Modeling of the bullet perforation of textile targets by using combined woven structure – membrane approach

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Abstract: An efficient finite element model of the ballistic impact and perforation of the woven fabrics structures has been developed in LSDYNA. The bullet has been considered as a deformable body in contact with the fabric package presented by interwoven yarn structure. The simplification of the model has been achieved by presenting the multifilament yarns by thin shell elements the thickness of which represents the real thickness of yarns as it can be measured in the weave. The zones of the fabric remote from the point of impact have been presented as a roughly meshed uniform membrane model. The junction between the two types of zones of the fabric has been performed by means of the tie constraint and by proper adjustment of material parameters ensuring the minimum cumulative wave propagation speed error along selected directions. The model has been verified by comparing the response of the structure with the reference solution obtained by solving the full woven structure model. Physical and numerical experiments have been performed in order to identify the material model parameters.

Key-Words: high-velocity impact, textiles, finite elements, LSDYNA.

1 Introduction

The results obtained during the investigation of multi-layer textile packages designated for the clothes ensuring the ballistic protection imply that the protection level is defined by the structure and properties of multi-filament yarns, weave type of a fabric, number of layers and interconnection technique of a textile package, etc.,[1]. Quick rise and variety of new materials on the market [2] promotes the further theoretical and experimental investigations of textiles packages by establishing their regularities and relationships. The design of the structure of a multi-layer package could be significantly facilitated by the deeper understanding of the behavior of a single textiles layer and interaction of several layers with a bullet that can be carried out by computer simulations.

During the last decade numerous studies have been carried out on the ballistic impact upon high strength fabric structures [3,4,5,6]. The problems including flexible textile structures such as clothes are very difficult to represent by equivalent anisotropic solid models as after the failure of yarns the geometry of the model becomes very complex. In [7] a computational model in LSDYNA has been presented that enabled to consider the geometry of the weave by using shell elements. Numerous approaches have been presented where yarns of a weave were modeled by using 3D solid elements [6,8,9].

The aim of this work was to develop a computational model of interaction of a deformable projectile(bullet) against a multilayer textile package enabling to simulate shooting experiments performed in order to test the ballistic strength of textile body armor. Comparisons with the experimental results have been carried out in order to determine the dynamic parameters of the material behavior and to validate the model.

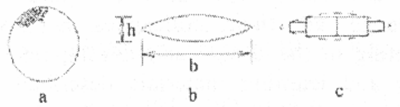


Fig.1: Circular cross-section of a free yarn (a); cross-section of an interwoven yarn (b); cross-section of an interwoven yarn approximated by rectangular cross-sections of four shell elements (c)

2. The model of a fabric package

2.1 Mezzo-mechanical model of a woven patch

A fabric is made of yarns of certain linear density woven together. Each yarn consists of filaments the number of which can vary from several hundred to several thousand. The computational model of a fabric at the level of filaments is rather unrealistic because of limited computer resource, so we develop a mezzo-mechanical model in which a yarn has been considered as primary component comprising a fabric. The properties of an individual yarn are defined empirically by making several assumptions.

It s commonly accepted that the cross-section of a free yarn not interwoven into a textiles is close to a circle made of cross-sections of a certain number of individual filaments, Fig.1,a. In a fabric the yarns are being compressed because of forces acting in overlapping areas. As a result, the geometry of the cross-section of each yarn is being changed depending upon the constitution of the yarn, its density, its type and technological parameters of the weave. We assume it to be close to the combination of two circular segments (Fig.1,b) the dimensions of which are calculated basing upon the given characteristics of the textiles. E.g., the height and length of the paraaramid yarns in the textiles CT709 are b=0.952mm and h=0.15mm. The cross-section of a yarn interwoven into a fabric has been modeled as shown in Fig.1,c. As its height is much smaller than the width we used four shell elements the thickness of which was selected in order to fit two circular segments form.

The bending stiffness of the yarn we assumed to be negligible. In order to eliminate the bending stiffness in LSDYNA, we used the Hughes-Liu shell with single integration point through the thickness of the element. The technique of obtaining the model of a woven yarn patch has been described in our recent work [7].

