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Finite Element Analysis of Ballistic Properties of a Multilayer Textile Package in LSDYNA

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A finite element model for paraaramyde Twaron multilayer fabrics package structure has been developed in order to simulate the shooting-through test and to clarify the process taking place during the mechanical contact interaction between the package and bullet. The simplification of the model has been obtained by means of "mezzo-mechanical" approach which avoids the direct modeling of filaments that comprise a yarn. Instead, yarns have been modeled by using thin shell elements the thickness of which represents the real thickness of yarns which can be measured in the weave. Bending stiffness has been eliminated by selecting a single integration point over the shell height because in reality it is expected to be very small due to the multi-filament structure of a yarn. The interaction model consists of a small sheet of a woven structure that comes into mechanical contact with an elastic-plastic model of a bulled moving with high velocity. Basing on the data obtained during uniaxial tension experiments, the Twaron material is assumed to be elastic up to its failure limit. The influence of different boundary conditions, number of layers in a package and inter-layer friction has been examined. The simulation has been performed by means of the LSDYNA software.
Keywords: multilayer package, finite elements, explicit modeling, LSDYNA.

INTRODUCTION

The clothes ensuring the ballistic protection must be designed in a way that their ballistic strength considerably exceeds the rates intended in regulating standards and ensures the required protection level. For the estimation of the ballistic safety the worldwide spread USA standard NIJ 01.01.03 is employed. During the experiments the interception of a bullet by a multilayer package have been registered for a wide spectra of values of bullets' kinetic energies depending upon mass and velocity of a bullet, as well as, the type of a weapon. As a result of experimental investigations of numerous packages of different constitutions, optimization of package structures for each protection level and for different types of fabrics can be performed. The results obtained during the investigation of multilayer textile packages designated for bullet-resistant vests at the Lithuanian textile institute [1] imply that the protection level is defined by the following basic factors:

- yarns: the number of filaments comprising a yarn, linear density, maximum force and elongation, stiffness modulus;
- fabrics: weave type, surface density, isotropy of the weave, tensile characteristics, trimming;
- fabrics package: number of layers and their interconnection technique.

The quick rise and variety of new materials on the market [2] promotes the further theoretical and experimental investigations of fabrics packages by establishing their regularities and relationships. The design of the structure of a multilayer package can be significantly facilitated by the deeper understanding of the behavior of a single fabric layer and interaction of several layers with a bullet that can be carried out by computer simulations. The results could expedite the selection of a structure of a package designated for ballistic tests and simultaneously decrease the expenditures needed for optimization of packages made of fabrics of different surface density and different constitution.

The ballistic protection clothes undergo the high velocity contact-impact interaction. The theoretical publications in this field of research are not very abundant at the moment [3]. The results of fundamental investigations dealing with the high velocity impact mechanics of metals and composites [4] are of interest as they present the basic properties of propagation of elastic and elastic-plastic shock waves the principles of which can be applied to the design of multilayer textile packages. Already in the work [4] issued in 1992 the attention has been paid to the numerical simulation of the impact interaction and great opportunities and perspectives for computational mechanics have been predicted in creating and investigating close-to-reality mathematical models.

The very high velocity contact interaction problems are among the most complicated in computational mechanics. The failure processes that follow the interaction are initiated in micro-volumes considerably smaller than the measurements of the interacting bodies. It is practically impossible to model the behavior of the material at the micro-level – the number of degrees of freedom of such a model would be too large and unrealistic for computer resources nowadays and probably

