PROTECTION PERFORMANCE OF THE MONOLAYER AND MULTI-LAYERED STEEL PLATES AGAINST 7.62-MM APM2 PROJECTILE IN ARMORED VEHICLES

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ABSTRACT

This paper evaluates the protection performance of the steel plates made of Armox560T, Hardox 400 and Weldox 700E which are used in armored vehicles. The steel plates monolayer 12 mm , double-layered 2×6 mm, triple-layered 3×4 mm and triple layered 3×4 mm with spacing 5mm between them were impacted by a 7.62 mm APM2 projectile in the initial velocity 830 m/s in all tests. The effect of the combination of different steel materials in a double- and triple-layered model on the resistance to projectile penetration was also analyzed. Numerical three-dimensional nonlinear finite element models were developed using the explicit finite element code LS-DYNA. The main results of calculations include the residual velocity of the projectile after penetrating and the pattern of the plate failure mechanism for each model. It was found that double-layered plates made of the same steel material have a worse ballistic protection performance than that of monolayer plates, and a better than that of triple-layered plates whether with or without spacing.

Keywords: protection performance, steel alloys, 7.62 mm APM2 projectile, monolayer plates, double-layered plates, triple-layered plates, numerical simulation.

INTRODUCTION

In recent years, optimization design of steel shields for protection against small projectile impact has long been of interest in military and civilian applications. The idea of using layered plates instead of a monolithic one in order to increase the ballistic perforation resistance is not new, because armour materials are not always manufactured to the required thickness, and multiple layers are necessary to fabricate shields that meet design specifications. However, results by various authors are contradicting and detailed experimental and numerical work is still required.

Although there are a number of studies dealing with the ballistic behavior of multi-layered plates, their study remains an open research topic since conclusive results of its effectiveness have not been obtained to date, In addition, these studies are limited in the open literature, as is remarked in investigations [1-2].

An investigation conducted by Dey *et al*. [3] and Borvik *et al*. [4] on the ballistic resistance of Weldox 700E steel shows in [3] that 12 mm monolithic plate has better ballistic performance against ogival projectiles when compared with double-layered plates with same thickness, while the opposite effect is observed when blunt projectiles are used. While they were found in [4] that the ballistic limit velocities of monolithic and double-layered plates 7.62-mm APM2 projectiles were identical.Investigations by (Teng *et al.* [5], Børvik *et al.* [6] [7], Teng *et al.* [8] [9]) on the ballistic performance of monolithic and double-layered steel plates showed that the ballistic resistance depends on several factors, including projectile nose shape, projectile mass, impact velocity, configuration of the plates and material properties.

A recent numerical study conducted by Flores-Johnson *et al*. [10] was observed that monolithic plates perform better than triple-layered plates, which is more noticeable for an impact velocity of 800 m/s. The difference in performance between monolithic and double-layered plates was not significant.

In our previous study [11], we studied the thickness effect of 5 types of steel alloys on penetration resistance. it was found that the monolayer 6 mm, 8 mm and 10 mm thick plates from all the investigated steel alloys do not provide a protection level of "BR7" (with an initial bullet velocity of 830 m / s) and, on the other hand, the double-layers plates from the alloys Armox 560T, Domex protect 500, and Armstal 500 with a total thickness of 12 mm provide such level of protection. At an initial velocity of 920 m / s a bullet penetrated double-layer 2x6 mm thick plates from all the steel alloys under consideration, while with a thickness of 2x8 mm the bullet could not penetrate (except the Weldox 700E alloy plate).

In the present study, we will study the effect of using monolayer 12 mm, double-layered 2x6 mm, triple-layered 3x4 mm and triple-layered 3x4 mm with spacing 5 mm between them, of the steel plates made of Armox 560T, Hardox 400 and Weldox 700E, impacted by a 7.62 mm APM2 projectile in the velocity 830 m/s in all tests. For numerical simulations we use the explicit finite element code LS-DYNA [12] to predict the performance of monolithic and multi-layered. All plates and a projectile were modeled as the deformable ones with modified Johnson-Cook constitutive relation and Cockcroft-Latham failure criterion. Material data for the projectile and plates were mainly taken from the literature.