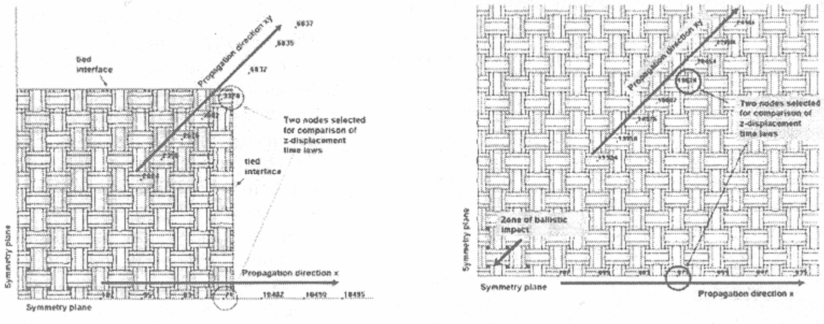
2.2 Macro-mechanical model of a layer

The zone of a fabric proximately taking place in the contact interaction for a 9mm bullet comprises only about 20-60mm in diameter. However, in order to represent properly the dynamics of the interaction process much larger pieces of a fabric should be modeled. The duration of the interaction process is generally conceived as the time from the beginning of the impact until it reaches zero velocity embedded into the multilayer or until the time moment when the fabric is completely perforated. During this time, the longitudinal deformation wave propagating from the point of impact travels much larger distances, so the linear dimension of the fabric being modeled should be ~at least 200-400mm. Unfortunately, the weave step being about 1mm, such "fully woven" models are prohibitive because of their huge dimensionality. As an example, the dimension of 12 fabric layers quarter-symmetry model may reach $\sim 10^8$ nodes. In order to obtain smaller models the macro-mechanical approach is being used. The zones of the fabric remote from the interaction zone are modeled by means of orthotropic shell(membrane) elements that can be much bigger than the elements presenting the mesh of the yarns.

Sudden transitions in mesh density of finite element models are permitted by using tied interfaces. This feature may decrease the effort to generate the meshes since it reduces the need to match nodes across interfaces of merged parts [10]. In LSDYNA the finely and roughly meshed zones are connected by using the *CONSTRAINED_TIE-BREAK constraint. We prohibit the failure of the constraint by using very large failure strain values and no-failure material model for the yarns neighbouring to the membrane model nodes. The reason for such numerical "failure prevention" measure is that the obviously the algorithm of implementation of tied interface constraints in LSDYNA tends to overestimate the strain values in local zones of refined mesh adjacent to the roughly meshed membrane domain. Sometimes a situation may occur when the locally overestimated strain value may cause a failure of a yarn where it appears to be not realistic physically. Such fictitious strain effects may cause to some extent numerical distortions or reflections of waves propagating across the tied interface.

Uniform membrane-type surrounding of the woven patch cannot be expected to present an identical dynamic behaviour as the woven yarn structure. However, satisfactory approximation is possible provided that the appropriate selection of geometrical and physical properties of the membrane zone is made. We proceed as follows.

Two models of the fabric layer with different dimensions of the woven patch are built, Fig2.



a b

Fig.2. Fragments of woven fabric quarter symmetry models with indicated wave propagation directions and numbers of nodes for comparisson of dynamic properties
a – woven patch 10x10 yarns; b – woven patch 60x60 yarns (reference model)

The model containing a larger patch has been considered as a reference model (in our study it contained 120x120 yarns), and the smaller one was 20x20 yarns; we take it be at least twice greater than the diameter of the zone at which the failure of yarns may take place. By taking into account the quarter-symmetry of the model we have to build 10x10 and 60x60 yarn woven patch models correspondingly. The size of membrane-type surrounding of the patches is much larger than the woven patches, however, the total linear dimension of each model is the same.

The membrane is presented by 1-integration point shell elements exhibiting no bending stiffness. The membrane thickness can be assumed as known, however, the values of mass density ρ, Young's modulus E and shear modulus G of the orthotropic material have to selected in order to obtain the ballistic response of both models as close as possible to each other. In LSDYNA the orthotropic material can be defined as *MAT_ORTHOTROPIC_ELASTIC or *MAT_FABRIC. The best results can be expected if the selection of parameters is accomplished for the dynamic behavior close to the specific analysis situation. In this work the numerical tests are performed for the 270m/s impact and perforation of the fabric by the lead bullet.

