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Numerical Simulations of Penetration of 9 mm Parabellum Bullet into Kevlar Layers – Erosion Selection in Autodyn Program*

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Abstract. A numerical model was performed of penetration of 9 mm Parabellum bullet into Kevlar layers, with the use of the AUTODYN software program. Simulations were conducted with a bullet modelled by means of the Smooth Particle Hydrodynamics-method (SPH) and with an armour coded by a Lagrange grid. The simulations were performed for 20 layers of Kevlar (one layer: thickness – 0.3 mm, surface density – 220 g/cm^2) and for impact velocity of 350 m/s. The comparison included the mean velocity of the bullet (which takes into account the velocities of particles that separated from the part of the bullet penetrating the armour) and the velocities at gauge points established near the axis of symmetry of the bullet. The gauge point representative for velocity of the bullet was indicated. With regard to excessively large deformations of the grid, that caused interruption of the initial simulation, the criteria of erosion (cells removal) were introduced. From effective strains available in the AUTODYN software, the *effective instantaneous geometric strain* was selected. Influence of the erosion strain (value of strain for which cells are removed) onto the mass of removed cells and the residual velocity of the bullet were investigated. Simulations with neglect and respect to mass of removed cells in further calculations were performed. The erosion criteria for which further simulations should be conducted were indicated.

Keywords: numerical simulations, AUTODYN, SPH method, Lagrange method, Kevlar, 9 mm Parabellum bullet, erosion in simulation

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1. INTRODUCTION

Numerical simulations of 9 mm Parabellum bullet penetration have been carried out with the use of the AUTODYN software program for bullets with a lead core and brass coating (with a mass of 8 g) penetrating into 20 layers of Kevlar (a single layer with a thickness of 0.3 mm and 220 g/m^2 of surface density). The bullet has been modelled by means of SPH (Smooth Particle Hydrodynamics) method using 0.1 mm elementary particles. The Lagrange grid has been applied to present Kevlar layers (elementary cell with a dimension of 0.15 mm).

The bullet velocity at impact of $V_x = 350$ m/s and the kinetic energy of the impact of 490 J have been adopted as initial conditions. The simulations have been carried out at the axial symmetry in a two-dimension (x, y) coordinate system. A boundary condition of continuous velocity in the direction of the x and y axes ($V_x = 0$, $V_y = 0$) has been imposed to the nodal points of Kevlar layers placed in the extreme distances from the axis of symmetry.

2. EROSION AS PRESENTED BY THE AUTODYN PROGRAM

Removing deformed particles or elementary cells of the model is called erosion in the AUTODYN program. It may be used to show the physical phenomena of ablation but in most cases it is applied as facilitation allowing to conduct calculations. The erosion is commonly used in case of the Lagrange grids.

The cells or particles are removed after their effective strain exceeds the adopted before value of the erosion strain (*ES*). The AUTODYN program provides three kinds of effective strains: an effective plastic strain (*EPS*), an effective incremental geometric strain (*EGS/Inc*) and an effective instantaneous geometric strain (*EGS/Inst*).

In case of removing deformed cells the influence of their mass on the Lagrange grid may be taken into consideration or omitted in the subsequent calculations. Marking the RIOEN *(retain inertia of eroded nodes)* option makes it possible to ascribe the removed cells mass to their nodal points. In each case (with or without consideration of the removed cells mass) the compressive strength as well as the internal energy of the removed cell material are not being maintained and do not appear in the sub-sequent calculations (they are lost). Other specific criteria of the erosion may be defined by the EXEROD user subroutine.

3. EROSION ADJUSTMENT FOR SIMULATION OF 9 MM PARABELLUM BULLET PENETRATION INTO KEVLAR LAYERS

According to the data available in the specialist literature [1], the velocity V_{50} of the 9x19 mm M882, 124-grain NATO Ball bullet (124 gr ≈ 8 g) equals 440 m/s when striking into 20 layers of Kevlar (fabric type: Schwebel Style 706; yarn type: Kevlar KM2, 600 denier; a single layer with a thickness of 0.23 mm; a surface density of 20 layers of 3600 g/m^2).

