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PhD Thesis Summary

Contribuţii la studiul protecţiei balistice pentru structurile elicopterelor militare

Contributions to the study of ballistic protection for military helicopter structures

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CHAPTER I
THE CURRENT STATE REGARDING BALLISTIC PROTECTION SYSTEMS

1.1. Introduction

In the conditions of the contemporary space of multidimensional confrontation, during the conduct of missions, helicopters may face asymmetric threats, with battles between armed groups carried out on large areas of land with technologically advanced elements of the air defense system of the conventional adversary, with lack of navigation systems on the ground or with hazardous phenomena to the intended or unforeseen flight.

1.2. Ballistic threats on military helicopter structures

In recent conflicts, unguided rocket propelled grenade attacks and small arms fire directed to helicopters have caused numerous casualties. In response, development of helicopter self-protection packages as well as threat detection and countermeasures against these aircraft began.

Emphasis is now being placed on how technical means such as airbags and bulletproof seats, as well as materials and coatings resistant to unguided reactive projectiles, originally intended for the protection of armored vehicle personnel, can be incorporated into the construction of today's helicopters and those that will be manufactured in the future.

An attack helicopter is an armed helicopter capable of attacking ground targets such as: enemy infantry, tanks and armored vehicles. Weapons used on these helicopters may include machine guns, rockets and guided anti-tank missiles. They are also capable of carrying air-to-air missiles for self-defense purposes.

The threat spectrum is represented by the air or ground strike and/or reconnaissance components or, more precisely, by the adversary's ability to detect, identify and engage helicopters and can be classified into three levels of threat intensity, as follows: low, medium and picked up.

Helicopters, like any other aircraft, have critical/sensitive areas, areas that, if hit by air defense systems or even individual infantry weapons, can endanger the helicopter and crew. Thus, the critical areas of the helicopter can be classified into two categories:

- the compartment of the power plant and mechanical assemblies;
- cockpit and cargo compartment.

The materials from which the various constructive elements are made are, in the majority, light alloys - for the resistance parts, titanium - for the thermally stressed parts and layered plastic materials - for the parts that are not subjected to special efforts. In addition, certain areas, which must be light and rigid at the same time, are made of special materials, usually honeycomb [2].

a) Compartment of the power plant and mechanical assemblies

The power plant consists of two TURMO IV CA gas generator engines with a free turbine, located side by side, in the front of the helicopter, above the cabin (cargo compartment), connected directly to the main transmission box [3].

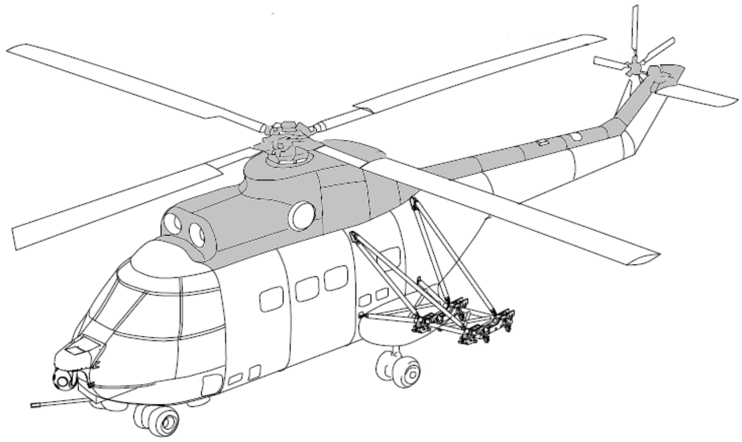


Fig. 1.1 Compartment of the power plant and mechanical assemblies [4]

This compartment of the power plant and mechanical assemblies, highlighted in figure 1.1, represents a critical and essential area of the helicopter. If this area would be hit by air defense systems or even individual infantry weapons, the helicopter would primarily be in danger of crashing.

a) Cockpit and cargo compartment

The second critical area of the helicopter is the cockpit and the cargo compartment, highlighted in figure 1.2. Unlike the power plant and mechanical assemblies compartment, these areas, if would be hit by projectiles, can directly affect the crew and passengers in the helicopter.

