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The Analysis of Terminal-Ballistic Behaviour of a Pistol Bullet Penetrating a Block of Substitute Biological Material*

Juraj HUB[1], Jan KOMENDA[2], Frantisek RACEK[2]

[1]University of Defence, Department of Aircraft and Rocket Technologies, Kounicova 65, 66210 Brno, Czech Republic
[2]University of Defence, Department of Weapons and Ammunition, Kounicova 65, 66210 Brno, Czech Republic

Abstract. This article presents an experimental and numerical approach to estimate the ballistic limits of the pistol hollow point bullet of the Action 5 cartridge penetrating a block of substitute biological material using a wide range of bullet velocities. The bullet has an expansion ability enabling it to increase its wound potential in the case of it reaching the specific impact velocity limit. The expansion process of the bullet and the process of the evolution of the temporary cavity in the substitute material is investigated. The influencing factors of the penetration process are also discussed. The aim of the Finite Element Method (FEM) simulation of the penetration process based on experiments are also to estimate the minimal thickness of a substitute material that achieves the maximum expansion effect when impacting an aircrafts fuselage structure by firing on-board. Introduced are three levels of expansion limits defined as the bullet‘s velocity. The first one is the low expansion limit, when the expansion dimensions of the front part of the bullet reaches the dimensions of the bullet’s calibre, followed by the upper expansion limit with the maximum expansion of the bullet, and the destructive expansion limit, when the expanded front part of the bullet is destroyed.
Keywords: terminal ballistics, wound ballistics, penetrating, pistol bullet

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1. INTRODUCTION

A cartridge with expansion bullets is ammunition with increased wound potential. The expansion bullet deforms in its front part during the penetration of a soft target, and the so called expansion occurs. The functional deformation of the bullet increases the radial dimensions of the bullet and the resistance of the bullet's front area. Therefore the bullet transmits more energy into the target. The evaluated service pistol cartridge of 9 mm calibre with a commercial designation Action 5 manufactured by RUAG Ammotech contains a homogeneous brass bullet with its front expansion hollow covered by a plastic cap (Figure 1 and Figure 4).

Fig. 1. The Action 5 cartridge and its parts – from the left the Action 5 cartridge, two 9 mm caliber bullets and the cartridge case with primer and a cut of an Action 5 cartridge

The Action 5 cartridge is a part of an arsenal of many armed forces in various countries and the basic ballistic characteristics are shown in Table 1.

This article presents the investigation into the Action 5 bullet's expansion during the penetration of a substitute biological material, followed by the bullet's expansion limits and also the temporary cavity character in a penetrated substitute material block.

Table 1. Ballistic characteristics of the cartridge 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: * The values of the specific energy are valid for the bullet before and after its deformation into the substitute material. The cross section area of the front part of the bullet increases from the original value of 64 mm² to 156 mm² corresponding to the deformation diameter of 14.1 mm, that means an increase in the cross section area to the value of 245% at its standard velocity.*

2. DEFINITION OF EXPANSION LIMITS

The deformation of the expansion bullet is dependent not only on the resistance characteristics of the targets but also the material characteristics, geometry of the bullet and the impact velocity of the bullet.

At different impact velocities the same bullet deforms differently. The degree of bullet deformation is expressed by a dimensionless coefficient of bullet expansion K_e, defined by this equation

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

where: *D* means mean diameter of the front expanded part of the bullet and it is approximately equal to the diameter of the cylinder circumscribing the deformed bullet (Figure 2) and *d* means the calibre of the bullet equal to the guide part of the bullet.

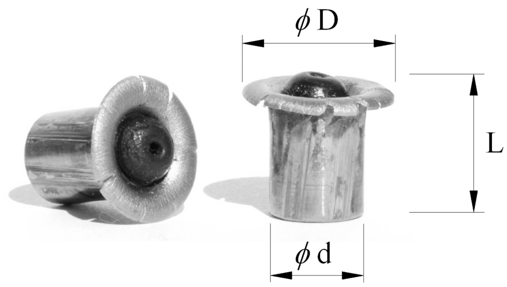


Fig. 2. Dimensions of the expanded bullet required for expansion coefficient estimation; shown here is an expanded bullet with standard deformation caused by the penetration of a substitute material (ballistic gel) with the expansion coefficient value of 1.53 (shot No. 6)

The higher the level of deformation of the bullet also causes a higher coefficient of expansion and wound potential. In practice, the coefficient of expansion usually reaches a value between 1 and 2 for the most common types of bullet.

