NUMERICAL OPTIMIZATION OF MULTI-LAYERED COMPOSITE ARMOR

A. BRAGOV[1]., F. ANTONOV[2], S. MOROZOV[3], D. KHOMINICH[3].

[1]*Insitute of mechanics of Nizhny Novgorod State University, 603950, Gagarina Av. 23, Nizhni Novgorod, Russia*

[2]*Skolkovo Institute of Science and Technology, 143025, Novaya St. 100, Skolkovo, Russia*

[3]*DATADVANCE, 109028, Pokrovsky boulevard 3 building 1Б, Moscow, Russia.*

Abstract. The work is focused on methodology of penetration modelling of multi-layered KE protection plates. The method described, intended for penetration process modelling and bulletproof estimation of multi-layered barriers, is based on three-dimensional computer simulation. The nonlinear material behaviour models are proposed for the most common protection materials, like metals, aramid fabrics, ceramics, UHWMPE. For the proposed models, the methods for identifying the parameters of governing equations and failure criteria are given, based on Split Hopkinson bar technique. The finite element model database on projectiles is developed, including standard projectiles, mentioned in NATO and RF standards on ballistic protection. The material database structure is developed, which includes the parameters of suggested material models for each material used. On the basis of proposed method, the software interface for LS-DYNA® code is developed, combining all the mentioned databases and allowing to perform penetration calculations of different barriers with different projectiles, velocities and impact angles. With the developed software tool, the sample optimization problem for multi-layered armour penetration was solved using pSeven optimization software by DATADVANCE®. It was shown that the nontrivial solution of such problem exists, confirming that the optimal thickness ratio can be obtained for given set of materials in multi-layered amour concept.

Keywords: multi-layered armour, modelling, penetration, optimization.

1. Introduction

In the statement and solution of a problem of barrier penetration with deformable projectile it is necessary to account for characteristic set of geometrical and material factors, inherent to the majority of nonlinear dynamic strength problems. The most important of these are dynamic hardening, thermal softening, large plastic strains, materials discontinuities due to local failure, dynamic contact boundaries. Depending on characteristic velocities of the dynamic deformation process, the influence of these factors is different, which can lead to significant changes in the penetration problem statement. The most difficult for modeling strain rate range is a range of relatively slow dynamic deformation processes (10^2-10^4 1/s), when quasistatic, on one hand, and hydrodynamic, on the other hand, approaches are unacceptable. Due to the complexity of adequate problem statement, rigorous analytical methods for solving the penetration problems have not been developed substantially, and currently experimental, semi-empirical and computational methods are mainly used for this purpose.

Nowadays, the most effective instrument for solving the majority of mechanical problems is direct computer modeling using rather finite element, finite difference or other numerical methods, utilizing a characteristic set of physical material behavior models, local failure criteria and contact algorithms. Dynamic penetration and failure problems are not an exception. Despite the significant nonlinearity of such problems (both physical and geometrical), there are efficient numerical methods for their solution. For modeling the materials, most common for protective structures, various physical behavior models are used. Thus, for modeling the dynamic behavior of metals, different modifications of plastic flow theory accounting for dynamic and thermal factors, are traditionally used as governing equations. For the modeling of ceramics, the models based on damage mechanics are used, composite materials are using various macro- and micro-mechanical models. The most developed and widely used practical method for solving local penetration problems, as well as many other mechanical problems, is well-known finite element method (FEM). Finite element method with explicit time integration allows to accurately describe the wave processes and various nonlinear effects occurring in problems of impact interaction. For this and other reasons, the FEM is embodied in a large number of commercial software products and has extensive industrial applications. In current work, the method for solving nonlinear impact and penetration problems is proposed, based on explicit FEM modeling, allowing accurately predicting penetration velocities of projectiles, damage distribution in barriers and optimization problem statement.

