18th International Conference
ENGINEERING MECHANICS 2012
Svratka, Czech Republic, May 14 – 17, 2012

pp. 453–460
Paper #95

EXPANSION LIMIT ESTIMATION OF PISTOL HOLLOW POINT BULLET PENETRATING THE BLOCK OF SUBSTITUTE MATERIAL

J. Hub[*], J. Komenda[**], M. Novák[***]

Abstract: *The article presents a numerical model of expansion pistol hollow point bullet penetrating the block of simulator representing the organic material (tissue). The hollow point bullet has an expansion ability to increase its wound potential, but only in case of exceeding the specific limit impact velocity. The simulation using FEM system Ansys Autodyn v14 presents 2D results of estimation the bullet velocity limit for expansion occurrence based on experiments. Also the analysis and influencing factors of the penetration process are presented as well. The results obtained help to evaluate the bullet post-penetrating characteristics.*

Keywords: ***Pistol cartridge, expansion bullet, wound effect, expansion limit, FEM simulation.***

1. Introduction

Expansion bullets, so called hollow point bullets, are characterized by functional deformation of the front part (so called expansion) while penetrating a soft target. Functional deformation of the expansion bullets in the target increases its radial dimensions and its front cross section (Rosenberg, 2002). The bullet transmits more energy into the target and is therefore considered as the bullet with enhanced wound potential. Pistol cartridges with these bullets are prohibited in the civil sector and the ammunition is applied especially for special police units. Among such ammunition is the cartridge Action 5, which is used in the experiments and analysis described in this article. The cartridge Action 5 is of the caliber 9 mm Luger with a homogeneous brass bullet with front expansion hollow covered with a plastic cap (see Fig. 1, 2). The basic ballistic characteristics of this cartridge are shown in Table 1. The cartridge is the product of the company RUAG Ammotech and is ranked among others in service of some security forces within the Czech Republic.

Fig. 1: The cartridge Action 5 (right) and its components – from the left the cartridge case with the primer, the bullet of caliber 9 mm and propellant charge (powder)

[*] Ing. Juraj Hub, Ph.D.: Department of Aircraft and Rocket Technology, University of Defense, Kounicova 65, 662 10 Brno; CZ, e-mail: juraj.hub@unob.cz

[**] Assoc. Prof. Ing. Jan Komenda, CSc.: Department of Weapons and Ammunition, University of Defense, Kounicova 65, 662 10 Brno; CZ, e-mail:jan.komenda@unob.cz

[***] Ing. Miroslav Novák, Ph.D.: Prototypa-ZM, Hudcova 533/78c, 612 00 Brno; CZ, e-mail: miroslav.novak@prototypa.cz

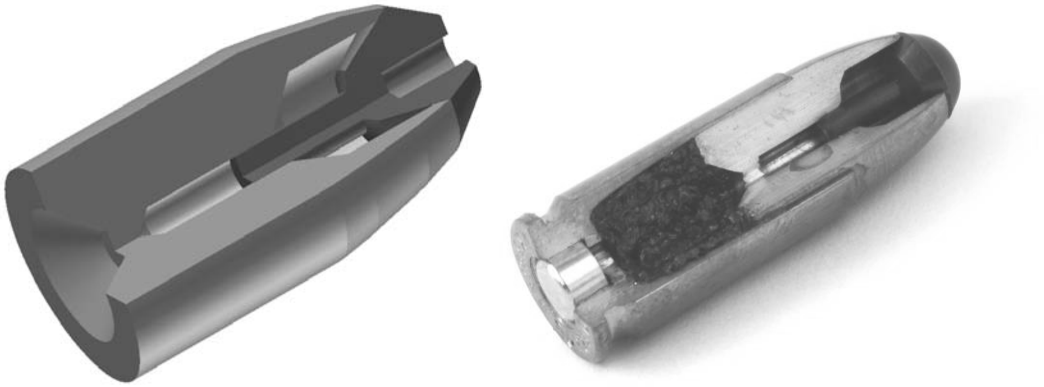

Fig. 2: Longitudinal cut of the bullet and cartridge Action 5; on the left the model used in FEM simulation and on the right the actual cartridge; the plastic cap is visible in the front part of the bullet