Generally, the increase in the bullet's impact velocity leads to an increase in the bullet's deformation and thus the wound potential, in equal conditions. This is valid only to a certain extent. When exceeding a certain value of impact velocity, a partial destruction and reduction of the wound potential of some kinds of bullets might occur during the penetration of the tested block. Such destruction is typical for the Action 5 bullet and less frequently for the bullets with a lead core.

The typical hollow point bullet does not usually deform at very low impact velocities into the target. The bullet begins to deform when it reaches a certain minimum impact velocity, marked v_{d0}. In practical terms, this velocity is not essential. In terms of the evaluation of the wound effects the deformation of the bullet is more significant when the maximum radial bullet diameter exceeds the original calibre of the bullet, i.e. the bullet radial deformation exceeds the original bullet diameter.

The bullet's impact velocity reaching such deformation is considered the lower expansion velocity limit, marked v_{d1}.

The largest deformation of the bullet with a maximum coefficient of expansion and thus with maximum wound effect is achieved at the velocity v_{d2}. Such bullet impact velocity is considered as the upper expansion velocity limit.

A certain bullet impact velocity can lead to the destruction of the bullet or partial defragmentation of the front part of the bullet. This velocity is marked v_{dd} and represents the destruction velocity limit of the bullet. Reaching or exceeding this velocity, begins to significantly reduce the wound potential of the bullet, while the piercing potential of the bullet increases.

Expansion limits of the bullet depend on the type of substitute material penetrated by the bullet. The expansion limit does not depend on the thickness of the used substitute material, since the expansion of the bullet is usually completed at a short trajectory of a few centimetres and also movement of the bullet does not change the shape of the bullet's expansion. Therefore the experimental estimation of bullet expansion requires a relatively short bullet trajectory into the material with which the expansion of the bullet is completed.

Knowing the expansion limits, especially the upper expansion limit, is important for the correct choice of the ballistic properties of the cartridge as a part of its development with respect to the optimization of the bullet's wound properties. To achieve the maximum level of bullet wound potential, it is desirable that the bullet impacts the target with the velocity corresponding to the upper limit of expansion, eventually with the velocity slightly higher and without exceeding the limit of the destruction of the bullet. The lower impact velocity of the bullet compared with the upper expansion limit causes a reduction in the wound potential of the bullet and the higher impact velocity and exceeding the destruction limit may cause a significant reduction in the bullet's wound potential.

All expansion limits are to be treated and proved experimentally using Finite Element Method (FEM) simulation tools.

3. EXPERIMENTAL SHOOTING

Action 5 cartridges of an identical series marked SX 9×19 A5 – DAG10EE0842 were used for shooting at a distance of 5 m from the muzzle of a ballistic measuring device to uncovered gel blocks of Kraton 15% (Figure 3). The dimensions of the gel are as follows: the width of the rectangular face area – 200 mm, the height – 140 mm and the length – 300 mm. In one case the width of the gel block was 150 mm. The velocity of the bullet $v_{2.5}$ was measured using non-contact optical gates with a 1 m basis.

During the experiment the behavior of the tested gel blocks was captured using two high-speed cameras Redlake HG-100K and MotionXtra N4 to estimate the shape and size of the temporary cavities created in each block by the penetration of particular bullets.

The experiments covered original Action 5 cartridges and also de-elaborated cartridges. For the de-elaborated cartridges a modified propellant was used in order to achieve different impact velocities and various expansion behaviour of the bullet penetrating the gel block. The experiments also represented a foundation for the FEM simulations of the penetration process and expansion of bullets.

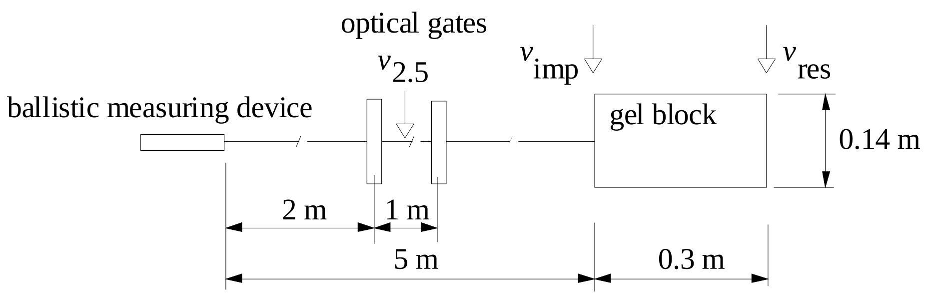


Fig. 3. Scheme of experiment

A total number of 19 shots were fired during the experiments. Four shots were of no use due to the bullets being stuck in the barrel because of the use of a reduced amount of the propellant. 13 of the rest of the shots that were of use used an original propellant. The basic ballistic data of the selected shots are shown in Table 2. The temperature of used the ammunition and gel blocks used was 20°C and the temperature of the shooting room was 10°C.

