Multi-Scale Modelling of Textile Structures in Terminal Ballistics

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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 LS-DYNA. The bullet has been considered as a deformable body in contact with the fabric package presented by interwoven yarn structure. The model of the weave has been created by presenting the multifilament yarns by thin shell elements the thickness of which represents the real thickness of yarns.

The total model of the fabric has been developed by employing the multi-scale approach. The "woven" zone in the vicinity of the bullet impact has been joined with the uniform surrounding areas of textile presented by membrane elements. 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.

Keywords:

Terminal ballistics, Multi-scale modelling, Textile structures

INTRODUCTION

The rapid rise and variety of new textile materials on the market promotes the further theoretical and experimental investigations of fabric packages by establishing their properties and regularities. The design of multi-layer fabric packages (MLFP) serving as components of lightweight body armor can be significantly facilitated by means of deeper understanding of the behavior of a single or several fabric layers during their interaction with bullets. The results obtained from computer simulations 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 experimental investigations of ballistic interaction are complicated because of very large velocities, deformations and failure of interacting structures. Conventional experiments mostly provide integral characteristics of the processes such as the pre- and post-impact velocities, extent of final failure of the projectile and the target, etc. The main shortage of such kind of results is their inability to provide the insight into the interaction processes and to clarify transient dynamic processes and failure mechanisms taking place at the contact zone. During the last decade numerous researches have been carried out on the ballistic impact on high strength fabric structures [1,2,3,4].

This paper presents experience in developing a computational model of interaction of a deformable projectile (bullet) against a MLFP in LS-DYNA enabling to simulate shooting experiments performed in order to test the ballistic strength of the textile body armor. For the sake of reduction of the dimensionality of the computational model the mezzo- and macro- mechanical approaches have been combined together. The mezzo-mechanical approach is employed in order to present multi-filament yarns by means of shell elements. In this way the ballistic interaction zone is presented as a structure of interwoven yarns. The macro-mechanical approach is being used for modeling of the surrounding of the woven patch of a fabric as a uniform membrane.

THE ARCHITECTURE OF THE MODEL

The bullets used during the ballistic strength evaluation tests can be very different subject to the required safety level. In this study we employ the finite element model of the 6mm lead bullet BALLE-22 presented in Fig.1.
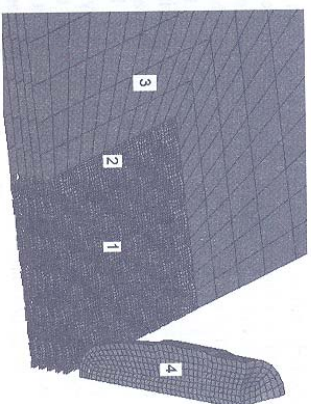
Fig.1. Woven structure model tied to the membrane model:
1- woven structure, material model with failure;
2- woven structure, no failure;
3- membrane zone;
4- bullet

Each fabric layer 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 model of a fabric at the level of filaments is 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 technique of obtaining the model of a woven yarn patch by using shell elements has been described in our recent work [5]. By using this technique the weave is obtained by solving the contact interaction equilibrium problem and is able to present the *warp* and *weft* yarns in the weave. The obtained model of a fabric is able to present the mobility of one yarn system with respect to the other and small shear stiffness in its plane.

In reality the de-crimping of yarns caused by the extension of the fabric is accompanied by the deformation of the cross sections of the yarns. It is necessary to note that the model of a yarn composed of shell elements is not able to present any further change of the thickness of a yarn caused by transverse forces perpendicular to the shell element. Consequently, the presented woven fabric model inherently has an enlarged tensile stiffness caused by lesser de-crimping of yarns as it is in reality. Nevertheless, an imitation of the through-thickness deformation in the model still may be achieved by selecting an appropriate value of the penalty stiffness coefficient that determines the magnitude of the repelling force when two surfaces are intending to penetrate into each other in the condition of a mechanical contact.

