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Penetration of the Transport Airplane Fuselage with Forward Obstacle by Handgun Expansion Bullet

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Abstract:

The article presents an experimental and numerical approach to estimate ballistic limits of handgun hollow point bullet Action 5 penetrating the target representing a transport airplane fuselage and a forward obstacle. The target containing the composite sidewall, the insulation glass wool layer and the duralumin skin plate is perforated in two combinations – directly and using forward obstacle in form of ballistic gel as substitute biological material to achieve the conditions of firing on-board by Air Marshals, for instance. The ballistic resistance of the fuselage structure fired directly is very poor and in case of firing the gel block first is limited to some extend due to expansion ability of the bullet. The simulation using Finite Element Method system Ansys Autodyn v.14 introduces 2D model presenting the estimation of the ballistic limit in form of gel block thickness for particular combinations of the target based on experiments.

Keywords:

Handgun ammunition, Action 5, hollow point bullet, ballistic limit, aircraft fuselage, gel, FEM

1. Introduction

Evaluating the ballistic resistance of airframe of transport airplanes is very important also in case of using a handgun on-board in order to avoid catastrophic consequences. Shooting on-board can take place in case of service procedure done by Air Marshals usually armed with a gun and hollow point ammunition (expansion).

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Firing on-board by handgun bullet and penetrating the airplane's fuselage can be very different. Firstly, a smooth penetration occurs with the surplus of energy with high velocity of the range 300 m/s to 400 m/s in case of striking the fuselage wall directly at angles close to the value of 90° without any forward obstacle using a standard handgun bullet. Such perforation does not cause a significant consequence on the fuselage functionality as the pressurized vessel.

Secondly, if the bullet penetrates a different target before the fuselage structure, e. g. human body as the primary target, the effect of the bullet on the fuselage wall may be than quite different. The bullet velocity is in this case reduced and furthermore a large deformation usually occurs, so called bullet expansion. Expanded bullet may cause unfavourable consequences to the following, so called secondary target.

In case of significant reduction of bullet energy the perforation of the fuselage structure consisting of composite sidewall, glass wool insulation layer and outer duralumin skin is not performed at all or fully finished. The expanded bullet may cause more serious damage of the outer duralumin fuselage skin in conditions close to the limit velocity when the perforation is complete. The damage in this case could be more serious due to the irregular hole after perforating the fuselage skin with the high potential for the propagation of unfavourable fatigue cracks.

1.1. Characteristics of Action 5 Handgun Ammunition

Presented analysis considers the service cartridge Action 5 of calibre 9 mm Luger with homogeneous brass bullet with expansion cavity in the front part covered with plastic cap, see Fig. 1. Selected ballistic characteristics of the cartridge are shown in Tab. 1.

Fig. 1 The cartridge Action 5 and its parts – from the left the cartridge Action 5, twice the bullet, the cartridge case with primer and the cut view of the whole cartridge

Table 1 Selected 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

The amount of energy given to the target is described through kinetic energy of the bullet. The kinetic energy of the bullet is generally described as the sum of translation and rotation energies upon equation:

$$E_k = \frac{1}{2} m_\mathrm{b} v^2 + \frac{1}{2} I_x \omega^2 , \tag{1}$$

where m_b represents the weight of the bullet, v is the bullet translation velocity, I_x is inertia moment of the bullet and ω is angular velocity of the bullet caused by barrel rifling of ballistic measuring device. The last part of the equation (1) is considered to be neglected for practical calculations and therefore the kinetic energy of the bullet corresponds to the first part of the equation (1).

The initial specific bullet energy is related as kinetic energy of the bullet with respect to the contact area between the bullet and the target. The values of the initial specific bullet energy e_0 in Tab. 1 are valid for the bullet before deformation / after standard deformation in the substitute material. The cross section area of the front part of the bullet increases from the original unexpanded value 64 mm^2 to the value 156 mm^2 corresponding to the expanded diameter of the front part 14.1 mm, that represents an increase of the front cross section area of the value 145 %.

1.2. Action 5 Expansion Process

The expansion process of the bullet varies upon the perforated material. In live targets, tissues or their substitutions is the expansion behaviour of the bullet following – firstly, the front plastic cap is pressed deeper into the bullet cavity soon after the contact with the surface layer of the tissue or substitute material block. This process starts to opens the cavity and the cavity is afterwards filled by target material that continues the cavity opening due to the hydrodynamic effect. Also the diameter of deformed front part increases and cracks occur on the rim, see Fig. 2.

Penetration of the fuselage structure as a hard target directly causes pressing of the cap into the bullet cavity as well, but the front part of the bullet does not expand due to lack of the hydrodynamic effect of the gel block material as a soft target.

The expanded bullet is shown in Fig. 2. A significant increase of the front area decreases the amount of specific energy transmitted into the target, see Tab. 1, and in spite of this increases the wound potential of the bullet. On the other hand, the ability of the bullet to penetrate following solid obstacles decreases. Wound potential and piercing potential of the bullet are intertwined.