Table 2. Ballistic data on experimental shooting

No.	$v_{2.5} = v_{imp}$	v_{res}	L	D	K_e	ΔE_k	$\Delta E_{k,rel}$
	m/s	m/s	mm	mm	1	J	%
0	origin cartridge		17.2	9.0	-	-	-
1	248	105	15.2	9.0	1.00	154	82
2	313	97	15.1	9.0	1.00	270	90
3	349	80	14.8	9.2	1.02	352	95
4	395	44	13.7	12.0	1.33	470	99
5	436	52	13.5	13.5	1.50	572	99
6	454[1)]	36	13.5	13.8	1.53	625	99
7	498	45	13.1	14.5	1.61	750	99
8	560[2)]	151	10.7	10.0	1.11	887	93

Notes:
[1)] *the original Action 5 cartridge without any propellant modification*
[2)] *the propellant S-011 was used*

The kinetic energy of the bullet E_k is generally defined as the sum of translation and rotation energies upon relation

$$E_k = \frac{1}{2} m_b v^2 + \frac{1}{2} I_x \omega^2 \tag{2}$$

where m_b is the weight of the bullet, v is the bullet translation velocity, I_x is the inertia moment of the bullet and ω is the angular velocity of the bullet caused by barrel bore. The last part of the eq. (2) is neglected and therefore the kinetic energy of the bullet corresponds to the first part of the eq. (2).

The difference between the impact and the residual kinetic energies of the bullet means the energy consumed during the perforation of the gel block ΔE_k and the same parameter in percentual units $\Delta E_{k,rel}$ is determined using following equation

$$\Delta E_{k,rel} = \frac{E_{k,imp} - E_{k,res}}{E_{k,imp}} \cdot 100 \tag{3}$$

The values $\Delta E_{k,rel}$ in Table 2 show, that the bullets with a higher coefficient of expansion transmit almost the whole of its energy into the gel block.

The behaviour of bullets and gel blocks was also documented during the experiments. Every bullet that penetrated the gel block was caught by a soft trap without any secondary deformation. The level of expansion of the particular bullets was different upon impact velocity. The overview of selected bullets corresponding with Table 2 is shown on Figure 4. Each shot was performed just once.

No.	0	1	2	3	4	5	6	7	8
v_{imp}	0	248	313	349	395	436	454	498	560
K_e	1	1,00	1,00	1,02	1,33	1,50	1,53	1,61	1,11

Fig. 4. Bullets on various impact velocity, No. – the number of bullet, v_{imp} – impact velocity [m/s], K_e – coefficient of expansion [1]

Each bullet faces some extent of expansion after penetrating of the gel block and the level of this expansion varies upon the impact velocity. The bullets with a lower impact velocity show a smaller expansion. The bullets with the impact velocity increasing up to the upper expansion limit show maximal expansion. Bullets exceeding the upper limit velocity and reaching the bullet's destruction limit show a reduced expansion due to a radical change in the shape of the bullet.

The evolution and character of temporary cavities will be evaluated along with the FEM simulation results.

4. FEM SIMULATION CONDITIONS

The FEM simulation is used in order to find a numerical model for the Action 5 bullet penetrating the gel block and to investigate the penetration process in more detail. Therefore an explicit nonlinear transient hydro-code Ansys Autodyn v 14.0 was used. The model of both the bullet and the gel block was created using 2D axial symmetry, so only half of all components were modeled.

The geometry of the bullet based on its real dimensions was a little simplified in order to create a suitable mesh for FEM analysis. The density of the bullet corresponds to achieving the same total weight of the simulation and real bullets.

The simulation gel block shape does not respect the real prismatic geometry due to the axial symmetry used with the FEM model. The shape of the simulation gel block is cylindrical with a diameter of 140 mm and a length of 300 mm.

For the bullet the mesh-based Lagrangian method is used and for the gel block, the mesh-free particle based Smooth Particle Hydrodynamics (SPH) method is used. The character and discretization of the model of both the bullet and the gel block is shown in Figure 5.

