HYBRID COMPOSITE MATERIALS FOR BALLISTIC PROTECTION. A NUMERICAL ANALYSIS

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Abstract: *Starting from the basic element of projectile-armor competition, approaching impact problems, applying the optimal elements synthesis in evaluation and results integration, the paper intends to provide a comparative analysis between an armor plate made of conventional materials and a hybrid armor plate.*

In this paper, the behavior of a steel armor plate and a multilayer plate are numerically analyzed in terms of dissipated energy. The structure's numerical model is validated, first and foremost by experimental tests performed in the range, observing the projectile yielding mode, and the impact on the armor plate simultaneously. The dissipated energy on the multilayer plate is further determined for certain armor inclination angles, and then compared with the steel plate.

Keywords: *armor plate, projectile, hybrid armor plate, multilayer plate, impact, amphibious armored vehicle, finite element modelling, sandwich structure, numerical analysis, specific weight, kinetic energy, dissipated energy.*

1. INTRODUCTION

The armed conflicts and social movements that characterized the 20th century beginning have conditioned the occurrence and diversification of both individual protection (bulletproof vest, ballistic helmet) and the automotive industry in equipping armed forces with combat machine, properly equipped to ensure the protection of both the crew who operate them and the fighters.

Such a type of technique is not only characterized by the degree of mobility and its ability to move smoothly on any type of terrain, but also by the protection against the firearms.

In order to achieve the protection against firearms, the aim is to manufacture a relatively resistant armor, but also with lower weight. At the first sight, these two aspects of the technology – mobility and armored protection – sound to be contradictory, due to the fact that in order to achieve a higher impact strength, the armor plate must have a maximum layer thickness, and furthermore to obtain a high mobility, the armor plate must be as light as possible. This obstacle can be defeated by using materials that provide greater specific stiffness and strength-to-weight ratio. Therefore, the materials selection is an important criterion for weight optimization, such as the use of improved composite materials.

The impact strength performance of such light structures made of composite materials is an important design criterion in the armor protection area.

2. DIRECTION TO IMPROVE ARMOR PROTECTION, TRANSPOSED IN PRACTICE, BOTH NATIONALLY AND INTERNATIONALLY

From the armed conflicts that have evolved over time perspective, it can be concluded that the main effort in the armor protection area, have been directed in manufacturing of new modern combat machines types, as well as towards the modernization of some technologies used for manufacturing their main components and subassemblies.

Contemporary armored vehicles are equipped with conventional, homogenous shielding materials, which are generally made of steel or aluminum alloys. (Fig. 1)

Today tendency, both nationally and internationally is to research new armor plates that are lighter as possible and resistant to multiple threats.

The actual armored vehicles efficiency requirements, including rapid displacement, increased drive distance and improved ballistic protection, significantly contribute to the increasing armored vehicles efficiency, and as a result, higher survival rate on the battlefield.

The present direction is to insist on obtaining armor plates made of lighter multilayer composite materials, which protect against the armor piercers and cumulative ammunition effects, such as reducing overpressure and explosion amplitude.