Tab. 1: Ballistic characteristics of the bullet Action 5

Weight of the bullet m_b [g]	6.1
Initial bullet velocity v_0 [m/s]	460
Initial momentum of the bullet H_0 [kg · m/s]	2.8
Initial bullet energy E_0 [J]	645
Initial specific bullet energy e_0 [MJ/m^2]	10.1/4.1*

Note: * Initial specific bullet energy is the initial bullet energy related to the cross section of the bullet. The values of the specific energy are valid for the bullet before the deformation / after the deformation in the substitute material. The cross-sectional area of the front part of the bullet increases from the original undeformed value 64 mm^2 to the value 156 mm^2 corresponding to the deformation diameter 14.1 mm, that means an increase of the cross section area of 145 %.

2. Expansion features of the bullet Action 5

A certain problem of the expansion bullets is their specific deformation behavior at different impact velocities and during penetration of different types of targets. In particular, different impact velocities can cause significant differences in wound effect and piercing ability of the same bullet in relation to an identical target. Important functional characteristics of the expansion behavior of each bullet are the expansion coefficient and the expansion velocity limits.

The coefficient of expansion of the bullet K_e is defined as the ratio of the maximum radial dimension of the bullet after and before the deformation, respectively, thus the ratio of diameter of the cylinder circumscribing the deformed shape of the bullet and the caliber of the bullet, see Fig. 3:

$$K_e = \frac{D}{d} \tag{1}$$

The increase of the bullet deformation causes the increase of the coefficient of expansion and the wound potential. In practice, the coefficient of expansion falls within the range of 1 to 2.

Deformation of the bullet generally increases with an impact velocity penetrating the live target, or its substitution, while other conditions remain the same. A very low impact velocity causes no deformation of the bullet. After reaching a particular minimum impact velocity, the bullet begins to deform. In practical terms, this velocity is not essential. In terms of assessing the effects of bullet such deformation of the bullet is significant, at which the maximum diameter of the bullet exceeds the origin bullet caliber. Impact velocity, at which such deformation is reached, is known as the lower limit (velocity limit) of the bullet expansion. This velocity has only approximate importance in practice and therefore the size of the velocity range at which the bullet shows increased wound effect.

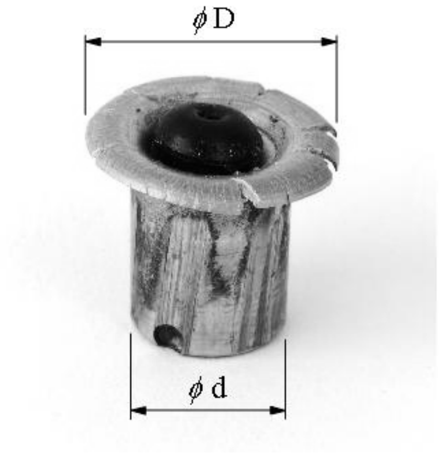

Fig. 3: Radial dimensions of expanded bullet required for expansion coefficient estimation; the bullet Action 5 with standard deformation caused by penetration of the substitute material – ballistic gel – with the expansion coefficient of the value 1.57 (shot No. 4)

In practice it is usually chosen the initial, and thus the impact, velocity of the bullet onto a target in order to provide the maximum deflection of the bullet with the maximum coefficient of expansion and thus with the maximum effect. Such an impact velocity is known as the upper limit (velocity limit) of the bullet expansion. The deformation of the bullet remains unchanged with further increasing of the bullet impact velocity. At a certain velocity threshold it may lead to disintegration of the bullet. This limit velocity is the limit of destruction (destructive limit). Reaching or exceeding this velocity leads to decreasing of the wound potential of the bullet while the piercing ability of the bullet increases.

