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NUMERICAL SIMULATIONS OF PENETRATION OF 9 MM PARABELLUM BULLET INTO KEVLAR LAYERS – EROSION SELECTION IN AUTODYN PROGRAMME

Abstract: Numerical model of penetration of 9 mm Parabellum bullet into Kevlar layers, with the use of AUTODYN programme was made. Simulations with bullet modeled by means of Smooth Particle Hydrodynamics-method and with armour coded by Lagrange grid were conducted. Simulations were performed for 20 layers of Kevlar (one layer: thickness - 0.3 mm, surface density - 220 g/m^2) and for impact velocity 350 m/s. Mean velocity of the bullet and velocities of gauge points were compared. Gauge point representative for velocity of the bullet was indicated. In regards to too large deformations of the grid, initial simulation was interrupted. Erosion (cells removal) criteria were established in order to realize simulation. 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. Erosion criteria for which further simulations should be conducted were indicated.

SYMULACJE NUMERYCZNE WNIKANIA POCISKU PARABELLUM 9 MM W WARSTWY KEVLARU – DOBÓR EROZJI W PROGRAMIE AUTODYN

Streszczenie: Z użyciem programu AUTODYN zbudowano model numeryczny wnikania pocisku Parabellum 9 mm w warstwy Kevlaru. Przeprowadzone zostały symulacje z pociskiem zamodelowanym metodą wygładzonej hydrodynamiki cząstek (SPH - *Smooth Particle Hydrodynamics*) i pancerzem przedstawionym za pomocą siatki Lagrange'a. Symulacje wykonane zostały dla 20 warstw Kevlaru (jedna warstwa: grubość – 0,3 mm; gęstość powierzchniowa 220 g/m^2) i prędkości uderzenia pocisku 350 m/s. Porównana została prędkość średnia pocisku z prędkościami punktów pomiarowych. Wskazany został punkt pomiarowy reprezentatywny dla prędkości pocisku. Ze względu na zbyt duże odkształcenia siatki, które we wstępnej symulacji spowodowały przerwanie obliczeń, wprowadzone zostały kryteria erozji (usuwanie zniekształconych komórek). Spośród dostępnych w programie AUTODYN wskaźników odkształcenia wybrany został chwilowy wskaźnik odkształcenia (*effective instantenous geometric strain*). Zbadany został wpływ odkształcenia erozji na masę usuniętych komórek oraz prędkość szczątkową pocisku. Przeprowadzone zostały symulacje z pominięciem oraz uwzględnieniem masy usuwanych komórek w dalszych obliczeniach. Wskazane zostały kryteria erozji, dla których powinny być przeprowadzone dalsze symulacje.

1. Introduction

Numerical simulations of 9 mm Parabellum bullet penetration have been carried out within the use of AUTODYN programme for bullets with lead core and brass coating (with a mass of 8 g) penetrating into 20 layers of Kevlar (a single layer of 0.3 mm of thickness and

220 g/m^2 of surface density). The bullet has been fashioned within SPH (Smooth Particle Hydrodynamics) method by using 0.1 mm elementary particles. Lagrange grid has been applied to present Kevlar layers (elementary cells measuring 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 dimensional (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 on the extreme distances from the symmetry axes.

2. Erosion as presented by AUTODYN programme

In AUTODYN, removing the deformed particles or elementary cells of the model is called erosion. Erosion may be used to show the physical phenomena of ablation but in most cases it is applied as facilitation for conducting calculations. It is commonly used for Lagrange grids.

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

If deformed cells are removed, the influence of their mass in the Lagrange grid may be taken into consideration or omitted in the subsequent calculations. Marking *retain inertia of eroded nodes* (RIOEN) 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 subsequent calculations. Other specific criteria of the erosion may be defined by EXEROD user subroutine.

3. Erosion adjustment for simulation of 9 mm Parabellum bullet penetration into Kevlar layers

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

Comparison of the numerical model applied here to the data mentioned in specialised literature: in the simulations, a similar bullet model has been used, together with an armour of 20 Kevlar layers with a surface density exceeding the one described in the literature by 22% (800 g/m^2). The impact velocity adopted for the simulations (350 m/s) is smaller as compared to V_{50} mentioned above by 20% (90 m/s). The desired result of the simulation, if you consider that adjust impact velocity is lower than velocity V_{50} suitable for less "stiff" armour (with lower surface density), is stopping the bullet by the armour. The carried out simulations are presented in Figure 1. In case of simulations with no erosion (removing) of the deformed cells, errors within the grid made it impossible to continue the calculations. Considering that, it was necessary to apply appropriate erosion criteria. From the effective strains available in AUTODYN programme, *effective instantaneous geometric strain* (*EGS/Inst*) (Chapter 2) has been selected. Simulations for various values of $ES_{EGS/Inst}$ erosion strain have been conducted with or without consideration of the removed cells mass.