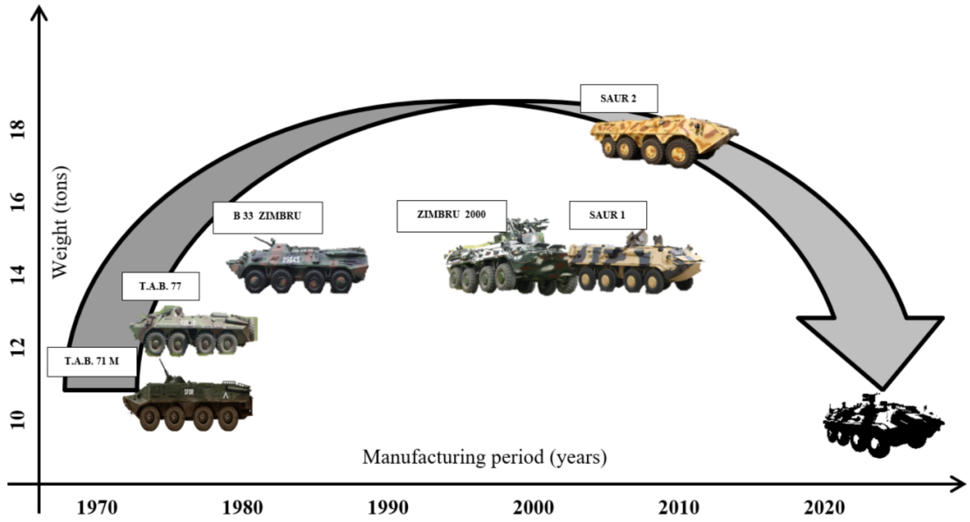


FIG. 1. The direction of reducing the weight of armored vehicles

3. THE MAIN CHARACTERISTICS AND DESTINATION OF AMPHIBIOUS ARMORED VEHICLES

The amphibious armored vehicles are means of transportation and combat for the infantry group, that ensure superior mobility, high fire power and adequate protection against light infantry weapons projectiles (5,45x39 mm or 7,62x39 mm caliber) and shrapnel, and can be exploited day and night, regardless of time and season or terrain.

In the table below are presented some technical and tactical characteristics, namely the armor plates thickness and their arrangement inside of the frame partitions, for the amphibious armored vehicles that equipped the Romanian army.

Global military operation has seen the demand increase for a vehicle that bridges the gap between deployable light forces, with their inherent low survivability, and more survivable heavy forces that are difficult to deploy and have high life cycle costs. PIRANHA IV has been developed in response to this need and takes advantage of the latest technologies to deliver class leading survivability, capacity and mobility with low through life costs and inherent growth capacity [3]. The PIRANHA V is a wheeled armored combat vehicle, being considered one of the most advanced platform for troop transport equipped with modern ballistic protection systems and fire power, at the highest endowment level available in NATO. It has an all-welded steel armor hull with integrated add-on composite modular armor system. This system provides unparalleled all round protection, particularly in the wheel well area that has traditionally been vulnerable to IEDs on armored combat vehicles.

Table 1. The thickness of the armor plates for the T.A.B. that equipped the Romanian army [1, 2]

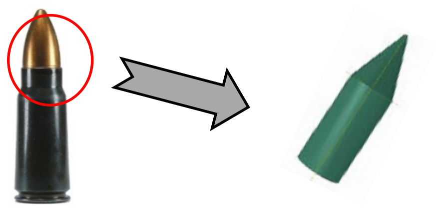
Parameter	TAB-71	TAB-71M	TAB-77	TAB-77-30M
Thickness of the armor plate (mm)	***Arrangement***			
4	ceiling and ceiling shutters		the ceiling of the energy room, the wings of the niches	
5	-	-	ceiling and ceiling shutters	
6	upper and lower sides, upper front, back welded			
8	-	-	the sides of the niches	
10	windshield		windshield lower front	
12	turret shield		-	-
13	lower front		plate angle on the lateral sides	
20	vertical face plate, observation deck			

The armor has a very high influence on the armored vehicle weight. As first method of increasing the ballistic protection, is represented by the armor plate thickness increase, primarily this solution was preferred. Weight gain leads first to high vulnerability considering the mobility point of view, proportionally increasing the engine power. The requirements to increase the armor thickness lead to the occurrence of the *equivalent armor* concept, referred to the armor plate angle, that provides better protection (equivalent, reported to the same real thickness) and, through the constructive solution adopted (maintaining the equivalent thickness, therefore of the equivalent ballistic protection, with the plate leaning), you can get an vehicle mobility increase [4].

