NUMERICAL ANALYSES OF CERAMIC/METAL BALLISTIC PANELS SUBJECTED TO PROJECTILE IMPACT

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Abstract

The paper concerns research and development on modern, ceramic-based, protective layers used in the armour of tanks, combat vehicles and aeroplanes. A task of ceramic panels is reduction and dispersion of localized kinetic energy before a projectile or its fragment approaches the interior of protected object.

The numerical investigations have been performed to determine the ballistic resistance of ceramic/metal panels subjected to projectile impact. The impact of the 7.62mm armour-piercing projectile on the ceramic elements backed by a metal plate was analyzed. The tested panels were composed of a ceramic layer (Al_2O_3, SiC or B4C) and a metal layer (7017 aluminium alloy, Armox 500T steel or Ti6Al-4 titanium alloy). Different shapes of ceramic elements were analyzed, including hemispheres and pyramids, with respect to standard flat tiles. The influence of the impact point location was also taken into considerations.

The computer simulations were performed with the Finite Element Method implemented in LS-DYNA code. Full 3D models of the projectile and targets were developed with strain rate and temperature dependent material constitutive relations.

The conclusions presented in the paper can be applied to develop modern impact protection panels in which the appropriate balance between the mass and protection level must be accomplished.

Keywords: *computational mechanics, impact problem, armour perforation, ballistic resistance, ceramic armour*

1. Introduction

The nature of the tasks that are currently being placed in the Armed Forces around the Word sets the minimum requirements for a ballistic panel, which is necessary for protection of the lightweight combat vehicles in the current peacekeeping missions, as well as on the battlefield. The main task for the engineers that design a protective panel is a need to minimize risks of damage caused by small arms fire from the use of antitank ammunition 7.62 x 54R B32. This is a bullet, which creates a high risk because it has a steel core. Protection against this type of projectile is currently under research in many countries.

Protection elements should be characterized by low weight, due to the dynamic characteristics of the vehicle, and strong ability to absorb impact energy. In this paper, these features are incorporated into the system of protection against the effects of hitting a bullet with small arms, such as the modular structure of the armour. A ballistic panel construction enables easy installation and quick and easy repair of armour (even on the battlefield), if the protective plate has been damaged partially.

The topic of this work has focused on the issue of passive safety of the military vehicle crew against armour perforation. The proposes innovation concerns the use of additional layers of protection for armoured vehicles which are designed to reduce the speed of a bullet – and thus its kinetic energy – before hitting the steel armour. An additional layer is placed on the armour, using spacer element. Another effect of the protective layer is a blunt projectile, which leads directly to reduction in the efficiency of its impact on the structure.

2. Numerical models

The analysis of the effectiveness of the ceramic/metal panels was performed using a numerical model of 7.62x54Rmm projectile. The geometric characteristics and the numerical model of the hard steel core are presented in Fig. 1. The proper dynamic behaviour of HRC 62 was realized by application of the Johnson-Cook (JC) constitutive model with the Gruneisen form of the Equation of State (EOS). The values of appropriate parameters are included in Tab. 1.

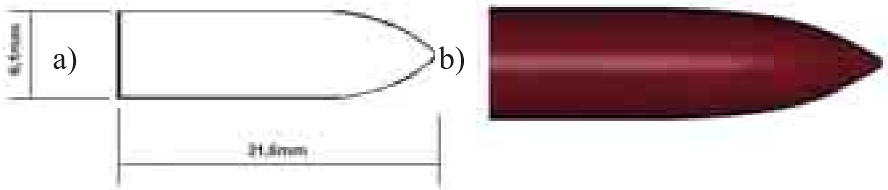

Fig.1. A scheme and a numerical model of the 7.62mm x54mm B32 projectile's hard steel core

Tab. 1. Johnson-Cook model and Gruneisen EOS constants

parameter	units	HRC 62	parameter	units	HRC 62
JC			EOS		
ρ	kg/m³	7850	c	m/s	4570
A	GPa	2.6989	S_1		1.49
B	GPa	0.2113	S_2		0.0
C		0.003	S_3		0.0
m		1.17	γ_0		1.93
n		0.89			
T_m	K	1800			
T_r	K	293			
c_p	J/kgK	450			
a		0.5			

Numerical models of two-layer armour, consisted of a layer of ceramic and metal layer (the support), were tested for their resistance to destruction. Six numerical models of the armour samples were developed. All of them were formed on the hexagonal base plate. Two models with flat front layer of Al_20_3 ceramic are show In Fig. 2. These models were called reference models. The A1 model is 13 mm thick and consists of the following layers: Al_20_3 ceramic layer with thickness of 8mm and 7017 aluminum alloy with thickness of 5mm. In A2 model, a ceramic layer was reduced by half.