2. Bulletproof estimation methodology

It is well known that there are two main approaches to describing the behaviour of a continuous medium – namely the Lagrangian and Eulerian approaches. Lagrangian approach assumes the description of motion of continuum media in coordinates, associated with the medium, while Eulerian approach describes the motion in a fixed in space coordinate system. Numerical implementation of these two approaches results in deformable mesh concept for Lagrangian approach and non-deformable (fixed in space) mesh for Eulerian approach. There is also a combined numerical approach for the description of motion of a continuum media, known as Arbitrary Lagrangian-Eulerian (ALE) approach [1].

Each of these concepts has its advantages and disadvantages, restrictions and application fields. Applied to penetration problems, Lagrangian (strength) approach is optimal for modelling impact of solid bodies with relatively low (transonic) velocities. Advantages of this approach in this case are the ability to account for strength effects, like plug formation during barrier penetration, spallation, cracking etc. Presence of these effects in simulation is due to the option of modelling of brittle failure with element erosion technique, when the elements with excessive strains or stresses are removed from calculation. The most important role in the formulation of the problem in that case is a definition of the material governing equations - the relationship between the deviatoric stress and strain tensors, as well as the failure criterion and its parameters. The main drawbacks of this method is an observed dependence on the mesh density and partial mass loss due to element erosion, and inability to accurately account for very large strains due to excessive distortions of elements, leading also to solution and contact instabilities.

At hypersonic impact velocities, strength effects do not play decisive role in the penetration process. In that case the analysis of shock waves, generated in solid media, is performed using Eulerian (hydrodynamic) approach. It is supposed that colliding solids behave as a viscous fluids, and the decisive role in problem formulation is given to equations of state, or the relation between hydrostatic pressure, density and temperature of the matter. The presence of brittle fracture is neglected.

In the impact velocity range of 500 to 1000 m/s, which is of the most practical interest for the bulletproof analysis, strength, on the one hand, and hydrodynamic, on the other hand, approaches may be unacceptable. This is due to the fact that in that type of problems it is necessary to account for brittle failure, while allowing large distortions as well as in the barrier and in impactor. While Eulerian approach allows to account for brittle failure using the methods of damage mechanics, it is unable to consider for dynamically changing boundaries, as well as for the formation of new contact surfaces, which limits its use for the simulation of multi-layered barrier penetration with combined projectiles. It is therefore the problem statement for impact and penetration of multi-layered barrier with ballistic projectile remains uncertain.

The armour piercing (AP) projectile generally consists of soft brass (or bimetal) skin, lead filler and hard metal or ceramic core. During the modelling of AP projectile interaction with armour, the presence of the soft shell usually neglected, and the interaction is observed only for the core and the barrier. Thus, well-known solutions of the problem are limited to the penetration of the long rods into elastoplastic semispace [2, 3]. However, consideration of the influence of the projectile shell on the penetration process is significant for real applications. This is primarily due to the fact that the shell is usually half of the mass of the projectile, and hence, bears one half of its kinetic energy. The presence of the shell also affects the nature of interaction of the bullet and the barrier. During the collision with metal or ceramic barrier, the shell peels, and the armour piercing core slides into the armour. Shell in that case acts as “grease” for the core. Interacting with the woven composite, rubber, polyethylene or other soft barrier, the shell doesn’t peels, and, deforming, forms a spherical dome, increasing the contact area and spreading the impact pressure.

Modelling of the soft shell with FEM using Lagrangian approach leads to the number of difficulties, caused by the presence of large deformations. The solution of the problem in Eulerian formulation is also unacceptable, as in that case it is hard to account for effects occurring in the layered structure of the barrier, as well as for spallation, fragmentation, macrocracks, etc.

Thus, in this paper it is proposed to consider the following model of penetration: the interaction is modelled by the finite element method with explicit time integration scheme. Barrier is modelled using Lagrangian formulation, taking into account the formation of new surfaces as a result of local fracture, and allowing simulating penetration of multilayer composite barriers. The armor-piercing core (if available) is also modelled using Lagrangian formulation, accounting for its possible fragmentation and the subsequent interaction with the barrier. Soft bullet shell (or filler, or soft core) is represented with the Euler formulation that allows the presence of large deformations in the material without the distortion the contact elements and numerical instabilities. The contact interaction with prescribed friction law is introduced between solid (Lagrangian) parts of the model. Between solid and liquid (Eulerian) parts of the model the fluid-structure interaction [4] is set, ensuring non-penetration of the parts.