4. THE CONFIGURATION AND THE CONSTITUENT MATERIALS USED TO APPROACH THE IMPACT PROBLEM

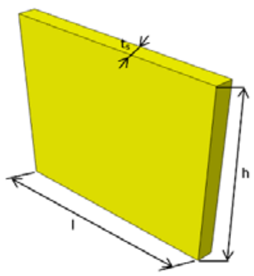
The elements used in this paper, in approaching the impact problem are the penetrating object (projectile) and the target (armor plate).

The projectile belongs to the 7,62 mm light infantry weapon (7,62x39 mm cartridge, steel core bullet, steel tube) [5], and the armor plate is made of steel used in armored vehicles manufacturing, for protection against high-impact projectiles [6].



(a) (b)

FIG. 2. The projectile used in analysis a) 7,62x39 mm cartridge [5], b) 3D model 7,62x39 mm cartridge



l = 100 mm- the armor plate lenght
h = 100 mm - the armor plate height
t_s = 8 mm – the armor plate thickness

FIG. 3. The geometrical parameters of the armor plate model

5. NUMERICAL ANALYSIS

The numerical analysis is based on a FE model, developed in commercial software Abaqus, the structure being analyzed from a dynamic point of view. In order to perform the analysis, it is necessary to obtain the material constitutive low. This law allows numerical simulation of the technological processes that involve high rates of strain, as well as impact problems. The material model statement establishes the relationship between stress, specific strain, rate of strain and the temperature and involve the material parameters knowledge.

5.1 Geometry and mesh type. The geometrical configuration numerically analyzed are shown in the figure below, the modification being imposed by tilting the armor plate under a certain angle of incidence, therefore providing a better protection, through the adopted constructive solution and obtaining an increased vehicle mobility.

(a) (b)

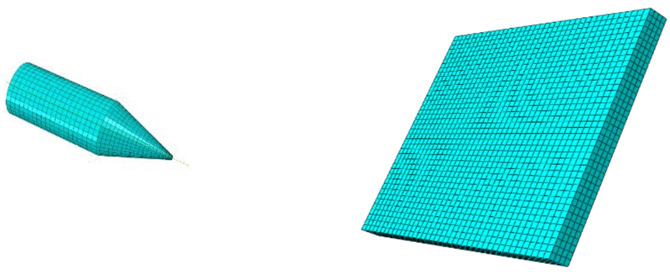
FIG. 4. Armor plate tilt angle a) initial position - angle of incidence 0°, b) modified position- angle of incidence 20°

Table 2. Angle of incidence α

Angle of incidence α [°]	0	20	40	50	60

The geometry of the two elements used in the analysis (projectile and the armor plate) was created selecting type *Solid*, to simulate as much as possible the properties of the physical model properties.

The mesh sensitivity in the projectile was studied by considering the element size of 0,75 mm, for the target an element size of 2,5 mm, and for the width a 4 elements size.



(a) (b)

FIG. 5. Finite element model a) projectile, b) armor plate

5.2 Material properties. For the analyzed model, a projectile impact speed of 690 m/s was chosen, taking into account that the shooting on the target distance is 25 m. [7]

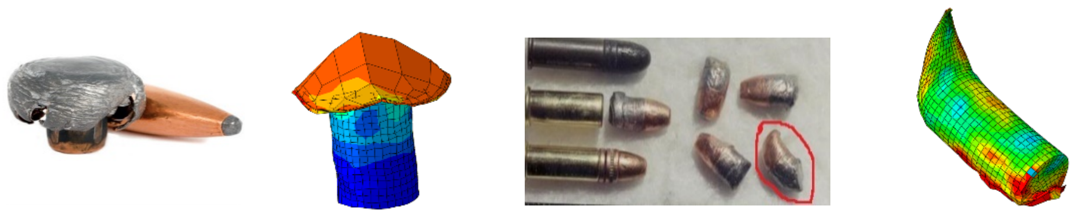
The Johnson-Cook constitutive model material parameters were used to predict the ballistic steel target performance and model failure in order to predict the material damage behavior.