The overall approach is similar to the convergence investigation of models with different levels of refinement. The "exact" numerical solution may be regarded as known as we are able to make a stand-alone numerical experiment by employing the fully woven model. Further a series of models with different sizes of the woven patch are investigated and the physical constants of the surrounding orthotropic membrane established in order to ensure a convergent behavior in the sense that the solutions obtained by using every model are close to the exact one. This could be referred to as the verification of the model of a fabric layer arranged by employing a combination of mezzo- and macro-mechanical approaches. We limited the analysis to comparison of the dynamic behavior of two models only because of limited amounts of the computational resource.

In our investigation the comparisson of the dynamic behavior of the two models has been performed in terms of :

- the variation of the propagation speed of the longitudinal and transverse in the vicinity of the tied interface of the model. Two wave propagation directions are investigated: direction x along axis Ox and direction xy along the line $y=x$, Fig.2;
- the time laws of z displacement of two selected nodes;
- the time instant of initiation of failure of the fabric;
- the time instant of full perforation of the fabric.

In order to estimate the wave propagation speed as the wave propagates in between two nodes of the structure we fix time moments t_1, t_2 when the displacements of the nodes reach a pre-selected level, see Fig.3a and b. For instance, the average speed of the wave propagating along direction x may be estimated as $v = \dfrac{\Delta x}{t_2 - t_1}$, where $\Delta x = x_2 - x_1$ - distance between the nodes. The longitudinal and transverse wave propagation speed estimated along direction x is presented in Fig.3,c,d. The discontinuities in the wave propagation speed relationships are eliminated at each nodal point by taking the average of the propagation speeds in two neighboring inter-nodal segments of the wave propagation line. The curves representing the variation of longitudinal and transverse wave propagation speeds estimated along the diagonal direction xy are presented in Fig.4.

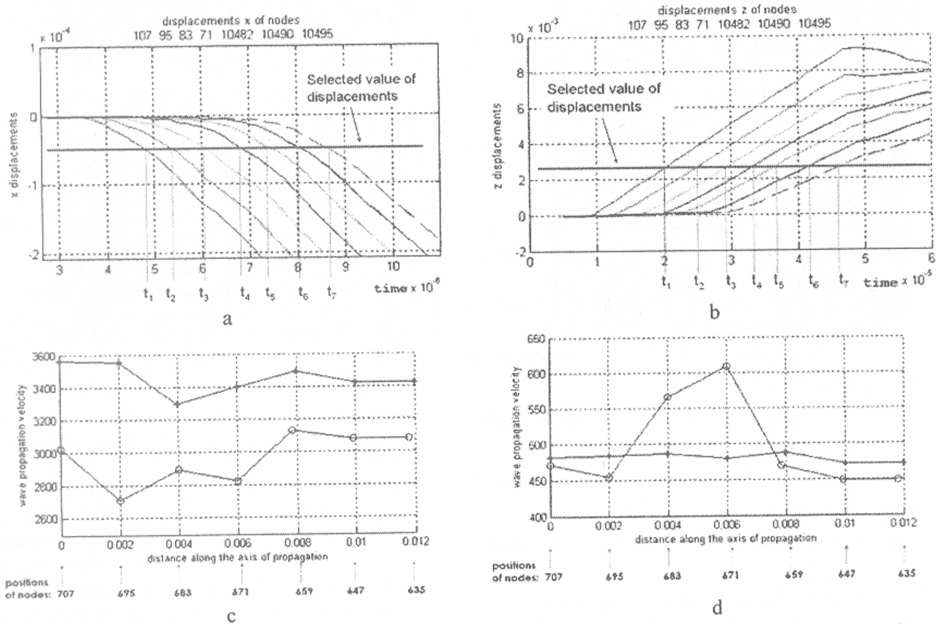
The results presented in Fig.3 and 4 are obtained by using one of "successful" sets of membrane material constants as

$$\frac{\text{Surface density of the membrane}}{\text{surface density of the woven patch}} = 0.8;$$

$$\frac{\text{Young's modulus of the membrane}}{\text{Young's modulus of the yarn}} = 0.3;$$

$$\frac{\text{Shear modulus of the membrane}}{\text{Young's modulus of the membrane}} = 0.0042.$$