3. Multilayer barriers

The use of multilayer armor, consisting of different materials, may have significant advantage over homogeneous armor. The results of numerical simulations show, that multilayer medium significantly affects the characteristics of stress waves distribution. Appropriate combination of layers form different materials with different acoustic impedances allows to significantly increasing the attenuation of stress waves. The use of layered structures in protective elements may decrease and even eliminate internal cracking of the barrier, caused by wave effects.

Back in the 40s of the last century, A.A. Ilyushin showed analytically 5], that the multilayer armor made of the same material is significantly more effective than single layered armor of the same weight in the presence of the geometric gaps between the layers. This effect is due to the presence of large bending plastic deformations in each layer.

On the other hand, Zukas [6], and Zukas and Sheffler [7] have conducted the numerical comparison of the effectiveness of a monolithic barrier and equivalent multilayer barrier of the same material under local impact. It was assumed that there are no gaps between the layers. It was also mentioned, that in the simulation of multilayer barrier using Eulerian formulation, in virtue of inability to account for the formation of free surfaces between the layers, the effect of layer splitting is not present, wave reflection does not occur.

Thus, the use of multilayer armor is appropriate only in case when adjacent layers are significantly dissimilar. The most effective variant of multilayer armor is the combination of material layers with different acoustic properties, so that the stiff layers are backed with the soft ones, ensuring large banding deformations of the hard layers and effective stress wave attenuation, leading to the spalls.

The majority of contemporary solutions in the field of protective barriers has multilayer structure. However, the choice of materials for such barriers, their thicknesses and mutual arrangement is carried empirically and does not have a strict mathematical basis. In other words, the question of the optimal combination of layers in the structure of multilayer barrier remains open. In the same time, due to the fact the advantage of multilayer barriers over homogeneous ones is confirmed by multiple experiments, the problem of optimization of multilayer barrier should have a nontrivial solution.

4. Software tool for bulletproof estimation

The proposed interaction model can be implemented for modelling specific penetration processes. In that case, for each possible problem statement, including the description of geometry and materials of the projectile and the barrier, initial projectile velocity (linear and angular), barrier clamping conditions, the boundary value problem must be formulated, the FEM model is built, the material models are chosen and their properties are set. This process is quite time consuming and doesn’t allow to explicitly solve the main research problem – the problem of optimization of multilayer barrier.

Therefore, in present work the software suite was developed, providing the preparation of computational model on the basis of three interconnected databases, allowing simulating penetration processes of different barriers with different impactors, estimating and analysing results, and conducting optimization. The scheme of the software suite is shown in Figure 1.

