3D SIMULATION ANALYSIS OF AIRCRAFT PROTECTION MATERIAL IMPACTING BY 7.62 MM AMMUNITION

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Abstract
The article presents 3D numerical model of the penetration of 7.62 × 54R bullet into three kinds of armour material using explicit hydrocode Ansys Autodyn. Add-on armour materials are used also in transport aircraft cockpit in order to protect personnel on board. Analysed are following materials: steel HARDOX 450, aluminium alloy 7039 and titanium alloy Ti-6Al-4V. The analysis estimates the ballistic limit thickness to avoid complete penetration of the target. Another evaluating parameter is weight of protection system in order to find the material of minimum area density to save aircraft performance. Using the titanium alloy reduces the weight of protective system approximately twice when comparing to steel and aluminium alloy materials. The results obtained can be useful in the analysis of the airframe structures facing ballistic threat during war operations or terrorist attacks

Keywords: Projectile 7.62 × 54R, penetration, ballistic limit, aircraft protection system, Finite Element Method

1 Introduction

Operation of military vehicles brings also various threats to face. Protection of the vehicle occupants against gunfire is possible to provide by ballistic restraint materials (armours). This is the case also for protection of flight crew in transport airplanes cockpit against a certain level of threat on the flight missions in hazard areas. Such protection is optional many times and is provided additionally according to the level of threat.

Various types of materials are used in aircraft protective systems. Such materials include steel, composite, fabric, ceramic materials and their combinations. For the aircrafts the minimum weight protective material and its thickness are of crucial importance. Increasing of the aircraft weight reduces flight performance and payload of the aircraft. Additional equipment in cockpit area reduces ability of the crew to handle controls.

This article deals with three types of basic protective materials - steel HARDOX 450, aluminium alloy Al 7039 and titanium alloy Ti-6Al-4V. Armour materials are considered separately without consideration of the forward airframe structure.

The ammunition penetrating the armour material is of type 7.62 × 54R. This cartridge represents possible anti/aircraft machine gun ammunition used in war or terrorist operations. Possible threat from such ammunition to aircraft crew influences operational capabilities of the aircraft, abilities to fly, to return to the airbase and landing. The boat tail bullet 7.62 × 54R is of 9.63 g mass, of 7.95 mm diameter in cylindrical part and of 32.3 mm length. The bullet 7.62 × 54R, known also as 7.62 - 59, is of three-part design with a core, an envelope and a jacket.

The aim of the article is to present a 3D simulation approach to estimate the ballistic resistance of evaluating armour material in form of material thickness able to resist the impact effect of the bullet 7.62 × 54R firing from very close distance. Next goal is to estimate the material with minimum weight to save aircraft performance. Ballistic limits are evaluated by explicit non-linear transient hydrocode Autodyn implemented in the Finite Element Method (FEM) system Ansys Workbench v.14.5.

2 FEM model of the bullet and the target

2.1 Simulation model

The FEM model of the bullet is created upon the real geometry with equal outer dimensions and is simplified to some extent. The volume and density of the steel core, lead envelope and gilding metal jacket is modified in order to meet the total weight of actual bullet.

The model of the target has prism shape with particular thickness. The periphery of the target is clamped. The front square size of the target is 50 mm that represents impact of the bullet close to the gripping of the armour plate in the cockpit. The character and discretization of the model of the bullet and the target using Lagrange mesh is shown in Fig. 1. The bullet impacts the target with velocity v = 854 m/s in perpendicular direction in all cases as the most critical case of interaction of the bullet and the target. The spin of the bullet caused by barrel bore is considered of the value 3502 RPS and the air drag is not considered. The simulation methodology is based upon [2]. The goal is to find minimal thickness of the target material able to resist complete penetration (perforation) of any fragment of the test specimen or test bullet. Such thickness is considered as the limit thickness for ballistic resistance of the particular protective material.

