ballistic performance of stratified packs are useful in reducing the time for laboratory tests, understanding the failure process and identifying key factors to improve the architecture of the packs [1], [2], [8].

Models for ballistic impact (projectile - target) are complex and are designed for particular cases [7], [11], [15], [20], including materials of the pack and the threat (velocity, shape, materials for the projectile etc.) only for giving an example of complexity and particular solving of a case, it is worthy to mention the Grujicic’s study that include a mezo model two yorns in a thermoplastic matrix [5], similar to that presented in Pirvu [10], and a macro model of a stratified pack.

The aim of this study is to design and run a model for the impact between a bullet and the stratified pack in order to restrain the number of layers in a pack for future experiment work.
2. The model

This model of impact include two systems of solids: the stratified pack made of 24 identical layers and bullet made of two materials (Table 1). The solving method is based on a Lagrange solver of the Ansys Autodyn analysis program [21]. The dimensions of each layer are 200 mm x 200 mm x 0.35 mm. The layers are considered a group of bodies, using the option multiple materials. A similar model was proposed by Soltani et al. [12], Grujicic et al. [6], Tan et al. [13], Yen et al. [17], Zhang et al [18] (with rigid projectile), Zhu et al. [19] (impact with spherical rigid penetrator).

| Material                  | Young modulus, Pa | Poisson coefficient | Bulk modulus, Pa | Shear modulus, Pa | Yield limit, Pa | Tangent modulus, Pa | Maximum Equivalent Plastic Strain, EPS |
|---------------------------|-------------------|---------------------|------------------|-------------------|----------------|------------------|----------------------------------------|
| Layer 7x10\textsuperscript{10}  | 0.35              | 7.77x10\textsuperscript{10} | 2.59x10\textsuperscript{10} | 6.3x10\textsuperscript{8} | 1.9x10\textsuperscript{10} | 0.06         |
| Copper alloy (bullet jacket) | 1.1x10\textsuperscript{11} | 0.34              | 1.14x10\textsuperscript{11} | 4.10x10\textsuperscript{10} | 2.8x10\textsuperscript{8} | 1.15x10\textsuperscript{9} | -                                      |
| Lead alloy (bullet core)  | 1.6x10\textsuperscript{10} | 0.44              | 4.44x10\textsuperscript{10} | 5.55x10\textsuperscript{9} | 3x10\textsuperscript{7} | 1.1x10\textsuperscript{8} | -                                      |

Taking into account the available resources and the impact that is perpendicular to the target, the model is reduced at a quarter, the impact direction also being the symmetry axes for all the involved bodies. The layers are considered a group of bodies (option: multiple materials), the bullet having the same option, but for this body the connexions are “bonded”. There is friction among the layers of the pack, the friction coefficient being constant (\( \mu = 0.4 \)), and there is friction between each layer and the bullet, if they are in contact: \( \mu = 0.3 \). Many research work have taken into account the friction between the bullet and the target and even the friction between yarns in the woven fabric [9] in order to design more realistic models.

The discretisation (mesh). The maximum value of the side of the elements: \( 2 \times 10^{-4} \) m.

The analysis is of structural type, in Explicit Dynamics, using the solver AutoDyn.

Initial conditions. The bullet velocity just before the impact is set at 400 m/s on Z direction (normal impact on the target). The bullet velocity just before impact was 400 m/s, a velocity characterizing the average values obtained with a ballistic barrel [10] and the bullet model (Figure 1) is following the shape and dimensions of the 9 mm FMJ (full metal jacket).

![Figure 1. The model of the impact between a 9 mm FMJ and a stratified target](image-url)
Boundary conditions. The layers (have) the lateral edges fixed. It is worthy to mention that many studies have accepted this condition [3], [4], [14], [16], even if, for the packs for individual protection, this is a symplified hypothesis because, actually, the pack is set on the support material (standard ballistic clay). The maximum number of cycles is $10^7$ and the accepted maximum error for energy is 0.9.

The authors present the results of simulating the bullet impact on a packs made of 24 layers, taking into consideration the friction between layers ($\mu = 0.4$) and the friction between bullet and layers ($\mu = 0.3$). The aim of this study is to obtain a number of layers that allows for the bullet arrest in the packs and to have several layers undamaged in order to offer a high level of safety for this kind of packs that could be included in individual armors. This model was useful for evaluating the number of destroyed layers for packs made of stratified layers of LFT SB1 [10], in order to start an experimental plan. The model takes into account the yield and fracture limits of the two materials the bullet is made of and those for one layer, here considered as an orthotropic material, having maximum equivalent plastic strain of 0.06 (see Table 1). All materials have bilinear isotropic hardening behavior. After documentation [1], the model was designed as isothermal, as the thermal influence upon the impact is considered low for this impact velocity. The model was developed with the help of Ansys 14.5.