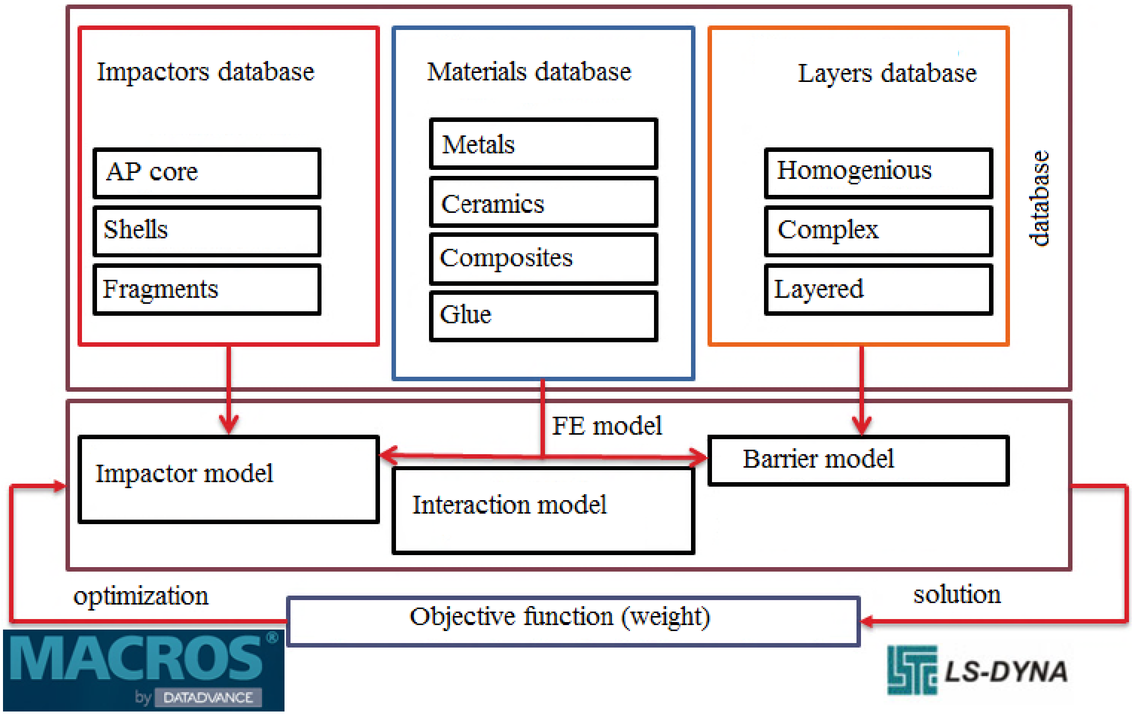

Figure 1. Software suite scheme.

The suite is based on interconnected databases – impactors database, materials database, and armour layers database. Impactors database includes FE models of projectiles, damage agents, fragments and other impactors, developed in accordance with the proposed methodology. Examples of FE models are shown in Figure 2.

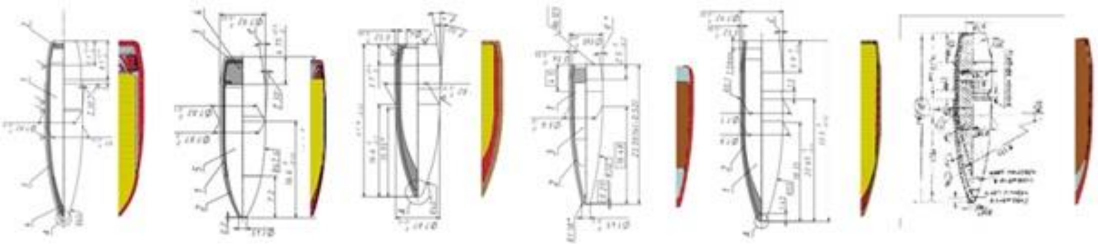

Figure 2. FE models of chosen projectiles.

The database is connected with the materials database, where for each material used mathematical model parameters are stored, which describe material behaviour under impact loads. Currently, the database consists of more than 20 models for different materials, like steels, aluminium, titanium, ceramics, woven composites.

The layers database consists of FE models of combined (discrete) layers, other than plates. For example different forms of discrete ceramics (hexagonal prism, cylinder, sphere) with or without compound, multilayer plates and so on.

As a whole, the software suite gives an opportunity to interactively choose the initial composition of multilayer armour, impactor type, fire angle, optimization parameters and criteria. The principle of the suite operation is as follows: interactive user interface provides the access to databases and assembles the input file for commercial explicit FEM software (currently LS-DYNA), provides connectivity with optimization tool (currently pSeven by DATADVANCE), and runs the optimization problem.