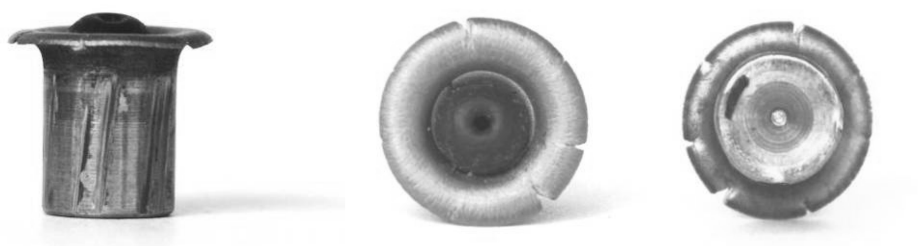


Fig. 2 Deformed bullet Action 5 after standard expansion in ballistic gel: from the left the profile of the bullet, next top axial view and bottom axial view

1.3. Scope of the Article

One aim of the article is setting the limit gel block thickness in order to achieve a specific effect on particular parts of the fuselage structure. Ballistic resistance of targets facing the impact of handgun arms bullets is possible to evaluate theoretically and experimentally. The experimental method is firing that needs repeated shots to find results searched. One of the useful theoretical methods is the Finite Element Method (FEM) simulation that demands for correct representation of the behaviour of investigated subject including material characteristics. This can be done also using experimental firing. A limit velocity of the gel block thickness will be estimated using simulation model to reduce the number of firing experiments.

In experimental and theoretical approach the difference of air pressure and temperature on both sides of fuselage structure significant in real flight airplane conditions are not considered.

Investigated will be following three cases of impacting the fuselage structure by the ammunition Action 5 when penetrating the gel block first:

Case 1: Complete perforation of the fuselage structure at minimum residual velocity of the bullet.

Case 2: Complete perforation of both the composite sidewall and the insulation layer, while the bullet is stopped by the duralumin skin allowing partial deformation.

Case 3: Complete perforation of the inner composite sidewall solely, while the bullet is stopped by the insulation layer or by the duralumin skin avoiding any plastic deformation of the skin.

Last two cases are important to prevent the leak of air pressure due to keeping the integrity of the fuselage duralumin skin and for extent of following structure repair.

2. Shooting Experiments

Shooting experiments were performed using the ammunition Action 5 and barrel of calibre 9 mm Luger of the length 150 mm and universal ballistic breech UZ 2002, producer Prototypa-ZM, Ltd. Brno. An etalon target was used in two combinations – without and with forward obstacle in form of gel block. One shot into each target combination was conducted at the distance 5 m from the muzzle of the measuring device to the front plane of the etalon target, see Fig. 3. The experimental shooting represents firing on-board at the angle of 90° towards the front plane of the target, so the bullet aims out of the aircraft fuselage.

The velocity of the bullet v_{3m} was measured using non-contact Doppler radar DR01. The process of perforation was captured by two high-speed cameras MotionXtra N4 and Redlake HG-100K in order to record the impact and residual velocities of the bullet. The temperature of used ammunition and the gel block was 20 °C and the temperature of the shooting range Prototypa, Inc., Brno, was 18 °C.

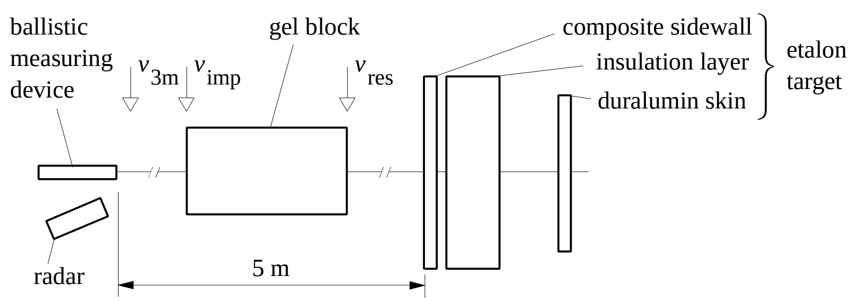


Fig. 3 Scheme of experiment and target combinations

2.1. Etalon Target Description

The first experiment contained just the etalon target as the assembly representing the commercial transport aircraft fuselage structure, see Fig. 4a. The etalon target consists of three rectangular parts – glass-epoxy composite sidewall of the dimensions 260 mm × 260 mm and the thickness 1.2 mm, insulation glass wool layer of the dimensions 260 mm × 260 mm and the thickness 35 mm and both parts have clamped edges not included in mentioned dimensions. The duralumin skin has the total dimensions 250 mm × 250 mm upon [1], the active dimension is 220 mm × 220 mm and the thickness 0.8 mm, see Fig. 4b. The insulation layer consists of lightweight, flexible thermal insulating glass wool blanket Microlite AA of the density 9.6 kg/m^3 packed in plastic bag reinforced by fibres. The sheet metal plate used for outer skin of the fuselage is represented by the material Al 2024-T3 ALCLAD.

The distance between particular parts is following: between gel block and composite sidewall is 50 mm, between composite sidewall and insulation layer is 1 mm and between insulation layer and duralumin skin is 60 mm.

a) b)

Fig. 4 Scheme of fuselage structure assembly (a) and mounting of the duralumin fuselage skin on experimental frame (b)

The second experiment consisted of two kinds of targets. The first part was the gel block Kraton 15 % of the prismatic shape with length 200 mm and rectangle cross-section of dimensions 200 mm × 140 mm. The second part was the etalon target used in the first experiment.