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 modelled 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 implemented 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 [6]. In LS-DYNA the finely and roughly meshed zones are connected by using the *CONSTRAINED_TIE-BREAK constraint, Fig.1. 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 algorithm of implementation of tied interface constraints in LS-DYNA 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.
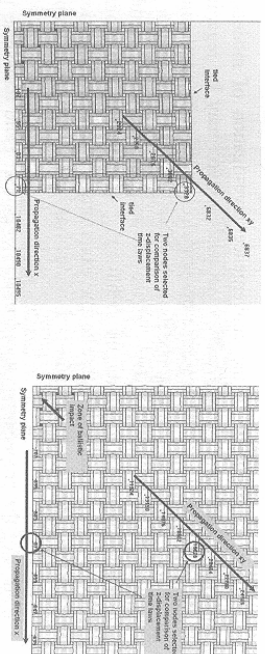
a

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 – fragmengt of the woven patch 60x60 yarns (reference model)

A uniform membrane-type surrounding of the woven patch cannot be expected to present an identical dynamic behavior 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. Two models of the fabric layer with different dimensions of the woven patch are built, Fig.2. 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 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 may 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 dynamic response of both models as close as possible to each other. In LS-DYNA 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 270-300 m/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. In our investigation the comparison of the dynamic behavior of the two models has been performed in terms of:

1. 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 line $y=x$, Fig.2;
2. Time laws of z displacement of two selected nodes;
3. Time instant of initiation of failure of the fabric.
4. Time instant of full perforation of the fabric.

The displacements and wave fronts obtained by using 10x10 woven yarn model are close to the results obtained by using the reference model as can be observed from the results presented in Fig.3. Our investigation demonstrated that it is hardly possible to select the membrane material properties ensuring very good approximation to the woven structure behaviour 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.3, 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 LS-DYNA).
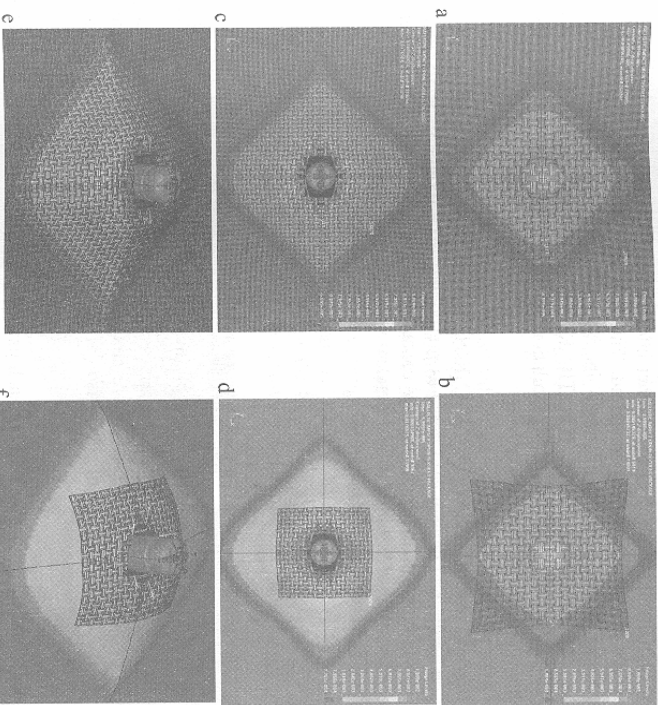
a b
c d
e f
g h

Fig.3 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.

MATERIAL MODELS

The materials taking place in the contact interaction of a bullet against the multilayer fabric are the lead and the pararamid. The lead is an elastic-plastic material, and pararamid is perfectly elastic up to its failure limit. Only two material models: *MAT_ELASTIC and *MAT_PLASTIC_KINEMATIC are used in this analysis. *MAT_ELASTIC during all the calculation is maintained only for yarn elements neighboring to membrane region.

For the lead material *MAT_PLASTIC_KINEMATIC is used with elasticity modulus, Poisson's ratio and density considered as prescribed. 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 Cowper-Symonds material model [6]:

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

(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. Constants C, p and the tangent modulus of the lead, as well as, failure strain of pararamid at high strain rates are finally specified on the base of comparison of the results of properly planned numerical and physical experiments.

The dry contact friction law between each pair of contacting fabric layers and between yarns interacting in the weave is assumed. The value of the friction coefficient exhibits a marked influence upon the interaction behavior. The procedure of determining the friction coefficient values and argumentation on this issue is discussed further in the text.

