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SELECTED ASPECTS OF NUMERICAL ANALYSIS OF LAYERED FLEXIBLE STRUCTURES SUBJECTED TO IMPACT OF SOFT CORE PROJECTILE

The aim of the study is to identify the relevant aspects of numerical analysis of impact of projectiles with soft cores into a package composed of thin flexible plies located on the plastic backing. In order to illustrate the problem, normal impact of 7.62 mm TT projectile into an unclamped package comprising 36 plies of Dyneema SB71 supported on the plastic backing was selected. The problem was solved with the use of the finite element method (FEM) with the explicit integration scheme (central difference method) of motion equations in the matrix form. Based on the conducted numerical computations, it was revealed that obtaining the extreme deformations of a projectile soft core and the backing material in Lagrangian description requires employment of adaptive methods. The proposed R-adaptive method performs its role but must be used carefully due to the mass loss which may appear during calculations.

1. Introduction

The subject of the study is to identify the relevant aspects of numerical analysis of impact of projectiles with soft cores into a package composed of thin flexible plies located on the plastic backing. Nowadays, it is extremely difficult to overestimate the importance of modeling methods and computer simulations to solve problems of terminal ballistics. Nevertheless, in certain cases, unexpected difficulties may appear. Numerical analyses of problems in the field of solid mechanics are dominated by Lagrangian material description. In many cases, the finite element method (FEM) commonly used in construction analysis is also selected for solving problems in the area of penetration/perforation of a ballistic shield with kinetic projectiles. A material

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description implies serious problems when a soft core of the projectile and/or plastic backing undergoes extreme deformation during the impact. The techniques used to deal with such cases, operating under the name of numerical erosion (removal of excessively deformed finite elements from calculations), known from crash analyses [1] or analyses of the penetration/perforation of hard components by projectiles with brittle cores [2] should not be used. Numerical erosion applied to the soft core or plastic backing may result in a significant change of final solution understood as a deformation form of the core or the maximum depth of depression in the backing as well as its diameter. Meanwhile, the depth of depression is a fundamental measure of effectiveness of a ballistic package used in the body armor in a number of normative documents, e.g., PN V 87000 2011, NIJ 0101.06.

Tools accessible in the field of CAE propose alternative methods to solve problems of solid mechanics with extreme deformations. The most far-reaching thesis suggests abandoning the Lagrangian description for the Eulerian one, which is a natural choice for the analysis of fluid dynamics [3]. Unfortunately, the obtained benefit allowing any deformation to be expressed is achieved with additional problems related to the description of contact interaction between the components of the physical system and the description of mass, momentum and energy transport between the neighboring finite elements, the so-called advection, which is not included in Lagrangian description. The other approach assumes the use of ALE (Arbitrary Lagrangian-Eulerian) description in combination with smoothing which is a technique of numerical mesh quality correction. Unfortunately, this method proved to be unreliable in the case of projectile mushrooming. None of the available kind of smoothing was able to cope with increasing deformations of finite elements near to the core beating. The last possibility, which is at the same time the subject of the work, is to use a cyclic recurrent procedure of numerical mesh rebuilding, the so called R-adaptive method. The physical and mechanical parameters after generation of a new mesh are determined on the basis of the previous data and the least squares method. Accessible computing systems (e.g. LS-Dyna) allow the use of R-adaptive technique only for solid elements with tetrahedral topology. The drawback of this solution is a noticeable mass loss when the frequency of mesh rebuilding and a permissible size of elements are too high. This fact is also reflected in the global energy balance. The consequence of the mentioned disadvantages is the necessity to control and keep the mass loss at an acceptable level.

2. Problem formulation

In order to illustrate the problem described above, normal impact of 7.62×25 mm TT projectile into an unclamped package composed of 36 plies of Dyneema SB71 and supported on the plastic backing was selected. The initial velocity of the projectile was assumed to be 420 m/s. The scheme of the problem is shown in Fig. 1, where the basic dimensions: length of projectile, thickness of ballistic package, depth and width of backing are equal to 14 mm, 8.2 mm, 76.5 mm and 95 mm, respectively. Ballistic Plasticine, with the trade name Roma NO. 1, was used as the backing material.