Table 3. Material parameters for the projectile and armor plate [8, 9]

Parameter	Unit	Notation	Value (projectile)	Value (armor plate)
Modulus of elasticity	N/m^2	E	202×10^9	210×10^9
Poisson´s ratio	-	υ	0,32	0,33
Density	Kg/m^3	ρ	7850	7850
Johnson-Cook plasticity constitutive model	N/m^2	A	2700×10^6	980×10^6
	N/m^2	B	211×10^6	2000×10^6
	-	n	0,065	0,83
	-	c	0,005	0,0026
	-	m	1,17	1,4
	-	$\dot{\varepsilon}_0$	0,0001	0,0001
	K	T_m	1800	1800
	K	T_{tr}	293	300
Johnson-Cook damage constitutive model	-	D_1	0,4	0,05
	-	D_2	0	0,8
	-	D_3	0	-0,44
	-	D_4	0	-0,046
	-	D_5	0	-2,9

6. RESULTS AND DISCUSSION

The FE model is validated by comparing deformed the projectile shape after impact by experimental determination, in the real firing tests carried out in the firing ranges, with the results obtained numerically in the present work. At the same time, the evaluation of the hole formed in the target is also considered.



(a) (b) (c) (d)

FIG. 6. The deformed shape of the projectile after impact a) [10] and c) experimental results, b) [11] and d) numerical results

In "FIG. 6." a) and b) is presented the projectile deformation mode at a frontal impact (angle of incidence - 0°). It can be observed that the deformation mode obtained by the experimental determination and the numerical solution is quite similar, both models are very much deformed, being in a crushing state.

In "FIG. 6." c) and d) is presented the projectile deformation mode at an angle of incidence dissimilar to 0°. It can be observed that the deformation mode obtained by the experimental determination and the numerical solution, same as in the previous case, is quite similar, both models having a specific strain when the projectile bounces on impact.

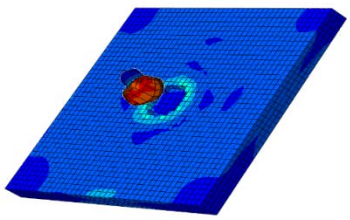


FIG. 7. Deformation of armor plate

FIG. 7. illustrates the armor plate behavior in a frontal impact. It can be observed that the projectile pierces into the armor plate without penetrate it.

According to the technical and tactical specification of amphibious armored vehicles, their armor provide protection against light infantry weapons, resulting that the numerical solution obtained behaves like the physical model. Therefore, it is concluded that FE model predicts very well the experimental behavior, both for the projectile and the armor plate.

7. IMPACT STUDY FOR A HYBRID MULTILAYER PLATE

Based on the validated FE model, an impact analysis was performed on a hybrid multilayer plate, intending to obtain a lighter armor, but at the same time with the properties to respond in the front of the current threats.

The same projectile, impact velocity and angles of incidence will be also applied in this case. During the simulation, the multilayer plate behavior will be compared with the obtained steel plate results.

7.1. The configuration and the constituent materials. Further, a multilayer armor plate is proposed, in which architecture several layers of materials are grouped: *first layer* is made of ceramic composite materials (alumina 99,5%); the *second layer* is made of fiber based composite materials (glass fiber reinforced polymer – gfrp); the *third layer* is a sandwich structure (core and shell acrylonitrile butadiene styrene – abs); the *fourth layer* is made of metal (al7075-t651).

Adhesive was used to join the plates. The main purpose of the adhesive is to maintain homogenous the armor before and after impact as well as to absorb the deformation and delamination.