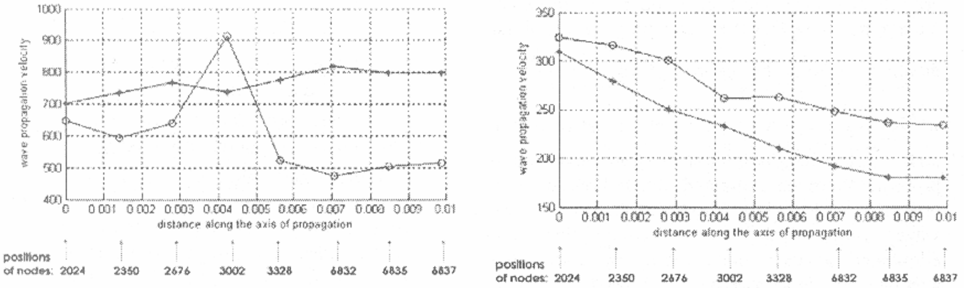
Rather small value of Young's modulus of the equivalent membrane enables to present the de-crimping driven deformation of the fabric which can be expected to prevail in zones remote from the point of impact. Very small values of shear modulus are quite natural to expect because of small shear stiffness of a woven structure at small strains. However, the value of shear modulus has to be selected with care as it makes a significant influence basically upon the shape of the front of the transverse wave, as well as, upon its amplitude.



a b

c d

Fig.3. a,b – time laws of longitudinal (a) and transverse (b) displacements of nodes and determining impact wave propagation speeds along direction x in the vicinity of the tied interface;
c,d –estimated propagation speeds of longitudinal (c) and transverse (d) waves along direction x in the vicinity of the tied interface:
-o- obtained by using model (Fig.2a);
-*- obtained by using the reference model(Fig.2b).



a

b

Fig.4. Estimated propagation speeds of longitudinal (a) and transverse (b) waves along direction *xy* in the vicinity of the tied interface:
-o- obtained by using model Fig.2a;
-*- obtained by using the reference model Fig.2b .

It should be noticed that the wave propagation speed relationships of the reference model and 10x10 woven patch model may have significant (up to ~20%) differences. In order to quantify the differences we introduce the relative cumulative wave propagation speed error (CWPE) as $err = \frac{\int_0^L \left|v - v_{ref}\right| dx}{\int_0^L |v|\, dx}$, where v, v_{ref} - wave propagation speeds estimated by using both models, L – length of the selected wave propagation path.

The CWPE values for the case presented in Fig.3 and 4 are as follows:

- In propagation direction *x*, displacement direction *x:* $err_x^x = 0.19$;
- In propagation direction *x*, displacement direction *z:* $err_z^x = 0.068$;
- In propagation direction *xy*, displacement direction *x:* $err_x^{xy} = 0.35$;
- In propagation direction *xy*, displacement direction *z:* $err_z^{xy} = 0.16$.

CWPE values in the diagonal direction *xy* are about twice larger than in direction *x*. Anyway, the change of the membrane material parameters causes the changes in CWPE as well. However, CWPE relationships corresponding to different wave propagation directions may exhibit different tendencies to increase or decrease as a consequence of the same change of the membrane material parameters. Though the obtained CWPE values are not very small even in engineering sense, the resultant displacements and wave fronts obtained by using 10x10 model are close to the results obtained by using the reference model as can be observed from the results presented in Fig.5.

Our investigation demonstrated that it is hardly possible to select the membrane material properties ensuring very good approximation to the woven structure behavior in all stages and aspects of its motion. For example, the model that properly represents the process of failure of the fabric may produce certain displacement errors in representing its motion after the perforation, see Fig.5,g,h. On the contrary, a model adequately representing the after-perforation motion of the fabric may produce inaccuracies in estimating the time instant of the initiation of the failure. In the ballistic interaction problem the proper representation of the time moment of beginning of failure of the fabric is of primary importance, therefore by adjusting the membrane layer parameters it has been achieved that the failure begins in both models at the same time instant.

Better results can be expected by using non-linear material models of the membrane, however, we did not perform such investigations in this study. On the other hand, non-linear material models often suffer from the lack of stability when the tangent of the stress-strain curve increases with increasing strain (e.g. *MAT_NON_LINEAR_OTHOTROPIC of LSDYNA).