4. Material models

Different materials are used in the structure of multilayer barriers, beginning with traditional high-strength steels and ceramics, composite materials, ultra high molecular weight polyethylene (UHWMPE) and others. All these materials are different in nature and react differently to the high speed deformation. For the description of the behaviour of different materials under impact, specific material models are used, allowing accounting for such effects as rate hardening, and thermal softening in metals, brittle fracture in ceramics, internal friction, nonlinear shear and layered nature of woven fabrics, delamination in UHWMPE. Each of these models contains a set of physical parameters, which definition is, in itself, a difficult task. This is due to the need to account for the features of material response under high strain rates. The most general approaches for the determination of dynamic properties of materials of different nature could be provided by modifications of Kolsky method the split Hopkinson Bar (SHB) [8, 9]. In the framework of observed software suite the material property database structure is proposed and material parameters are defined for several materials. Brief description of material models used is given below.

4.1. Metals

Among the main effects, inherent to metals under dynamic loadings, are the mentioned above effects of rate hardening, thermal softening due to adiabatic heating, and the dependence of local failure on the stress state. In engineering practice for the modelling of behaviour of metals under transient impact processes, the well-known mathematical models accounting for the mentioned factors are typically used: Johnson-

Cook model [10], Zerilli-Armstrong model [11], Steinberg model [12], Gurson model [13] and many others. However, none of these models is fully universal. In current work, for the description of nonlinear behaviour of metals, the approach is used, based on the tabulated assignment of material properties [15]. In that case, the strain rate hardening is given by the set of σ-ε diagrams for different strain rates with linear interpolation and extrapolation of data in between, thermal softening is given by quasistatic σ-ε curves at different temperatures, and failure criterion is given by the curve (surface), representing the dependence of plastic failure strain on triaxiality ratio and Lode angle.

4.2. Woven fabrics

There is a number of publications [16-17] devoted to the investigation of penetration of woven fabrics using computer modelling. There are two most common approaches in modelling the penetration of woven barriers. First is a so-called meso-scale approach, where the fabric is represented at high level of detail, accounting for interaction between yarns in the layer and the geometry of the weave. This approach has a relatively simple implementation, but not effective for the simulation of multilayer fabrics due to computational expenses. The second approach is a macro-scale, based on homogenization of geometrical and material properties of fabric, is not that computationally expensive but requires a number of verification experiments for the identification of its internal parameters. In present paper, the approach is used, based on the homogenization of woven fabrics, as for the real barriers the number of woven layers can be very large, and for optimization problems computational efficiency of the model is more important than its predictive accuracy. The model used is described in paper [18].

4.3. Ceramics

For the ceramics, phenomenological models of damaged media are the most common approach. In current work, the well-known Johnson-Holmquist model [18] is used. The adequacy of this model is confirmed by numerous computational studies, including the comparison with experimental results. This model was developed for the simulation of mechanical behaviour of brittle materials, like ceramics, glass, concrete and others under high rates of deformation, including impact loading.

5. Sample optimization problem

To illustrate the concept, within this section the sample optimization problem is shown, obtaining the optimal solution for multilayer armour concept on particular impact conditions and materials set.

Let us consider an impact of standard 20 mm NATO fragment simulation projectile (FSP) on multilayer armour, consisting of three independent layers of ceramics, UHWMPE and aluminium. The velocity of the fragment is 900 m/s, impact angle is 90°, which corresponds to the fragment thread section of IV class of STANAG 4569 standard. The problem layout is shown in Figure 3.

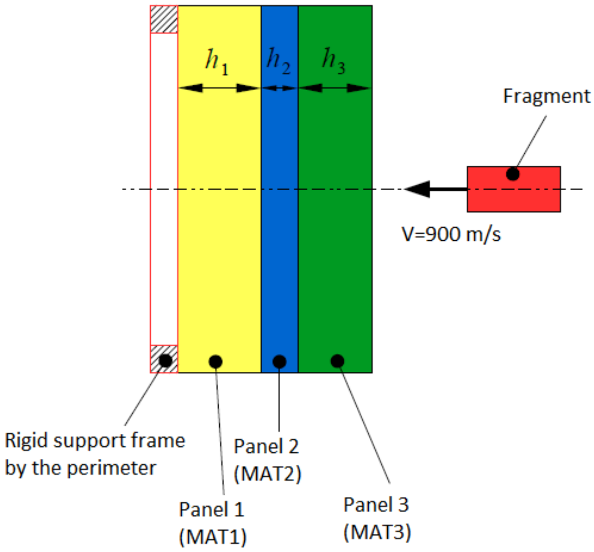

Figure 3. Sample problem layout.