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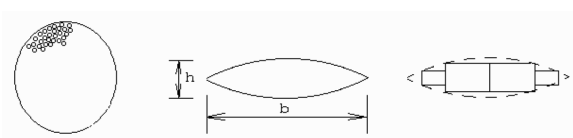
in the nearest future as well. In practice, usually the computations are performed by using macroscopic material models that approximately describe real processes taking place in the material. In [5] and [6] real and numerical shooting-through experiments are presented for the Nextel fabrics and the Kevlar-epoxy shield. The micro- and mezzo-mechanical models have been used to simulate the behavior of small specimens, and by comparison of the numerical results with experimental data the material model characteristics have been found. The stiffness coefficients were used for determining the deviatoric stresses and by means of the equation of state the relationship between the pressure and volume change was established. Further computations have been performed by using the macro-mechanical model where a layered structure has been presented as the porous continuum. It enabled to disregard the real geometry of the weave and to present the averaged strength parameters of the fabrics. The resulting model was axisymmetric, of reasonable dimension, and the obtained results were satisfactorily close to experimental ones.

The aim of this work is to develop the finite element computational model for the single Twaron fabric layer and for a multilayer package in order to investigate the ballistic impact made by a bullet. We follow the terminology used in [5], [6] and develop a mezzo-mechanical model that allows to consider the geometry of the weave explicitly.

THE MODEL OF A SINGLE FABRIC LAYER

The textile packages of bullet-resistant vests created at the Lithuanian Textile institute consist of the multilayer fabrics made of paraaramyd Twaron yarns. The number of layers can be different depending upon the protection level of a vest.

Each layer of a fabrics is made of yarns of a certain linear density which are woven together. Each yarn in its turn consists of filaments the number of which can vary from several hundred to several thousand. The model of a fabric at the level of filaments is unrealistic because of limited computer resource, so we developed 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.



.a b c

. **Fig.** 1. Cross-sections of yarns
a - circular cross-section of a free yarn;
b - cross-section of an interwoven yarn approximated by two circular segments;
c - cross-section of an interwoven yarn approximated by rectangular cross-sections of four shell elements

It s commonly accepted that the cross-section of a free yarn which is not interwoven into a fabric is close to a circle made of cross-sections with a certain number of individual filaments (Fig.1a). In fabrics the yarns are compressed because of forces acting in overlapping areas. As a result, the geometry of the cross-section changes depending upon the constitution of a yarn, density, type and technological parameters of a weave, etc. After the examination of the cross-section of the yarn extracted from the Twaron fabrics, we assumed it to be close to the combination of two circular segments (Fig.1b). The dimensions of the circular segments comprising the cross-section are calculated on the basis of the given characteristics of the fabrics, e.g., the height and length of the Twaron yarns in the fabric CT709 are b = 0.952mm and h = 0.15mm, the density of the material is 1440kg/m^3, and the stiffness modulus in extension is 90GPa.

The cross-section of a yarn interwoven into a fabrics has been modeled as shown in Fig.1c. As its height is much smaller than the width, we used four shell elements the thickness of which were selected in order to fit two circular segments form.

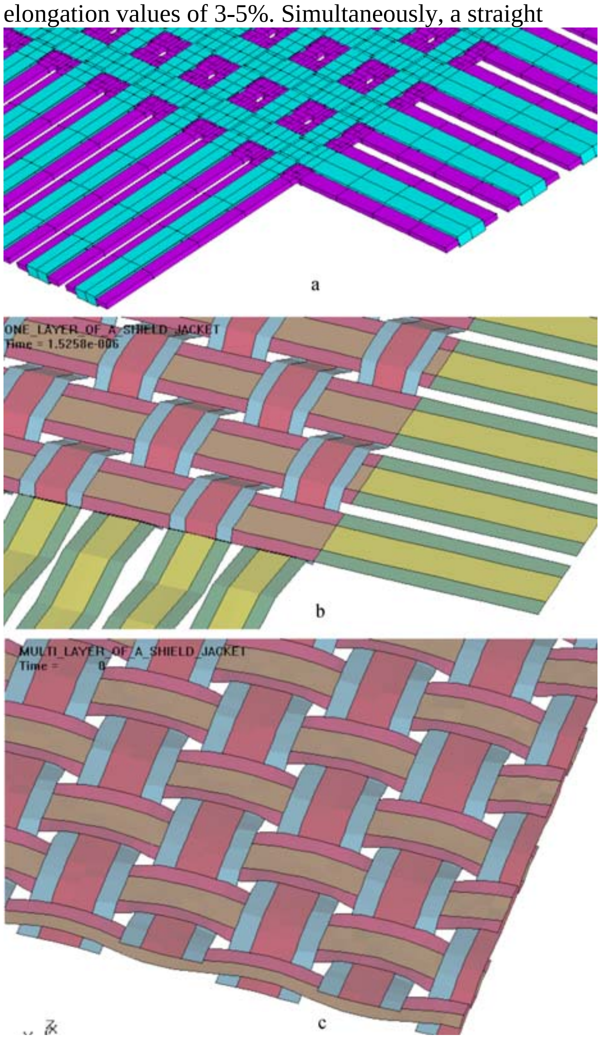
The bending stiffness of a yarn we assumed to be negligible. In order to eliminate the bending stiffness in LSDYNA, we used the Hughes-Liu shell with single integration point through the thickness of the element (*SECTION SHELL,,ELFORM=11,,NIP=1). So actually we assumed that a multi-filament yarn is made of three thin bands connected together the middle one of which is presented by two elements across its width. In this way our model of a yarn retains the shear and bending stiffness in the plane of the fabric. Probably a real yarn has very small values of the latter as well, however, there is no possibility to eliminate them from shell elements.