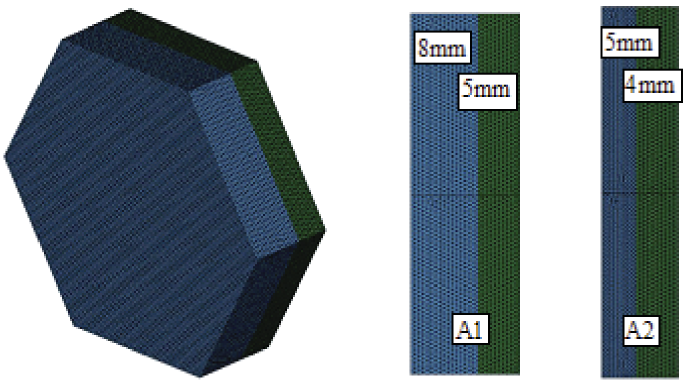

Fig. 2. Reference models A1 and A2 (Al_2O_3 ceramic)

For the purpose of the study of the frontal surface shape influence on the armour perforation four geometric models of the targets were built: convex and concave type, Fig. 3. Two kinds of convexities and concavities were considered. First, they were formed as regular pyramids with hexagonal base (B1 and C1 models). The pyramids are regularly spaced, starting from the centre of the target. Additionally, ceramic hexagonal base plate was located behind the pyramids layer. The second type of the rough surface was prepared in a very similar way, however the convexities/concavities were formed by hemispheres (D1 and E1 models).

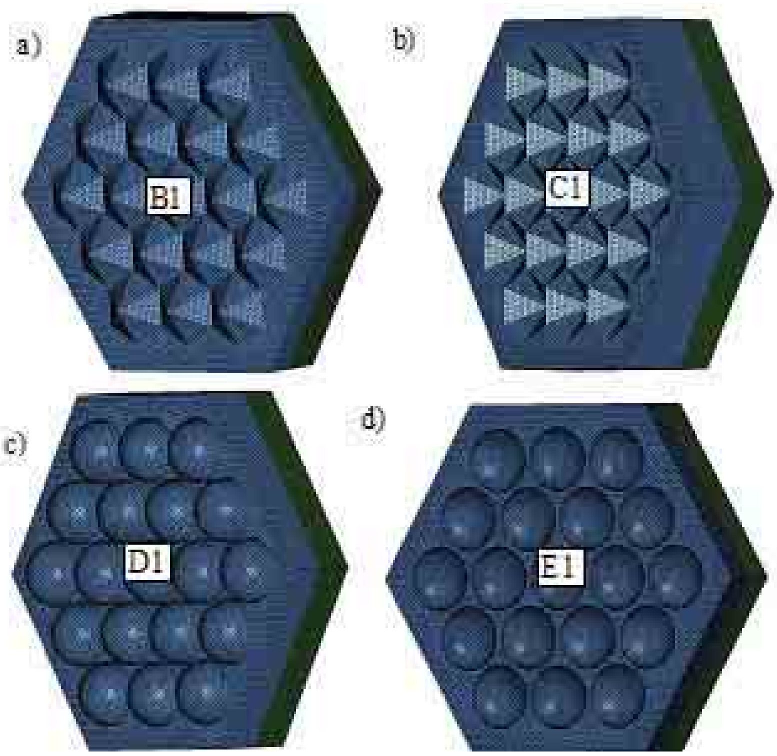

Fig. 3. Numerical models of the structures: a), b) formed by regular pyramids, c), d) formed by regular hemispheres

In order to investigate the influence of ceramic type on ballistic resistance of the structures, numerical models were created using B4C and SiC ceramic properties. It was assumed that the thickness of ceramic layers is the same in all models. The thickness of metal layer was chosen so that the surface density of the compared models was identical, Tab. 2.