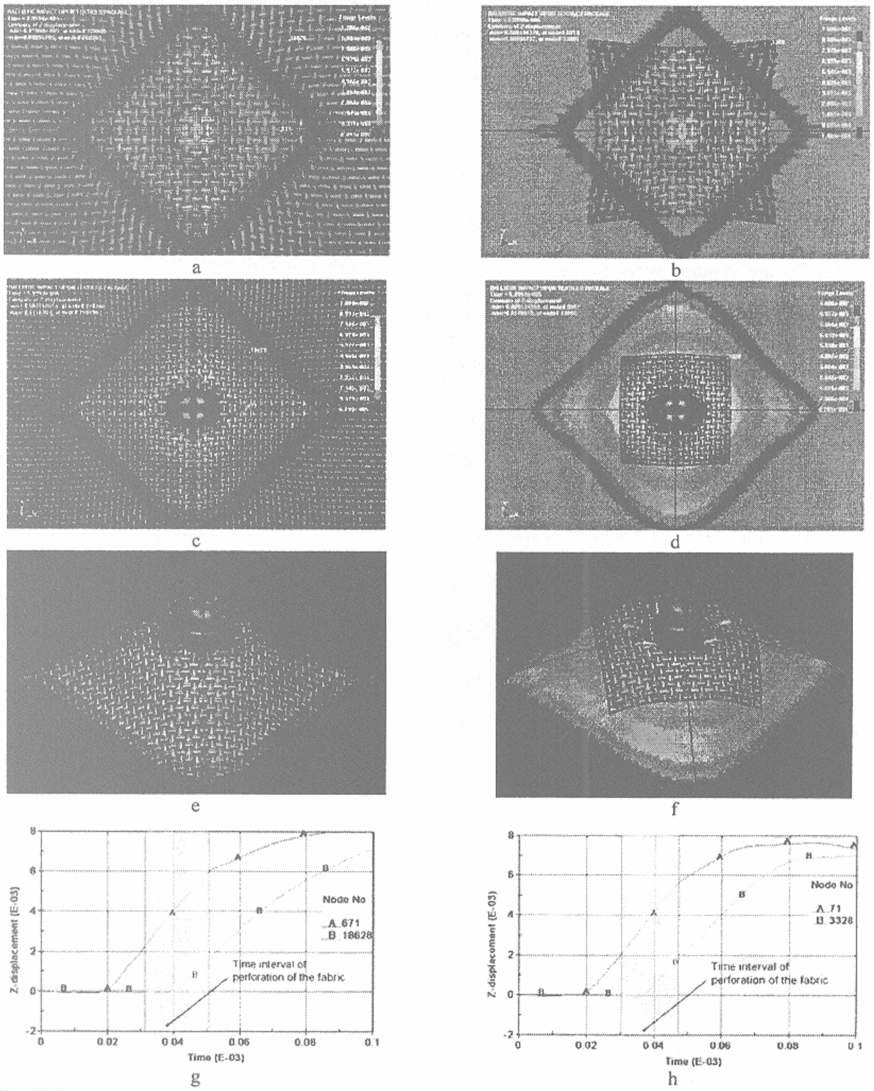


Fig.5 The shape of the transversal wave front and z-displacement contour plot obtained by using reference model (a,c,e) and 10x10 combined model (b,d,f) :

a,b - at time instant $3x10^{-5}$ s (beginning of the failure);
c,d, - at time instant $6x10^{-5}$ s;
e,f - at time instant $6x10^{-5}$ s (axonometric view);
g,h - z-displacement time laws of two selected nodes as indicated in Fig.2.

2.3 Interaction model

The developed model of a single fabric layer has been used for the analysis of the ballistic impact of a bullet upon the multilayer textiles package. The model enables to simulate the failure caused by impact loads similar to the loads to which the fabric is subjected during the shot.

Two different bullet models have been used in this analysis. The finite element model of the 9mm full metal jacket bullet consists of the brass shell and solid lead stuff presented as two separate parts that are in contact interaction with each other. In the contact interaction model the brass shell interacts with the multilayer textile package. In some calculations the finite element model of the lead bullet BALLE 22 has been used. The view of the contact model symmetric with respect to xOz and yOz planes is presented in Fig.4.