The numerical simulations have been compared for the variations of the bullet velocity in time. AUTODYN programme enables specifying the average velocity as well as the velocities

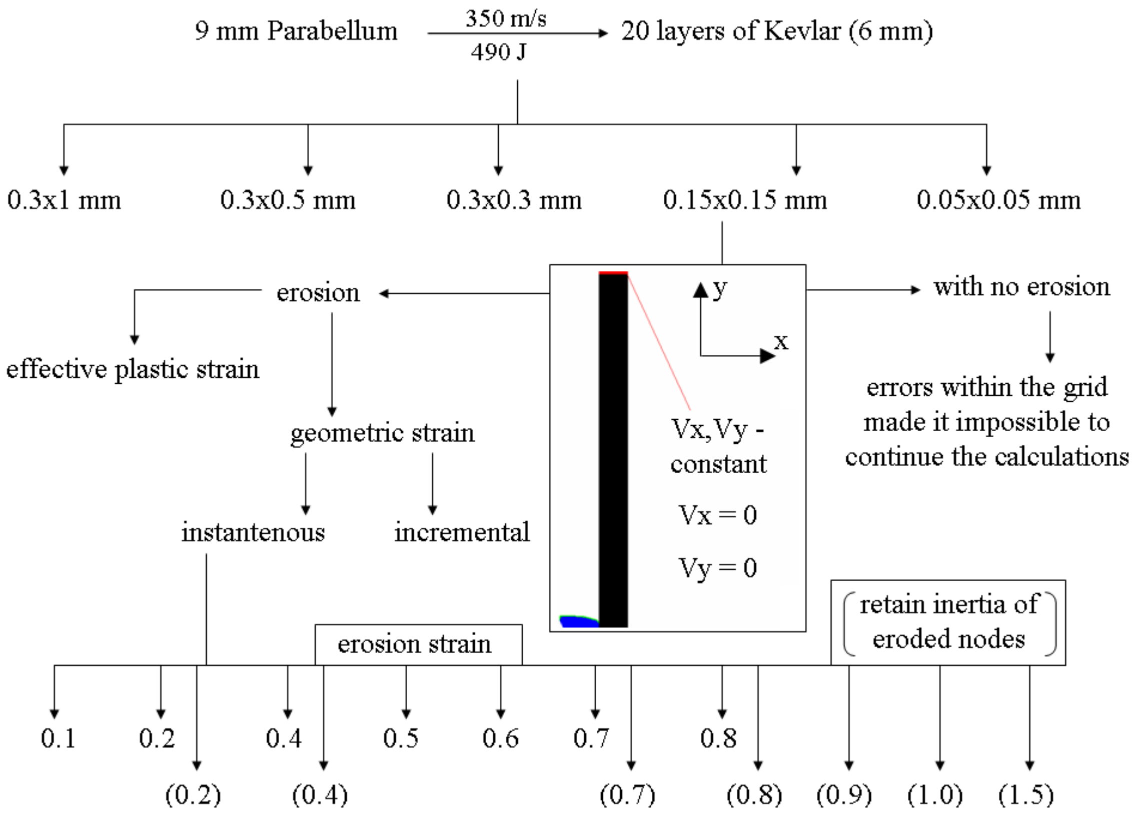


Fig. 1. The conducted simulation scheme

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), there have been 11 gauge points indicated (Fig. 2a). In the initial simulation (instantaneous geometric strain - *EGS/Inst* and erosion strain adopted amounting to 0.6), among all gauge points a differentiated course of velocity variations in the direction of the penetration axis V_x to the moment of the armour perforation (as of the moment of the armour perforation, the velocities of all gauge points are approximately similar) has been observed (Fig. 2b).