NUMERICAL SIMULATIONS

Constitutive relation and failure criterion

The targets and projectile were modelled using a modified version of the JohnsoneCook (MJC)

constitutive material model implemented in LS-DYNA (Material model 107) [12,13,14]. The equivalent stress is expressed as [13]

$$\sigma_{eq} = \left(A + B\varepsilon_{eq}^{n}\right)\left(1 + \dot{\varepsilon}_{eq}^{*}\right)^{C}(1 - T^{*m}) , \qquad (1)$$

where ε_{eq} - is the equivalent plastic strain, $\dot{\varepsilon}_{eq}^{*} = \dot{\varepsilon}_{eq}/\dot{\varepsilon}_{0}$ is the dimensionless strain rate where $\dot{\varepsilon}_{eq}$ and $\dot{\varepsilon}_{0}$ are the strain rate and a user-defined strain rate, respectively; A, B, n, C and m are material constants. The homologous temperature is defined as

$$T^{*} = \frac{T - T_{r}}{T_{m} - T_{r}} , \qquad (2)$$

where T is the absolute temperature, T_r is the ambient temperature and T_m is the melting temperature.

The temperature change due to adiabatic heating is calculated as

$$\Delta T = \int_{0}^{\varepsilon_{eq}} \chi \frac{\sigma_{eq} d\varepsilon_{eq}}{\rho C_{p}} , \qquad (3)$$

where ρ is the material density, C_p is the specific heat and χ is the Taylor-Quinney coefficient that represents the proportion of work converted into heat.

Failure is modelled using a criterion proposed by Cockcroft and Latham (CL) [14] which is implemented in Material model 107. This criterion is expressed as

$$W = \int_{0}^{\varepsilon_{eq}} < \sigma_{1} > d\varepsilon_{eq} \leq W_{cr} , \qquad (4)$$

where σ_1 is the major principal stress, $< \sigma_1 > = \sigma_1$ when $\sigma_1 \geq 0$ and $< \sigma_1 > = 0$ when $\sigma_1 < 0$; W is the plastic work per unit volume and W_{cr} is critical value of W which can be determined from uniaxial tensile test.

The MJC material model has successfully been used to model impact on steel [3, 4, 11, 16, 17]. The values of the material model parameters used in the simulations, are given in tables 1, 2, 3 [3, 11, 18].

Table-1. General material constants for the MJC constitutive relation.

Material	E (MPa)	ϑ	$\rho[kg/m^3]$	$C_p[j/kgK]$	χ	$\alpha[K^{-1}]$	T_c^*
Allsteelalloys	210000	0.33	7850	452	0.9	1.2×10^{-5}	0.9
Leadcoreandcap	1000	0.42	10660	124	0.9	2.9×10^{-5}	0.9
Brassjacket	115000	0.31	8520	385	0.9	1.9×10^{-5}	0.9

Table-2. Bullet material constants for the MJC constitutive relation and CL failure criterion.

Material	Yield stress	Strain hardening		Strainrate hardening		Temperature softening			CL
	A (MPa)	B (MPa)	n	$\epsilon_0^*[s^{-1}]$	C	$T_r[K]$	$T_m[K]$	m	W_{cr}(MPa)
Allsteelalloys	1200	50000	1	5×10^{-4}	0	293	1800	1	-
Leadcoreandcap	24	300	1	5×10^{-4}	0.1	293	760	1	175
Brassjacket	206	505	0.42	5×10^{-4}	0.01	293	1189	1.68	914

Table-3. Target material constants for the MJC constitutive relation and CL failure criterion.

| Material	Yield stress	Strain hardening		Strain rate hardening		Temperature softening			CL
	A (MPa)	B (MPa)	n	$\epsilon_0^*[s^{-1}]$	C	$T_r[K]$	$T_m[K]$	m	W_{cr}(MPa)
Armox 560T	2030	568	1	5×10^{-4}	0,001	293	1800	1	2310
Hardox 400	1350	362	1	5×10^{-4}	0,0108	293	1800	1	2013
Weldox 700E	819	308	0,64	5×10^{-4}	0,0098	293	1800	1	1486

Numerical models

The projectile and the impact region in the plate were modeled taking into account the studies carried out by us earlier [19], namely: the element size in the impact region was 0.2×0.2×0.2 mm and the element size in the APM2 projectile was 0.3 mm can produce good results. Contact between the different parts of the bullet with the target was modelled using an eroding surface to surface formulation [12].