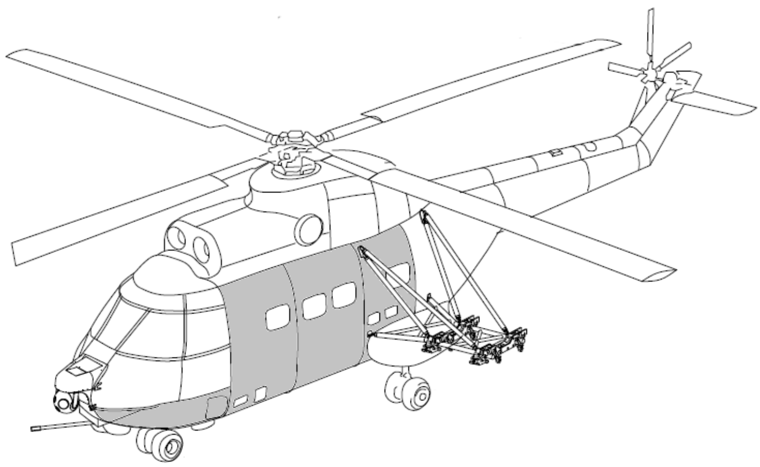


Fig. 1.2 Cockpit and cargo compartment [4]

1.3. The main materials used in the construction of military helicopter structures

Aircraft manufacturing can be seen as one of the most dynamic cases in terms of the application of research results, starting with the materials used and ending with aerodynamic solutions and new technological processes. The use of materials with minimum mass and maximum strength determines the evolution, from classic natural materials such as wood, to steels, metal alloys, as well as composite materials.

The use of different materials in engineering applications is based on their quality to meet the design and operation requirements, requirements based on their mechanical and physical properties. Mechanical properties refer to the relationship between mechanical stresses and resistance to deformation or breaking of the material.

The helicopter is a motorized aerial vehicle, which is part of a wide class of aircraft, called rotary-wing aircraft, or, as it is sometimes found in the specialized literature, gyroplanes. They are characterized by the fact that the lift is fully or partially achieved by large-diameter rotors with a vertical axis. The main qualities are given by the fact that they can land in narrow spaces and stay in the air at a fixed point[5].

The materials from which the various constructive elements of the IAR 330 Puma helicopter are made are, for the most part, light aluminum alloys, especially for the resistance parts and titanium, for the thermally stressed parts, and the tanks are made of self-sealing rubber. Also, layered plastic materials are used, for the parts that are not subjected to special efforts. In addition, certain areas, which must be light and rigid at the same time, are honeycomb constructions.

The panels, hoods and fairings that are fixed to the mechanical floor, on the anti-torque rotor beam and on the oblique pylon protect various mechanical, transmission and service organs, placed on the outer structure of the fuselage. Two fairings fixed laterally, at the rear of the lower structure, profile and protect the main landing gear [6].

1.4. Characteristics of ammunition frequently used against helicopters

In order to be able to study and design a ballistic protection system, it is necessary to first study what threats occur, by threats we mean the ammunition of anti-aircraft defense systems or individual infantry weapons.

Ammunition is the means of combat in the organization of which explosive or pyrotechnic elements are found and whose purpose is to destroy or neutralize the enemy's personnel, to cause destruction or damage to combat technique, to create a disruption in the conduct of combat actions, but also favoring the actions of own troops [23].

The ammunition consists of the following four main components (figure 1.3):

- warhead or ignition device (a);
- combat component (b);
- the propeller (c);
- the steering and trajectory stabilization system (d).

The warhead is a set of mechanisms and devices specially built and intended to cause the initiation of an explosive system, at the desired point of the trajectory (before or after hitting the target).

Explosive system (projectiles, launcher bombs, mines, rockets, aviation bombs) means a set of elements intended for the destruction or neutralization of various objectives.