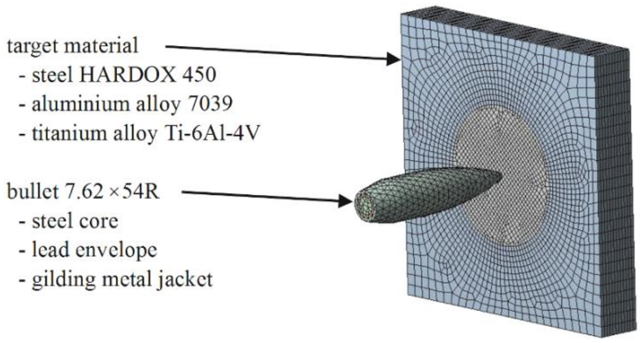

Fig. 1 *Simulation model of the bullet and the target*

2.2 Material models

All material models for the targets and the bullet are taken from the Autodyn material library and modified due to the fact, that experimental searching for the dynamic material characteristics facing high strain rates needs a different approach and very special equipment [3, 4]. Also there is still limited published data available on the dynamic material properties of used materials. Three components are used to describe dynamic material behaviour of presented materials - equation of state, strength (constitutive) model and fracture model.

The steel target material HARDOX 450[1] uses modified steel material V250 validated according to [1] using a different ammunition .338 Lapua Magnum 300 gr HPBT Scenar and .338 Lapua Magnum 16.2 g Lock Base FMJBT. The hydrodynamic shock equation of state relating stress to deformation and internal energy is in the Grüneisen form [5]:

$$p = p_H + \Gamma\rho\left(e - e_H\right), \tag{1}$$

where p is hydrostatic pressure, p_H is Hugoniot pressure, Γ = 2.00 is Grüneissen Gamma, ρ = 8129 kg/m^3 is density, e is internal energy, e_H is Hugoniot energy. The pressure is based on a linear Hugoniot relation between shock velocity u_s and particle velocity u_p [5]:

$$u_s = C_0 + S_1 u_p, \tag{2}$$

where C_0 = 3980 m/s is initial sound speed and S_1 = 1.58 is Hugoniot slope coefficient.

The Steinberg-Guinan constitutive model of material HARDOX 450 is a semi-empirical strain-rate independent model for the yield stress and shear stress [6]:

$$Y\left(P,T\right) = Y_0\left[1+\beta\left(\varepsilon+\varepsilon_i\right)\right]^n\left[1+\frac{Y'_P}{Y_0}\frac{P}{\eta^{1/3}}-\frac{G'_T}{G_0}\left(T-300\right)\right], \tag{3}$$

$$G\left(P,T\right) = G_0\left[1+\frac{G'_P}{G_0}\frac{P}{\eta^{1/3}}-\frac{G'_T}{G_0}\left(T-300\right)\right], \tag{4}$$

where Y_0 = 1560 MPa is the yield strength, G_0 = 71800 MPa is the shear modulus, ε is the strain, and η is the compression. This model is an elastic-perfectly plastic model and includes the enhancement of strength due to pressure P and work hardening β = 2.00 with hardening exponent n = 0.5, and softening due to temperature T.

The failure model of material HARDOX 450 uses the value 0.5 for plastic strain and the value 1.1 for geometric strain.

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[1] For armour applications it is used more the steel material HARDOX 500 and ARMOX 600 and material HARDOX 450 is used here due to available material characteristics validated by firing experiments.

The aluminium alloy Al 7039 uses hydrodynamic shock equation of state according equation (1) with following parameters: Γ = 2.00, ρ = 2770 kg/m^3, C_0 = 5328 m/s and S_1 = 1.338.