The materials taking place in the contact interaction are brass, lead and paraarmid fabric. The brass and lead are elastic-plastic materials, and paraaramid material is assumed to be perfectly elastic up to its failure limit.

As during the deformation volumetric, as well as, deviator strains and stresses are important, all the materials are presented by using the *MAT_PLASTIC_KINEMATIC.

At ~300m/s impact velocity the problem is classified as high velocity contact-impact interaction problem where the yield stress value is assumed to be dependent upon the strain rate in accordance with the Symonds-Couper material model [10]:

$$\sigma_Y = \sigma_{Y0}\left[1+\left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{p}}\right], \qquad (1)$$

where σ_Y, σ_{Y0} - yield stress limits of the material defined with and without the influence of strain rate $\dot{\varepsilon}$; C and p - constants.

3. Model validation and results

3.1 General approach

The adequacy of the obtained results to reality is a highly important question in any simulation. In the case of the system under consideration two reasons which may cause an inadequacy of the results can be mentioned:

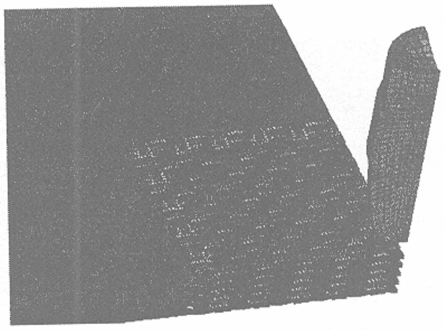


Fig.6. The geometry of the contact interaction between fabric package and the deformable bullet

- the "mezzo-mechanical" concept of the model, where the multi-filament structure of a thread is highly simplified;
- the use of the "macro-mechanical" concept for presenting the "infinite" fabric environment of the woven patch;
- unknown dynamic values of the material parameters. At ~300m/s impact velocity static relationship of yield stress against the plastic strain does not adequately describe the real physical phenomena. This circumstance is important for all materials participating in contact interaction – paraaramid, lead and brass.

Though we used simplest model (1) to modify the yield stress value by taking into account the strain rate, a series of physical and numerical experiments is necessary in order to obtain physically adequate values C and p, as well as, some other parameters describing the behavior of the material. Also the selection of proper hardening model may appear as crucial for obtaining adequate results. We assume the elasticity and shear modules, yield stress, tangential modulus and mass density of each material as known. Values C and p in relation (1) and hardening hypothesis (kinematical, isotropic or the combination of the two) can be assumed as parameters the values of which need to be determined in order to achieve the adequacy of simulation results to reality. The following experiments have been made:

- shooting the lead bullet Balle22 against the 10mm thickness lead plate;

- shooting the 9mm full metal jacket bullet consisting of brass shell and lead stuff against 10mm thickness lead plate;
- shooting the bullet against the textile fabric or against the multi-layer textile package.

3.2 Determining the lead material parameters

As an experiment for validation of lead material parameters we used numerical and physical experiments of shooting the lead bullet into 10mm thickness lead plate in order to have only one unknown material, [11,12].

The values of elasticity modulus E, Puasson's ratio PR and mass density RO were considered as given above. The coefficients *C* (SRC)and *p* (SRP) of relationship (1), as well as, tangent modulus ETAN and parameter BETA were selected in order to obtain the simulation results close to experimental ones. The value of ETAN is known as 5.43E+07, however, our analysis demonstrated that the diminished value 1.5E+07 provides the adequate behavior of the model. The explanation for this may be that the contacting bodies are hot (the bullet is hot because of heat exchange in the rifle, and also the contact interaction releases considerable amounts of heat). Parameter BETA<1 determines the weight