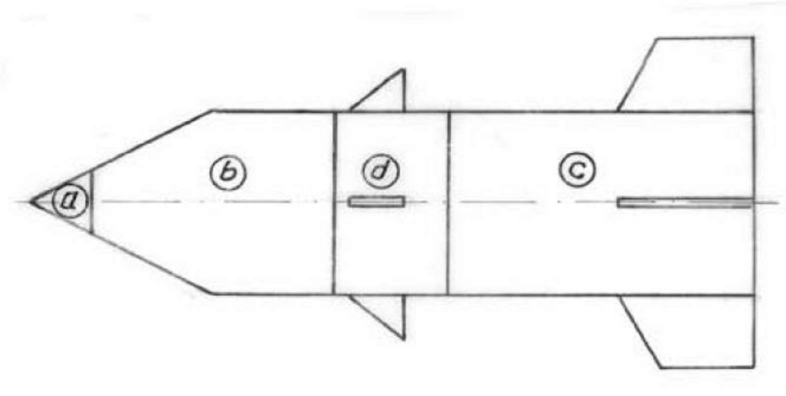


Fig. 1.3 General organization of ammunition [23]

The guidance and stabilization system on the trajectory has the role of achieving good precision when hitting the target, by collecting information on the flight parameters of the ammunition and by taking the necessary measures to bring them to the values established by the flight program. In the case of guided munitions, this compartment is automated and electronic, containing devices for gathering and processing information and command and execution components. The simplest stabilization block consists of an armament arranged at the back of the projectile, bomb, missile [23].

The combat component is the useful part of the ammunition, which achieves the effect on the target. As representative types of combat components we can mention: the projectile, the bullet, the machine gun, the combat component of the missile or the torpedo [23].

The manufacture, improvement and continuous modernization of light weapons is, at present, worldwide, one of the main concerns of military constructors and designers. Being in the equipment of every fighter, whether he is an infantryman, a tankman, an aviator or a sailor, portable weapons form, in a modern war, the most widespread technique, without which it is not possible to achieve success in battle [30].

Being so widespread, this small infantry weapon represents the main threat to helicopters in theaters of operations.

Automatic infantry weapons include: the machine gun, the automatic rifle and the machine gun, as individual weapons, as well as the machine gun, as collective weapons.

1.5. Current ballistic protection requirements and solutions

At the moment, a current and very important issue is the ballistic protection of helicopters. Considering the fact that helicopters carry out attack missions as well as transport, it is necessary that they benefit from protection against air defense systems, in order not to endanger the crew and any passengers.

The battlefields of the future will be characterized by automatic weapons systems, an integrated coordination of the categories of armed forces and the use of cybernetic systems, used to complement the physical limitations of combatants. Thus, the armored technique maintains a dominant position during the battle due to the degree of protection, mobility and firepower.

The concept of protection in the field of armored technology is defined as representing the totality of the capabilities of the military vehicle to deal with attacks carried out by different methods: projectiles, mines, grenades, improvised explosive devices, infantry weapons and to provide protection to personnel during the execution of missions.

Currently, armor protection can be defined as a set of constructive and tactical measures aimed for avoiding the detection of the vehicle by any enemy, avoiding being hit by performing repositioning maneuvers, as well as surviving in the event of a hit by the enemy.

Accordingly, the armor can be considered as a set of plates that are intended to ensure the protection of personnel in the event of an armed attack [34].

Adding ballistic protection systems to helicopters, in order to protect crew and passengers, when performing missions in war zones, has always represented a compromise between installing an additional element of protection and increasing the mass of the helicopter, while reducing the payload this one.

The ballistic protection system consists of plates, some of small size, others of larger size, depending on the arrangement of each one, precisely to allow their mobility and the ease of their exchange, in case they are hit or simply improved . Also, the helicopter, having a monocoque, cylindrical construction, increased protection and on as large a surface as possible, can only be provided with a greater number of small plates.

For example, the AH-1Z helicopter, built by the American company Bell Helicopters, has a cover-type protection made of plates measuring 300 mm x 400 mm x 12 mm, made of Kevlar, arranged inside the aluminum cover, on the side, in the back and at the bottom of the pilots' seats, but also in the area of mechanical assemblies and engines. The manufacturer estimates that the ballistic protection installed on this helicopter can withstand hits of up to 25 mm caliber.