2.2. Results of Shooting Experiment

The experimental results of bullet velocities and energies are shown in Tab. 2:

Tab. 2 Results of experimental shooting

No. of exp.	v_{3m}	v_{imp}	v_{res}	$E_{k,imp}$	$E_{k,res}$	ΔE_k	$\Delta E_{k,rel}$
	m/s	m/s	m/s	J	J	J	%
1	443	436	414	580	523	57	10
2	458	451	92	620	26	595	96

In the first experiment the bullet perforated the etalon target with surplus of energy of the value $E_{k,res}$ = 523 J calculated upon Eq. (1). The character of the hollows made by bullet is presented in Fig. 5. The perforation of the composite sidewall performed a cylindrical hollow of approx. diameter 6.2 mm with torn fibres, see Fig. 5a and 5d. A delamination process is visible at the back side of the composite sidewall of the square size approx. 35 mm × 35 mm, see Fig. 5d. The perforation of the insulation layer caused an irregular hollow of the diameter approx. 6.9 mm with torn plastic bag and fibres and the dimension and shape of both hollows is very similar, see Fig. 5b and 5e. The perforation of the duralumin sheet metal plate created a regular cylindrical hollow of the diameter 8.6 mm, see Fig. 5c and 5f.

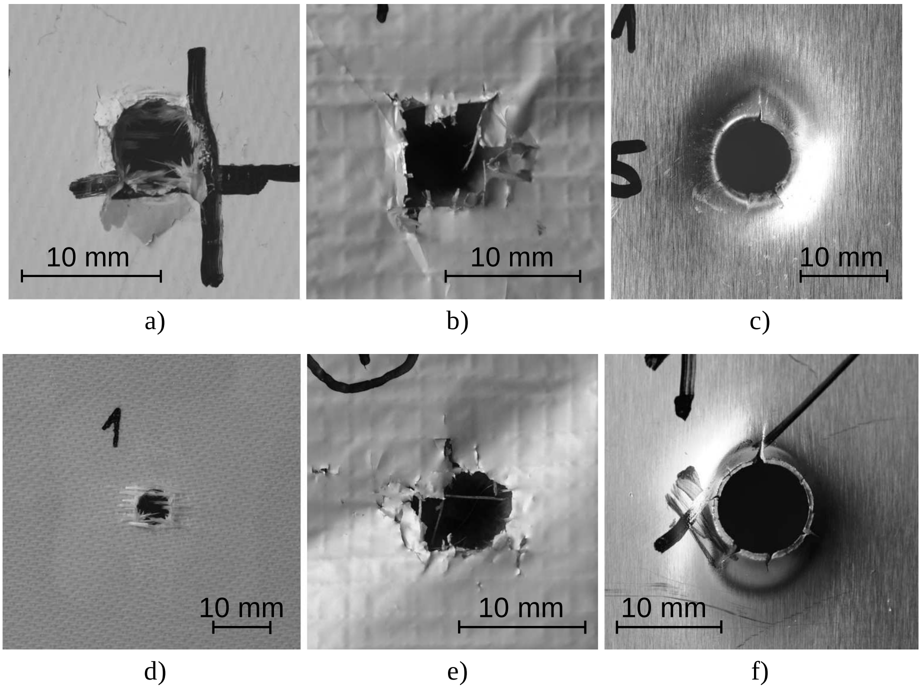
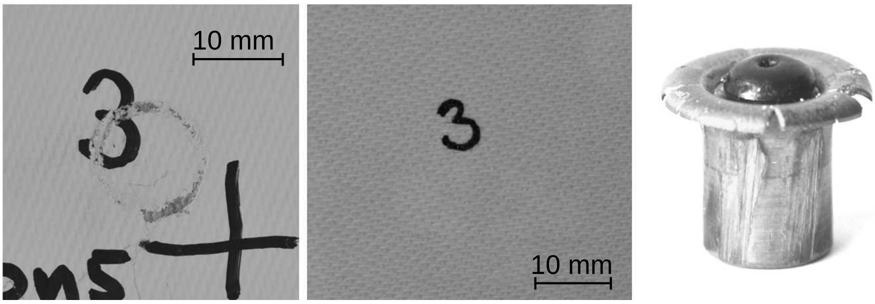


Fig. 5 Results of first experiment –hollows in parts of secondary target: front sides of sidewall (a), layer (b) and skin (c), back sides of sidewall (d), layer (e) and skin (f)

The circle hollow in duralumin sheet metal plate contains a relatively small plastic deformation around the hollow with cracks on the rim, see Fig. 5f. The character of hollow proved the absence of the bullet expansion; i. e. the deformed front part of the bullet did not exceed the size of the bullet calibre.

The deformed bullet was not found after the shooting, therefore the exact character and size of the bullet expansion was not known. It is supposed, that the bullet is slightly deformed on its front part and shorten in length without the massive expansion upon similar experiments presented in [2].