The target configurations used in this study are shown in Figure-1 which include the following configurations: monolayer 12 mm, double-layered 2x6 mm, triple-layered 3x4 mm and triple-layered 3x4 mm with spacing 5 mm between them, of the steel plates made of Armox 560T (Ar), Hardox 400 (Ha) and Weldox 700E (We), impacted by a 7.62 mm APM2 projectile in the velocity 830 m/s in all tests. The 7.62-mm APM2 projectile was modelled as four independent parts: Brass

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jacket, steel core, brass sabot and lead filler, are given in Figure-2. More details about APM2 projectile are showed in [4, 18].

| 12 mm | 2x6 mm | 3x4 mm | 3x4 mm with spacing 5 mm |

Figure-1. Finite element mesh of the target plates configurations.
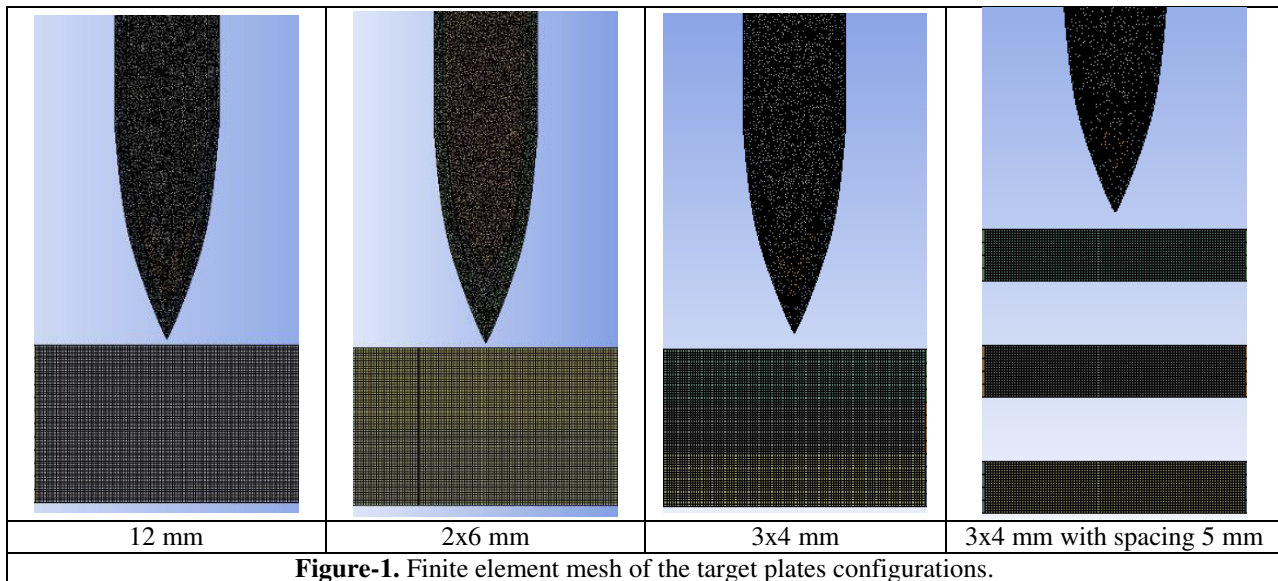
In addition to this, the effect of the combination of different steel materials in a double-layered and triple-layered model on the resistance to bullet penetration was also studied. The alloy steels that are used in our study have different hardness values: Armox 560T (530-590) HBW, Hardox 400 (370 - 430) HBW and Weldox 700E (530-590) HBW [11, 20]. The letters and numbers used in the target codes (histogram and figures) represent the layering configurations, thickness and the materials: Ar, Armox 560T; Ha, Hardox 400; We, Weldox 700E; Air, spacing air; while the numbers (12, 6, 5, and 4) represent the thickness of the targets and spacing.
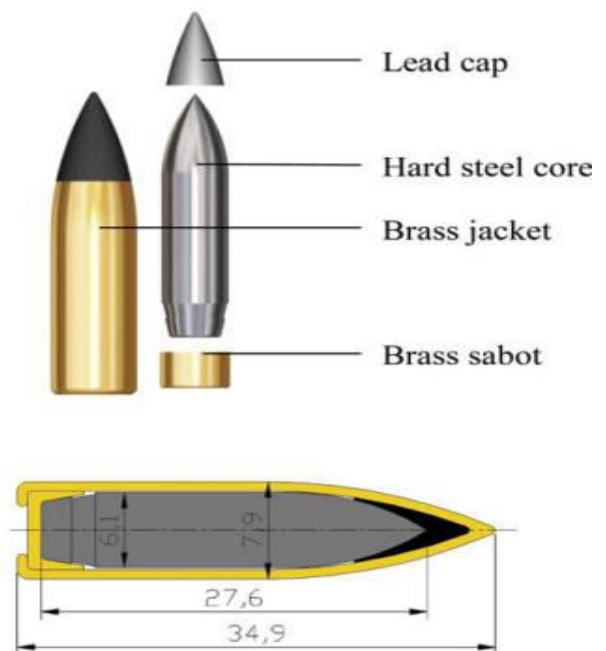