The bullet expansion limits are independent of the thickness of the material which penetrates the bullet. The process of expansion of the bullet is usually completed at the track of just a few centimeters after impacting the block and afterwards the shape of the bullet remains unchanged. Therefore the experimental determination of the limits of expansion is sufficient to run at a relatively short track of the bullet penetration in the material on which the expansion process of the bullet is completed.

Knowing the limits of expansion is important for the proper choice of ballistic properties of the cartridge as a part of its development regarding to optimizing the wound effect of the bullet. To achieve the maximum level of wound effect, it is desirable that an expansion bullet hits the target with the velocity corresponding to the upper limit of expansion, eventually of slightly higher rate, without exceeding the limit of bullet destruction. Lower impact velocity leads to reduction of wound effect of the bullet when comparing to the upper limit. Higher impact velocity and exceeding the destruction limit reduces the wound potential more significantly. When shooting at a greater distance, the bullet impact velocity decreases and thereby reduces the wound effect of the bullet. The rate of decline of the impact velocity determines the rate of expansion decline of the bullet effect on the target with respect to the width of interval between the lower and the upper limit of expansion, respectively.

A different impact velocity of the expansion bullet may significantly affect the rate of wound effect. Paradoxically, an unexpanded bullet with a low impact velocity penetrates deeper into the target with respect to the fast bullet that expands. In the case of penetration of the target the slower unexpanded bullet leaves the target with higher velocity than a fast expanded bullet. For a slow bullet the transferred energy rate is low and the bullet is not only less effective towards the selected target, but can also threaten more non-participating neighborhood in the case of penetrating the target.

3. Shooting experiments

Shooting experiments were conducted by the ammunition Action 5 of identical series (cartridge stamping 9x19 SX A5 - DAG10E0842) from the ballistic measuring device 9x19 NATO-H onto uncovered gel blocks of density 15% at distance of 5 m from the muzzle of the ballistic measuring device, see Fig. 4. The prismatic gel block has the length of 0.3 m and rectangle cross-section perpendicular to the bullet trajectory has dimensions 0.2 m x 0.14 m, see Fig. 5. Velocity of the bullet $v_{2.5}$ was measured using non-contact optical gates with the base 1 m and this velocity is considered equal to the velocity of gel block impact v_{imp}. Velocity of the bullet after the penetration of the block v_{res} was measured using two high-speed cameras Redlake HG-100K and MotionXtra N4.

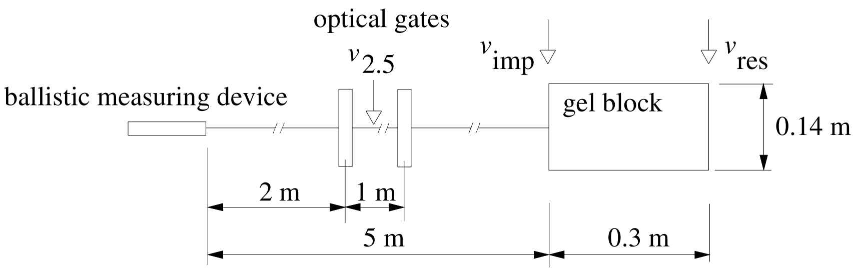

Fig. 4: Experimental scheme

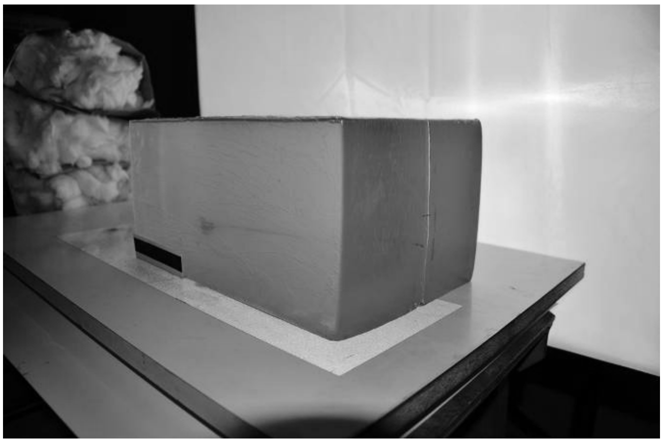

Fig. 5: Experimental gel block in firing position in shooting range Prototypa, Brno