In the second experiment the bullet perforated the gel block as the primary target first creating a temporary cavity in it. This bullet had reduced residual kinetic energy of the value $E_{k,res}$ = 26 J upon Eq. (1). The bullet showed lack of energy to penetrate even the composite layer as the first part of the secondary target and the bullet was bounced off by the composite layer leaving behind just small damage on the layer surface, see Fig. 6a. A delamination area is barely visible on the back side of the composite sidewall of the square dimension approx. 25 mm × 25 mm, see Fig. 6b. For the shape of deformed bullet see Fig. 6c. The bullet is expanded after perforation of the gel block, therefore the front area of the bullet is increased, the specific energy is decreased, see Tab. 1, and the bullet demands for more energy to penetrate the following obstacle.



a) b) c)

Fig. 6 Results of second experiment – damaged surface of front part of composite sidewall (a), back side of composite sidewall (b) and deformed bullet (c)

The Tab. 2 shows also the difference between impact and residual kinetic energies of the bullet ΔE_k as the energy consumed during the perforation of the gel block. The same parameter can be determined in percentage units $\Delta E_{k,rel}$ upon the equation:

$$\Delta E_{k,rel} = \frac{E_{k,imp} - E_{k,res}}{E_{k,imp}} \cdot 100 \,. \tag{2}$$

The values $\Delta E_{k,rel}$ of the first experiment show, that the bullet transmits only a minor part of its energy into the fuselage structure and has the value 10 %, see Tab. 2. A different situation is with the second experiment, when the bullet impacts the gel block first. In this case the bullet transmits into the gel block a major part of its energy of the value 96 % and therefore the expanded bullet performs limited ability to perforate the secondary target, which is the fuselage structure.

3. FEM Analysis

The FEM analysis using explicit nonlinear transient hydrocode Ansys Autodyn v 14.0 is introduced in order to find a numerical model based on firing experiments of the bullet Action 5 perforating the two combinations of the target. FEM model will be then used for finding the solution for particular cases defined in chapter 1.3.

3.1. Description of the Simulation Model

A 2D axial symmetry is used for the simulation model, therefore only a half parts of all components is modelled, see Fig. 7. The methodology is based on [2-4].

The geometry of the bullet is based on real dimensions and a little bit simplified in order to create a suitable mesh for the FEM analysis. The bullet uses the mesh-based Lagrangian method. The density of the bullet is modified in order to meet the equal total weight with the real bullet. The initial condition for the bullet is impact velocity v_{imp} equal to the experimental velocity; see Tab. 2. The air drag and rotation of the bullet by barrel bore are not considered.

The particular parts of the fuselage structure are based on experimental parts and have a rectangular shape in 2D projection that creates a disc using axial symmetry. The periphery of all discs is clamped.

The simulation gel block is used in order to simulate the second experiment. The shape of the simulation gel block is of cylindrical shape with diameter of 140 mm and length of 200 mm, so therefore it does not follow the real prismatic geometry due to the axial symmetry used. The gel block uses the mesh-free particle based Smooth Particle Hydrodynamics (SPH) method and the size of particles is 1 mm.

The main parameter for validating the simulation model is residual velocity of the bullet after perforation of particular parts of the target. In the case of the second experiment the next evaluating parameter is the shape of deformed bullet.

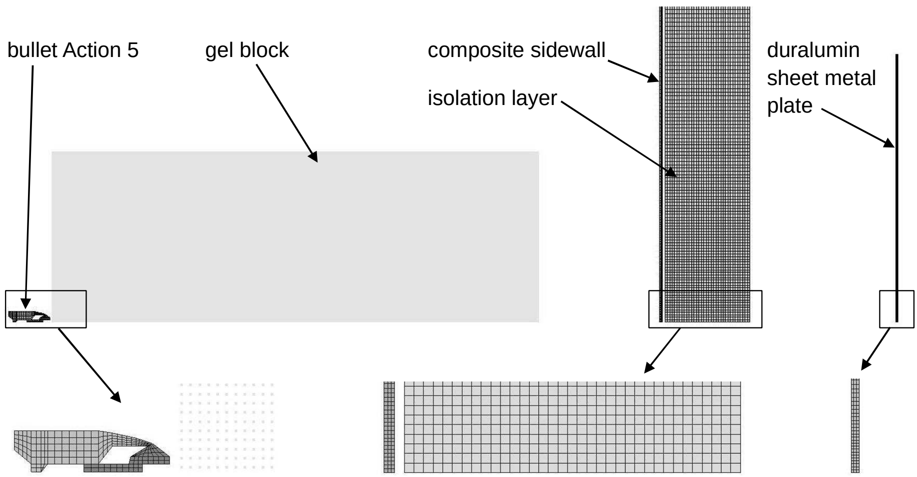


Fig. 7 FEM Simulation model

3.2. Material Models

Material models used in FEM analysis are based on Ansys Autodyn library and [2, 4].

The gel block as the primary target is represented by modified model WATER. This model uses shock equation of state (EOS) with parameters ρ = 760 kg/m^3, C_0 = 1647 m/s and the Hugoniot slope coefficient S_1 = 1.921.

The fuselage structure as the secondary target consists of three parts:

Part 1:The composite sidewall uses also retrieved model GLASS-EPXY with density ρ = 1840 kg/m^3. This model uses Puff EOS with following parameters: A_1 = 12130 MPa, A_2 = 17980 MPa, Gruneisen coefficient 0.15, expansion coefficient 0.25 and sublimation energy 2 MJ/kg. Next the composite sidewall uses von Mises strength constitutive model with shear modulus 4000 MPa and yield stress 143.1 MPa. The tensile pressure failure model of composite sidewall allows a maximum hydrodynamic tensile limit of the value of –159 MPa. Also erosion is considered in form of instantaneous geometric strain of the value 2.