Figure-2. Schematic drawing, geometry and cross-section picture of 7.62 mm APM2.

NUMERICAL SIMULATION RESULTS AND DISCUSSION

Effect of monolayer and multi-layered configuration

In this section we will present the results of the effect of using a monolayer, double-layered, triple-layered and triple-layered with spacing between them on the penetration of a projectile 7.62 mm APM2 in the velocity 830 m/s using three different alloy steels: Armox 560T, Hardox 400 and Weldox 700E.

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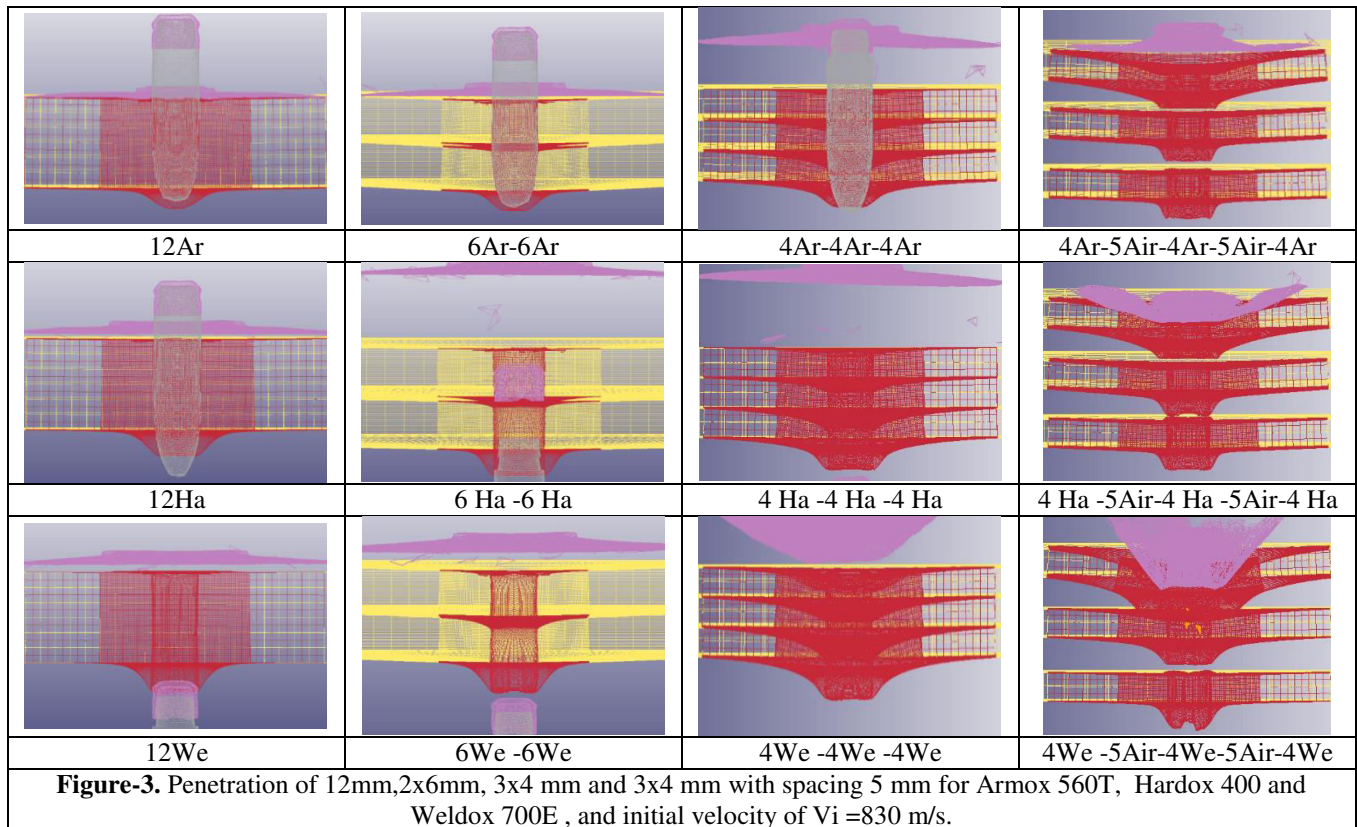
Figure-3. Penetration of 12mm, 2x6mm, 3x4 mm and 3x4 mm with spacing 5 mm for Armox 560T, Hardox 400 and Weldox 700E, and initial velocity of Vi =830 m/s.