The finite element model of a single layer of a yarn is obtained as follows:

- the yarns presented by four shell elements over their diameter are situated in the plane xOy, Fig.2a;
- by prescribing the displacements, the Ox directed yarns (the warp) are elastically deformed by moving their nodes in the direction Oz perpendicular to the plane of the layer in order to situate the Oy directed yarns (the weft) between the warp yarns, Fig.2b;
- after activation of LSDYNA contact search *CONTACT_AUTOMATIC_GENERAL, the yarns of the model are being left in the free condition to come to the elastic equilibrium. As a result, a structure similar to the real fabric is obtained in the same way as the warp and the weft yarns are flexed in fabric production, Fig.2c;
- after equilibrium is obtained, the elastic stresses and strains are being artificially removed in order to imitate the relaxation of stresses in real multi-filament yarns;
- in further analysis, the influence of possible deformation of the cross-section of a yarn can be evaluated to some extent by assuming the LSDYNA scale multiplier for the slave contact stiffness less than unity.

The obtained model of a fabric is able to present some important features and processes taking place in reality, e.g., the mobility of one yarn system with respect to the other and small shear stiffness of a fabrics in its plane.

The stress-strain relationship and failure force are calculated in the warp and weft directions. The elongation of fabrics in tension consists of two components: the elongation caused by rectification of yarns and their tensile elongation. As the strain-stress relationship of the Twaron material remains practically linear up to the tensile failure limit, the longitudinal strain can be measured as σ/E, where σ - the traction applied to the yarn, E - the Twaron stiffness modulus. The relation of this rate against the relative elongation $\hat{\varepsilon}$ of the fabrics obtained by employing the one fabrics layer finite element model described above is presented in Fig.3. The obtained theoretical relationship is close to experimental results. The results of specimens' tensile testing shows that failure takes place at the elongation values of 3-5%. Simultaneously, a straight



. Fig. 2. The finite element model of one layer of fabrics:

a- The warp and weft yarns are situated in the plane xOy. Contact interaction is being ignored;

b- The warp yarns are elastically displaced in the direction perpendicular to the fabrics plane in order to imitate the formation of gapes;

c- After activating the contact search in LSDYNA, the previously deformed yarns are being left in the free

Twaron yarn fails at 3 percent elongation. By selecting a proper value of the scale multiplier SFS for the slave contact stiffness in the range between 0.01 and 1 we can control the shape of the curve of the above mentioned relationship and make it closer to the experimental one. Fig.3 presents the relationships obtained by simulation of one fabrics layer at different values of the SFS coefficient.