Part 2: The insulation layer is simplified and it is considered to be of one homogenous material without dividing between the glass wool blanket and reinforced plastic bag. The EOS is of linear form and erosion failure model in form of instantaneous geometric strain is of the value 2. Bulk modulus is considered of 1 kPa.

Part 3: A sheet metal plate made of aluminium alloy ASTM 2024-T3 uses Gruneisen form of EOS upon [5] with following values: Gruneisen Gamma $\Gamma = 2.0$, density of the alloy $\rho = 2780$ kg/m^3, initial sound speed $C_0 = 5328$ m/s and Hugoniot slope coefficient $S_1 = 1.338$. The constitutive model uses an empirical Johnson-Cook model [6] with following constants: yield uniaxial stress $A = 368.5$ MPa, strain hardening coefficient $B = 683.9$ MPa, strain hardening exponent $n = 0.73$, strain hardening coefficient $C = 0.0083$ and thermal softening exponent $m = 1.7$ upon [7]. The failure criterion upon Johnson-Cook [8] uses following constants: $D_1 = 0.112$, $D_2 = 0.123$, $D_3 = 1.5$, $D_4 = 0.007$, $D_5 = 0$ according [7].

The bullet Action 5 used in simulation is described through various models.

The gilding metal jacket uses EOS with values: $\rho = 7985$ kg/m^3, $\Gamma = 2.0$, $C_0 = 3958$ m/s and $S_1 = 1.497$. The constitutive model of modified COPPER model uses the Piecewise Johnson-Cook model with 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 of the bullet considers the polyurethane material POLYURETH and uses shock EOS with bulk modulus $K = 2000$ MPa and density $\rho = 1265$ kg/m^3. Strength model of the plastic cap uses elastic form and failure model uses the maximum value of principal stress. The shear modulus has the value of 5 MPa.

3.3. FEM Model Validation

The FEM simulation approaches to fit the both experimental and simulation perforation process parameters – the bullet velocity and the deformation character both of the bullet and the target; for comparison of velocities see Tab. 3:

Tab. 3 Comparison of experimental and simulation velocities of the bullet

No. of shot	v_{imp}	v_{res}	$v_{res,sim}$	Δv_{res}
	m/s	m/s	m/s	%
1	436	414	419	1
2	451	92	89	3

The expression $v_{res,sim}$ means simulation residual velocity of the bullet. The expression Δv_{res} means the deviation of both experimental and simulation results estimated as the relation between the difference of both experimental and simulation residual velocities with respect to the lower value of both residual velocities. The correspondence of velocities difference Δv_{res} of both shots is very good.

The simulation result for the first shot is shown in Fig. 8, when the bullet perforates the fuselage structure directly without any forward obstacle. The plane of composite sidewall is distorted and also nearby the area of the hollow as well. Those distortions do not follow the experimental behaviour due to the fact that the experimental sidewall remains flat in the whole its plane. The material model of the sidewall should be improved using additional experiments.

The insulation layer simulation behaviour follows the experimental results with one exception. The simulation hollow is of higher diameter than observed in experiment. Also the simulation model of the insulation layer should be improved.

The behaviour of simulation sheet metal plate follows the behaviour of experimental plate quite well except two parameters. The simulation diameter of the hollow is higher than experimental one; the simulation value is 9.7 mm and experimental value is 8.6 mm. The second difference is the size of the rim; the height around the simulation hollow has the value 3.2 mm and the experimental value is 4.4 mm. The reasons for observed differences can be the limited number of shooting experiments, next the simplification of the FEM model, e.g. using 2D model that cannot meet the crack propagation on the rim of the sheet metal plate hollow.

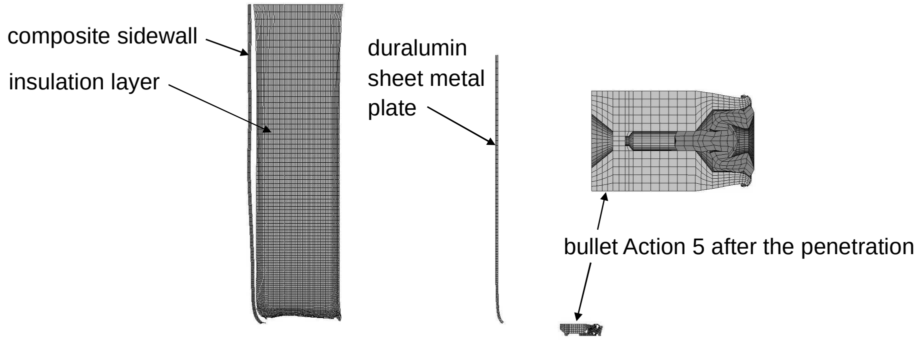


Fig. 8 FEM result of the first shot of perforating the fuselage structure

Fig. 8 shows also the shape of deformed bullet. The expansion process occurs just slightly on the front part, which agrees with the presumption made in chapter 2.2. The plastic cap is pushed inside of the bullet cavity.

The shot No. 2 when the bullet penetrates the gel block first is shown in Fig. 9.