Two kinds of Action 5 cartridges were used for the experimental shooting – original cartridges and delaborated cartridges with modified propellant with lower weight in order to reduce the velocity of the bullet. Dimensional and weight characteristics of the bullets are shown in Table 2. The aim of the experiments was to achieve different impact velocities to prove various expansion behavior of the bullet penetrating the substitute material. In addition, the experiment results and observations are necessary inputs for simulation part of the presented work as well.

Tab. 2: Characteristics of bullets used in experiment

No of shot	Propellant weight	Bullet weight	Velocity $v_{2.5} = v_{imp}$	Velocity v_{res}	Bullet length L	Bullet diameter D	Coef. of expansion K_e
	g	g	m/s	m/s	mm	mm	1
1	0.30	6.03	248	105	15.2	9.0	1.00
2	0.35	6.01	349	80	14.8	9.2	1.02
3	0.40	6.02	395	44	13.7	12.0	1.33
4	0.44	5.97	454	36	13.4	14.1	1.57

The temperature of the bullet and gel block, respectively, was 20°C and ambient temperature in Prototypa shooting range was 10°C.

Deformed bullets are shown in Fig. 6 along with simulation results.

The course of the impact velocity of the bullets v_{imp} with respect to the residual velocity v_{res} is shown on graph in Fig. 8 along with simulation results.

4. FEM simulations

In order to simulate the penetration process an explicit nonlinear transient hydrocode Autodyn v14.0 was used, implemented into Finite Element Method system Ansys Workbench. The model of the bullet and gel block was created using 2D axial symmetry, so only a half of the parts of all components were modeled.

The model of the bullet Action 5 was created upon real geometry with equal main dimensions. The geometry was slightly simplified in order to model the suitable mesh. The volume and density of the brass bullet body and plastic cap was modified in order to achieve equal total weight of the bullet. The simulation gel block does not fully respect the original prismatic shape of the gel block due to the axial symmetry used within FEM model. The shape of the simulation gel block is cylinder with diameter of 0.14 m and length of 0.3 m.

The bullet uses mesh-based Lagrangian method and the gel block uses mesh-free particle based Smooth Particle Hydrodynamics (SPH) method. Therefore the model for the gel block is suitable only for simulation the opening process of the block cavity during penetration process and does not cover the process of cavity closing. The character and discretization of the model of both the bullet and gel block is shown in Fig. 6.

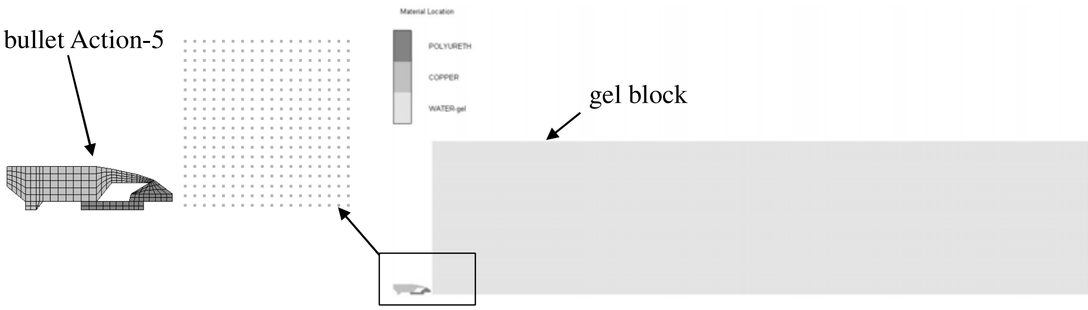

Fig. 6: FEM model of the bullet Action 5 and the gel block using axial symmetry

The rotation of the bullet caused by barrel bore and air drag are not considered. The simulation methodology is based on (Hazell, 2009; Hub, 2011).