Tab. 2. Thickness of the ceramic layers and surface density

structure	Thickness of the ceramic Al_20_3 [mm]	Thickness of the ceramic B4C [mm]	Thickness of the ceramic SiC [mm]	surface density [kg/m^2]
B1	5	6.3	7.6	31.0
C1	5	7	8.8	39.7
D1	5	6.5	8	33.7
E1	5	6.8	8.5	37.1

The material parameters adopted for the models are summarized in Tab. 3 and 4.

Tab.3. Johnson-Cook model (JC), Gruneisen EOS constants and modified Johnson-Cook model (MJC)

parameter	units	7017Al alloy	Armox 500Tsteel	Ti6Al-4V alloy	
JC				MJC	
ρ	kg/m³	2470	7850	ρ	4428
A	GPa	0.435	0.849	A	1.051
B	GPa	0.343	1.34	B	0.924
C		0.01	0.00541	C	0.00253
m		1.0	0.87	m	0.98
n		0.41	0.0923	n	0.52
T_m	K	878	1800	T_m	1878
T_r	K	293	293	T_r	296
c_p	J/kgK	893	450	c_p	580
EOS				Strain at fracture	
c	m/s	5240	4570	D_1	-0.09
S_1		1.4	1.49	D_2	0.27
S_2		0.0	0.0	D_3	-0.48
S_3		0.0	0.0	D_4	0.0
γ_0		1.97	1.93	D_5	3,87
a		0.48	0.5		

Tab. 4. Johnsona-Holmquista model constants

parameter	units	Al_2O_3 ceramic	B4C ceramic	SiC ceramic
JH-2				
ρ	kg/m³	3840	2510	3163
A		0.88	0.927	0.960
B		0.45	0.7	0.35
C		0.007	0.005	0.0
m		0.6	0.85	1.0
n		0.64	0.67	0.65
T	GPa	0.462	0.26	0.37
HEL	GPa	7.81	19.0	14.6
D_1		0.0125	0.001	0.48
D_2		0.7	0.5	0.48
EOS				
k_1	GPa	210	233	204.8
k_2	GPa	0.0	-593	0.0
k_3	GPa	0.0	2800	0.0

3. Numerical simulations and analysis of the results

Numerical simulations were carried out in two steps. First, the ballistic resistance of three types of ceramics (Al_20_3, SiC and B4C ceramics) was tested, Fig.4. The projectile velocity and kinetic energy after target perforation were compared and identified a case for which the projectile velocity was the lowest. In the second step, the material of metal layer was chosen (Al7017, Armox 500T, Ti6Al-4V), so that the surface density of the models was identical.

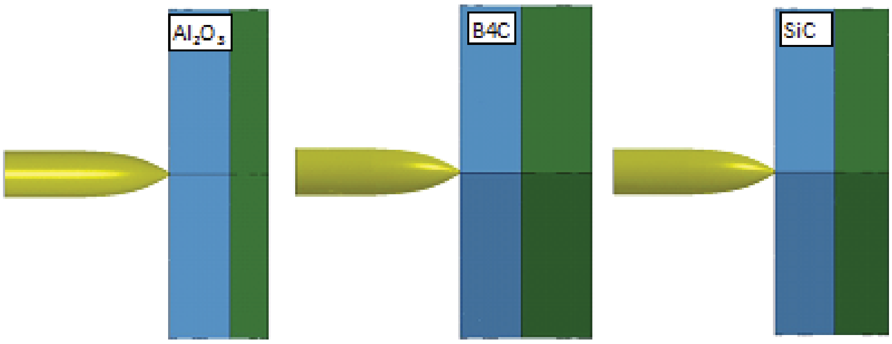

Fig. 4. Reference models A1 and bullet 7.62x54R mm type B32 (the initial velocity v_0=854m/s)

Perforation process of Al_20_3 ceramic model is show in Fig. 5. The next shots show the position of the projectile at intervals of every 15 µs. The time of projectile penetration through the structure is approximately 55 µs. The projectile velocity after target perforation is 340 m/s.