In this work the developed model of a single fabrics layer was used for the analysis of the multilayer textile package of the bullet-resistant vest. It enables to simulate the failure caused by impact loads similar to the loads the fabrics undergoes during a shot.

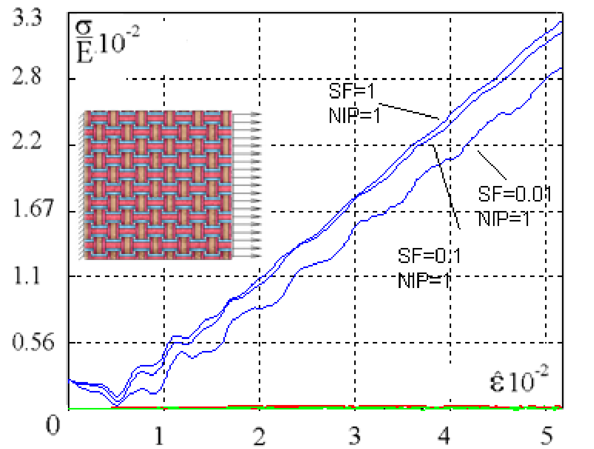


Fig. 3.The relationships of the longitudinal strain σ/E in a yarn against the relative elongation $\hat{\varepsilon}$ of the fabrics in the warp direction at different values of the slave contact stiffness scale multiplier SFS

CONTACT INTERACTION MODEL

Geometry. In order to form a multilayer textile package by combining the woven structures of fabrics layers described above, the result of the single layer equilibrium analysis has been saved as <dynain> file by using *INTERFACE_SPRINGBACK_DYNA3D. The <dynain> information is multiplicated the number of times equal to the number of layers in a package. The ends of yarns are made longer, so that they stick out of the fabrics. They are used in order to obtain the necessary fixation stiffness along the fringe of the investigated model of the rectangular fabric piece. The idea is to have the boundary condition of the small piece of fabrics fixed at the fringe similar to that as in a real fabric package when the extent of fabric is much larger. Here we employ the following characteristics of the yarn ends: the length equals 15% of the linear dimension of the fabric and stiffness modulus 9Gpa comprises 1/10 of the yarn stiffness. The density value is artificially selected to be 144kg/m^3 in order to have the same wave propagation speed as in the main body of the yarn.

The finite element model of the 9mm bullet consists of the brass shell and solid lead stuff presented as two separate parts that are in contact interaction with each other. The brass shell is in contact interaction with the multilayer textile package. The view of the contact model symmetrical with respect to xOz and yOz planes is presented in Fig.4.

It is difficult to determine the contact friction law in complex interaction conditions between parts in this problem. For the sake of simplicity we employ the dry

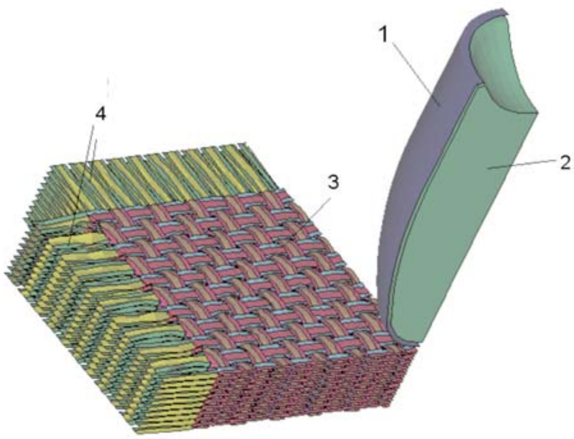


Fig. 4.The geometry of the contact interaction between sandwich cloth packet and the bullet in LSDYNA: 1- brass shell of the bullet; 2 – lead stuff of the bullet; 3 – sandwich cloth packet; 4 – elastic supports

friction law with the friction coefficient 0.5 and the structural damping ratio 0.75

Control of the time integration step. During the contact interaction process the elements of the fabrics, as well as, of the bullet are highly deformed and require to decrease the time integration step that in explicit integration techniques cannot be greater than the least time duration during which the elastic longitudinal wave passes the smallest element of the structure. As the simulation goes on, the time step tends to become shorter and solution may never end. We use the following methods to control time step size which are implemented in LSDYNA:

- artificial increase of the mass of shell elements that are causing the decrease of the time step under the prescribed limit;
- deletion of solid elements that are causing the decrease of the time step under the prescribed limit.