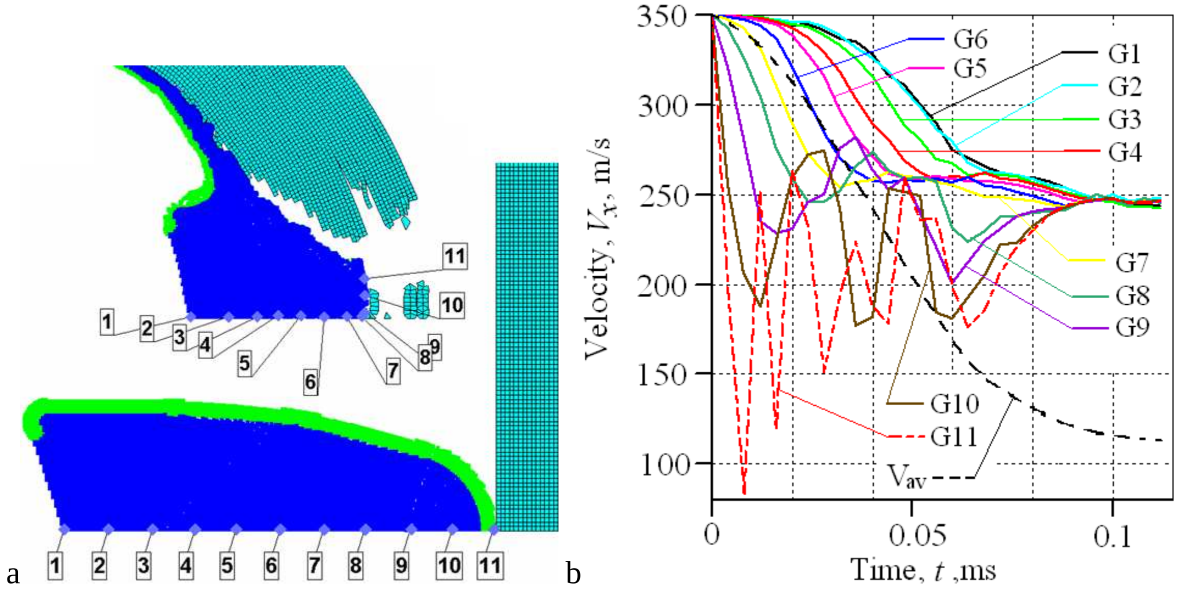


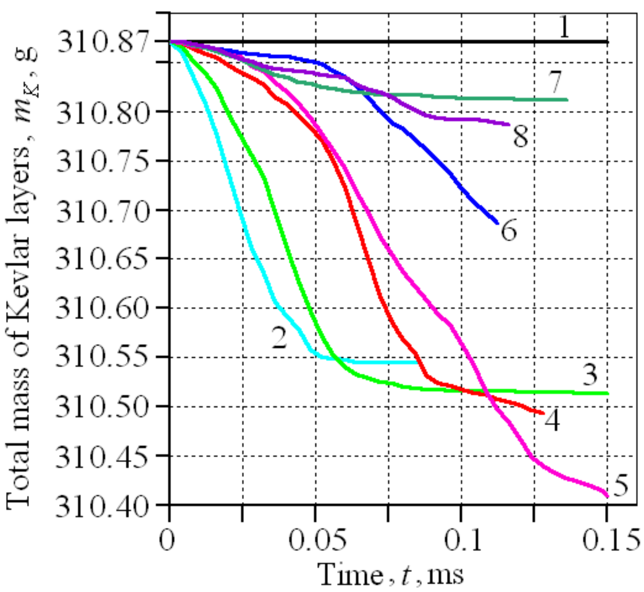
Fig. 2. Defining the bullet's velocity: a – gauge points, b – V_x velocity changes diagrams for average bullet velocity V_{av} and gauge points $G1 \div G11$ velocities

The average bullet velocity graph 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% (as compared to the residual velocity established according to the gauge points) results from taking into account the velocities of all particles (inclusive of those that separated from the part of the bullet penetrating the armour).

Gauge point G1 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 conducting the comparison between the simulations.

In the simulations cells, whose 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 erosion strain values examined, the total mass (total mass of the cells, separated or not) of the armour (Kevlar layers) remained stable. Without consideration of RIOEN, Kevlar layers mass reduced contingent on the cells erosion – the course of this process was different for various erosion strain values (Fig. 3). The increasing of the erosion strain value between 0.1÷0.5 (simulations where the armour was actually perforated), from a moment given on, reduced the decrease of the total Kevlar layers mass (reduced quantity of the cells removed). 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 cells removed increases, together with increase of the limit strain value where the cells are being removed (within the scope of values between 0.1÷0.5).