Figure-3 shows the perforation and interaction of plates of 12Ar, 6Ar-6Ar, 4Ar-4Ar-4Ar, 4Ar-5Air-4Ar-5Air-4Ar, 12 Ha, 6 Ha-6Ha, 4Ha-4Ha-4Ha, 4 Ha-5Air-4Ha -5Air-4Ha, 12We, 6We-6We, 4We-4We-4We and 4We-5Air-4We-5Air-4We configurations, and initial velocity of Vi=830 m/s. It is seen that monolayer plates exhibit bigger resistance of the bending and the penetration than double-layered and triple-layered configurations, and double-layered plates better penetration resistance than triple-layered plates, while triple-layered with a spacing show small resistance of the bending and the penetration than triple-layered without a spacing, where the projectile penetrated all steel alloy with a spacing.

It can be seen in Figure-4 that the residual velocity of Armox 560T increases significantly with a spacing between plates, while the residual velocity is greatly increased when using double-layered, triple-layered, and triple-layered with a spacing for Hardox 400, as for of Weldox 700E, the difference between the residual velocity in the case of monolayer and double-layered is very small, with an increase in the case of triple-layered, and triple-layered with a spacing. It can be noticed that the difference in the residual velocities of the Weldox 700E is less than Armox 560T and Hardox 400.
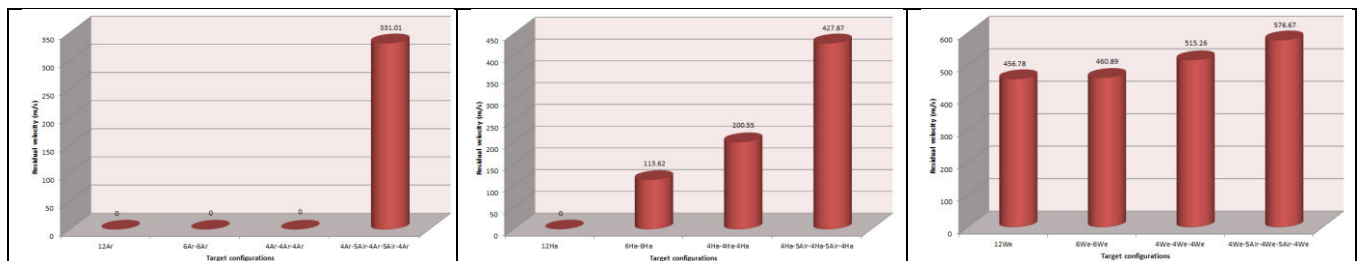
Figure-4. Residual velocity for monolayer 12 mm, double-layered 2x6 mm, triple-layered 3x4 mm and triple-layered 3x4 mm with spacing 5 mm of the steel alloys plates Armox 560T, Hardox 400 and Weldox 700E, impacted by a 7.62 mm APM2 projectile in the initial velocity 830 m/s.