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

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

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 rate of deformation as [8]:

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

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

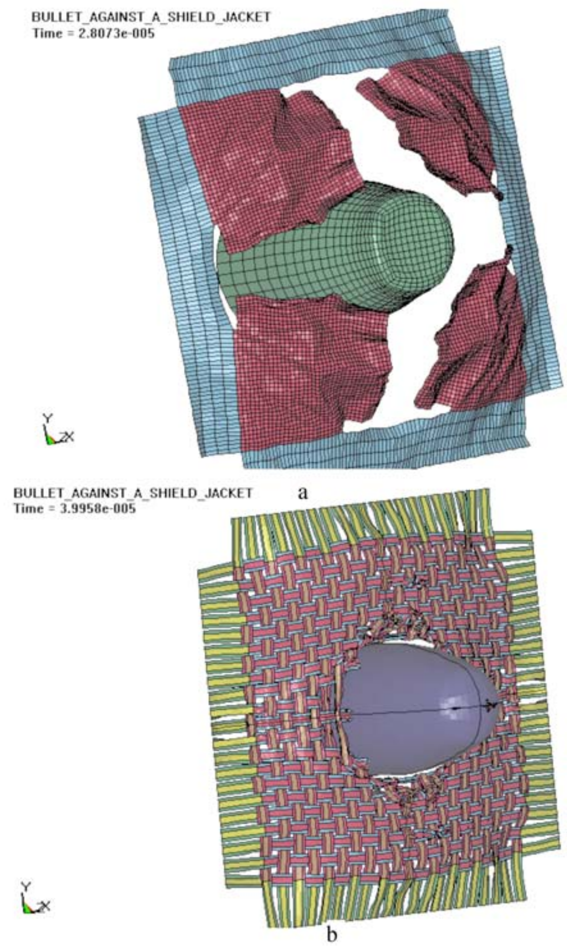


Fig. 5. Response of a single Twaron layer against the 9mm bullet:a - macro-mechanical model (cloth layer as continuous membrane); b - mezzo-mechanical model (individual yarns and weave presented)

RESULTS OF THE ANALYSIS

The analysis of the above described multilayer textile package interaction against the bullet model requires large amount of computer resource, e.g., the shooting through process through a 15 layers package of the size 20x20mm can be simulated in approximately 30 hours on Pentium IV 1.7MHz computer. It is very expensive to perform large amount of numerical experiments or to investigate the piece of fabric package of the size sufficient for comprehensive representation of the mechanical phenomena.

As the preliminary approach, it appears natural for evaluation of ballistic properties of the multilayer package to employ a simpler and much less expensive continuous membrane model that could be regarded as “macro-mechanical". The behavior of both macro- and mezzo-mechanical models in the shooting-through simulation is presented in Fig.5. The obtained results regarding the contact process and failure differ significantly in both cases.