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



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

If the removed cells mass was omitted in the subsequent calculations, a differentiated course of V_x bullet velocity changes (for gauge point 1) is observed for various erosion strains

($ES_{EGS/Inst}$=0.1, 0.2, 0.4, 0.5, 0.6, 0.7 and 0.8) (Fig. 4a). In simulations with erosion strain between 0.1÷0.6 the armour was perforated. Contingent on augmentation of the erosion strain from 0.1÷0.5, the bullet residual velocities were gradually reduced. As compared against the strain erosion 0.6, the residual velocity for the erosion strain 0.5 increased. In the scope of erosion strain values between 0.1÷0.6, the residual velocity of the bullet respectively decreases/increases together with the increasing/decreasing of the number of cells removed. 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.

If the mass of 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 in cases of erosion strain amounting to 0.2, 0.4 and 0.7, and the bullet was stopped if erosion strain equalled 0.8÷1.5. Likewise the simulations where the removed cells mass was omitted, a relation between the reduction of the residual velocity and an augmentation of the erosion strain was observed. For $ES_{EGS/Inst} \geq 0.8$ value, the course of the bullet velocity changes is approximately similar (V_x deviations as compared to the value corresponding with $ES_{EGS/Inst}$=0.8 do not exceed 0.5 m/s) (Fig. 4b). The reason for that is the fact that only a limited number of cells is subject to effective strain over 0.8. There probably exists $ES_{EGS/Inst}$ value which if exceeded it would not influence the course of the penetration any more.

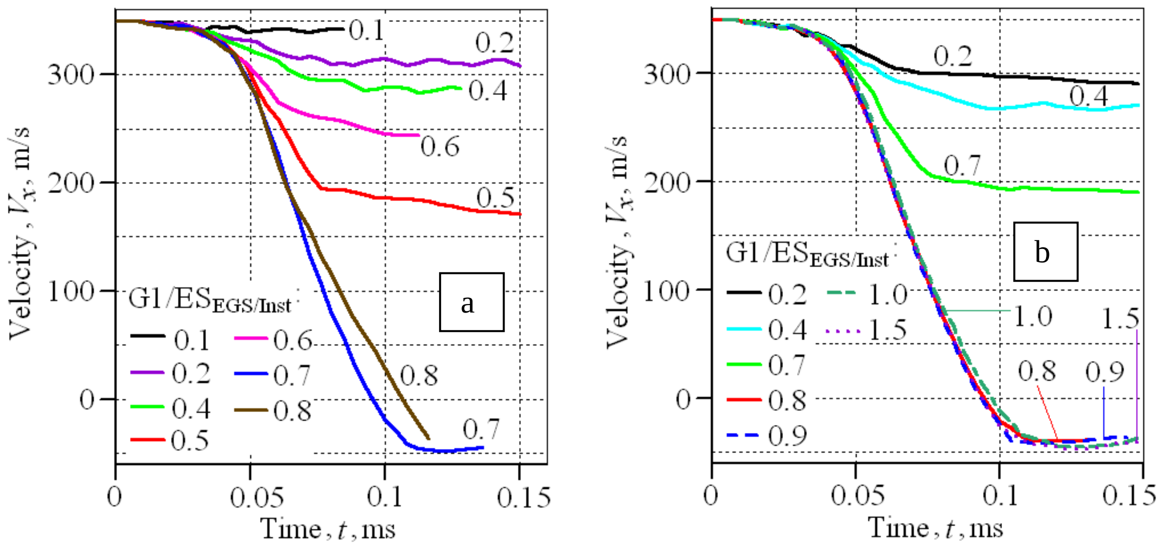


Fig. 4. Change of V_x velocity in time for various values of the limit cell erosion strain: a – simulations with removed cells mass omitted, b – simulations with removed cells mass taken into account

Differences in the simulation course (changes of V_x velocity) for 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.

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.