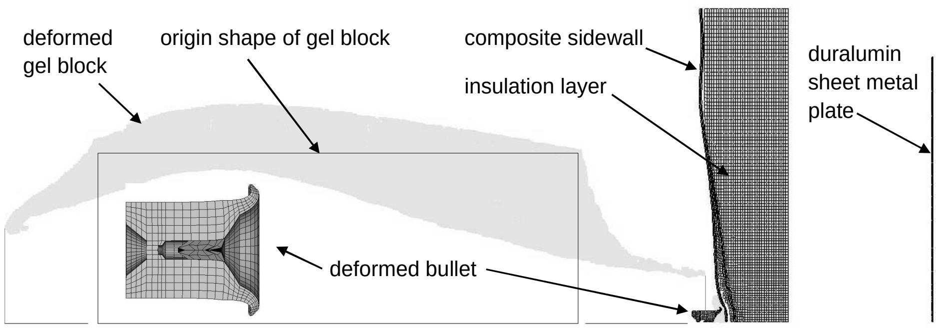
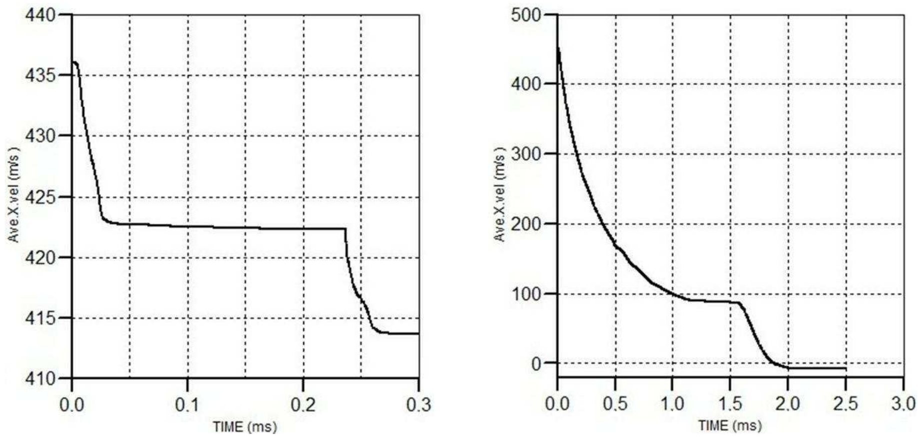


Fig. 9 FEM results of the second shot of perforating gel block and fuselage structure

The interaction of the bullet and the gel block causes the deformation of the bullet in form of expansion and the deformation of the gel block in form of temporary cavity. The bullet expresses high level of expansion and the expansion is finished in very short distance of the depth 31 mm after impacting the front face of the gel block.

The bullet was not able to perforate the first part of the secondary target, that is composite sidewall and it was bounced back causing just plastic deformation on the sidewall surface. The most of the centre area of the sidewall was pressed towards the insulation layer located 1 mm behind the sidewall.

The bullet velocity dependence of the fuselage etalon target perforation is shown in Fig. 10a. The first downwards quasi-linear dependence starting at the time approx. 0.01 ms shows the process of penetration of the composite sidewall, the velocity reduction is approx. 13 m/s and represents the most resistant part of the target upon simulation. The next slight slope starting at the time approx. 0.04 ms shows the penetration process of insulation layer, the velocity reduction is approx. 1 m/s. Finally the last nonlinear dependence starting at the time approx. 0.23 ms shows the penetration process of duralumin skin, the velocity reduction is approx. 8 m/s. Both graphs are drawn from Autodyn.



a) b)

Fig. 10 The dependence of bullet velocities: perforating of fuselage structure solely (a) and perforating of gel block and fuselage structure (b)

The bullet velocity dependence of the gel block perforation first and consequently the fuselage etalon target is shown in Fig. 10b. The first nonlinear downwards dependence shows the process of perforation of the gel block with massive reduction of bullet velocity of the value 362 m/s. Next nonlinear downward dependence starting at the time approx. 1.58 ms shows the process of bullet impacting the first part of the fuselage etalon target that is composite sidewall. The energy of expanded bullet running at the velocity of 89 m/s is short to perforate the sidewall, the bullet velocity is decreasing due to sidewall resistance and finally the bullet is bounced back according to the experimental behaviour.

FEM results of the second shot enables to draw a comparison of the shape of experimental and simulation bullet. Tab. 4 presents the basic dimensions of both bullets and both bullets are presented in Fig. 11.

Tab. 4 Comparison of experimental and simulation bullet dimensions

	D_{min}	D_{max}	D_{avg}	L_{cap}	L_{min}	L_{max}	L_{avg}
	mm	mm	mm	mm	mm	mm	mm
Experiment	14.0	14.2	14.1	13.1	12.0	12.2	12.1
Simulation	12.4			12.4			
Deviation	–	–	14 %	6 %	–		2 %

The parameter D is the mean diameter of front expanded part of the bullet; D_{min} means the minimum value, D_{max} means the maximum value and D_{avg} means the average value. The parameter L means the length of the deformed bullet; L_{cap} is the overall length of the bullet containing the plastic cap, L_{min} is the minimum value with plastic cap absence, L_{max} is the maximum value and L_{avg} is the average value. The Deviation represents the relation between the difference of both experimental and simulation values with respect to the lower value of both values expressed in percentage units.