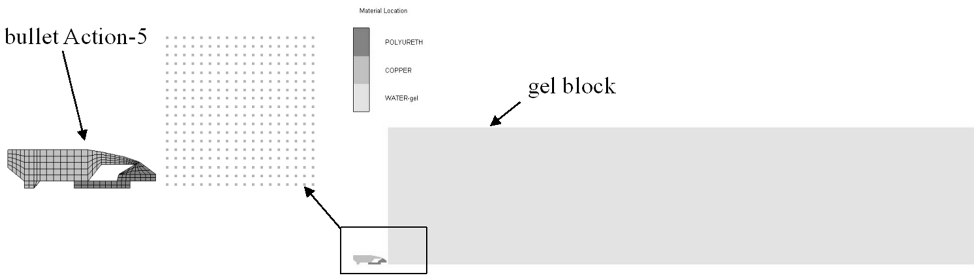


Fig. 5. FEM model of Action 5 bullet and gel block using axial symmetry

The rotation of the bullet caused by barrel bore and air drag is not considered. The simulation methodology follows [1, 2].

The material models for all parts used in simulation were retrieved from the Autodyn library and in some cases modified. The bullet consists of a brass body and plastic cap. The brass body is represented by a modified copper material and is described through the shock equation of state (EOS) and the Piecewise Johnson-Cook strength model. The EOS parameters: $\rho = 8354$ m · s^{-3}, $\Gamma = 2.0$, $C_0 = 3985$ m · s^{-1} and $S_1 = 1.497$. The Piecewise J-C model parameters: $G = 68800$ MPa, $Y_0 = 120$ MPa, $\varepsilon_{P1} = 0.3$, $Y_1 = 450$ MPa, $Y_2 = 450$ MPa and $m = 1$. The plastic cap follows the modified polyurethane material model described though linear EOS and the elastic strength material model with the following parameters: $\rho = 1265$ m · s^{-3}, $K = 2000$ MPa and $G = 5$ MPa.

The substitute ballistic gel material is represented by the modified water material model using the following EOS parameters: $C_0 = 1647$ m · s^{-1} and $S_1 = 1.921$.

The density of the gel block varies upon the impact velocity of the bullet as the parameter to achieve in accordance with the experimental and simulation results. The particular values of density are reported in Table 3.

5. RESULTS OF THE FEM SIMULATION AND COMPARISON TO EXPERIMENT

This chapter presents the simulation results of the expansion process of the bullet and the evolution of the temporary cavity accompanied by the penetration process of the gel block.

5.1. Bullet penetration process

The FEM simulation using Ansys Autodyn is focused on reaching the accordance of the velocity, character and deformation of the bullet after the penetration process obtained during the experiments. Therefore the initial experimental parameters were taken as input parameters for the FEM simulations. The results of the simulation and experiments are shown in Table 3.

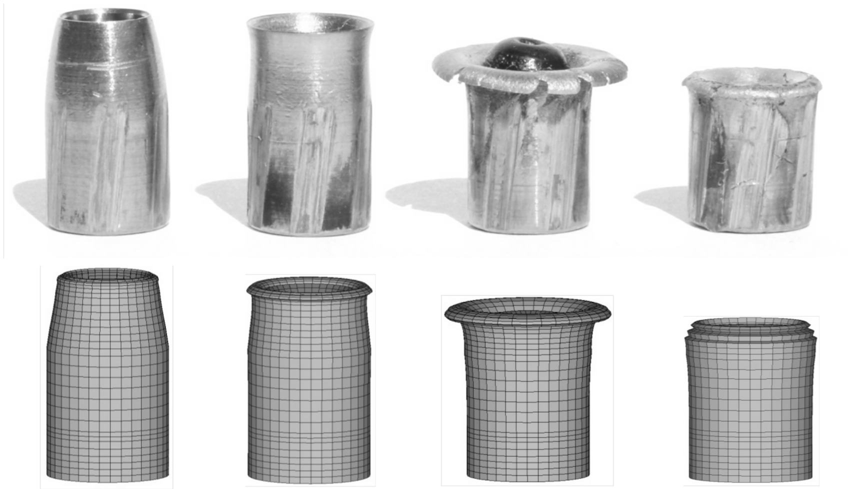
Table 3. Comparison of experimental and simulation results on the Action 5 bullet

No. of shot	Dens.	Bullet velocity				Bullet max. length			Bullet max. diam.		
	ρ_{sim}	v_{imp}	$v_{res,e}$	$v_{res,s}$	Δ_v	L_{exp}	L_{sim}	Δ_L	D_{exp}	D_{sim}	Δ_D
	$kg \cdot m^{-3}$	m/s	m/s	m/s	%	mm	mm	%	mm	mm	%
1	510	248	105	106	1	15.2	14.8	3	9.0	9.0	0
2	590	313	97	106	9	15.1	14.3	6	9.0	9.0	0
3	650	349	80	79	1	14.8	14.1	5	9.2	9.2	0
4	740	395	44	43	2	13.7	13.4	2	12.0	10.5	14
5	740	436	52	47	11	13.5	12.7	6	13.5	11.9	13
6	750	454	36	37	3	13.4	12.4	8	14.1	12.2	16
7	720	498	45	46	2	13.1	12.2	7	14.5	12.6	15
8	650	560	151	154	2	10.7	11.1	4	10.0	9.7	3