MODEL VALIDATION AND RESULTS

The adequacy of the obtained results to reality is a highly important question in any simulation. A series of case oriented experiments has been performed in order to determine the model parameter values step by step. The basic experiments we made in order to validate the model were as follows

a. Shooting a lead bullet against the 10mm thickness lead plate thus considering a problem with only one unknown material – the lead;

b. Shooting a lead bullet against a single fabric layer. The properties of the bullet model having been determined during the previous step, now again we had single unknown material – the pararamid weave, friction coefficients of which could be determined;

c. Shooting a lead bullet against a MLFP. The experiment provided the data enabling to qualify the correction of the pararamid failure strain value for the range of strain rates corresponding to ~300m/s impact.

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. The data obtained from the physical experiment were the measured linear momentum supplied by the bullet to the plate and the deformed shape of the bullet imbedded into the target. The obtained values of material parameters were obtained by revealing material parameters responsible for this or that feature of the solution rather than by simply trying 'mixes' of parameters. For example, the geometrical shape of the highly deformed bullet is mainly dependent upon coefficient BETA defining the relative contributions of isotropic and kinematic hardening of the material, Fig.4.
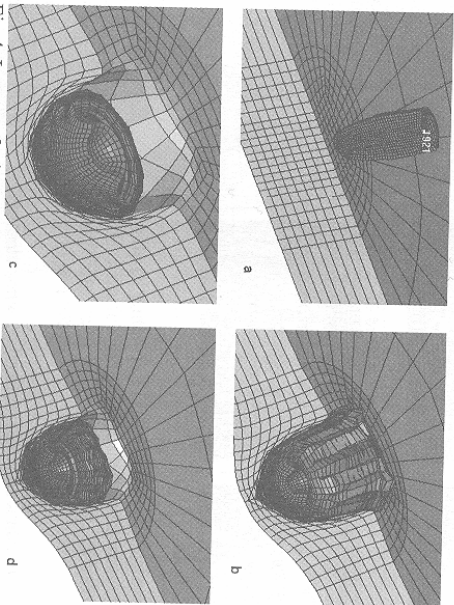

Fig.4. Impact of a lead bullet against a lead plate:
a – initial position, velocity 270m/s;
b - final position (velocity 0) by using parameter BETA=0;
c - final position (velocity 0) by using parameter BETA=1;
d - final position (velocity 0) by using parameter BETA=0.2, satisfactory coincidence with the experiment

As an experiment for validation of material parameters of the fabric we used numerical and physical experiments of shooting the lead bullet through the single layer of the fabric. As the lead bullet material parameters have been already determined, only the fabric structure parameters remain to be qualified during this model validation step. As a base assumption we used the purely elastic paraaramid material properties to the failure limit. This is a well-known experimental fact obtained by static tests of paraaramid yarns. The values of elasticity modulus E, Poisson's ratio PR and mass density RO were considered as prescribed. The elastic failure limit of the material is modeled by assuming the plastic material with failure strain 0.04.

The parameters values to be determined by comparing the computed results against the experimental ones are the yarn-to-yarn sliding friction coefficient FSs and bullet-to-yarn sliding friction coefficient FSk between the yarns of the woven structure and the surface of the bullet. For the sake of simplicity we do not introduce additional parameters specifying the dependency of the friction coefficient against the velocity of sliding. It should be noticed that the established parameters are valid only for the range of velocities taking place at ~300m/s ballistic interaction.

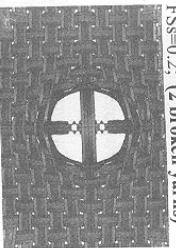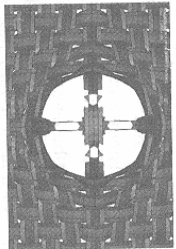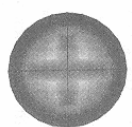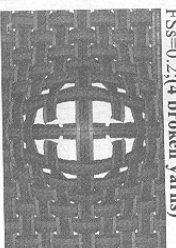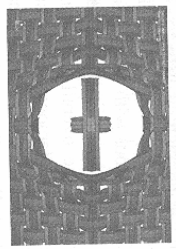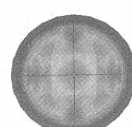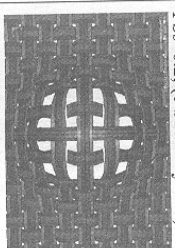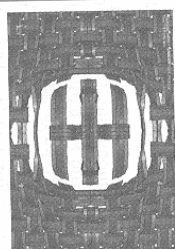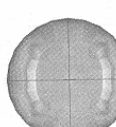| FSk	Pattern of broken yarns at the moment of initiation of the failure of the fabric	Pattern of broken yarns at the moment of full perforation	Pattern of plastic deformation zones on the tip of the bullet
0.	FSs=0.2; (2 broken yarns)		
0.1	FSs=0.2;(4 broken yarns)		
0.2	FSs=0.2; (6 broken yarns)		