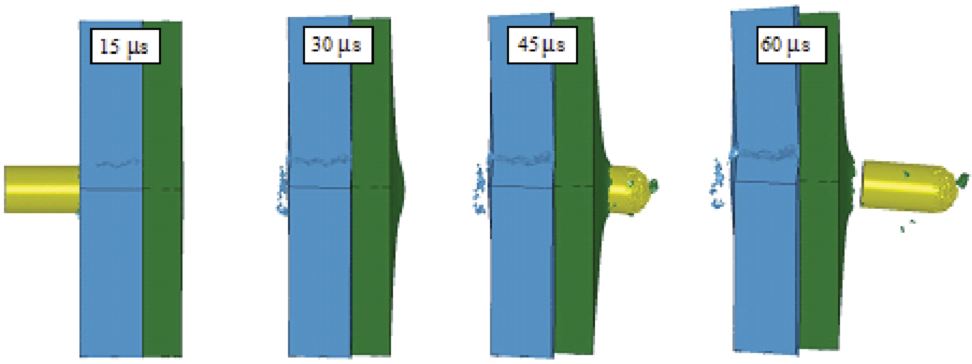

Fig. 5. Perforation process of Al_20_3 ceramic model

Comparision of changes in speed of the projectile when hitting the A1 and A2 structures are shown in Fig. 6, 7. Summary of projectile velocities for the studied variants of the structures is shown in Fig. 8.

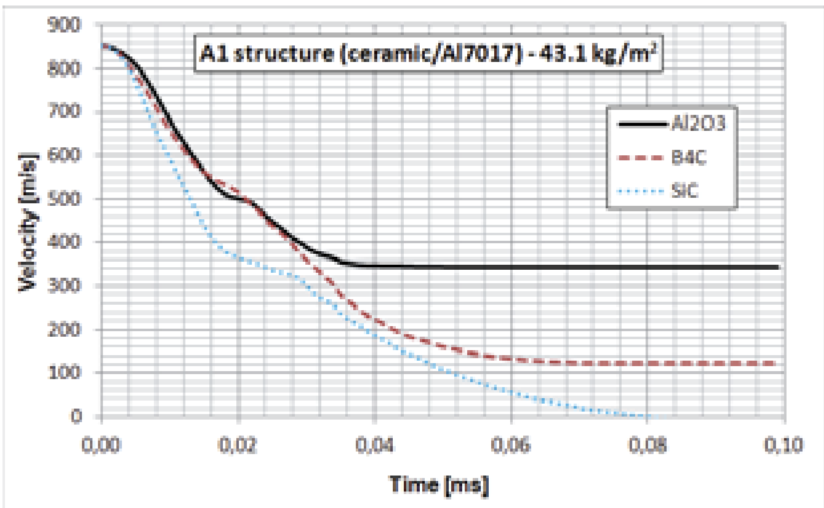

Fig. 6. The course of the projectile velocity 7.62x54mm on impact with the reference structure A1

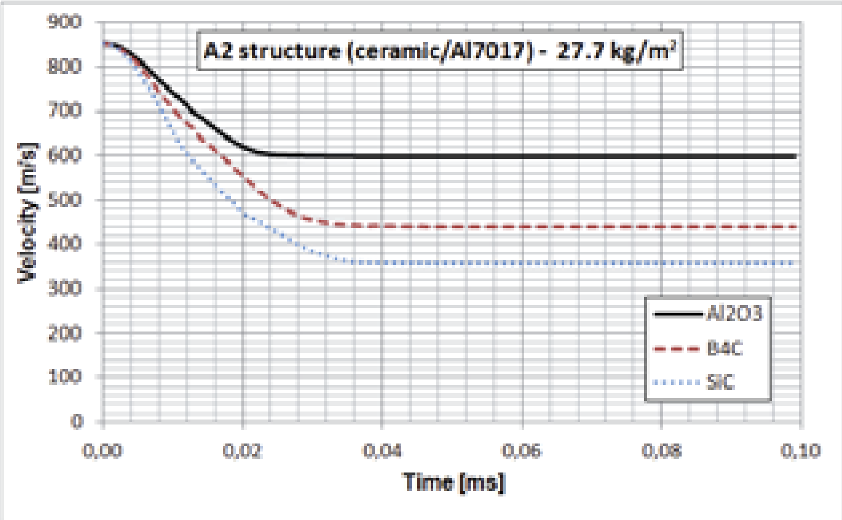

Fig. 7. The course of the projectile velocity 7.62x54mm on impact with the reference structure A2