Effect of double-layered mixed configuration

The effect of double-layered mixed configuration on the ballistic protection performance was studied using a combination of Armox 560T, Hardox 400 and Weldox 700E with an initial impact velocity of 830 m/s. Figure 5 shows the residual velocities of the following double-layered configurations: 6Ar-6Ar, 6Ar-6Ha, 6Ar-6We, 6Ha-6Ha, 6Ha-6Ar, 6Ha-6We, 6We-6We, 6We-6Ar and 6We-6Ha. It can be seen that the double-layered mixed configuration 6Ar-6We has the better performance than

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6We-6Ar and 6Ha-6We has the better performance than 6We-6Ha. The use of double-layered mixed configuration of Armox560T and Hardox 400 is almost equal to double-layered configuration of Armox 560T.
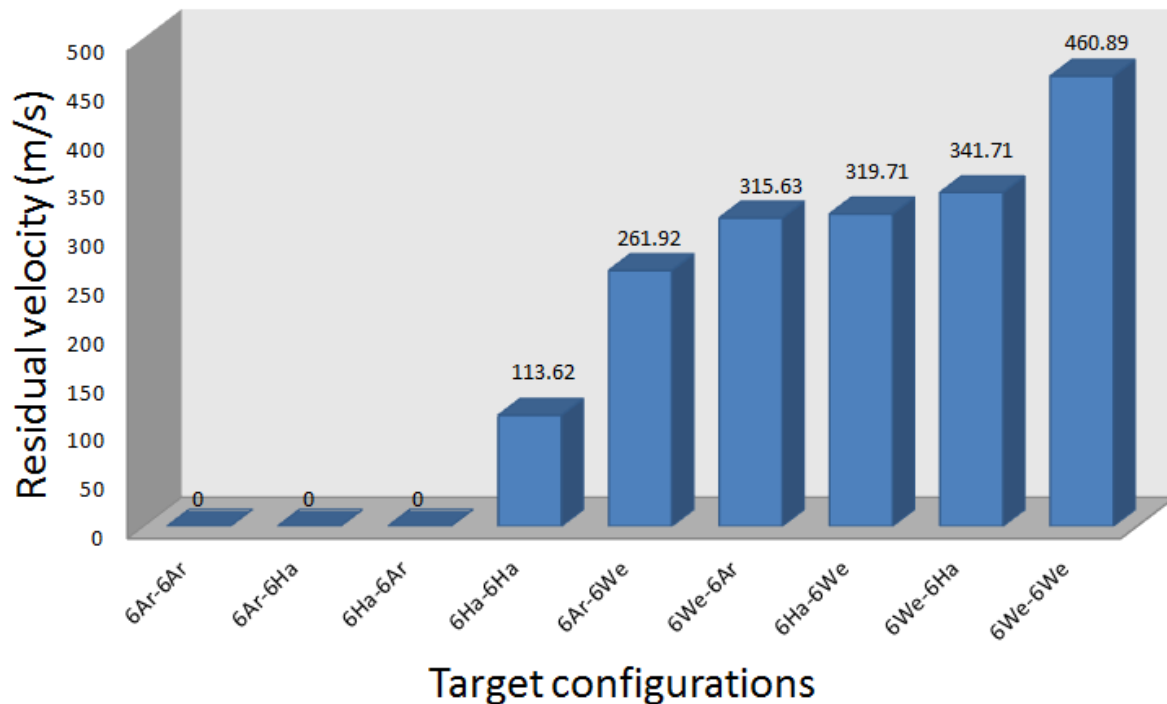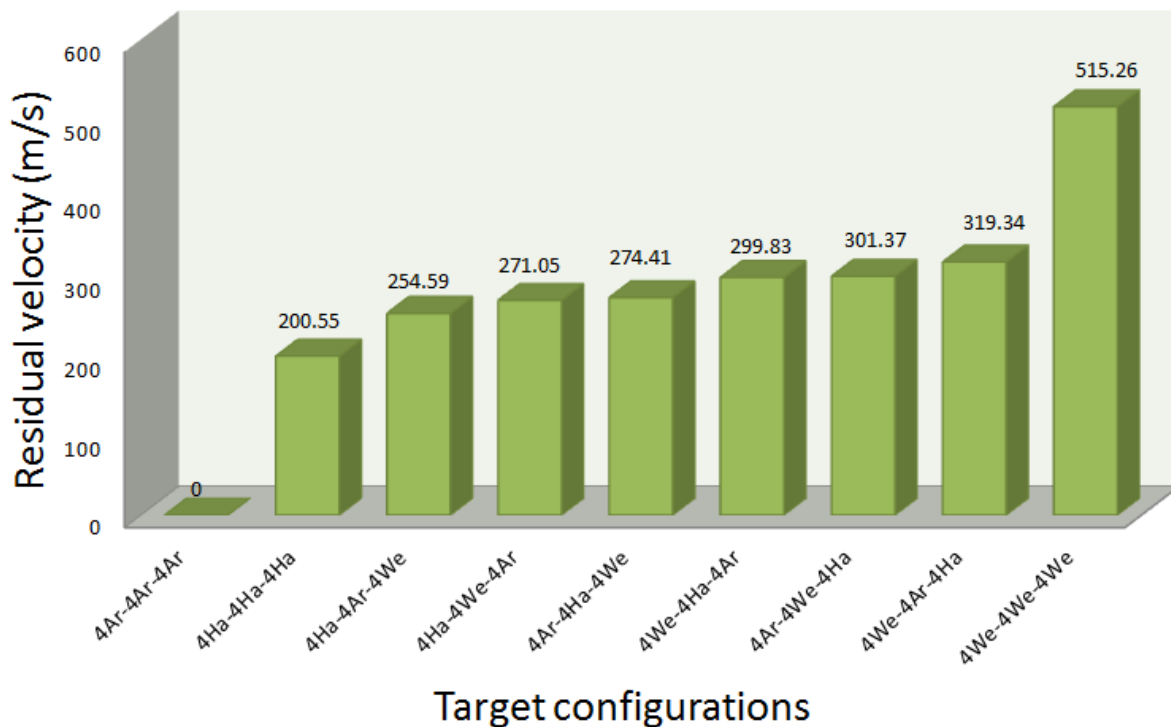