In comparison to the data mentioned in the cited literature in the carried out simulations a similar bullet model and the armour of 20 Kevlar layers with a surface density exceeding the one described in the literature by 22% (800 g/m^2) have been applied. The adopted for the simulations impact velocity (350 m/s) is lower than the velocity V_{50} mentioned above by 20% (90 m/s). If we consider that the adopted impact velocity is lower than the velocity V_{50} suitable for less "stiff" armour (with a lower surface density), the desired result of the simulation is the bullet stopping by the armour. The carried out simulations are presented in Figure 1.

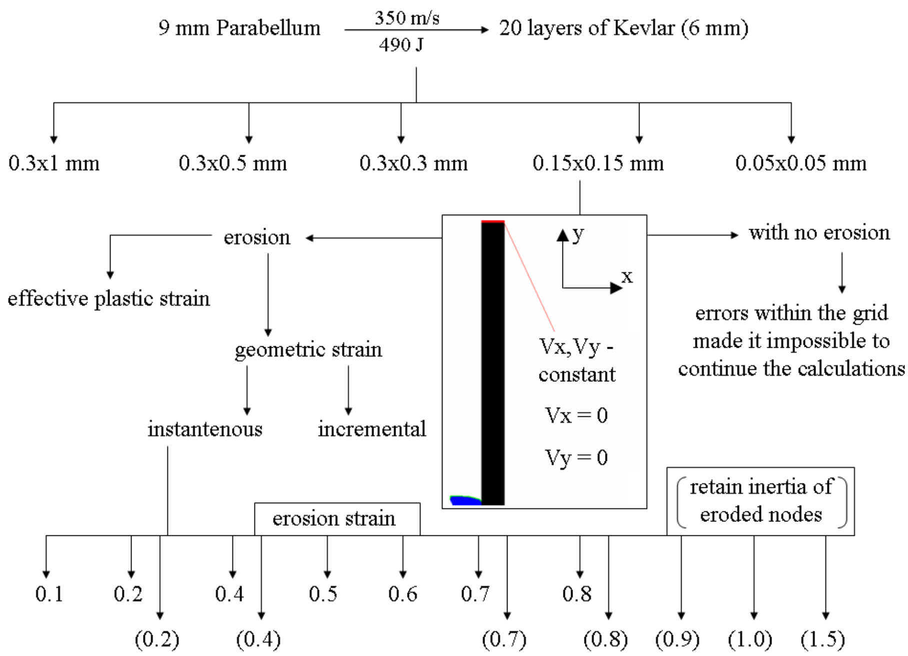


Fig. 1. The scheme of conducted simulations

In case of simulations with no erosion (removing) of the deformed cells, errors within the grid caused interruption of the calculations. Considering that, it was necessary to apply the appropriate erosion criteria. From the effective strains available in the AUTODYN program, *effective instantaneous geometric strain* (*EGS/Inst*) (Chapter 2) has been selected. Simulations for various values of the $ES_{EGS/Inst}$ erosion strain have been conducted with or without consideration of the removed cells mass.

The carried out numerical simulations have been compared with regard to the variations of the bullet velocity in time. The AUTODYN program enables description of the average velocity and the velocities of the gauge points. In the distance of 0.05 mm from the bullet symmetry axis, at equal mutual distances (measured from the rear of the bullet to its head), 11 gauge points have been indicated (Fig. 2a). For the initial simulation (the adopted instantaneous geometric strain – *EGS/Inst* and the erosion strain: 0.6) it has been observed for all the gauge points to the moment of the armour perforation a differential course of velocity variations in the direction of the penetration axis V_x (from the moment of the armour perforation the velocities of all gauge points are approximately similar) (Fig. 2b).