3. Results

(a) $t = 2 \times 10^{-5}$ s the first broken layer

(b) $t = 3 \times 10^{-5}$ s

(c) $t = 4 \times 10^{-5}$ s

(d) $t = 5 \times 10^{-5}$ s

(e) $t = 6 \times 10^{-5}$ s

(f) $t = 7 \times 10^{-5}$ s

Figure 2. Sequential images of simulating the impact
Figure 2 presents the impact of the bullet on the stratified pack made of 24 layers of material having properties close to those exhibited by the material to be tested in the laboratory. Based on this simulation, the laboratory tests were done for packs made of actual 24 layers of aramid unidirectional fabrics.

The impact starts at \( t = 1 \times 10^{-5} \) s (see plots for velocity - figure 4 and for the acceleration - figure 5 for the central point on the bullet).

At \( t = 2 \times 10^{-5} \) s, the stress concentration is bellow the bullet, but in the following steps of \( 10^{-5} \) s, one may notice that maximum values of von Mises stresses are spread towards the periphery of the impact zone, but not reaching its limits. These maximum values cause the break of the bullet jacket (in actual tests) and, at least, a thinning process of the jacket.

The maximum displacement of the pack is obtained at \( t = 6...7 \times 10^{-5} \) s.

After \( t = 6 \times 10^{-5} \) s, the failed layers tend to cover the bullet and the bullet continues to deform under the first layers above it.

This simulation allows for distinguishing the stages of the impact: the deceleration of the bullet (during here between \( 1 \times 10^{-5} \) s and \( 2 \times 10^{-5} \) s) when hitting the first layer, the failure of several layers (2 \( \times 10^{-5} \) s...5 \( \times 10^{-5} \) s), the compression of the remaining layers under the bullet (6 \( \times 10^{-5} \) s...8...9 \( \times 10^{-5} \) s) and the recoil of the pack (9 \( \times 10^{-5} \) s...15 \( \times 10^{-5} \) s). Because of computer resources, the simulation is done only for \( 2 \times 10^{-4} \) s (Figure 3).

Analysing the plots for velocity (Figure 4) and acceleration (Figure 5) for a point situated at the top of the bullet, each change of plot path in the same direction may indicate succession of the layers’ failure. From Figure 4, there are 7...8 changes in the acceleration plot, this being the failed layers in the pack made of LFT SB1, in actual tests.
Figure 4. The velocity of the central point of the bullet

Figure 5. The acceleration of the central point of the bullet

Figure 6 presents the evolution of maximum value for von Mises stress in the analysed system. The failure of layers is characterized by the maximum values over passing $2 \times 10^9$ Pa (that is during the period between $1 \times 10^{-5}$ s...$5 \times 10^{-5}$ s), followed by values around the compression stage of pack.

Figure 6. Plot of the maximum values of von Mises stress

For the model, the bullet is not so flattened as the actual ones [10] because of the material modelling as isotropic bilinear. The introduction of a strength limit for each material the bullet is made of could improve the model to have the jacket broken in the zones where the maximum stress occurs (Figure 3, the red spots in the jacket material).

Layer VII

a) the front face
b) the back face

Figure 7. Details of a typical last failed in the pack made of 24 layers of LFT SB1. The seventh layer has only some broken fibers from a yarn
4. Conclusions
In order to have useful simulations of the impact projectile - target, the model will be elaborated at one or more levels (micro, mezo or macro), depending on the complexity of both bodies (projectile and target). The macro level of modelling the impact process could use simplified hypothesis, but the results have to be validated and extrapolation far from the initial conditions introduced in the model are not reliable.

This paper presents the result of simulating the impact behavior of the system 9 mm FMJ bullet - stratified pack made of homogenous material.

This simplifying hypothesis could be acceptable for fabrics with sublayers with different orientation of unidirectional fibers, like LFT BS1 (with orientation 0/90) or LFT SB1plus (with orientation 0/90/45/-45) [22], [23], as this type of fabrics reduces the difference in properties on the axes. For the analysed model, the thickness of the strata is close to that of the fabric LFT SB1. The model and the results concerning the number of broken layers were validated by experiments, as the number of broken layers for the actual pack was also seven...eight (see Figure 7) [10].