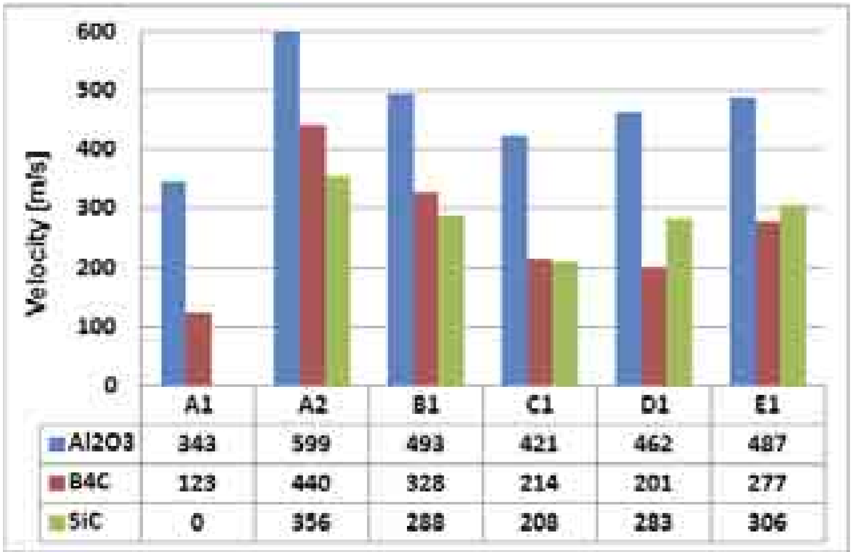

Fig. 8. Summary of projectile velocities for the studied variants of the structures

In the selection of ceramics, it was showed that the worst results (i.e. highest projectile velocity after perforation) are obtained for ceramics Al_20_3. For the investigated structures, the lowest speed of the projectile after perforation was achieved for SiC ceramic – with the exception of the C1 structure. In this case, the best results were obtained for B4C ceramic. For structures A1 (SiC-am / Al7017-5mm) with a surface density of 43,1 kg/m^2 there was no perforation of the armour – the bullet was stopped in metal layer. For ceramics with concave and convex frontal surfaces, there was performed an analysis of sensitivity of the simulation results on the place of the projectile impact. The analysis was carried out with the use of simulation with projectile impact into the places at the thickest and thinnest layer of ceramic. Structures B1 and C1 were less sensitive to the point of impact of the bullet. The smallest velocity of projectile was obtained for the C1 structure (SiC ceramic) and it is equal to 208 m/s.

In the second step, the simulation was conducted in order to select a metal layer. For A1 structures (SiC-8mm / metal layer) with surface density of 64.6 kg/m^2, in all cases the bullet was stopped in the metal layer. Identical results were obtained for A2 structures (SiC-4mm / metal layer) with surface density of 51.9 kg/m^2. When surface density of A2 structures was reduced to 44.1 kg/m^2 (the thickness of the ceramic remained the same as in the first step), perforation occurred only in the structure with titanium alloy. Results are shown in Fig. 9-11.