Figure-5. Residual velocity for double-layered mixed configuration 2x6 mm of the steel alloys plates Armox 560T, Hardox 400 and Weldox 700E, impacted by a 7.62 mm APM2 projectile in the initial velocity 830 m/s.

Effect of triple-layered mixed configuration

In the case of triple-layered and three steel alloys Armox 560T, Hardox 400 and Weldox 700E, we studied the following configurations: 4Ar-4Ar-4Ar, 4Ar-4Ha-4We, 4Ar-4We-4Ha, 4Ha-4Ha-4Ha, 4Ha-4Ar-4We, 4Ha-4We-4Ar, 4We-4We-4We, 4We-4Ar-4Ha and 4We-4Ha-4Ar (Figure 6). It is seen that the triple-layered mixed configuration 4Ha-4Ar-4We has the best performance while 4We-4Ar-4Ha has the worstone, where the difference in the residual velocity between these two configurations is 64 m/s. We can notice that the order of plates related to the middle plate has a fundamental meaning in determination the best performance against 7.62 APM2 projectiles.

Figure-6. Residual velocity for triple-layered mixed configuration3x4 mm of the steel alloys plates Armox 560T, Hardox 400 and Weldox 700E, impacted by a 7.62 mm APM2 projectile in the initial velocity 830 m/s.

SUMMARY AND CONCLUSIONS

A numerical simulation of the ballistic protection performance of monolayer and multi-layered targets made of Armox 560T, Hardox 400, Weldox 700E steel or a combination of these materials against 7.62-mm APM2 projectiles was made, for the velocity of 830 m/s and target thicknesses 12 mm. The results obtained in this research are based on numerical investigation, so the numerical model developed in this research can be used to design experimental testing and thus reduce the number of tests and the resources required.

Based on the results of this study the following conclusions are made:

▪ The double-layered plates made of the same steels material have a worse ballistic performance than that of monolayer plates, and a better than that of triple-layered plates whether with or without spacing;

▪ The monolayer plate of Hardox 400 has bigger resistance of the penetration than double-layered and triple-layered configurations;

▪ The difference in resistance of the penetration against 7.62 mm APM2 projectiles between monolithic and double-layered plates of Weldox 700E was very little;

▪ When using double-layered mixed configuration, it is recommended that the plate with better penetration resistance characteristics would be placed in the direction of the threats;

▪ In the triple-layered mixed configuration, the order of plates related to the middle plate has a fundamental meaning in determination the best performance against 7.62 mm APM2 projectiles, where it is found that 4Ha-4Ar-4We has the best performance while 4We-4Ar-4Ha has the worst one;

▪ The spacing between steel alloys plates, even small, reduces significantly the penetration resistance performance. Therefore, it is not recommended to use plates with spaces in armored vehicles.

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