The models for ballistic impact are useful when they are particularly formulated for resembling to the actual system projectile - target.

5. References
[1] Barauskas R 2000 Multi-Scale Modelling of Textile Structures in Terminal Ballistics Proceedings of 6th European LS-DYNA Users’ Conference pp 4.141-4.154
[2] Bhatnagar A 2006 Lightweight ballistic composites (Boca Raton Boston New York: CRC Press)
[3] Gopinath G, Zheng J Q and Batra R C 2012 Effect of matrix on ballistic performance of soft body armor Composite Structures 94 pp 2690–2696
[4] Gorfan J E and Key C T 2013 Damage prediction of rib-stiffened composite structures subjected to ballistic impact International Journal of Impact Engineering 57 pp 159-172
[5] Grujicic M, Arakere G, He T, Bell W.C., Cheeseman B A, Yen C-F and Scott B 2008 A ballistic material model for cross-plied unidirectional ultra-high molecular-weight polyethylene fiber-reinforced armor-grade composites Materials Science and Engineering A 498 pp 231–241
[6] Grujicic M, Glomski P S, He T, Arakere G, Bell W C and Cheeseman B A 2009 Material Modeling and Ballistic-Resistance Analysis of Armor-Grade Composites Reinforced with High-Performance Fibers Journal of Materials Engineering and Performance 18 pp 1169-1182
[7] Hub J, Komenda J and Novák M 2012 Ballistic Limit Evaluation for Impact of Pistol Projectile 9 mm Luger for Aircraft Skin Metal Plate Advances in Military Technology 7 pp 21-29
[8] Năstăsescu V, Ştefan A and Lupoiu C 2001 Analiza neliniară prin metoda elementelor finite. Fundamente teoretice și aplicații (București: Academia Tehnică Militară)
[9] Nilakantan G and Gillespie Jr J W 2012 Ballistic impact modeling of woven fabrics considering yarn strength, friction, projectile impact location, and fabric boundary condition effects Composite Structures 94 pp 3624–3634
[10] Pirvu C 2015 Contribuții la studiul experimental și numeric al pachetelor de protecție balistică cu fibre aramidice - PhD thesis (Galati: Dunarea de Jos University)
[11] Safta I 2011 Contribuții la studiul teoretic si experimental al mijloacelor individuale de protecțiune balistica (București: Academia Tehnica Militara)
[12] Soltani P, Keikhosravy M, Oskouei R H and Soutis C 2011 Studying the Tensile Behaviour of GLARE Laminates: A Finite Element Modelling Approach Applied Composite Materials 18 pp 271-282
[13] Tan V B C and Khoo K J L 2005 Perforation of flexible laminates by projectiles of different geometry International Journal of Impact Engineering 31 pp 793–810
[14] Tasdemirci A, Hall I W, Gama B A and Guden M 2004 The Effects of Layer Constraint on Stress Wave Propagation in Multilayer Composite Materials Contract DAAD19-01-2-0001
[15] Tasdemirci A and Hall I W 2006 Numerical and experimental studies of damage generation in a polymer composite material at high strain rates *Polymer Testing* **25** pp 797–806

[16] Villavicencio R and Guedes Soares C 2013 Impact response of rectangular and square stiffened plates supported on two opposite edges *Thin-Walled Structures* **68** pp 164–182

[17] Yen C-F 2012 A ballistic material model for continuous-fiber reinforced composites *International Journal of Impact Engineering* **46** pp 11-22

[18] Zhang D, Sun Y, Chen L, Zhang S and Pan N 2014 Influence of fabric structure and thickness on the ballistic impact behavior of Ultrahigh molecular weight polyethylene composite laminate *Materials and Design* **54** pp 315-322

[19] Zhu D, Vaidya A, Mobasher B and Rajan S D 2014 Finite element modeling of ballistic impact on multi-layer Kevlar 49 fabrics *Composites Part B* **56** pp 254-262

[20] Zohdi T I 2002 Modeling and simulation of progressive penetration of multilayered ballistic fabric shielding *Computational Mechanics* **29** pp 61-67

[21] *** 2012 *AutoDyne composite modeling* (USA: ANSYS Inc.)

[22] *** *Ballistics Teijin Aramid - Ballistics material handbook*

[23] *** Twaron – a versatile high-performance fiber *Teijin Aramid brochure*