The constitutive model of the aluminium alloy Al 7039 expressing the relation between the shear stress and strain uses Johnson-Cook model representing the strength behaviour of materials subjected to large strains, high strain rates and high temperatures as the solving high-speed impact is. The empirical Johnson-Cook model [7] for the von Mises flow stress, σ, decouples the effect of strain, strain rate and temperature, namely,

$$\sigma = f\left(\varepsilon,\dot{\varepsilon},T\right) = \left[A + B\varepsilon^n\right]\left[1 + C\ln\dot{\varepsilon}^*\right]\left[1 - T^{*m}\right], \tag{5}$$

where ε is the equivalent plastic strain, $\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0$ is the dimensionless plastic strain rate for $\dot{\varepsilon}_0$ = 1.0 s^{-1} and T^* is the homologous temperature. The five material constants are as follows: A = 337 MPa is the yield uniaxial stress, B = 343 MPa is strain hardening coefficient, n = 0.41 is strain hardening exponent, C = 0.01 is strain rate hardening coefficient and m = 1 is thermal softening exponent.

The failure model of material Al 7039 uses the value 2.0 for geometric strain.

The titanium alloy Ti-6Al-4V uses hydrodynamic shock equation of state according equation (1) with following parameters: Γ = 1.23, ρ = 4419 kg/m^3, C_0 = 5130 m/s and S_1 = 1.028. The Steinberg-Guinan constitutive model according to equations (3, 4) uses following parameters: Y_0 = 1330 MPa, G_0 = 41900 MPa, β = 12.0, n = 0.1. The failure model uses the value 2.0 for geometric strain.

The bullet 7.62 × 54R consists of three parts: the steel core, the relatively soft lead envelope and the gilding metal jacket (tombac).

The steel core uses retrieved material STEEL 1006 with hydrodynamic shock equation of state including following parameters: Γ = 2.17, ρ = 7985 kg/m^3, C_0 = 4569 m/s and S_1 = 1.49. A constitutive model Johnson-Cook according to equation (5) includes following parameters: A = 350 MPa, B = 275 MPa, n = 0.36, C = 0.022 and m = 1. The failure model uses the value 2.0 for geometric strain.

The lead envelope uses retrieved model LEAD with hydrodynamic shock equation of state according equation (1) with following parameters: Γ = 2.74, ρ = 10623 kg/m^3, C_0 = 2006 m/s and S_1 = 1.429. The Steinberg-Guinan constitutive model according to equations (3, 4) uses following parameters: Y_0 = 8 MPa, G_0 = 8600 MPa, β = 110, n = 0.52. The failure model uses the value 2.0 for geometric strain.

The gilding metal jacket uses a shock equation of state as well and the Piecewise Johnson-Cook constitutive model of modified material COPPER retrieved from Autodyn library. The hydrodynamic shock equation of state according equation (1) includes following parameters: Γ = 2.00, ρ = 8950 kg/m^3, C_0 = 3958 m/s and S_1 = 1.497. This model is a modification of the Johnson-Cook model, where the dependence on effective plastic strain represented by the term (A+$B\varepsilon^n$) in equation (5) is replaced by a piecewise linear function of yield stress Y versus effective plastic strain ε_p [8]. The strain rate dependence and thermal softening terms remain the same as in the Johnson-Cook model. The failure model uses the value 2.0 for geometric strain.

3 Ballistic limit and target material thickness estimation

In order to estimate the target limit thickness, simulations with a different target material thickness and constant bullet velocity were performed. The simulations aim to achieve the absence of complete penetration, it means to avoid perforation. The gradation of the target thickness is 1 mm.

The ballistic limit of considered armour materials impacted by the projectile 7.62 × 54R is presented in Tab. 1 in form of limit thickness t_L.