All material models of the bullet and the gel block were retrieved from the Autodyn material library and they are in some cases modified. The bullet consists of the brass body and the plastic cap.

The material behavior of the brass body represents the modified copper material and is described through the shock equation of state (EOS) and the strength model. The brass body uses EOS (Steinberg, 1996) with following parameters: $\rho = 8354$ m · s^{-3}, $\Gamma = 2.0$, $C_0 = 3958$ m · s^{-1} and $S_1 = 1.497$. The Piecewise Johnson-Cook constitutive strength model contains the following parameters: $G = 68800$ MPa, $Y_0 = 120$ MPa, $\varepsilon_{P1} = 0.3$, $Y_1 = 450$ MPa, $Y_2 = 450$ MPa, $m = 1$.

The plastic cap follows the modified polyurethane model with density $\rho = 1265$ kg · m^{-3}, linear EOS with bulk modulus $K = 2000$ MPa and the elastic strength model with shear modulus $G = 5$ MPa.

The ballistic gel material represents the modified water model with EOS using parameters $C_0 = 1647$ m · s^{-1} and $S_1 = 1.921$. The density of gel block varies upon impact velocity of the bullet as the parameter to achieve the correspondence between experimental and simulation results. The density of simulation model of the gel block has the value of 520 kg · m^{-3} for the shot No. 1, next 650 kg · m^{-3} for No. 2, next 740 kg · m^{-3} for No. 3 and 750 kg · m^{-3} for No. 4.

The initial condition for the simulation represents the impact velocity of the bullet and it is equal to the velocities $v_{2.5}$ and v_{imp} according to the values shown in Table 2. The output simulation parameters are the geometry of deformed bullet after the penetration and residual velocity of the bullet after penetrating the gel block. Those parameters will be compared to experiments.

The example of graphical result of FEM simulation is shown in Fig. 7 for both the shot No. 1 (the lowest impact velocity) and for the shot No. 4 (the higher impact velocity), respectively.