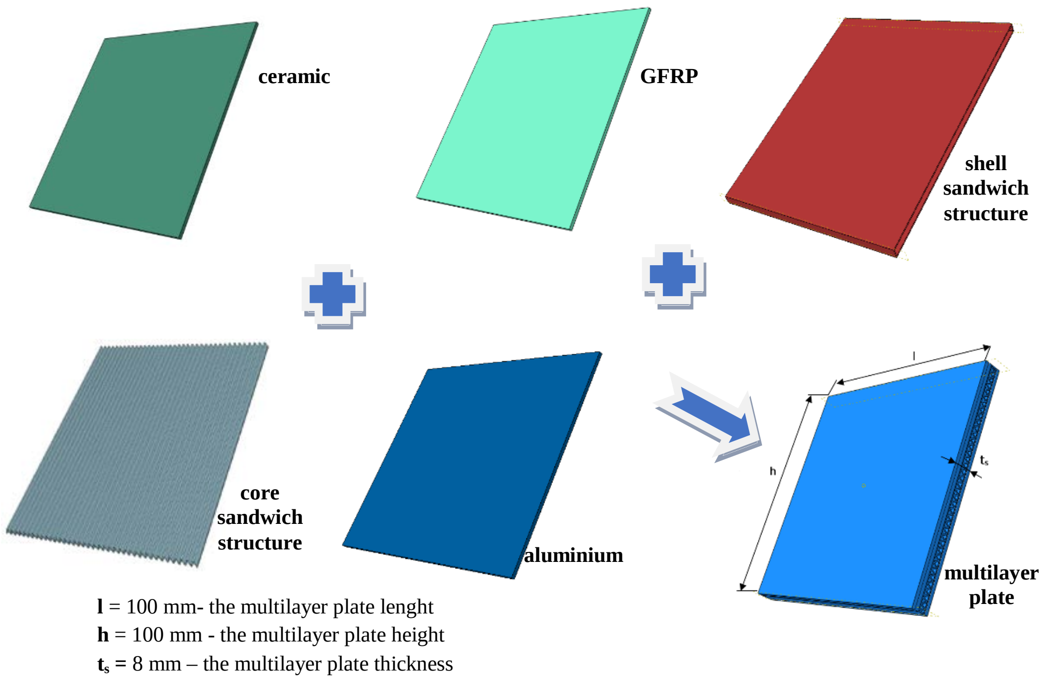


FIG. 8. The geometrical multilayer plate model parameters

7.2 Geometry and mesh type. The geometry of the elements used in the analysis was created of *solid* type, and in addition the ceramic plate and the gfrp plate were modeled as composites.

The mesh sensitivity in the ceramic plate, GFRP plate and aluminum plate was studied by considering the element size of 2,5 mm, and width of 2 elements. For the shell sandwich structure an element size of 3 mm, and a width of 3 elements were considered in. In the case of core sandwich structure, an element size of 3 mm, and a width of 2 elements were considered.

FIG. 9. Finite element model for multilayer plate

7.3 Material properties. The projectile was impacted normally with an incidence velocity 690 m/s, counting that the shooting distance on the target is 25 m.

In order to simulate the behavior of the material on impact, the Johnson-Cook plasticity and damage constitutive model for the material parameters was used on sandwich structure and aluminum. For the composite materials, the Hashin criterion was applied.

Table 5. Material parameters for Al and ABS [12, 13, 14]

Parameter	Unit	Notation	Value (Al)	Value (ABS)
Modulus of elasticity	N/m^2	E	$71,7 \times 10^9$	$2,9 \times 10^9$
Poisson´s ratio	-	υ	0,33	0,422
Density	Kg/m^3	ρ	2810	2810
Johnson-Cook plasticity constitutive model	N/m^2	A	520×10^6	39×10^6
	N/m^2	B	477×10^6	48×10^6
	-	n	0,52	1,5
	-	c	0,0025	0,544
	-	m	1,61	0,879
	-	$\dot{\varepsilon}_0$	0.0005	0,00081
	K	T_m	893	513
	K	T_{tr}	293	300
Johnson-Cook damage constitutive model	-	D_1	0,096	0
	-	D_2	0,049	0
	-	D_3	3,465	0
	-	D_4	0,016	0
	-	D_5	1,099	0