Table 1 *FEM results of ballistic limits, density and area weight for particular armour materials*

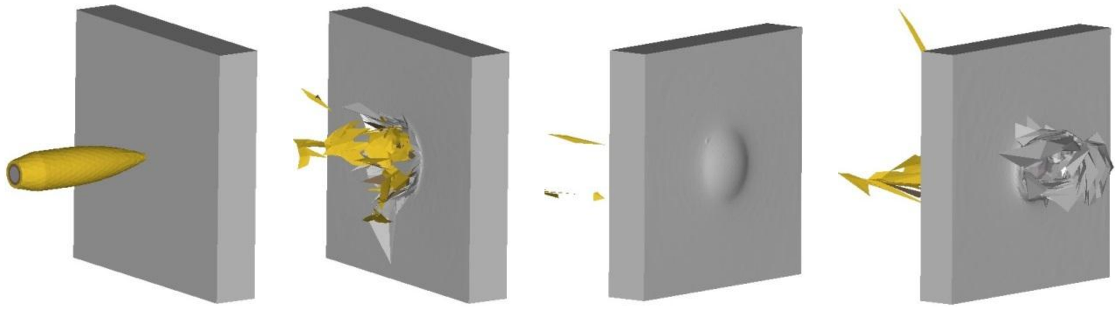
No.	Material	t_L [mm]	$t_{L,2D}$ [mm]	Density [kg/m^3]	Area weight [kg/m^2]	Order No.
1	HARDOX 450	9	10	8129	73.2	3
2	Al 7039	23	23	2770	63.7	2
3	Ti-6Al-4V	8	8	4419	35.3	1

The simulations were performed also with absence of spin of the bullet. The effect of rotation is found to be negligible and the results remain the same.

The simulations were performed also for 2D model using equal material characteristics in [2]; the results obtained contains Tab. 1 with designation $t_{L,2D}$. The results are the same for the target materials Al 7039 and Ti-6Al-4V. The difference is with material HARDOX 450, where the thickness of 2D model is of 1 mm higher when comparing to presented 3D model.

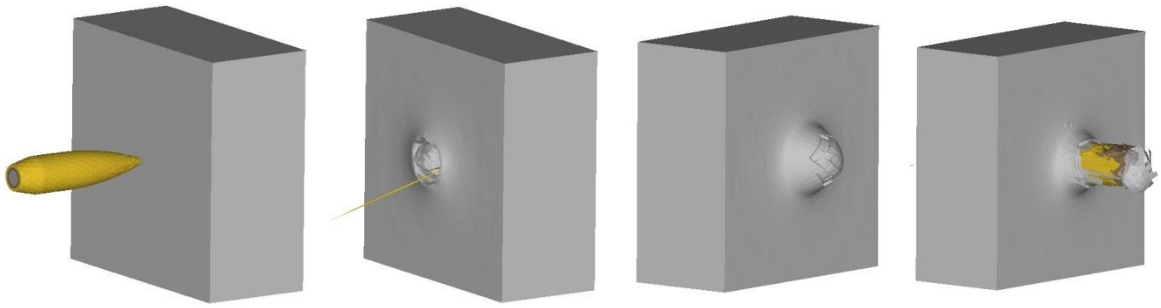
Tab. 1 introduces also the density of particular materials. The highest density is related with steel material HARDOX 450 and the lower density is related with aluminium alloy Al 7039. The parameter important for evaluating the minimum weight of protective material is area weight of evaluated target materials. Area weight is calculated as the weight of square meter of particular material with the limit thickness t_L. Therefore area weight implies the order of target materials from the point of view of their total weight. The order No. 1 in Tab. 1 means the material with the lowest weight and it is titanium alloy Ti-6Al-4V.

The Fig. 2, Fig. 3 and Fig. 4 show simulation results of the target material with the thickness avoiding the complete perforation; just penetration. Figures includes also the results of the target thickness of 1 mm lower that limit thickness enabling perforation. The penetration of the bullet through the target materials causes massive change of the bullet shape and erosion of particular bullet parts. The deformed bullet creates a cylindrical channel of higher diameter than the bullet calibre.