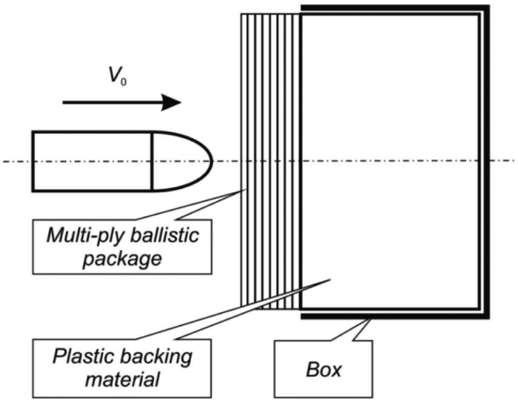

Fig. 1. Scheme of physical system

3. Description of numerical model

To solve the problem, the finite element method (FEM) with the explicit integration scheme (central difference method) of equations of motion in the matrix form was used. Implementation of FEM available in the commercial software LS-Dyna [4] and software tools for pre- and post-processing as TrueGrid and LS-PrePost were planned to complete the above formulated task. Solid and shell finite elements were used to mesh geometry of the physical system.

The Johnson-Cook (JC) in both a standard and modified form (MJC) as well as Gruneisen equation of state (EOS) were used to describe the mechanical response of metallic materials. This model is typically applied in the study of explosive metal forming, armor perforation and impacts, so the situations that are accompanied by high strain rate deformations. In the calculation of the yield stress, the JC model takes into account plastic strain,

strain rate and the thermal effects. The yield stress according to the MJC constitutive relation is expressed by the following formula:

$$\sigma_y = \left(A + B\varepsilon_p^n\right)\left(1 + \dot{\varepsilon}_p \big/ \dot{\varepsilon}_0\right)^C \left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right]. \tag{1}$$

And the standard form of the JC model is described by the equation:

$$\sigma_y = \left(A + B\varepsilon_p^n\right)\left[1 + C\ln\left(\dot{\varepsilon}_p \big/ \dot{\varepsilon}_0\right)\right] \left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right]. \tag{2}$$

The necessary parameters are taken from the literature, in particular from the work of Borvik [5] and Adams [6]. These values are included in Tables 1 and 2 for the lead alloy and the steel used to build the projectile's core and jacket respectively.

Table 1.

Constitutive data for modified Johnson-Cook model (MJC) [5]

Parameter	**Symbol**	**Units**	Lead PbSb10
Component			Projectile's core
Density	ρ	g/cm^3	10.1
Young's modulus	E	GPa	18.4
Poisson's ratio	ν	–	0.42
Specific heat	C_p	J/kgK	124
Taylor-Quinney coefficient	χ	–	0.9
Thermal expansion coefficient	α	1/K	2.9E-5
Reference strain rate	$\dot{\varepsilon}_0$	1/s	5E-4
Melting temperature	T_m	K	760
MJC parameters	A	MPa	24
	B	MPa	40
	n	–	1
	C	–	0.01
	m	–	1
Cockcroft-Latham failure parameter	W_c	mJ/mm^3	n/a

In turn, the material model of laminated composite fabric was employed to describe behavior of Dyneema SB71. In summary, the selected model is a linear elastic material model bounded by a failure surface in the form of Hashin failure criteria [8]. The material model addresses the non-linearity

Table 2.

Constitutive data for Johnson-Cook model (JC) [6,7]

Parameter	**Symbol**	**Units**	Steel
Component			Projectile's jacket
Density	ρ	g/cm^3	7.85
Young's modulus	E	GPa	207
Shear modulus	G	GPa	79.6
Poisson's ratio	ν	–	0.3
Specific heat	C_p	J/kgK	486
Reference strain rate	$\dot{\varepsilon}_0$	1/s	1
Melting temperature	T_m	K	1811
JC parameters	A	MPa	250
	B	MPa	175
	n	–	0.36
	C	–	0.022
	m	–	1.0
Gruneisen EOS parameters	c	m/s	4570
	S_1	–	1.49
	γ	–	1.93
	a	–	0.5
Failure parameters	D_1	–	–0.8
	D_2	–	2.1
	D_3	–	0.5

observed in the material response by off-axis material orientations. It assumes that deformation in the material introduces micro cracks and cavities causing stiffness degradation leading to nonlinear deformation [9].

The Dyneema single ply was modeled as six UD layers with configuration 0°/90°/0°/90°/0°/90° according to its real structure. The elastic and strength parameters of the single UD layer were presented in Table 3. These values were obtained by the experimental investigation.

The model of isotropic material with piecewise linear plasticity was selected to represent the properties of the backing. The flow curve for gray Plasticine [10], shown in Fig. 2, was taken as $\sigma_y(\varepsilon)$ curve for backing material.

Initial conditions included the natural state of the physical system and initial velocity of the projectile which was equal to 420 m/s. Boundary con-

Table 3.