Three materials were used in the initial setup – dural D16 (MAT3, density 2.7 g/cm^3), ceramics Al_2O_3 97% (MAT2, density 3.7 g/cm^3), and UHWMPE Dyneema HB25 (MAT1, density 0.9 g/cm^3). Fragment material was AISI 4340 steel. Using the initial layout, the optimization problem was solved, characterized by 4 parameters: three continuous parameters – plate thicknesses and one discrete parameter – material combination (1-2-3, 1-3-2, 2-1-3, 2-3-1, 3-2-1 or 3-1-2). Total mass was set as an objective function, with the condition of non-penetration. The surrogate based optimization method for used in order to find the optimal solution. This approach allows to find the global minimum of an objective function with minimal number of costly (time consuming) calculations. The number of handlings to the solver was limited to 60 for each material combination. A total of 300 calculations were conducted and the optimal configuration was chosen. Table 1 shows the best result for each material combination.

Table 1. Optimal solutions for each material combination.

Combination	h_1, mm	h_2, mm	h_3, mm	Areal mass, kg/m^2	Residual velocity, m/s
[1-2-3]	23.55	5.61	1.00	44.66	-60.64
[3-2-1]	22.12	12.25	12.64	116.40	-12.90
[2-1-3]	1.00	23.29	15.92	67.64	-95.51
[1-3-2]	21.53	1.00	8.32	52.91	-97.58
[3-1-2]	1.00	21.64	7.82	51.10	-3.84
[2-3-1]	7.93	23.89	25.00	116.35	-10.87

The optimal solution was found to be the 5.5 mm thick ceramics layer with 23.5 UHWMPE backing, resulting in 44.5 kg/m^2 areal weight.

The optimization history for [1-2-3] set is shown in Figure 4.

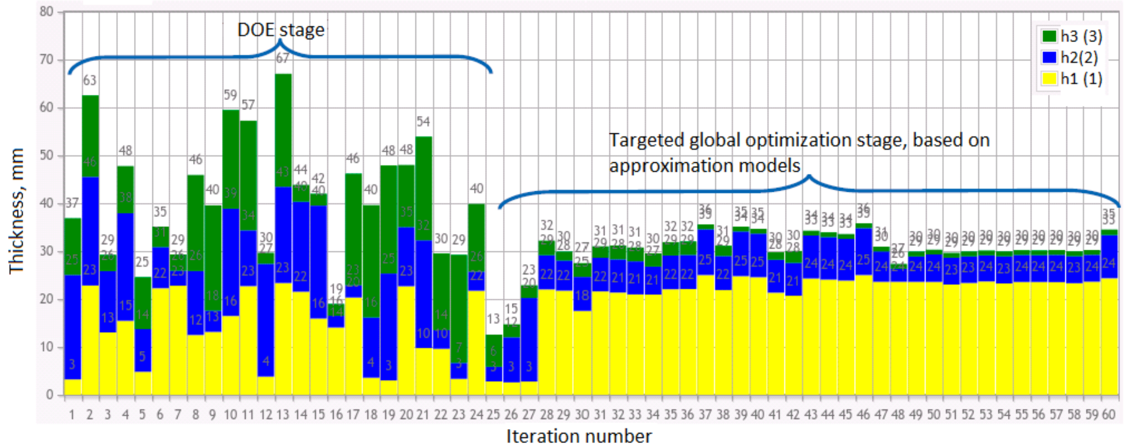

Figure 4. Optimization history for [1-2-3] material combination.

The optimization history for objective function is shown in Figure 5.