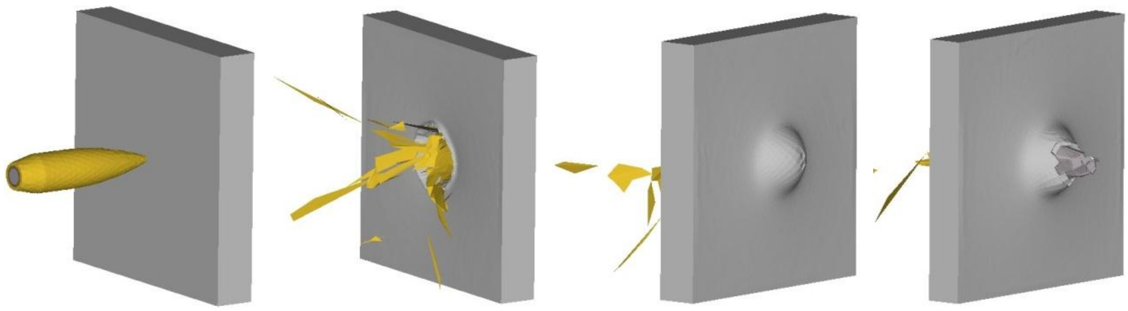
a) b) c) d)

Fig. 2 *Simulation model of the bullet and target HARDOX 450 of thickness 9 mm: a – initial state, b – front side after penetration, c – rear side after penetration, d – rear side of target thickness 8 mm after perforation*



a) b) c) d)

Fig. 3 *Simulation model of the bullet and target Al 7039 of thickness 23 mm: a – initial state, b – front side after penetration, c – rear side after penetration, d – rear side of target thickness 22 mm after perforation*



a) b) c) d)

Fig. 4 *Simulation model of the bullet and target Ti-6Al-4V of thickness 8 mm: a – initial state, b – front side after penetration, c – rear side after penetration, d – rear side of target thickness 7 mm after perforation*

Character of rear deformed shape of targets Al 7039 and Ti-6Al-4V on Fig. 3c and Fig. 4c indicate proximity to ballistic limit condition. In case of designing the protective system a higher thickness should be used.

Note: Debris of bullet parts with ray shape is a product of Lagrange mesh.

4 Conclusion

In protecting aircraft, every kilogram of weight matters, due to the potential degradation to performance and reduction in payload. Aircraft armour is therefore designed to provide protection of given level with only a minimum of weight added. The article presents the FEM estimation of ballistic resistance of HARDOX 450, Al 7039 and Ti-6Al-4V armour materials against the impact of the bullet 7.62 × 54R. Such protection of the aircraft follows the standards STANAG 2920, STANAG 4560 and NIJ Standard 0108.01 [2]. The evaluating simulation parameter is the armour thickness in order to achieve the limit velocity of the bullet as the minimum bullet velocity avoiding any complete penetration of the target.

The thicknesses for given materials are 9 mm for HARDOX 450, 23 mm for Al 7039 and 8 mm for Ti-6Al-4V. The materials HARDOX 450 and Ti-6Al-4V are very similar in thickness; aluminium alloy Al 7039 demands for 2.5 and 2.9 higher thickness, respectively.

The area weight shows weight effectiveness of considered materials and from this point of view the lowest weight possesses the titanium alloy Ti-6Al-4V. Therefore from the point of view of the minimum weight, the material Ti-6Al-4V is an optimum choice for the protection ballistic add-on cockpit system. The order of weight effectiveness is also presented in Tab. 1. The area weight of the material HARDOX 450 is higher 2.0 times with respect to the material Ti-6Al-4V and the area weight of the material Al 7039 is higher 1.8 times with respect to the material Ti-6Al-4V. Both the materials HARDOX 450 and Al 7039 are quite close, the difference of the area weight is 13.9 % related to the medium value of both area weight values.

Validation of proposed results demands for firing experiments.

The material of lowest area weight Ti-6Al-4V is also of the lowest thickness that is positive in terms of possible add-on implementation of the protective material in airplane cockpit area, because add-on structure reduces inner space of the cockpit.

The choice of appropriate protective material contains not only the weight criterion, but also the aircraft structure itself, cost expenses, technology procedures like formability or machinability and servicing or repair. Those parameters need to be taken into account as well.

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