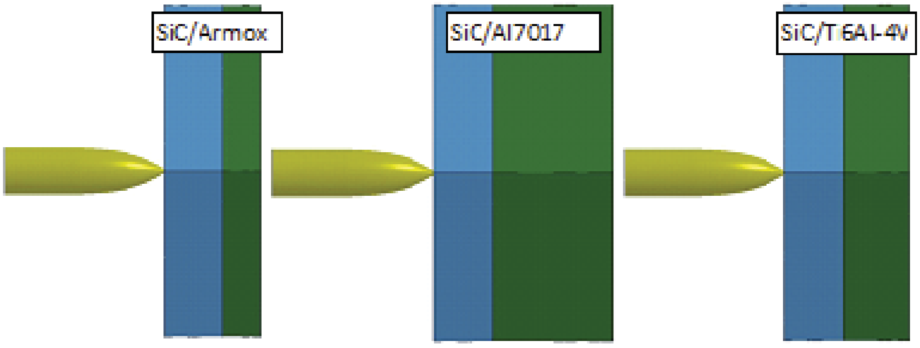

Fig. 9. Reference models A2 and bullet 7.62x54R mm type B32

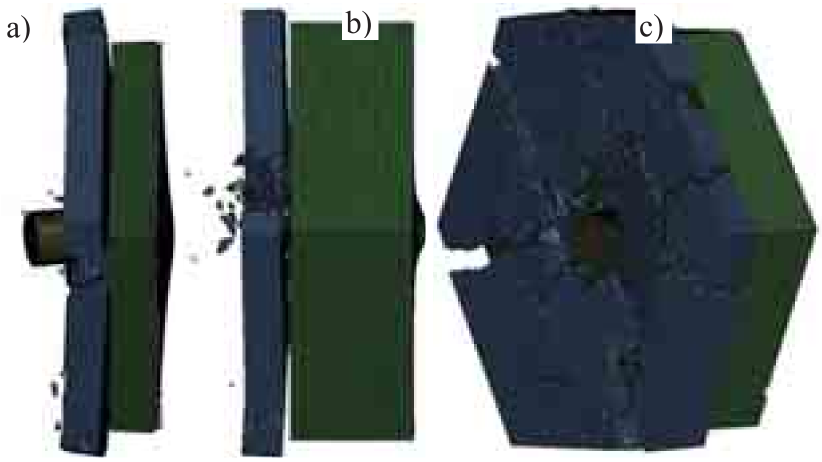

Fig. 10. Models A2 (surface density - 51.9 kg/m^2) after being hit by the projectile: a) SiC/Armox structure, b) SiC/Al7017 structure, c) SiC/Ti6Al-4V structure

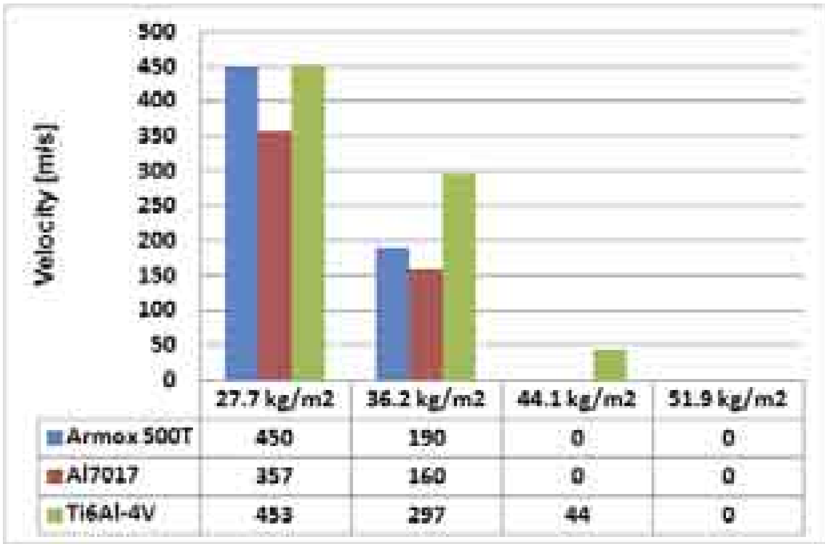

Fig. 11. Summary of projectile velocities for the A2 structures (SiC ceramic layer – 4mm)

5. Conclusions

The all performed calculations should provide reliable data because they are based on the well-validated and verified numerical models. The studies conducted in this paper identified very interesting and promising dependencies with regard to a role of the frontal surface shapes in the perforation problems.

It was showed that thickness of front ceramic layer is important, however not dominated. The surface shape is also very significant. Analyses show that the type of ceramic has a significant influence on the speed of the projectile after perforation. At the same density, better results are obtained for a thicker layer of ceramic.

The conclusions presented in this paper can be applied to develop modern impact protection panels where the appropriate balance between the mass and protection level must be accomplished.

Acknowledgements

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