Over the years, the United States Aviation Protocol Integration and Weapons Research Department has developed ballistic protection systems for several helicopters, the Boeing CH47 Chinook and the well-known UH60 Black Hawk, manufactured by Sikorsky. Using composite materials, they managed to develop effective ballistic protection systems with low mass, while offering protection against small arms up to 7.62 mm. On a CH-47 Chinook helicopter, this reduced the mass of the ballistic protection by about 900 kg, to a current mass of 1587 kg. Protection includes the cockpit floor, cargo cabin, side panels and armored windows. A similar reduction in mass was achieved for the ballistic protection of the UH-60 Black Hawk helicopter, by approximately 227 kg.

According to [42], the UH-60 Black Hawk benefits from increased ballistic protection of the cargo compartment (figure 1.4), the cockpit floor (figures 1.5, 1.6) and the side walls (figure 1.7). Sikorsky presents this ballistic protection system based on composite materials as being among the most advanced systems today, being characterized by low mass, resistance to multiple hits and high durability. The maximum mass of the protection can reach 532 kg.

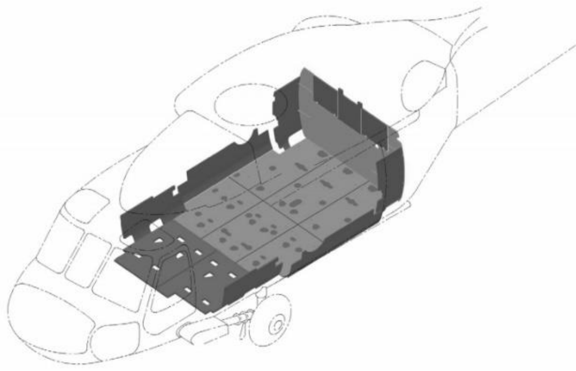


Fig. 1.4 UH-60 Black Hawk cargo floor [42]

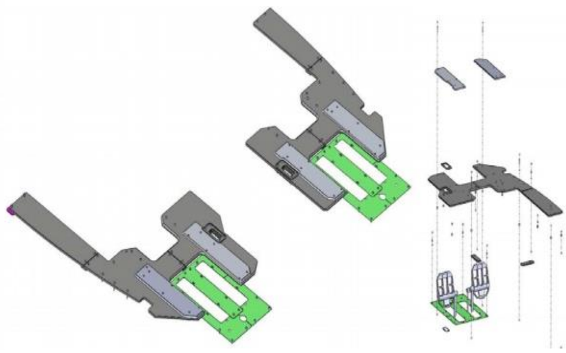


Fig. 1.5 UH-60 Black Hawk cockpit floor [42]

Fig. 1.6 UH-60 cockpit floor [42]

Fig. 1.7 UH-60 cabin side panels [42]

Another example of a helicopter that has ballistic protection installed is the AH-64 Apache. The supplier of this ballistic protection is Teledyne Ryan Aeronautical, and it presents this armor as being made of the following successive layers, from the inside out: Kevlar liner, high-hardness boron carbide core, and ballistic nylon shell. This armor can be seen in figure 1.8.

The pilots' seats are also protected, being equipped with Kevlar, a shield made of anti-explosion-fragmentation acrylate, but also a bulletproof glass [44].

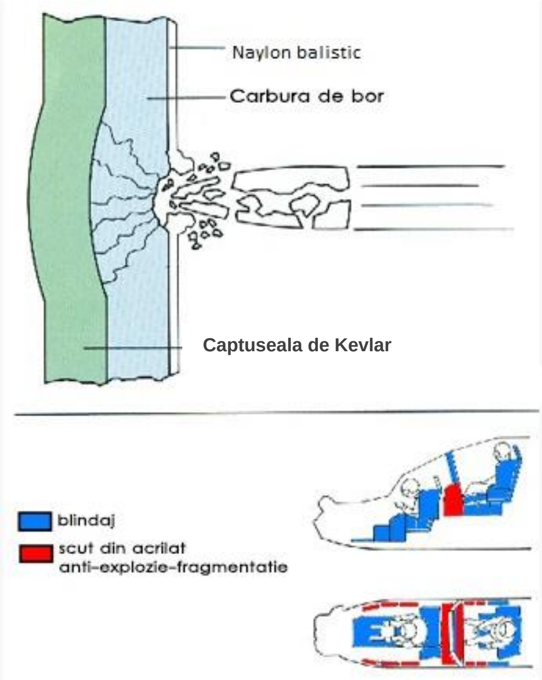


Fig. 1.8 AH-64 Apache cabin armor: layout and composition [42]