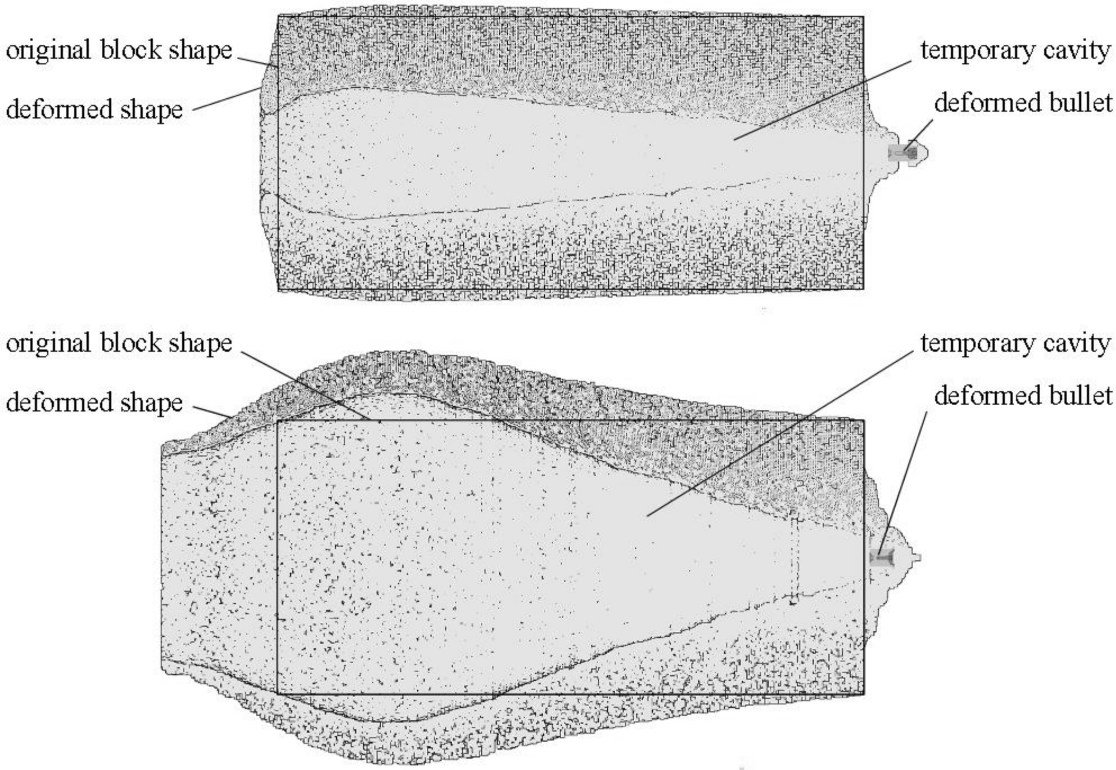

Fig. 7: Simulation results of penetrated gel block by the bullet Action 5; upper picture represents the shot No. 1 (impact velocity 248 m/s), the bottom picture the shot No. 4 (impact velocity 454 m/s)

The simulation results shown in Fig. 7 introduce a large temporary cavity made by penetrating bullet. Similar cavity was observed also on experiments. The volume of the cavity is larger for the bullet with higher level of expansion that means also higher impact velocity of the bullet and higher wound potential.

5. Simulation results and comparing to experiments

The FEM simulations using Ansys Autodyn aims to find good correlation for character and deformation of the bullet after penetration process. The second comparing parameter is residual velocity of the bullet after penetration of the gel block with respect to impact velocity of the bullet.

Every bullet showed some extent of the expansion after penetration of the gel block and the level of this extent varied upon the impact bullet velocity. Geometrical parameters of the bullets are contained in Table 3 and deformed shapes of the bullets are shown in Fig. 8.

Tab. 3: Comparing the experimental and simulation results

No of shot	Impact velocity	Bullet length L			Bullet max. diameter D			Residual velocity v_{res}		
		L_{exp}	L_{sim}	Δ_L	D_{exp}	D_{sim}	Δ_D	$v_{res,exp}$	$v_{res,sim}$	Δ_v
	m/s	m/s	m/s	%	mm	mm	%	mm	mm	%
1	248	15.2	14.8	3	9.0	9.0	0	105	110	5
2	349	14.8	14.1	5	9.2	9.2	0	80	79	1
3	395	13.7	13.4	2	12.0	10.5	14	44	45	2
4	454	13.4	12.4	8	14.1	12.2	16	36	37	3

No. 1 248 m/s | No. 2 349 m/s | No. 3 395 m/s | No. 4 454 m/s

Fig. 8: Bullets after penetration of the gel block – upper line shows the experimental results and the bottom line the simulation results

The bullets with lower velocity showed smaller expansion, the bullet No. 4 shows the greatest expansion with original propellant weight and original shooting velocity. In all cases the plastic cap was pushed inside of the bullet hollow. Every bullet penetrating the gel block was caught in the soft catch located behind the gel block without any secondary deformations.

The comparison of the change of bullet dimensions as well as the experimental and simulation velocities of the bullet after penetrating the gel block is shown in Table 3. The symbol *Δ* means a deviation of compared values calculated as the difference between compared values divided by the lower value of those compared.

According to the deviations shown in Table 3, the simulation follows the experimental values with respect to dimensions of the bullet very well and quite well with respect to the residual velocities.