Constitutive data for single ply of Dyneema SB 71 – experimental data

Parameter	Symbol	Units	Value
Density	ρ	g/cm^3	0.975
Young's modulus fiber direction *a*	E_a	GPa	100
Young's modulus transverse direction *b*	E_b	GPa	1
Poisson's ratio *ba*	ν_{ba}	–	0.0
Shear modulus *ab*	G_{ab}	GPa	5
Fiber direction tensile strength	X_T	GPa	1.8

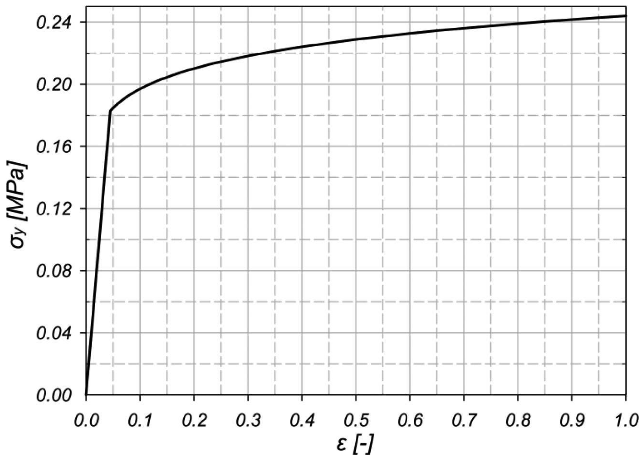

Fig. 2. Flow curve for backing material

ditions ensured the support of the system by fixing the bottom of the box and a description of contact interaction between parts of the physical system. A penalty-based approach with the contact stiffness scaled with respect to mass was used to model the contact problem. The contact algorithm detects penetration of one segment into another segment and then applies penalty forces to the segment nodes. The intensity of this force is proportional to the penetration depth.

The R-adaptive method was applied to the core of projectile and top part of backing material.

4. Discussion of results

The final maximum depression formed in the backing and the number of perforated layers were considered as a quantitative result. The corresponding values obtained by means of both the simulation and the experiment are given in Table 4. The mass change of remeshed parts depicted in Fig. 3 confirms the previously mentioned facts associated with the mass loss which is a result of the use of R-adaptive method. During mesh rebuilding, accuracy of shape preservation is limited by the minimal size of the element defined by the user. If ratio of radius of boundary surface curvature to the minimal size of the element is high, then volume of remeshed part is preserved very well.

Table 4.

Selected results of numerical analysis versus experimental results

Parameter	**Simulation**	**Experiment**
Number of perforated plies	17	11
Depression in backing	18.6 mm	23 mm

In turn, when ratio of radius of boundary surface curvature to the minimal element size is low, then the shape of part is not preserved, which results in mass loss. Internal and kinetic energy assigned to the los mass disappears as well. The shape of the projectile at the beginning of impact is round and rebuilding of its mesh has no effect on its mass. During impact, the projectile distorts and cracks in accordance with Fig. 6, which makes its edges sharp. Edges with such high curvature are poorly described after remeshing, which is visible in the mass change depicted in Fig. 3.

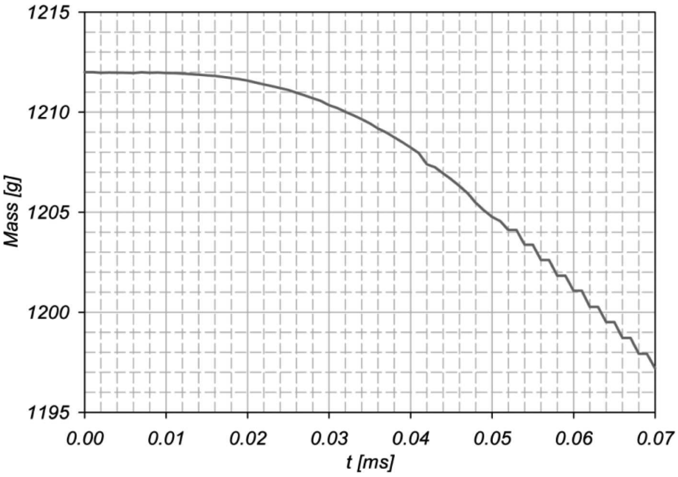

Fig. 3. Mass balance of remeshed parts

The mass of the projectile core and backing was decreased by 15 g. The mass of the projectile core was reduced by 25.51%, i.e. 1.01 g, while the change of backing mass was relatively lower, namely 1.16%. The reduction of core mass was significant but most of its mass was lost in the last stage of the simulation when the velocity of projectile was dropping to zero. Most of core momentum was transferred to ballistic package and backing material then.

The loss of mass can be also observed in energy balance of the entire model presented in Fig. 4. The stepped course of graphs of mass and energy balance results from cyclic nature of R-adaptive method. The mass and energy loss coincides with the remeshing frequency.