The simulation dimensions of the bullet match the experimental bullet to some extent. The simulation bullet shows eroded its plastic cap, see Fig. 9, therefore it is compared also the length of experimental bullet with plastic cap absence. Such length of the bullet is in a good agreement. The diameter of the front part of the bullet has the deviation of 14 % and do not fit the experimental behaviour completely due to the simplified nature of 2D model. Comparison of the shape and dimensions of expanded bullet will be more reasonable for the 3D simulation that is supposed to be able to cover also the complexity of cracks evolution.

a) b)

Fig. 11 Comparison of experimental (a) and simulation (b) deformed bullet

4. Estimation of the Ballistic Limits

The validated simulation model will be used in order to estimate the ballistic limits when firing the gel block first upon three cases defined in chapter 1.3. Therefore the different thickness of the gel block L_B was investigated for uniform firing velocity of the value $v_1 = v_{imp}$ = 451 m/s according to the second experiment, see Tab. 2 and 3.

4.1. FEM Results

The results of the simulation using a different gel block thickness are presented in Tab. 5 and graphical dependence of particular bullet velocities with respect to the gel block thickness is shown in Fig. 12a.

The velocities in Tab. 5 and Fig. 12a are as follows: v_2 is the velocity of the bullet impacting the front part of the fuselage etalon target, i.e. composite sidewall, v_3 is the velocity of the bullet after perforating the composite sidewall and insulation layer and is equal to the velocity impacting the duralumin skin, v_4 is the velocity of the bullet leaving the fuselage etalon target, i. e. after perforating the duralumin skin.

A proposal of polynomial approximation of the second order of velocity v_2 impacting the fuselage etalon target with respect to the gel block thickness L_B of the region 0 mm to 200 mm is introduced:

$$v_2 = 0.0055L_B^2 - 2.86L_B + 447 \tag{3}$$

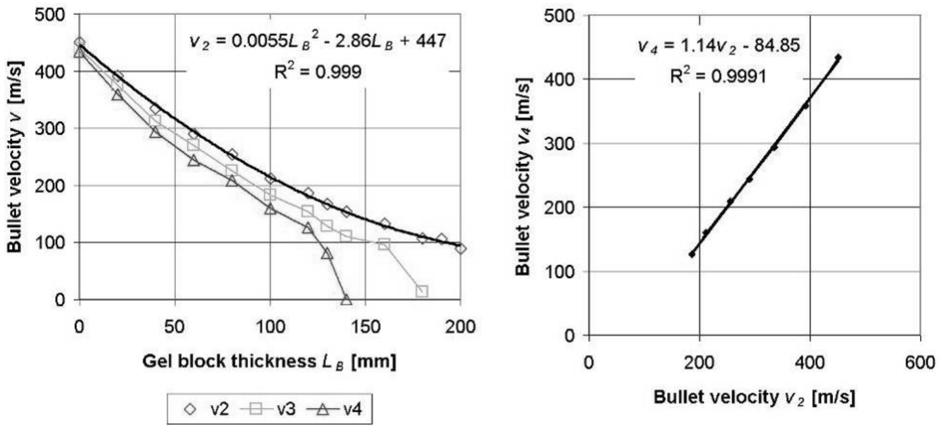
where the thickness L_B is set in [mm], the velocity v_2 in [m/s] upon graph in Fig. 12a.

The graph in Fig. 12b presents also the dependence of the residual velocity after perforation of the fuselage etalon target v_4 with respect to the velocity v_2 impacting the fuselage etalon target. The proposal linear dependence is valid only for the region of gel block thickness from 0 mm to 120 mm. In this region the bullet perforates both the gel block and the fuselage structure completely with surplus of energy. Above the value 120 mm the velocity v_4 starts its strong nonlinear character, see Fig. 12a, as it is typical for ballistic limit proximity [2, 9]. A proposed linear approximation enables to estimate the residual velocity v_4 depending on the impact velocity v_2 in form:

$$v_4 = 1.14 v_2 - 84.85 \tag{4}$$

Tab. 5 Simulation results of the bullet velocity in particular positions in the target upon gel block thickness L_B

L_B	v_1	v_2	v_3	v_4
mm	m/s	m/s	m/s	m/s
0	451	451	440	434
20		392	375	359
40		335	312	294
60		290	270	244
80		255	225	209
100		212	183	160
120		186	154	126
130		167	128	82
140		154	111	0
160		133	96	–
180		107	13	–
190		106	–	–
200		89	–	–



a) b)

Fig. 12 Course of bullet velocities versus gel block thickness (a) and relation between impact velocity of bullet v_2 into fuselage structure and bullet residual velocity v_4 (b)

Using both Eqs (3) and (4), it is possible to estimate the residual velocity of the bullet v_4 perforating completely both primary and the secondary target upon the gel block thickness L_B for the region of gel block thickness of the value from 0 mm to 120 mm.

4.2. Analysis of Ballistic Limit Cases

Three cases defined in chapter 1.3 are to be analysed:

Case 1: Perforation of the fuselage etalon target completely at minimum bullet residual velocity – the ballistic limit falls into the range of the gel block thicknesses from 130 mm to 140 mm, see Tab. 5. The expanded bullet perforates the whole fuselage etalon target with residual velocity of 82 m/s for the gel block thickness of 130 mm. The gel block of the thickness 140 mm enabled full perforation of the skin; however the bullet remained stuck in the skin and some fragments went through the skin. Therefore the ballistic limit of the gel block thickness for perforating the whole fuselage etalon target with minimum expanded bullet velocity is estimated to be approx. **135 mm**.