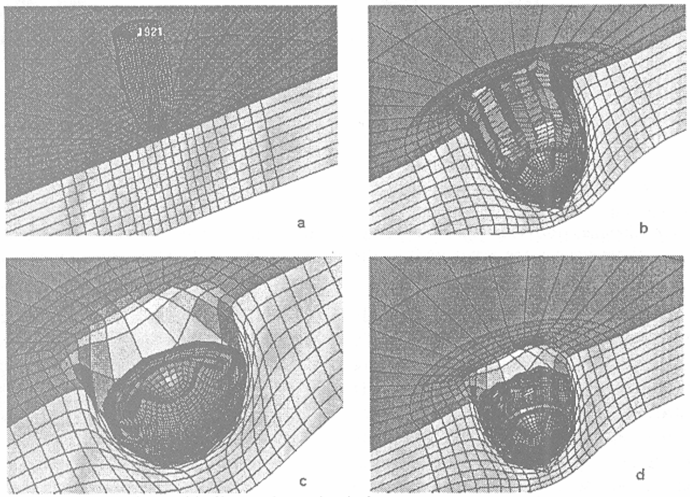


Fig. 7. Impact of a lead bullet against a lead plate:
a – initial position, velocity 270m/s;
b - final position (velocity 0) by using parameter BETA=0;
c - final position (velocity 0) by using parameter BETA=1;
d – final position (velocity 0) by using parameter BETA=0.2, satisfactory coincidence with the experiment

Table 1. Experimentally measured and numerically obtained values of geometric dimensions of the crater and of the bullet remains(see Fig.8)

D_k	d_k	h_k	h_i	D_{is}	h_{is}	m_l	D_v	h	l_v
13.27	9.34	1.82	13.34	14.89	4.77	2.36	8.93	9.75	3.03
-	11.00	-	11.30	19.00	3.20	2.23	10.2	9.40	3.80

Table 2. Parameters of lead material model used in LSDYNA (all units in SI)

Parameter	RO	E	PR	SIGY	ETAN	BETA	SRC	SRP
Value	11270	1.7E+10	0.4	8.00E+06	1.5E+07	0.1-0.2	600	3

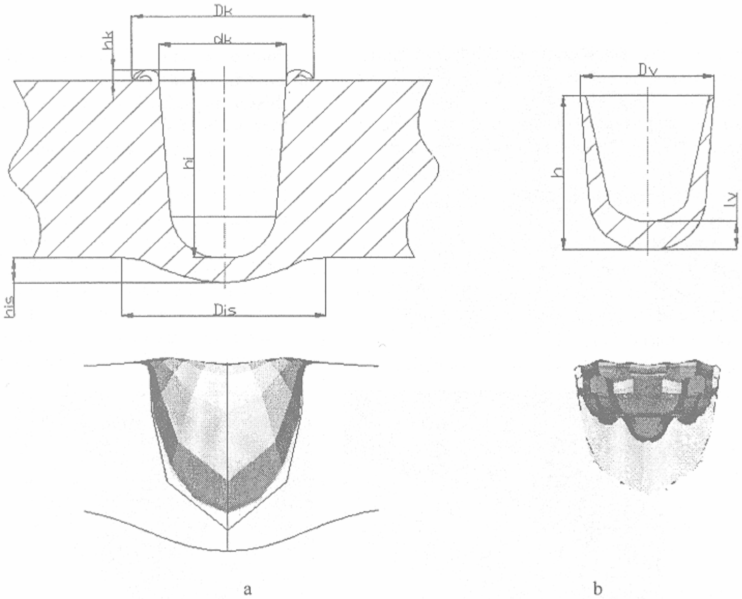


Fig. 8. Sketches (top) and simulated views(bottom) of the scheme of the experimentally measured dimensions of the crater made by the lead bullet in a lead plate (a) and of the remains of the bullet (b)

coefficient of kinematical hardening, and (1-BETA) gives the amount of the isotropic one. We chose BETA=0.2 value ensuring the hardening law closer to isotropic in order to get the results close to experimental. The choice of the type of hardening law may influence the results dramatically, Fig.7. Fig. 7a presents the original shape of the bullet and Fig.7,b,c,d demonstrate and deformed shape of the bullet imbedded into the plate by using three different values of BETA. The situation in Fig.7d with BETA=0.2 is in the best coincidence with experimental dimensions measured according to the scheme presented in Fig.8. Table 1 presents experimentally measured and numerically obtained values of geometric dimensions of the crater and of the bullet remains. The lead material parameters used in this calculation are presented in Table 2.