Notes:
Dens. ... Density of the gel block used in FEM simulation in order to achieve the experimental results
$v_{res,e}$, $v_{res,s}$ ... *experimental and simulation residual velocities of the bullet*
L_{exp}, L_{sim} ... *experimental and simulation length of the bullet after penetration*
D_{exp}, D_{sim} ... *experimental and simulation max. diameter of the bullet after penetration*

Table 3 also shows a comparison in velocity and geometrical values of both experimental and simulation bullets. The symbol Δ means a deviation of compared values calculated as the difference between compared values divided by the lower value of those compared.

Pictures of selected experimental and simulation bullets are shown in Figure 6. The simulation bullets on the second line are created by rotation of the 2D solution.



No. 1 248/105 m/s | No. 3 349/80 m/s | No. 6 454/36 m/s | No. 8 560/151 m/s

Fig. 6. Bullets after penetration of the gel blocks – No. means the number of the shot according to the Table 3 and bottom line reports impact/residual velocities of the bullet

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

Figure 7 presents the course of impact velocity with respect to the residual velocity of the bullet for both the experimental and simulation results.

The course of Figure 7 indicates three regions, where the behaviour of the bullet changes its character. A break of the course between the shot No. 2 and No. 3 indicates the increasing influence of bullet expansion and Table 2 shows exceeding coefficient of expansion equal to 1 in this region. Next break is around the shot No.4 where the tendency of progressive expansion is slowing down. Shot No.5 with increasing residual velocity is illogical and it is probably caused by the accuracy measuring.

The last break between shot No. 7 and 8 is caused by reaching the damage limit of the bullet when the front part of the bullet faces partial defragmentation (Figure 4 and Figure 6).

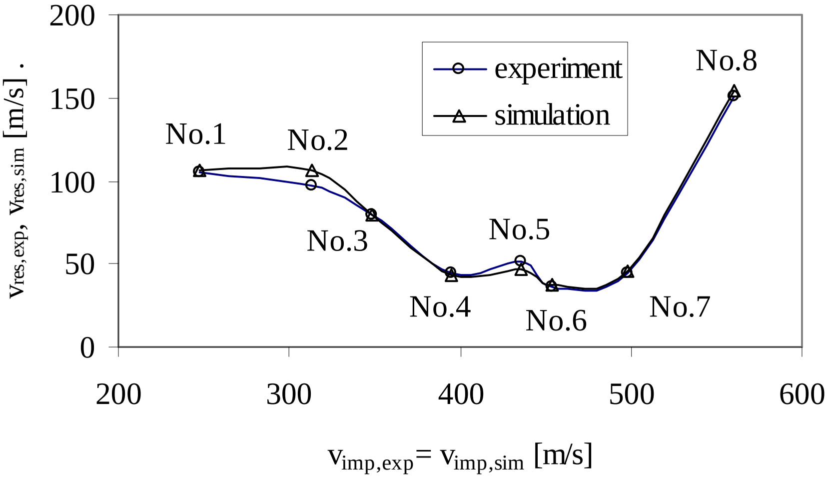


Fig. 7. Impact velocity of the bullet versus residual velocity of the bullet

5.2. Temporary cavity evolution

The Action 5 bullet creates a temporary cavity in the block. An example of the experimental results of the temporary cavity is shown in Figure 8 for the shot No. 2 at two bullet positions.

The first position is chosen to be 25% of the gel block length as is presented in Figure 8a. The second position of the bullet is the moment of leaving the penetrated block is presented in 8b. Shot No. 7 is likewise shown in Figure 9.

The volume of the cavity also depends on the level of bullet expansion. Bullet No. 2 does not expand due to the low shooting velocity and the temporary cavity is not as large as with the bullet No. 7 which expands almost fully due its standard shooting velocity.