Case 2: Perforation of both the composite sidewall and the insulation layer but stopping the bullet by the duralumin skin allowing partial deformation – the ballistic limit lays in the gel block thickness range from 140 mm to 160 mm, see Tab. 5. The thickness of 160 mm reduced the bullet velocity to the value not sufficient to penetrate the skin although some plastic deformation on the skin surface occurred. Therefore the ballistic limit of the gel block thickness for penetrating the composite sidewall and insulation layer but stopping the expanded bullet by the skin is estimated to be approx. **150 mm**.

Case 3: Complete perforation of the inner composite sidewall solely, while the bullet is stopped by the insulation layer or by the duralumin skin avoiding any skin plastic deformation – the case of catching the bullet by insulation layer is difficult to achieve due to the very low resistance of the insulation layer against perforation by the bullet Action 5. Nevertheless, the ballistic limit falls into the range of the thicknesses of the gel block from 180 mm to190 mm. Tab. 5 shows that the thickness of the gel block of 180 mm enables to perforate the insulation layer by the expanded bullet with residual velocity of 13 m/s. The thickness of the gel block of 190 mm reduces the bullet velocity to the value 106 m/s not sufficient to penetrate the first part of the fuselage structure – composite sidewall. Therefore the ballistic limit of the gel block thickness for perforating the composite sidewall but stopping the expanded bullet by the insulation layer or by duralumin skin is estimated to be approx. **185 mm**.

5. Discussion

The investigated fuselage structure expresses just a little ballistic resistance upon performed FEM simulation when facing direct impact of Action 5 bullet and the bullet perforates the structure with surplus of energy.

In case of impacting the substitute material first, the geometry of the bullet is changed due to the expansion and piercing ability of the bullet decreases. Nevertheless, the bullet is still able to penetrate the fuselage structure to large extend of the gel block thickness up to the value approx. 130 mm. Exceeding this value up to the value of 150 mm the bullet damages fuselage skin in form of plastic deformation. Any permanent damage of the outer skin should not occur exceeding the gel block thickness of 185 mm.

The bullet Action 5 proved its expansion ability during perforation of the soft target. The expansion does not develop in case of direct penetrating the hard target in form of the fuselage etalon target containing the composite sidewall as the front part. However, it is supposed that the single complete perforation of the fuselage by the handgun bullet does not represent the danger for the decompression of the fuselage and harm to passengers. The most common transport airplane fuselage structure represents the semimonocoque type and such structure distributes the load easily to adjacent parts in case of failure of particular structure parts. Therefore the effect of skin damage due to isolated or even multiple complete penetration of the Action 5 bullet on airframe strength and stiffness is supposed to be negligible as well [10]. The danger of damaging the inner systems by the bullet with more serious consequences remains to be occurred.

From the point of view of damage of the outer skin of the airplane the perforation of the expanded bullet running at low velocity is considered much more dangerous than perforation by the same bullet but running at high velocity without expansion due to the damage nature more inclined to fatigue problems. In spite of this, it is supposed, that this kind of damage could be dangerous just in terms of much longer further aircraft operation than the time needed for emergency descending, approaching and landing.

The character of damage caused by expanded bullet on the outer duralumin skin plays an important role when considering the repair of airplane damaged area. In case of completely perforation of the fuselage skin by both unexpanded and expanded bullet it is necessary to repair the skin damaged area using prescribed procedures due to breaking the integrity of the fuselage as the pressurized vessel considering also the consequences on fatigue damage. The complete exchange of damaged composite sidewall and the insulation layer is not so difficult and expensive. In case of plastic deformation of skin (Case 2) or absence of any permanent deformation of skin (Case 3) the repair of the structure is much less expensive.

6. Conclusion

Experiments and simulations done upon the gel block and the fuselage etalon target have proven a significant difference in piercing ability of the bullet Action 5 under various target conditions. In case of firing directly to the fuselage structure the bullet perforates the fuselage structure easily with high surplus of energy. After the simulated penetration of thin and thick parts of the human body that can be represented by the arm above the elbow and thighs of the leg, penetration ability of the bullet significantly decreases partly due to the bullet expansion causing increase of the front cross section of the bullet and partly due to lower bullet impact velocity as a result of massive resistance in the gel block. When considering a damage of the fuselage skin, the most critical case represents the firing through gel block of the thickness less than 150 mm. In this case an important damage of the skin could occur caused by low impact energy and expansion of the bullet, which could have negative consequences in real flight or repair.

A numerical model has been developed upon firing experiments that simulates the penetration of the substitute material and subsequent perforation of fuselage structure used in airplane structures by the bullet of mentioned projectile. Ansys Autodyn showed a good possibility for modelling the penetration process and taking an advantage of using implemented material models with the possibility of their modification to meet the real behaviour of the simulated objects. A methodology for evaluating the residual velocity of the bullet perforating both targets with respect to the gel block thickness has been estimated using Eqs (3) and (4).

For the future research it is recommended to increase the relevance of the results using wider extent of experimental shooting especially for particular parts of the etalon target, performing the 3D FEM simulation for covering the damage process of the expanded bullet rim, considering various angles of impact with respect to the plane of the target and considering the difference of pressure and temperature according to flight conditions influencing behaviour of the etalon target.

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