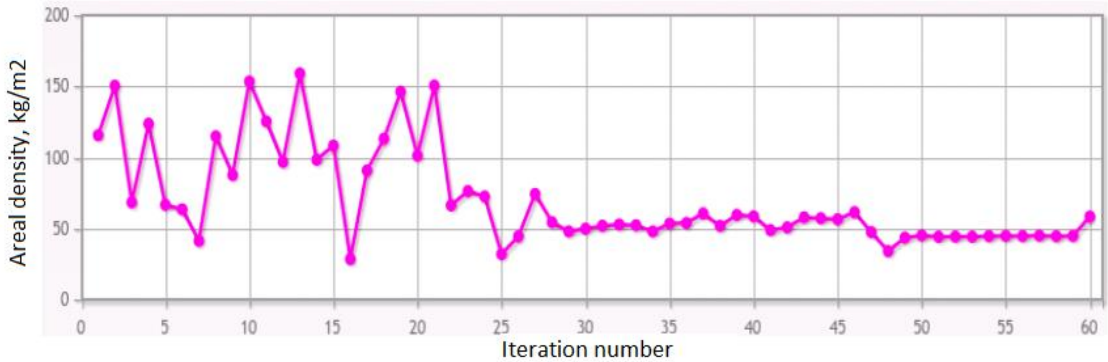

Figure 5. Objective function optimization history.

The modelling results for the optimal solutions are shown in Figure 6.

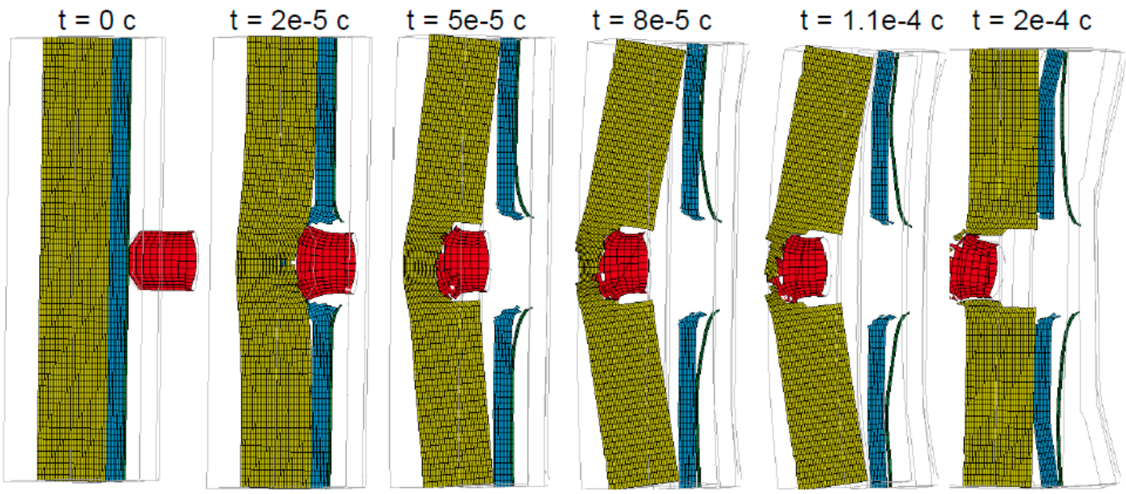

Figure 6. Simulation results for the optimal solution.

6. Conclusions

The new approach for the modelling of penetration of multilayer barriers with combined impactor is proposed. The approach is based on the use of direct computer modelling of barrier penetration process and allows accounting for the features of the process, associated with large deformations of impactor and barrier, fragmentation and changing contact boundaries. The approach is the basis of developed optimization software suite, which includes three interconnected databases, completion of which is the main focus of further work.

Using the developed tools, the sample optimization problem was solved for a given impact problem of penetration of three-layered barrier with high velocity fragment. The optimal solution (in terms of weight) was found, illustrating the capabilities of the proposed approach and confirming the effectiveness of multilayer berries over the homogeneous once.

The developed suite can be used for finding optimal light-weight armour solutions for different threats, without numerous full-scale experiments.

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