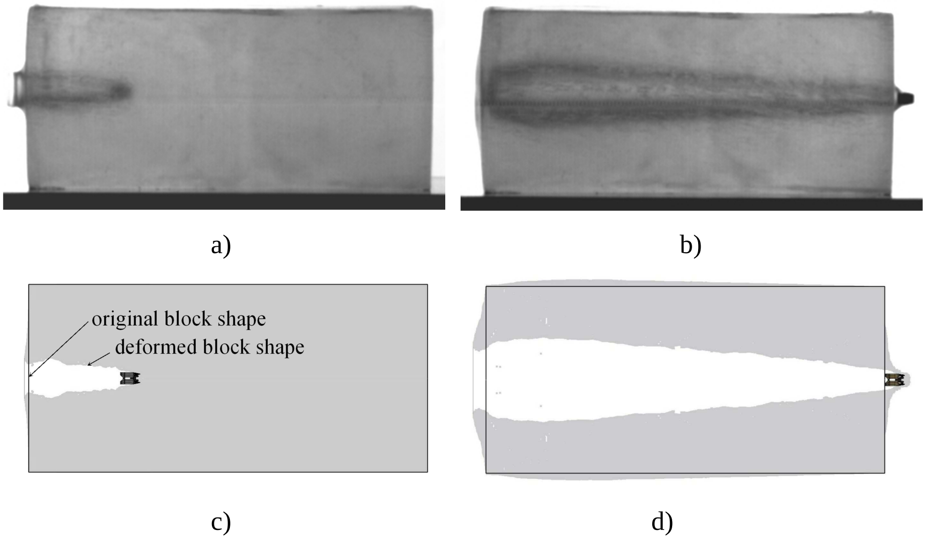


Fig. 8. An example of the temporary cavity for the bullet impact in the block of substitute material with the velocity of 248 m/s in experiment (a, b) and in simulation (c, d)

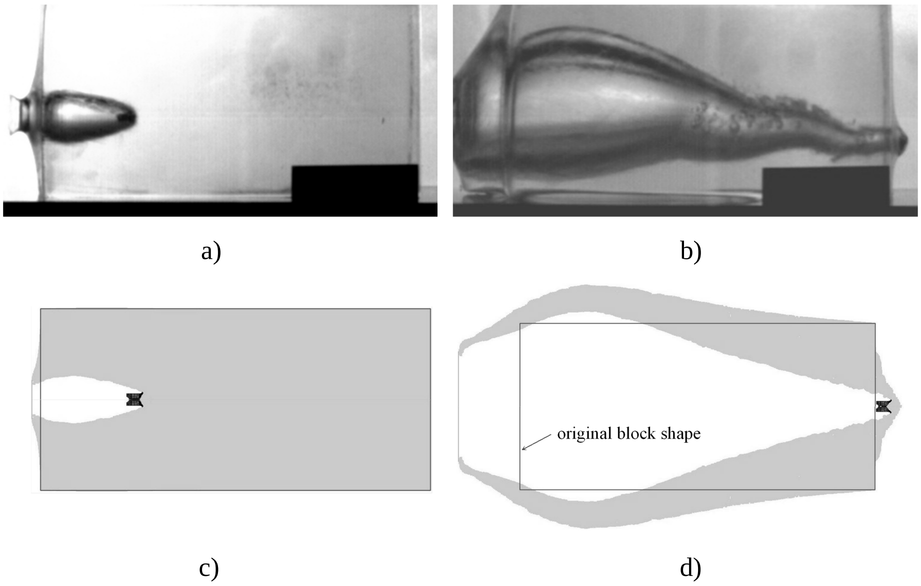


Fig. 9. An example of a temporary cavity for the bullet impact in the block of substitute material with the velocity of 454 m/s in experiment (a, b) and in simulation (c, d)

The characteristics of the experimental and simulation cavities in Figure 8 is similar as well as the volume of both cavities. The deformation of the gel block is not so obvious.

Figure 9 proves what influence the bullet expansion has on the volume of the temporary cavity in the gel block. In the case of the evolution of the bullet expansion the volume of the cavity increases. Conformity of the experiment and simulation is very high in cases a) and c), when the bullet is inside the gel block and the temporary cavity volume is not so large. In the case of the position b) of the bullet leaving the gel block for the experiment it is a visible non-symmetrical cavity and the rotation of the expanded bullet in last part of its trajectory.

The simulation d) in the same situation offers a symmetrical solution due to the 2D analysis with axial symmetry and the volume of the simulation cavity is much larger than the cavity made during the experiment (Figures 9 b and 9d).

The asymmetric character of the experimental case b) is probably caused by bullet hitting the gel block out of the centre of the front part of the gel block and higher proximity of the cavity to the bottom part of the block that lies on the experimental table.