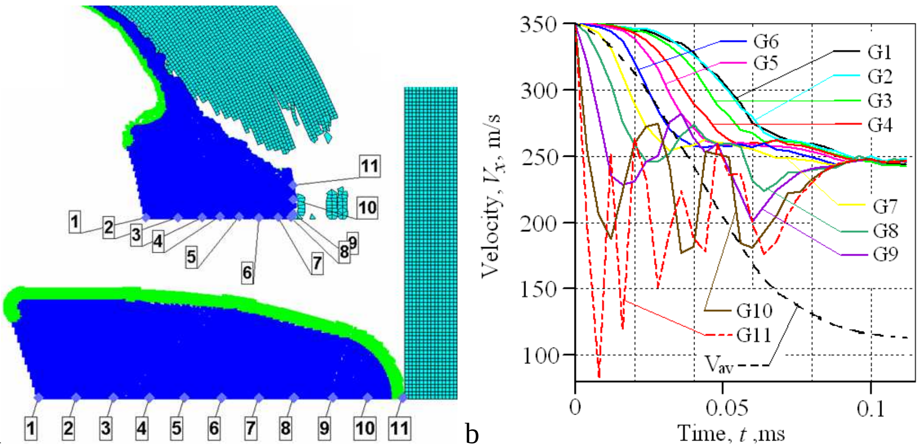
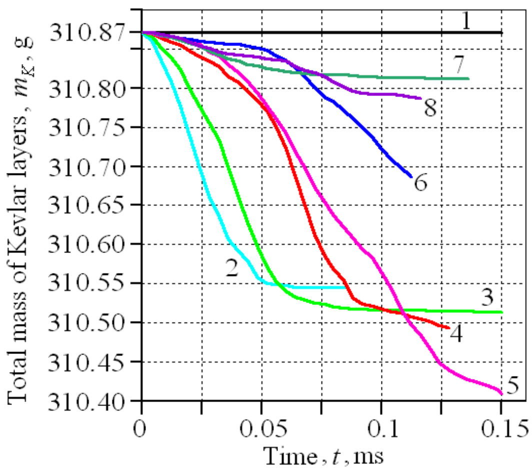


Fig. 2. Defining the bullet velocity: a – gauge points, b – V_x velocity change diagrams for the average bullet velocity V_{av} and the gauge points $G1 \div G11$ velocities

The graph of the average bullet velocity is different from the ones for V_x velocities for the gauge points – V_{xr} residual velocities amount to, respectively, 113 m/s and 246 m/s. The value of the averaged residual velocity reduced by 54% (in relation to the residual velocity established according to the gauge points) results from taking into account velocities of all particles (inclusive of those that separated from the part of the bullet penetrating the armour).

Gauge point *G*1 is the most representative for the whole bullet as it is placed at the rear part of it where the strains are most limited. Its V_x velocity has been used as a criterion for comparison between the carried out simulations.

In the simulations the cells, which effective strain exceeded the established erosion strain, have been removed. If *retain inertia of eroded nodes* (RIOEN) option was taken into account for all the examined erosion strain values, the total mass (total mass of the cells, separated or not) of the armour (Kevlar layers) remained constant. Without consideration of RIOEN option, the mass of Kevlar layers was reduced together with the cells erosion – the course of this process was different for various erosion strain values (Fig. 3). The increasing of the erosion strain value in the range of 0.1÷0.5 (simulations with perforation of the armour) from a certain moment caused lower decrease of the total mass of Kevlar layers (reduced quantity of the removed cells). However, following armour perforations took place later, therefore the state of stress between the armour and the bullet, which was the reason for the armour strain, has been sustained. As a result, the final quantity of the removed cells increases, together with increase of the limit strain value where the cells are being removed (in the range of value 0.1÷0.5).



1 – $ES_{EGS/Inst}$: 0.2; 0.4; 0.7; 0.8; 0.9; 1.0; 1.5;
2 – $ES_{EGS/Inst}$ = 0.1;
3 – $ES_{EGS/Inst}$ = 0.2;
4 – $ES_{EGS/Inst}$ = 0.4;
5 – $ES_{EGS/Inst}$ = 0.5;
6 – $ES_{EGS/Inst}$ = 0.6;
7 – $ES_{EGS/Inst}$ = 0.7;
8 – $ES_{EGS/Inst}$ = 0.8.