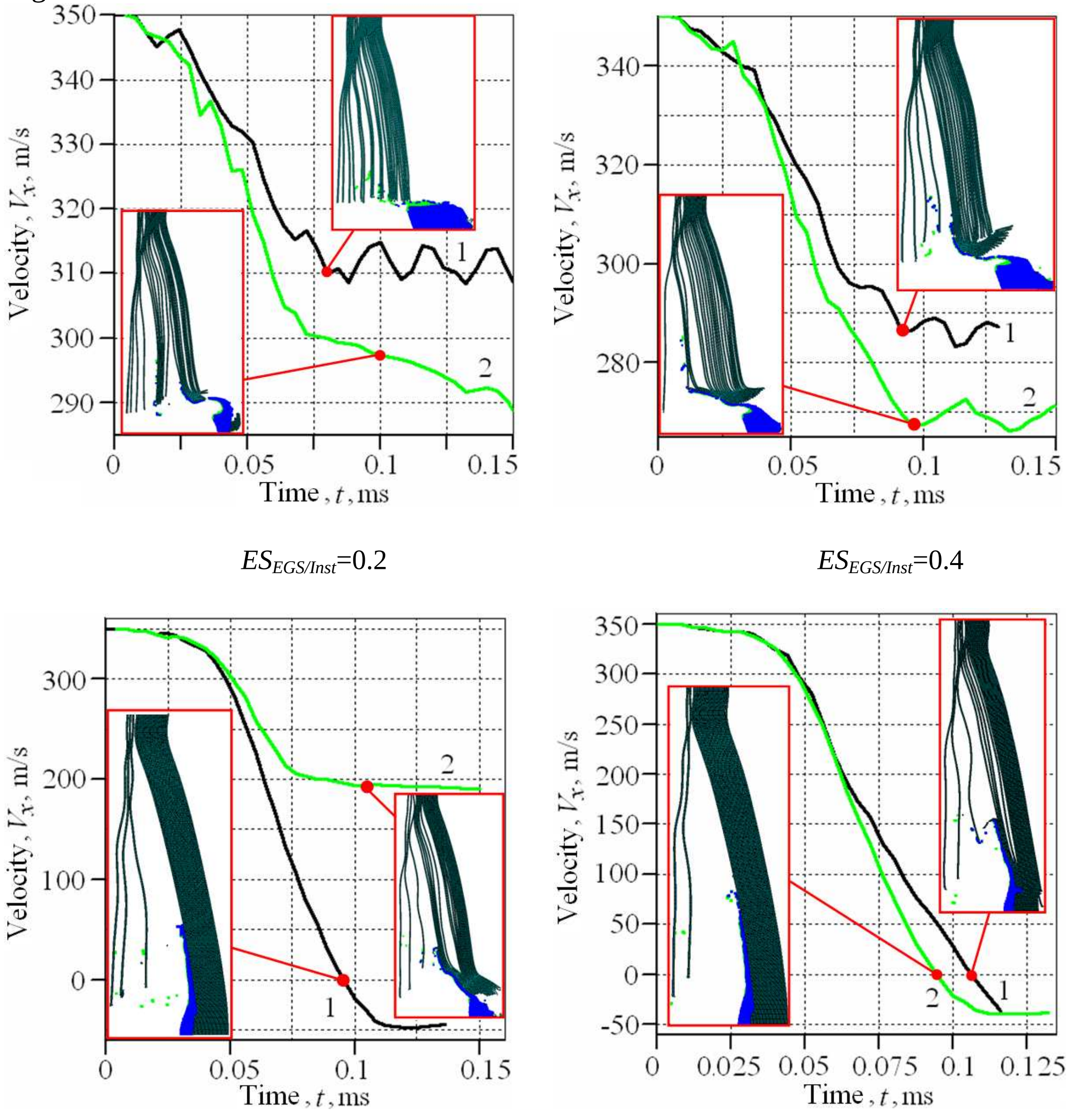


Fig. 5. Comparison of simulations with and without the retain inertia of eroded nodes option: 1 - removed cells mass omitted, 2 – removed cells mass ascribed to their nodal points