Table 4 presents the experimental volumes of temporary cavities in terms of absolute cavity volume V_{c} and relative cavity volume $V_{\mathrm{c,rel}}$. The relative cavity volume is defined as the relation of the cavity volume with respect to the original volume of the gel block before being penetrated by the bullet $V_{\mathrm{b,orig}}$. Deviation of compared values is calculated as the difference between compared values divided by the lower value of those compared. The volumes are approximately estimated.

The simulation results differ quite significantly when compared with the experimental results due to the different dimension of both experimental and simulation blocks (chapters 3 and 4 and also due to the different boundary conditions). The volume of the simulation cavity is larger and it is probably caused by free ends of the simulation model in all directions when the material deforms freely. In spite of this, the experimental gel block has had different boundary conditions on the bottom part of the block.

Figure 10 shows the course of bullet velocities with respect to the volume of the temporary cavity in the block caused by the bullet penetrating the block of substitute material. The volume of the temporary cavity helps to evaluate the wound potential of the expansion bullet and is captured at the moment that the bullet leaves the penetrated block.

Limit velocities are approximately determined by experimental shooting. The precise determination of limit velocities would require additional experiments.

The lowest bullet velocity for starting the expansion process of the bullet v_{d0} is 115 m/s upon simulation results.

The velocity v_{d1} has just approximate significance in practice and determines the left border of velocity range with increased wound potential of the bullet (Figure 10).

Table 4. Parameters of temporary cavities

No. of shot	Experiment			
	v_{imp}	$V_{b,orig}$	$V_{c,abs}$	$V_{c,rel}$
	m/s	dm^3	dm^3	%
1	248	7.84	0.26	4
2	313	6.30	0.34	6
3	349	7.84	0.73	9
4	395	7.84	1.25	15
5	436	7.84	1.42	17
6	454	7.84	1.39	17
7	498	7.84	1.77	21
8	560	7.84	1.14	14

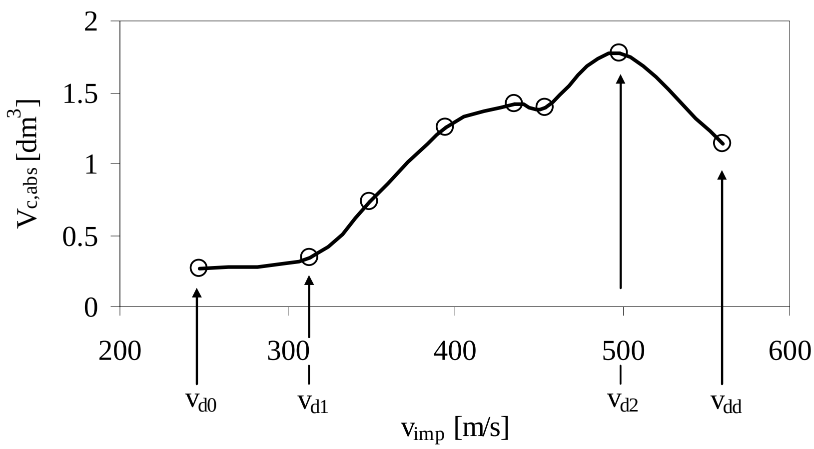


Fig. 10. Dependence of the temporary cavity volume with respect to the impact bullet velocity, describing the velocities:
V_{d0} – velocity of the beginning of the bullet expansion,
V_{d1} – velocity of reaching the expansion coefficient $K_e = 1$, low expansion limit,
V_{d2} – velocity of reaching the maximum bullet expansion, upper expansion limit, $K_e = K_{e,max}$,
V_{dd} – the lowest velocity of destruction of the bullet, destruction limit.

The convex course of the dependence shown in Figure 10 indicates the important influence of the expansion of the bullet.

5.3. Expansion process evolution

The proposed FEM simulation based on experiments enables us to discover the expansion process of the bullet in more detail when compared to the abilities of used experimental techniques currently being used. Therefore the expansion process is observed in order to estimate the distance of a particular bullet penetrating the gel block, on which the expansion process is finished. The results are shown in Figure 11. The diameter D_0 means the initial diameter of the front part of the bullet, *d* is the calibre of the bullet.

Figure 11 shows, that the deformation of the bullet of the standard Action 5 cartridge is completed after the penetration of the gel block in a trajectory depth of 30.9 mm.