Fig. 3. The loss of total Kevlar mass caused by the strained cells erosion: 1 – removed cells mass ascribed to their nodal points, 2÷8 – removed cells mass omitted

In the simulation where the erosion strain was established at $ES_{EGS/Inst}$ = 0.6 the armour perforation also took place. The reduction of total mass of Kevlar layers was smaller than in case of lower erosion strain values as fewer cells attained the effective strain equal to the threshold value of the erosion strain. The lowest number cells of the armour (Kevlar layers) were removed in case of the highest erosion strain values, i.e. 0.7 and 0.8. As a result, the less weaken armour has stopped the bullet.

In case the removed cells mass was omitted in the subsequent calculations, for various erosion strains ($ES_{EGS/Inst}$ = 0.1, 0.2, 0.4, 0.5, 0.6, 0.7 and 0.8) a differential course of V_x bullet velocity changes (for gauge point 1) is observed (Fig. 4a). In the simulations with the erosion strain in the range of 0.1÷0.6 the armour was perforated. Together with increasing of the erosion strain from 0.1÷0.5, the bullet residual velocities were gradually reduced. As compared against the strain erosion of 0.5, the residual velocity increased for the erosion strain of 0.6. In the range of value of the erosion strain of 0.1÷0.6, the residual velocity of the bullet respectively decreases/increases together with the increasing/decreasing of number of the removed cells. This result has not been fully interpreted yet. The bullet has been stopped as expected for the highest erosion strain values, i.e. 0.7 and 0.8.

In case the mass of the removed cells was taken into consideration (simulations executed for $ES_{EGS/Inst}$ = 0.2, 0.4, 0.7, 0.8, 0.9, 1.0 and 1.5) the perforation of Kevlar layers took place when the erosion strains amounted to 0.2, 0.4 and 0.7, and the bullet was stopped when the erosion strain equalled 0.8÷1.5. Likewise the simulations where the mass of the removed cells was omitted, a relation between the reduction of the residual velocity and the augmentation of the erosion strain was observed. For the value of $ES_{EGS/Inst} \geq 0.8$, the course of the bullet velocity changes is approximately equal (V_x deviations as compared to the value corresponding with $ES_{EGS/Inst}$ = 0.8 do not exceed 0.5 m/s) (Fig. 4b).

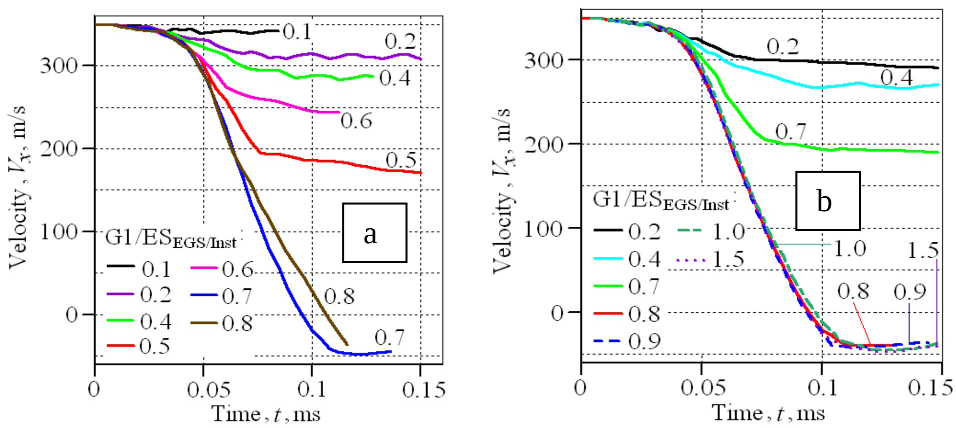


Fig. 4. Change of V_x velocity in time for various values of the limit cell erosion strain: a – simulations with removed cells mass omitted, b – simulations with removed cells mass taken into account

The reason for this is the fact that only a limited number of cells is subject to an effective strain over 0.8. There probably exists an $ES_{EGS/Inst}$ value which if exceeded would not influence on the course of the penetration any more.