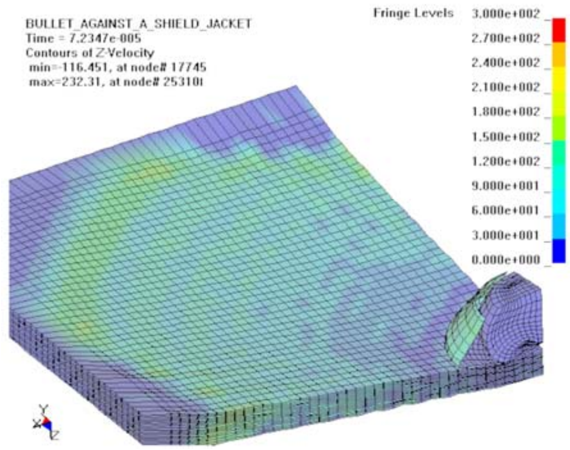
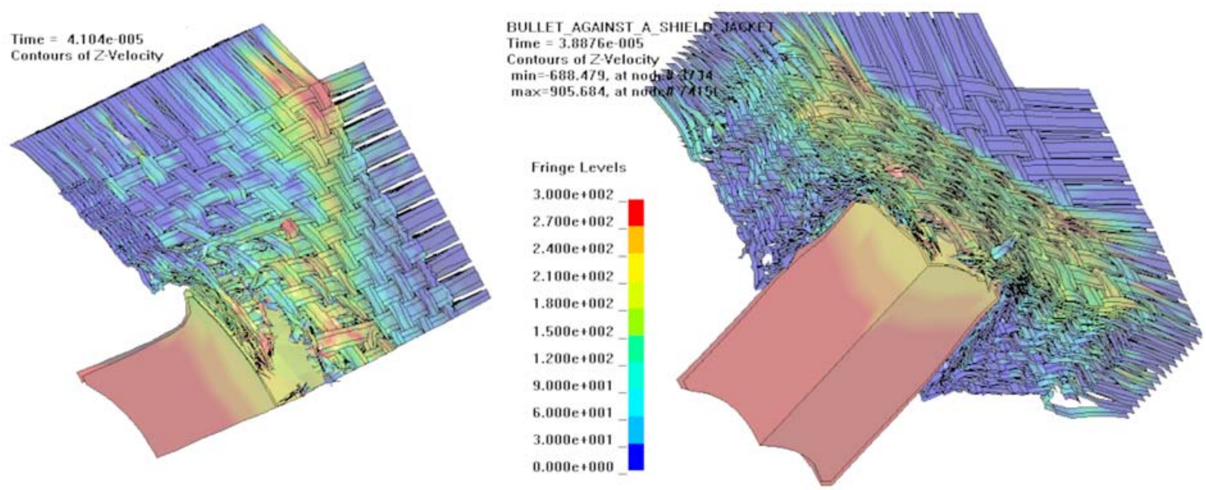


Fig. 6.Deformation of the simplified model of the multilayer fabric package and the bullet at the instant when the bullet stops: deformed geometry and velocities in the Oz direction. Each layer of the package is presented as continuous membrane

In the woven structure the failure of a yarn does not cause the quick propagation of the failure over all structure because the integrity of the fabrics is maintained by means of the unbroken yarns of the other system. The failure of the membrane can cause the quick propagation of the failure and resembles fracture with the sharp crack tip. The deformation of the tip of the bullet is much larger in interaction with the membrane model. However by increasing the structural damping of the membrane it is possible to localize the failure of elements in the vicinity of the interaction zone. The behavior of the tip of the bullet is also essentially different in the two models, as membrane appears to be much stiffer locally.

However, often is enough only to conclude if the package was shot through or not. In order to do this, as the first approach it is possible to work with much simpler "macro-mechanical" model where the material model and constants and, may be, some other parameters of the model are adjusted in a way that the results of a sample analysis of macro- and mezzo-mechanical models are close to each other. The reason is that the parameters at the mezzo-mechanical level we may consider as known – they are obtained from immediate experiments or taken as declared in material descriptions. The similar approach can be applied when establishing the equivalent characteristics of a yarn on the base of the micro-mechanical model representing individual filaments