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

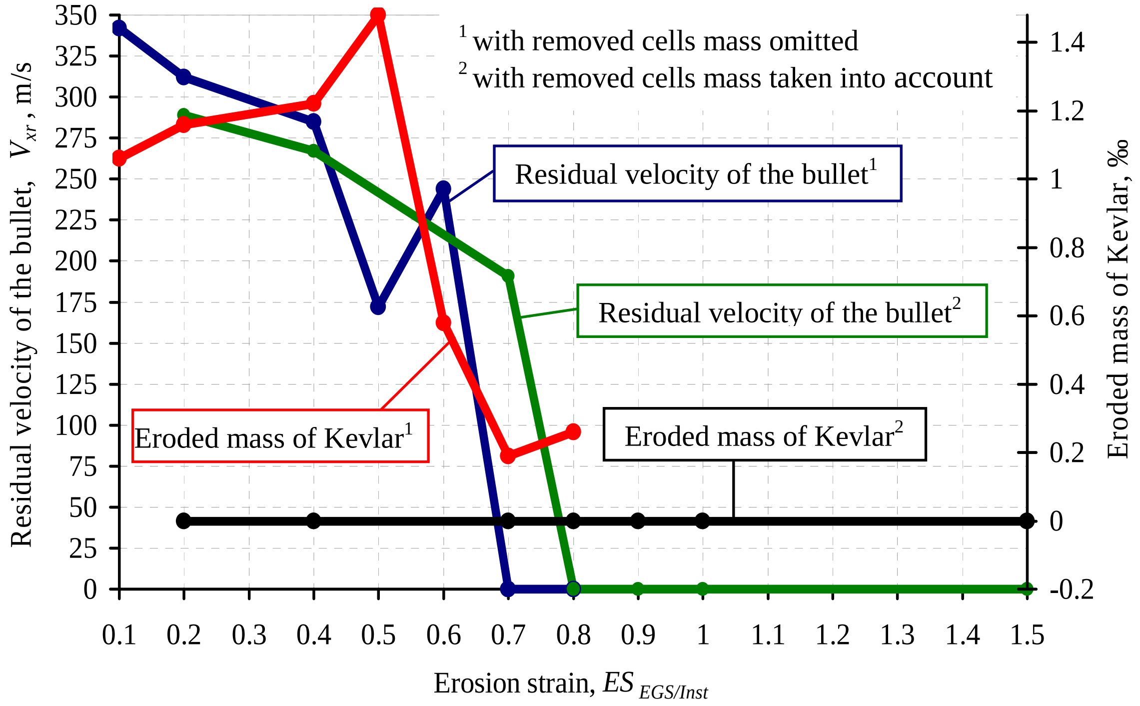


Fig. 6. Influence of the erosion strain value on Kevlar mass loss and the residual velocity of the bullet in case of allowance for and omission of the removed cells mass

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 size 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 specialised 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 would be 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 eroding cells quantity 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 removed cells mass into consideration in the subsequent calculations for different erosion strains affects in a different way the course of the 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 would be necessary to conduct more simulations to describe relation between effect of taking removed cells mass into consideration and increase of erosion strain.
5. Pursuant to the available information, it is not possible to precise which of the erosion strain values are most favourable for the simulations within AUTODYN programme. In specialised literature, it is generally believed correct to apply erosion defined on the basis of *effective instantaneous geometric strain* [3], ascribe the removed cells mass to their nodal points and apply the highest reasonable value of erosion strain [1].

References

[1] ANSYS Academic Research AUTODYN 12.1, *User's Manual*.

[2] N. L. RUPERT, *9-mm baseline data set for the calibration of fabric penetration models*, 20th International Symposium on Ballistics Orlando, Fl, 23÷27 September 2002.

[3] L. WESTERLING, *A note on an erosion criterion in AUTODYN*, June 2002, ISSN 1650-1942, Methodology report (FOI-R--0476--SE).

This work was financially supported by European Fund for Regional Development in Poland (Project "Smart passive body armours with the use of rheological fluids with nanostructures" under contract No. UDA-POIG.01.03.01-00-060/08-00) and carried out within consortium between Institute of Security Technology "MORATEX" (Instytut Bezpieczeństwa "MORATEX"), Warsaw University of Technology (Politechnika Warszawska) and Military Institute of Armament Technology (Wojskowy Instytut Techniczny Uzbrojenia).

Praca została współfinansowana przez Europejski Fundusz Rozwoju Regionalnego (Projekt "Inteligentne pancerze pasywne z zastosowaniem cieczy reologicznych ze strukturami nano", nr umowy UDA-POIG.01.03.01-00-060/08-00) i wykonana w ramach konsorcjum pomiędzy Instytutem Bezpieczeństwa "MORATEX", Politechniką Warszawską i Wojskowym Instytutem Technicznym Uzbrojenia.