Differences in the simulation course (changes of V_x velocity) for the erosion strains $ES_{EGS/Inst}$ = 0.2, 0.4, 0.7 and 0.8 between the simulation carried out without consideration of the removed cells mass and the one where their mass has been ascribed to their nodal points are demonstrated in Figure 5.

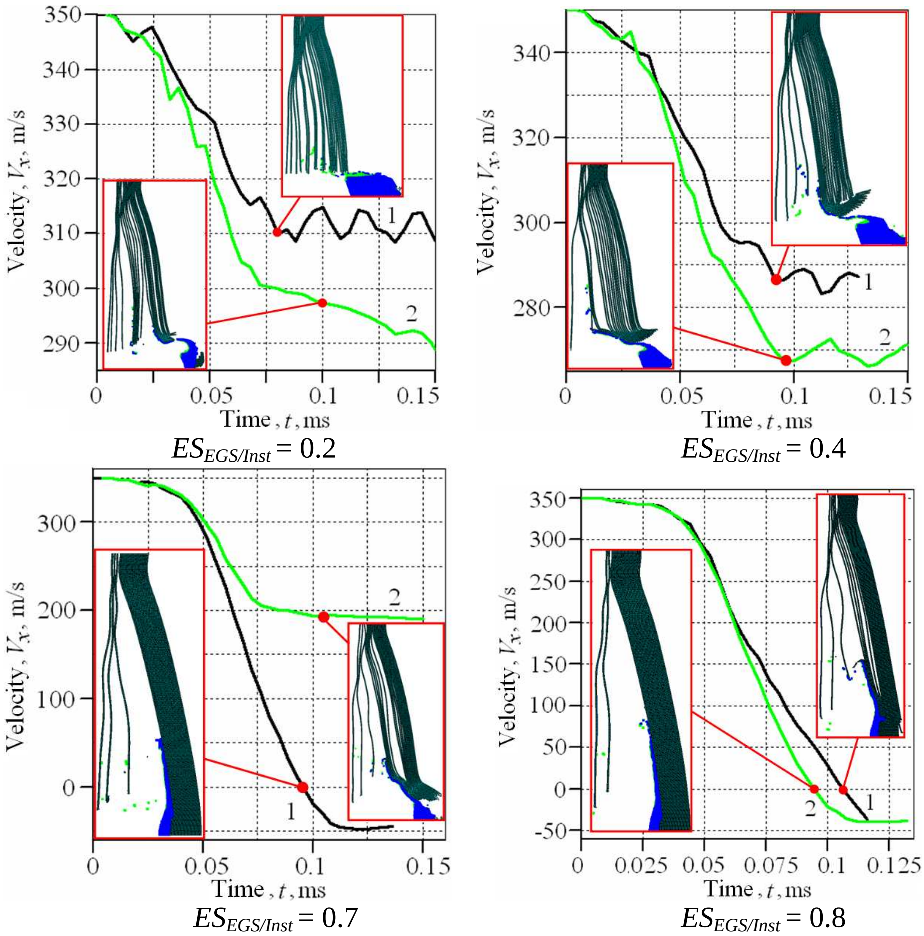


Fig. 5. Comparison of simulations with and without the RIOEN option: 1 – removed cells mass omitted, 2 – removed cells mass ascribed to their nodal points

Effects of ascribing of the removed cells mass to their nodal points (as compared to the simulation where their mass has been omitted):

- for $ES_{EGS/Inst}$ = 0.2 – reduction of the bullet residual velocity by 21 m/s (7.4%)
- for $ES_{EGS/Inst}$ = 0.4 – reduction of the bullet residual velocity by 18 m/s (6.3%)
- for $ES_{EGS/Inst}$ = 0.7 – perforation of the armour without stopping the bullet
- for $ES_{EGS/Inst}$ = 0.8 – stopping the bullet 0.01 ms later.

All data on the results for specific erosion strain values are presented in Table 1 and in Figure 6.