Table 6. Material parameters for Alumina and GFRP [15, 16, 17]

Parameter	Unit	Notation	Value (Alumina)	Value (GFRP)
Young modulus	N/m^2	E_1	$20,44 \times 10^9$	13×10^9
	N/m^2	E_2	$8,9 \times 10^9$	13×10^9
	N/m^2	E_3	$8,9 \times 10^9$	$2,4 \times 10^9$
Shear modulus	N/m^2	G_{12}	$1,64 \times 10^9$	$17,2 \times 10^9$
	N/m^2	G_{13}	$1,64 \times 10^9$	$17,2 \times 10^9$
	N/m^2	G_{23}	$3,03 \times 10^9$	$17,2 \times 10^9$
Poisson coefficient	-	υ_{12}	0,31	0,1
	-	υ_{13}	0,31	0,3
	-	υ_{23}	0,49	0,3
Density	Kg/m^3	ρ	1230	1800
Longitudinal tensile strength	N/m^2	Hashin criterion	$1,145 \times 10^9$	$0,32 \times 10^9$
	N/m^2		$0,13 \times 10^9$	$0,32 \times 10^9$
Longitudinal compressive strength	N/m^2		$0,65 \times 10^9$	$0,24 \times 10^9$
	N/m^2		$0,65 \times 10^9$	$0,24 \times 10^9$
Shear strenght	N/m^2		$0,34 \times 10^9$	$0,14 \times 10^9$
	N/m^2		$0,34 \times 10^9$	$0,14 \times 10^9$

8. RESULTS. DISSIPATED ENERGY

In this paper study, dissipated energy (lost) is represented as the difference between impact kinetic energy and kinetic energy remaining after impact.