3.3 Simulation of the impact of a bullet against a multilayer textile package

Numerical simulation of the interaction process of a bullet against the multilayer textile package has been performed by using a combined woven structure - membrane model and two models of a bullet. The obtained results indicate that the ballistic strength of the fabric package mainly depends on the number of textile layers and friction coefficient between the bullet and the fabric. The bullet holdup effect increases as the friction coefficient between layers is increased and when friction coefficient between the bullet and the textiles is decreased;

Fig.9,a-d demonstrates the still images of the interaction process between the BALLE22 lead bullet and 12 layers fabric package where only static material characteristics of paraaramid are employed by assuming C=0, p=0.

A series of numerical experiment results demonstrate that by employing only statically determined characteristics of materials the strength of the multi-layer textile package is obtained less as it is observed in reality. The direct way to improve the adequacy of the model is to assume the dependency of yield and strength limit against the strain rate as in formula (1). The key tab is that the static characteristics of the materials are known. For the sake of simplicity we assume p=1 and change only the value of C . The results close to experimental have been obtained when C=100000 – 500000. However, more detailed

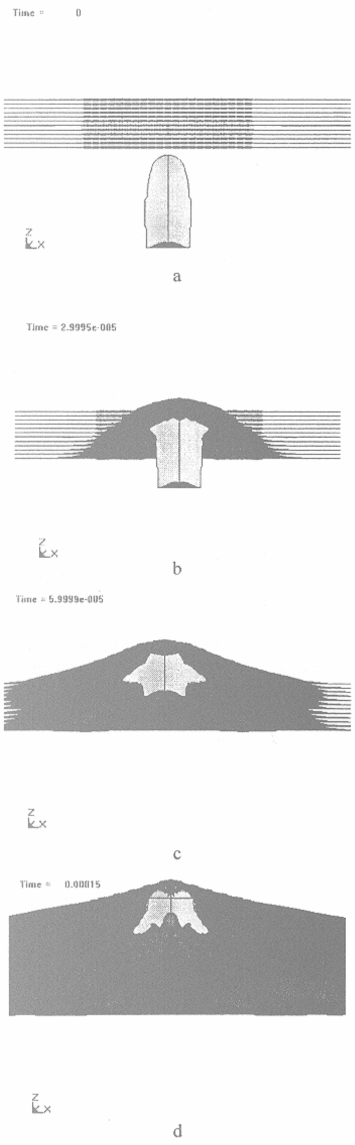


Fig.9 The hold-up of a lead bullet BALLE22 in the 12 layer fabric package.

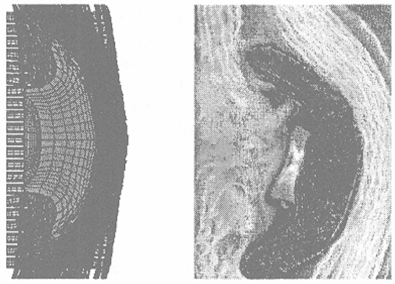


Fig. 10 Impact of a full metal jacket bullet against the multilayer fabric (bullet stopped): (a)–simulation; (b)-experiment (photo taken from the circular of Twaron textiles).

analysis and the comparison of the numerical results against the results obtained from the case-oriented experiments is necessary. Fig.10 illustrates the obtained simulation and experimental results when shooting a 9mm full metal jacket bullet against the multilayer fabric package.

4. Conclusion

The finite element analysis of the interaction process of the paraaramid multilayer fabrics against 9mm bullets has been performed in LSDYNA by taking into account real geometries and deformability of interacting parts. The size of the model was reduced to reasonable dimensions by presenting the yarns in the woven fabrics structure as narrow bands of a prescribed cross-section. It has been demonstrated that for obtaining models close to reality it is not sufficient to use the material properties determined by static or quasi-static experiments only. The model can be improved by scaling the yield stress limit subject to the strain rate value.

The process of shooting-through one fabric layer has been simulated and the combined model consisting of a woven patch tied to a uniform membrane has been proposed. In order to quantify the differences between the results obtained by using the woven structure and combined models the relative cumulative wave propagation speed error has been employed. Though the obtained error values were not small (~10-20%), the resultant displacements and impact wave front obtained by using the combined model were close to the results obtained by using the reference model. The main advantage of the combined model compared with the full woven structure model is the increased computational efficiency. The lead bullet against lead plate impact simulation and physical experiments have been performed in order to determine the material parameters ensuring adequate behavior of the model.

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