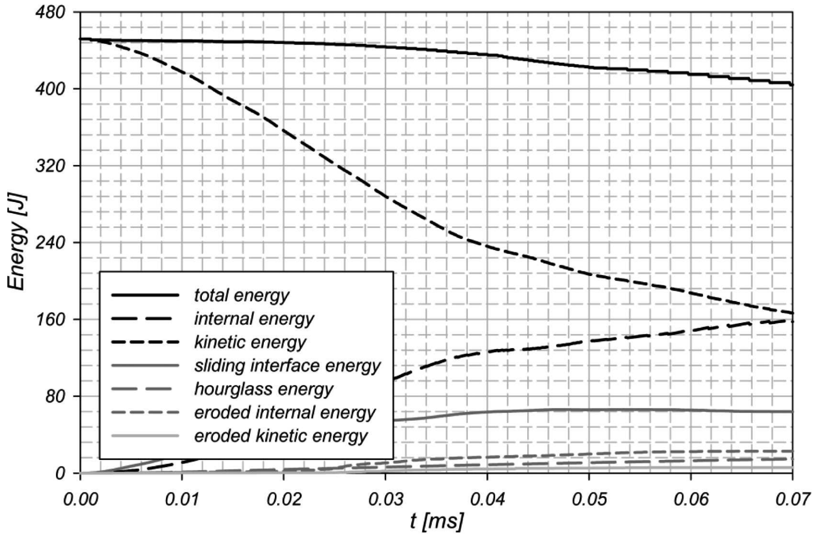

Fig. 4. Global energy balance

Fig. 5. Projectile deformation in the final stage – numerical result

The regular form of the projectile after impact shown in Fig. 5 compared to the shape of the projectile reached during the actual test is due to the fact that the model took into account the symmetry of the physical system. Edges of the real projectile are sharper than numerical edges whose sharpness is limited by the minimal element size. However, the final shape of the projectile obtained numerically is close to that obtained experimentally.

Fig. 6. Projectile deformation in the final stage – experimental result

Figures 5 and 7 present the projectile deformation and the depression formed in the backing, respectively. Obtaining such deformations, particularly for the projectile in Lagrangian description, is generally impossible without adaptive methods. The collected quantitative results listed in Table 4 require further work to improve compatibility with the experimental results.

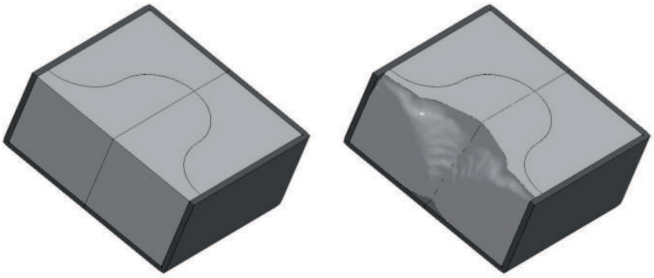

Fig. 7. Backing material deformation

5. Conclusions

The paper identifies the significant aspects of numerical analysis of impact of a projectile with a soft core into the package comprised of thin flexible plies supported on the plastic backing. The positive and negative effects of application of available adaptive methods were discussed herein. Taking normal impact of 7.62×25 mm TT projectile into a package composed of 36 layers of Dyneema SB71 as an example, the following conclusions were drawn:

1. Obtaining the extreme deformation of the projectile soft core and the plastic backing in Lagrangian description requires application of adaptive methods;
2. Available R-adaptive method performs its role, however, should be used carefully due to the mass loss which may appear during calculations.

3. Frequency of mesh rebuilding and permissible size of elements should be as low as possible to limit the mass loss.

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Szczególne aspekty numerycznej analizy uderzenia pocisków z miękkim rdzeniem w warstwowe struktury wiotkie

Streszczenie

Przedmiotem pracy jest wskazanie istotnych aspektów numerycznej analizy zagadnienia uderzenia pocisków z miękkim rdzeniem w pakiet cienkich wiotkich warstw ulokowanych na plastycznym położu. W celu ilustracji problemu wybrano normalne uderzenie pocisku 7,62×25 mm TT w pakiet 36 warstw Dyneema SB71 swobodnie oparty na podłożu plastycznym. Problem

rozwiązano z wykorzystaniem metody elementów skończonych (MES) z jawnym schematem (różnic centralnych) całkowania równania ruchu w formie macierzowej MES. Na podstawie przeprowadzonych analiz wykazano, że uzyskanie ekstremalnych deformacji miękkiego rdzenia pocisku oraz plastycznego podłoża w analizie numerycznej w ujęciu Lagrange'a wymaga zastosowania technik adaptacyjnych. Zaproponowana technika R-adaptive spełnia swoja rolę, ale musi być stosowana z rozwagą ze względu na negatywną cechę powodującą utratę masy modelu.