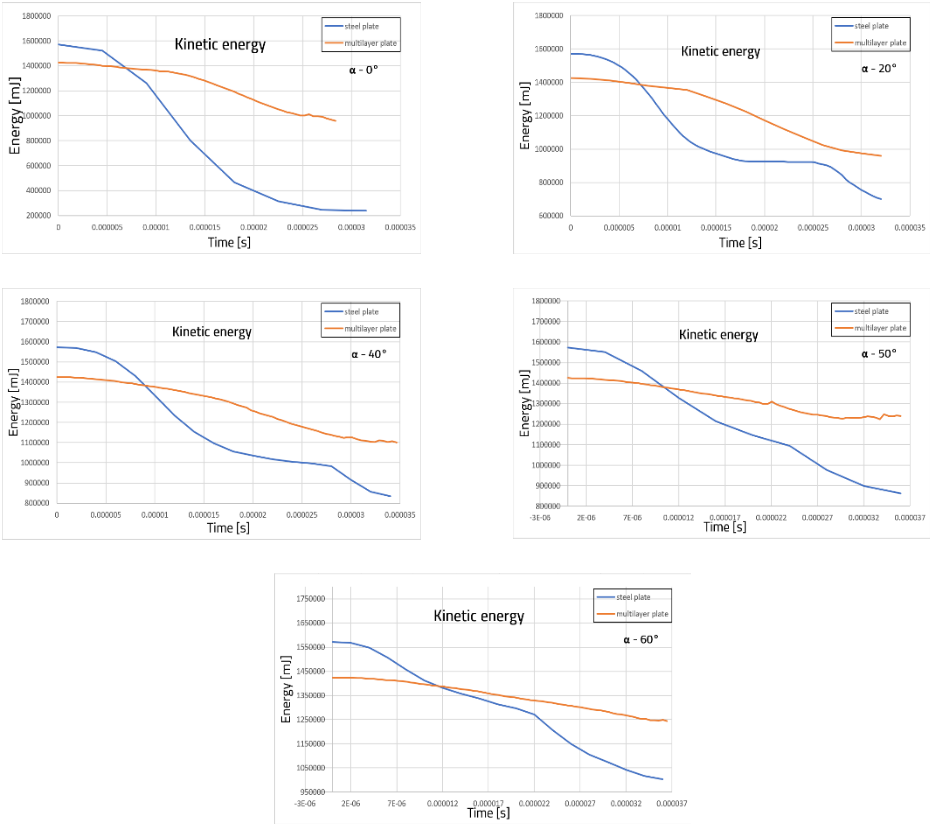


FIG. 10. Kinetic energy for the steel plate, respectively the multilayer plate

The energetic values for kinetic energy are calculated for t=0,000035 s. In the graphs above can be observed that the dissipated energy in the steel plate case is higher than in the multilayer plate case. This is happening due to higher weight of the steel plate compared to the multilayer plate.

To analyze the armor plates behavior at impact in terms of dissipated energy the E_d/m ratio will be used, where m represents the armor plates weight.

To calculate dissipated energy will be used the relation:

$$E_d = \frac{E_{kmax}}{E_{kmin}} \tag{1}$$

where

E_{cmax} represents the kinetic energy at the moment of impact (t = 0 s);

E_{cmin} represents the kinetic energy at the moment t = 0,000035 s.

The following values resulted from the calculation:

$$E_{Sd}(\alpha = 0°) = 2123.3\frac{J}{kg}$$

$$E_{Md}(\alpha = 0°) = 4006.9\frac{J}{kg}$$

$$E_{Sd}(\alpha = 20°) = 1389.6\frac{J}{kg}$$

$E_{Md}(\alpha = 20°) = 4014.9\frac{J}{kg}$

$E_{Sd}(\alpha = 40°) = 1176.4\frac{J}{kg}$

$E_{Md}(\alpha = 40°) = 2784.1\frac{J}{kg}$

$E_{Sd}(\alpha = 50°) = 1130.1\frac{J}{kg}$

$E_{Md}(\alpha = 50°) = 1590.9\frac{J}{kg}$

$E_{Sd}(\alpha = 60°) = 907.3\frac{J}{kg}$

$E_{Md}(\alpha = 60°) = 1549.4\frac{J}{kg}$

For solving numerical calculation was considered a weight of 0,628 kg. was considered for the steel plate and 0,116 kg. for the multilayer plate.

Based on results it can be observed a higher value of E_d/m ratio in all five analyzed cases, in the favor of the multilayer plate.

Referring to the structure weight can be concluded that the multilayer plate possesses a better behavior at impact, compared to the steel plate, in terms of dissipated energy.

CONCLUSIONS

Based on validated numerical model, a parametric study was performed to analyze the dissipated energy. The multilayer armor plate investigated in the paper is proved to be a competitive structure in terms of dissipated energy. This behavior is an added value in addition to its considerably light weight compared to a steel armor plate. The plate consists of four layers kept homogenous by an adhesive used in ballistic protection structures.

Although the structure has limited advanced over conventional armor plates, it can be used where light weight and dissipated energy are important.

Mixed armors made of composite, glass fiber, polymer, sandwich structure and more, seem to form a very efficient shield against low and high velocity impact, since they combine low density, high hardness, high rigidity, strength in compression, lightweight and ductility.

However, apart from material type, shape criterion is also important and it may represent an added advantage. An example of near optimal use of material is given by the sandwich concept, where the bending stiffness of the structure is increased by placing a lightweight and thicker core between two thin and stiff face sheets while the weight is negligibly increased. The continuing research on improving the overall mechanical performance of sandwich structures focuses also on developing novel core configuration, made of composite materials, in order to gain an improved mechanical behavior of the core. Although many of these structures provide competitive weight specific strength and stiffness, their main drawback is related to manufacturing steps which are often complicated and difficult to be integrated within a continuous production line. The more recent development of additive manufacturing technologies allows generating complicated and efficient cellular shapes but on a limited scale yet.

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