Fig.5. Computed patterns of broken yarns at time moment of initiation of failure (a), full perforation (b) and the plastic deformation of the bullet (c) at yarn-yarn friction coefficient value FSs=0.2 and three different values of the yarn-bullet friction coefficient FSk.

Fig.5 presents some computed results obtained by using the value of friction coefficient FSk=0.2 and three values of friction coefficient FSk=0, 0.1 , 0.2. The geometrical patterns of the yarn structure at time moments of the initiation of the fabric failure and at full perforation of the fabric, as well as, final plastic deformation pattern on the tip of the bullet are presented. They should be regarded as only characteristic sample situations. Much more computations have been performed during this investigation. The

comparison of the results indicated that perforation of the fabric model by breaking 4 yarns (it is the most often observed case in the reality) is possible in quite narrow range of values of friction coefficients as $0.1 < FSk < 0.2;\quad 0.1 < FSs < 0.2;\quad FSs + FSs < 0.3$.

SIMULATION OF THE IMPACT OF A BULLET AGAINST A MLFP

Numerical experiments of the bullet and MLFP interaction have been performed. The friction coefficient between two layers of fabric have been used the same as obtained in the previous section for yarn-against-yarn sliding interaction. Very probably the values of friction coefficients between the membrane zones of the model are not of primary importance. The frictional interactions between layers at zones distant from the impact point may be considered as weak because of initial clearances between the layers of the free-fabric package. Comparisons with the physical experiment have been performed at 'integer' level by evaluating the ability of the package to hold up the bullet. However, the results are realistic as the overall MFLP model is constructed of the parts the dynamic behavior of which demonstrates a satisfactory coincidence with the test experiments. The obtained results indicate that 10-12 layered pararamid MLFP package is nearly at the ballistic limit against a 6mm lead bullet moving at 300m/s. The bullet hold-up effect decreases as the friction coefficient between layers is decreased (e.g., when the humidity of the environment increases).

The experiment results demonstrate that by employing only statically determined characteristics of materials the strength of the multi-layer textile package is obtained somewhat less than it is observed in reality. The direct and simple way to improve the adequacy of the model to reality is to assume the dependency of yield (failure) limit against the strain rate as in formula (1). The key is that the static characteristics of the material are known and the material is elastic up to its failure limit. In our model we took into account the increase the yield limit of the material due to high interaction velocity failure strain simply by increasing the failure strain to 0.046 (the static experiments indicate the value 0.04). However, more detailed analysis and the comparison of the numerical results against the results obtained from case-oriented experiments are necessary.

CONCLUSION

The finite element analysis of the interaction process of pararamid multilayer fabric packages (MLFP) against a 6mm bullet has been performed. The main goal of the presented study was to develop a workable model suitable for simulation of the ballistic

interaction of MLFP of real dimensions by employing moderate computer resources and with satisfactory level of adequacy.

The modeling results provide a good insight into the passage of the ballistic interaction process in textile body armor. The adjustment of model parameters in order to obtain a satisfactory match against the experiment can be regarded as a primary stage of model validation. Numerical and physical experiments have been performed in order to determine the dynamic material parameters of the lead bullet ensuring adequate behavior of the model. The modeling results of shooting-through one fabric layer have been compared against the experiment in terms of the pattern of broken yarns and plastic deformation of the tip of the bullet. The range of realistic values of yarn-yarn and yarn-bullet sliding friction coefficients of the model have been found.

The presented research suggests prospective directions of the research of the ballistic response of free-fabric structures, such as further improvement of multi-filament yarn model, ballistic interaction analysis by taking into account the biomechanical properties of human body protected by the textile packages, etc.

ACKNOWLEDGEMENT

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