Nevertheless, the results obtained from the macro-mechanical model have to be treated very carefully. In practice, the results depend not only on the model parameters, but also upon the size of elements. It is also unreasonable to use very small elements in membrane models as they imply a possibility to generate stress concentrations that do not take place in woven fabrics. Bigger elements reduce the stress concentration mathematically by smoothing the stress gradient. Obviously it is possible to select the element size that is "optimum" for a given application in the sense that it makes the structural behavior close to the response of the woven model. Fig.6 presents the deformation of the piece of fabric package and the bulled at the moment when the bullet is stopped (the initial velocity of the 9mm bullet was 300m/s). The result was obtained by using the macro-mechanical membrane model. The impact wave at the moment of the bullet stop has just reached the fringe of fabrics package, therefore we can see more or less the smallest possible size (80x80mm) of the piece the deformations of which have influence upon interaction process and its result. However, the failure of layers has not taken place in this analysis, and the depth of



a b

.**Fig. 7**. 9mm bullet moving at the velocity of 300m/s against Twaron sandwich cloth package(velocities in Oz direction): a - 10 layers, static friction coefficient between cloth layers and between a layer and the bullet equals 0.5; b - 15 layers, no friction between cloth layers and between a layer and the bullet. In the absence of friction the perforation strength reduces significantly

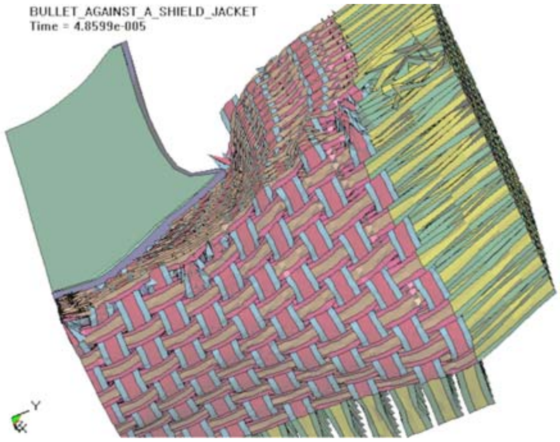


Fig. 8 .9mm bullet moving at at a velocity of 300m/s against a 15 layer Twaron sandwich cloth package. Static friction coefficient between cloth layers equals 0.5 and between a layer and the bullet equals 0. The perforation strength of the packet is higher than in the cases shown in Fig.7.

penetration is smaller as should be in reality.

Further numerical experiments were performed by using the woven yarns (mezzo-mechanical) model, Fig.7,8. Because of the limited computer resource the investigation was carried out on 20x20mm multilayer textile package. The model was supported elastically at the interaction process has been analyzed and the obtained results indicate that the interaction depends on:

- number of fabric layers. The 10-15 layer Twaron fabric package is shot through by 9mm bullet made of brass shell and lead stuff and moving at the velocity of 300m/s;
- friction coefficient between the bullet and the fabric and between layers of the package. The bullet holdup effect increases as the friction coefficient between layers is increased and when friction coefficient between the bullet and the fabrics is
- the touch stiffness between the piece of package and the bullet-resistant vest.

A series of numerical results demonstrate that by employing only statically determined characteristics of materials the obtained value of the multilayer textile package strength is 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 analysis and the comparison of the numerical results against the results obtained from case-oriented experiments is necessary.

CONCLUSIONS

The finite element analysis of the interaction process of the Twaron multilayer textile package of a bullet-resistant vest against the 9mm bullet has been performed in LSDYNA by taking into account real geometries of interacting parts and real material properties. The size of the model was reduced to reasonable dimensions by presenting the yarns of the fabrics as narrow bands of a prescribed cross-section.

This work can be regarded as primary stage of the model validation:

- the response of a single layer of the fabric to the uniaxial tension has been simulated and satisfactory coincidence of the obtained results against experimental ones has been demonstrated;
- the process of shooting-through of one layer of the fabrics has been simulated and the main differences between the responses of the woven yarn model and the membrane model have been demonstrated. The proper selection of model parameters enable to use the membrane model as the rough approximation, however, the obtained results depend on the element size and sometimes the model can work principally wrong. The woven yarn model is much more reliable in this sense;
- the holdup of a bullet and the shooting-through processes have been simulated;
- it has been demonstrated that for obtaining models close to the reality it is not sufficient to use the material properties determined by static or quazi-static experiments only. The model can be improved by scaling the yield stress limit subject to the strain rate value.

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