The graph in Fig. 9 shows the course of impact velocity with respect to the decrease of residual velocity for both experimental and simulation values. The relative decrease of the residual velocity is equal to the ratio between the difference of impact and residual velocities divided by the impact velocity expressed in percentage units:

$$\bar{v}_{res} = \frac{v_{imp} - v_{res}}{v_{imp}} \cdot 100 \qquad (2)$$

On the other hand, the decrease of the residual velocity shows how much velocity of the impacting bullet was consumed by the penetration process. The course is not linear and between the impact velocities 349 m/s and 395 m/s occurs a break region where the behavior of the expansion process changes its effect on deceleration of the bullet in the gel block. We consider this effect as increased influence of expansion shape of the bullet. It is probably caused by exceeding the caliber diameter by expanded front part of the bullet. This effect should be investigated in detail in the future and it would be helpful to conduct more shooting experiments with impact velocities between the values of 349 m/s and 395 m/s.

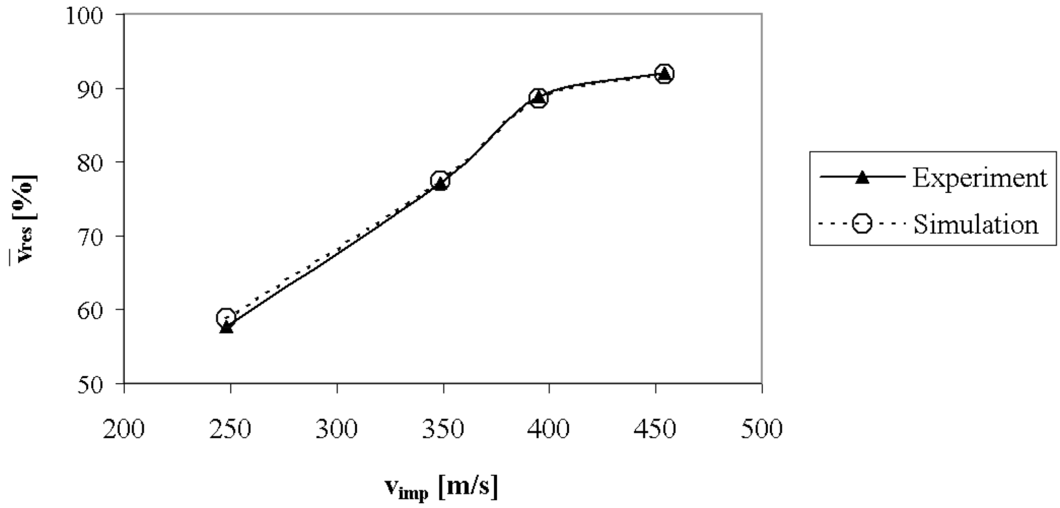

Fig. 9: Graph of the dependance of the decrese of residual velocity of the bullet with respect to the impact velocity

6. Conclusion

The above analysis in the article represents a detail view on the function of expansion bullet when penetrating a soft target (e.g. living tissue or its technical substitution). The results of the experiments and FEM simulations show fairly good correspondence. Based on the analysis of the function of the cartridge Action 5 in the terminal ballistics it can be stated that the basic characteristics of ballistic cartridge correspond to the physical and mechanical properties of the cartridge, i.e. the ballistic performance of the cartridge makes it possíble to reach optimum deformation of the bullet in soft targets (Jedlička, 2011).

According to presented anlysis it is possible to estimate following expansion velocity limits:

- lower expension limit – approx. 248 m/s (shot No. 1)
- expansion limit with expansion coefficient equal to 1 – approx. 349 m/s (shot No. 2)
- upper expansion limit – between 395 m/s and 454 m/s (shots No. 3 and 4).

Analysis of results allows to introduce the lower expansion limit of pistol bullet Action 5 and to estimate other limits of this cartridge. For their precise determination it is necessary to carry out further experiments with mentioned cartridge Action 5.

Acknowledgement

The work presented in this paper has been supported by the Ministry of Interior of the Czech Republic (security research project VG20112015037).

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