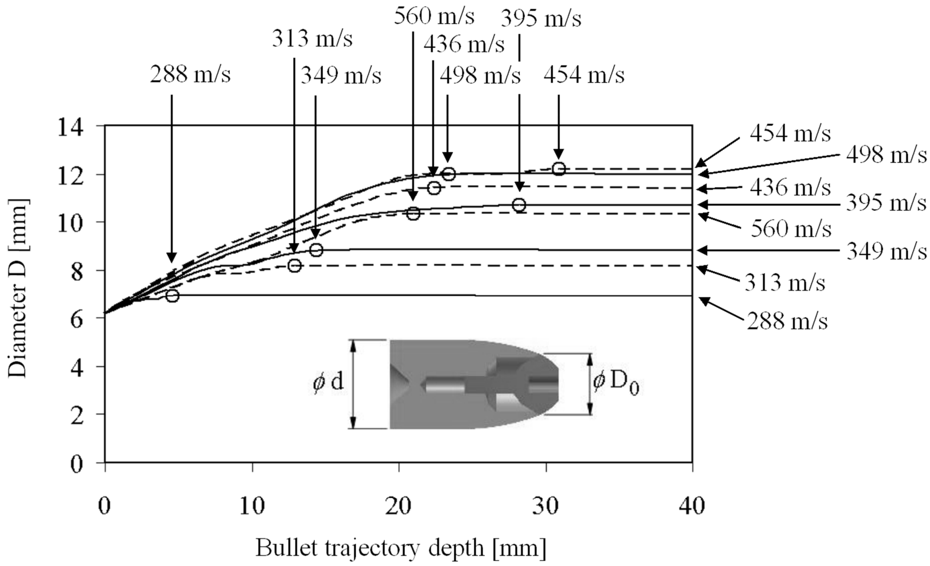


Fig. 11. Dependence of the increase of the expanded diameter of the bullet with respect to the bullet path

On the other hand, the cartridge with a low elaboration and velocity of 248 m/s completes its expansion in a trajectory depth of 4.6 mm. The trajectory of bullet deformation is therefore neglected with respect to the total bullet trajectory in the gel block. The relation of those trajectories changes upon various impact velocities.

The increasing impact velocity of the bullet causes:

- An extension in time of the trajectory in changing the bullet's deformation, i.e. higher deformation takes more time;
- A reduction in the relation between the total bullet trajectory in the tested block and the trajectory of bullet deformation;
- An increase in bullet deformation velocity and the course in Figure 11 is steeper; the average relative change of radial dimension along the bullet trajectory is 6/30.9 mm/mm for a standard bullet, i.e. every 5.1 mm of the bullet trajectory causes an approximate change of 1 mm in radial dimension.

The circular marks in Figure 11 define the moment the bullet completes its expansion process. The deformation of the bullet remains the same after exceeding this point. The increased bullet trajectory depth upon finishing the expansion process for velocities 359 m/s and 454 m/s are supposed to be caused by a different mechanism of deformation of the expansion part of the bullet.

The minimal thickness of the gel block to achieve complete expansion of the bullet with standard firing velocity 454 m/s is 35 mm with residual bullet velocity of 325 m/s.

The mentioned deformation behaviour of the bullet is possible to analyse using only FEM simulations. State of the art experimental techniques are not sufficient enough to provide such information, even when using high-speed cameras for capturing the penetration process.

6. DISSCUSSION

The expansion of the bullet and therefore its wound potential is not only dependent on the structural design but also on the overall concept of the cartridge, especially in the amount and type of propellant used to eject the bullet, as well as the type of weapon, especially taking into account the length of the barrel and the distance of the target. These factors can significantly affect the initial velocity of the bullet and the impact velocity on the target. A different bullet impact velocity may express a different wound potential and other properties concerning terminal ballistics. Paradoxically the unexpanded bullet with a low impact velocity penetrates deeper into the target with a higher level of piercing potential than the bullet with a higher velocity that expands. Therefore the residual velocity of the slow unexpanded bullet leaving the penetrated test block or live target can be higher than that of an fast expanded bullet. The transmitting level of energy into the target is lower with the slow bullet and such a bullet is less efficient for the target but it can also threaten a more non-participating neighbourhood in the case of penetrating the target. This may be an important risk factor for less ballistic resistant structures such as elements of the transport aircraft etc.

7. CONCLUSIONS

The analysis presented in this article introduces detailed views on the function of the expansion bullet penetrating a soft target representing living tissue or its technical substitute. The results of experiments and FEM simulations correlate rather well.

On the basis of the Action 5 bullet function analysis it is possible to assume, that the basic ballistic characteristics of the Action 5 cartridge correspond with the physical and mechanical characteristics of the bullet, i.e. the ballistic performance of the cartridge enables it to reach the optimum bullet deformation in the soft target.

Using the analysis of results, a low expansion velocity limit of the Action 5 pistol cartridge was estimated as well as the other limits for this cartridge. The precise determination of the mentioned limits requires further shooting experiments with the used cartridge.

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