Table 1. Results of simulations for different erosion strain values

Erosion strain $ES_{EGS/Inst}$		0.1	0.2	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5
without *rioen*[1]	result of simulation	P[3]					S[4]		—		
	eroded mass of Kevlar, ‰	1.06	1.16	1.22	1.48	0.58	0.19	0.26	—		
	residual velocity of the bullet, V_{xr}, m/s	342	312	285	172	244	0	0	—		
with *rioen*[2]	result of simulation	—	P[3]		—	—	P[3]	S[4]	S[4]	S[4]	S[4]
	eroded mass of Kevlar, ‰	0									
	residual velocity of the bullet, V_{xr}, m/s	—	289	267	—	—	191	0	0	0	0

[1] with removed cells mass omitted
[2] with removed cells mass taken into account
[3] armour perforation
[4] bullet stopping

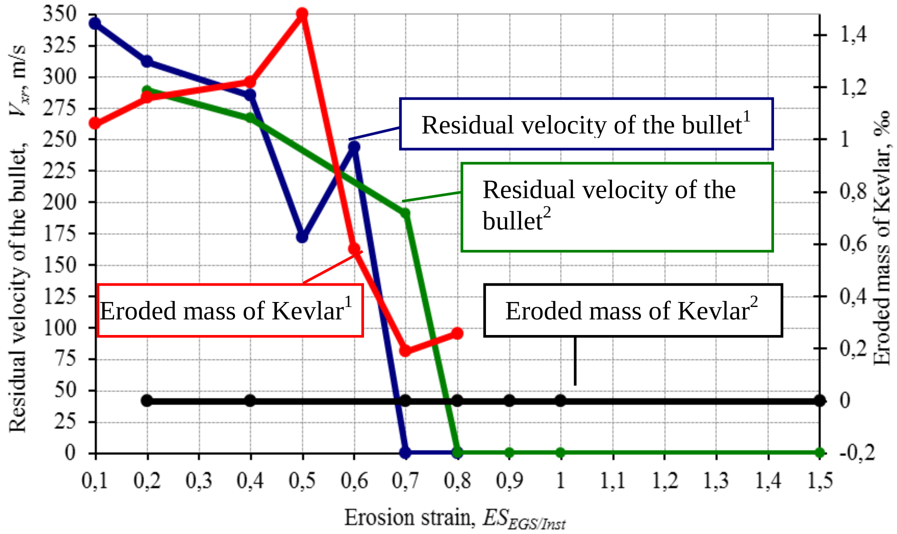


Fig. 6. Influence of the erosion strain value on Kevlar mass loss and the residual velocity of the bullet in case of allowance for and omission of the removed cells mass

4. CONCLUSIONS

1. The velocity of the gauge point placed as near as possible from the bullet axis of symmetry (in the distance of 0.05 mm – for SPH particles dimension of 0.1 mm) on the extreme rear part of the bullet is the most representative for the velocity of the whole bullet.
2. Stopping the bullet (a result conforming to the experimental data available in the specialist literature [1]) has been successfully obtained if the highest erosion strain values were adopted (if removed cells mass was omitted, those values amounted to 0.7 and 0.8; if removed cells mass was ascribed to their nodal points, they equalled 0.8÷1.5). It is necessary to conduct simulations also for higher values of this parameter as well as to define more criteria of comparing their results to the experimental data.
3. Reduction of the quantity of the eroding cells is not unambiguously connected with an increased limit strain value for which the cells are subject to erosion as this relation is also influenced by the time of penetration and other factors.
4. Taking into consideration mass of the removed cells in the subsequent calculations for different erosion strains affects differently the course of simulation ($ES_{EGS/Inst}$ = 0.2; 0.4 – reduction of the bullet residual velocity, $ES_{EGS/Inst}$ = 0.7 – perforation of the armour instead of stopping the bullet, $ES_{EGS/Inst}$ = 0.8 – delay in stopping the bullet). It is necessary to conduct more simulations to describe relation between the influence of taking into consideration the mass on the course of simulation and the increase of erosion strain.
5. Pursuant to the available information, it is not possible to specify which values of the erosion strain are most favourable for the simulations with the use of the AUTODYN program. In the literature it is assumed as correct to apply erosion defined on the basis of the *effective instantaneous geometric strain* [3], ascribe the removed cells mass to their nodal points and apply the highest reasonable value of the erosion strain [1].

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