1.6. Conclusions

Military helicopters play an important and integrated role in air, land and maritime operations, performing a number of essential missions, such as: reconnaissance missions, observation missions, aerial fire control missions, airborne command and control missions, troop/materiel transport, air strike and air assault missions and electronic warfare missions.

The threat spectrum is represented by the air or ground strike and/or reconnaissance components or, more precisely, by the adversary's ability to detect, identify and engage helicopters and can be classified into three levels of threat intensity, as follows: low, medium and high.

The use of composite materials in aircraft construction has experienced a sustainable and continuous development, evolving from the production of parts that cannot take high loads, in the case of aircraft that had low flight speeds, to the production of essential parts for high-speed aircraft.

A helicopter cannot be designed and built using only one type of material, but using several types of materials, combined, in order to reduce mass and increase resistance.

Small arms are the main threat to helicopters in theaters of operations. It includes: the submachine gun, the automatic rifle and the submachine gun, as individual weapons, as well as the machine gun, as collective weaponry. The infantry weapons currently in the armed forces have a caliber between 5.45 mm and 14.5 mm, with the tendency to expand this gap in values towards the lower limit.

The mass of the helicopter is an extremely important factor, especially during operations at high altitude, where the performance of the engines decreases due to the lack of oxygen. In order not to affect the flight configuration of the helicopter, first of all, it is necessary that the ballistic protection systems have a low mass. That is why composite materials are used in the manufacture of these armors, which offer, at the same time, reduced mass and increased protection.

CHAPTER II
OBJECTIVES AND ORGANIZATION OF THE DOCTORAL THESIS

2.1. The topicality of the thesis subject

The particularly important role of military helicopters emerges from the missions they perform, essential missions such as research, observation, airborne command and control, fire control, air strike and air assault, troop or material transport.

Current ballistic protection systems are in permanent development, by optimizing materials and protective structures and by discovering new materials, in order to achieve a balance between the variety of threats in theaters of operations and protection against them.

Adding ballistic protection systems to helicopters, in order to protect the crew and passengers, when performing missions in war zones, has always represented a compromise between installing an additional element of protection and increasing the mass of the helicopter, while reducing, at the same time, the load its usefulness.

Thus, at the moment, the ballistic protection systems, currently installed on some military helicopters, are modular plate systems, mounted in its critical areas, which ensure an increased level of protection, both for the aircraft and the crew, during execution of missions in theaters of operations.

The aeronautical industry is considered to be the most dynamic and competitive, especially from the perspective of research results on materials used in aircraft construction, aerodynamic solutions and new technological processes.

2.2. The importance of the subject of the thesis

Starting with the fundamentals of projectile/armor combat, the PhD thesis aims to increase the protection factor for military helicopter armor by identifying and testing new material configurations for their critical areas, leading to the design and development at low cost, in the framework of the national defense industry, of ballistic protection systems intended for helicopters belonging to the Romanian Air Force. These modular plate systems can be mounted in critical areas to provide protection to both the aircraft and the crew during the execution of missions in theaters of operations, in the event of attacks by light infantry weapons.

The topicality and complexity of the PhD thesis are especially strengthened by the fact that there are no public studies and data on ballistic protection systems installed on attack helicopters around the world. There is effectively no collaboration between companies developing such ballistic protection systems, but rather a competition, with the global ballistic protection materials market valued at approximately $8.8 billion in 2015, increasing to 11.03 billion dollars in 2022.

2.3. The objectives of the thesis

In order to design and develop a ballistic protection system for military helicopters, following the participation in peacekeeping missions, the implementation of new protection solutions may represent the only option to protect both the crew and the aircraft, a fact that determined the approach of this work.

The main objective of the work is the theoretical and experimental study for a new ballistic protection system, which is resistant to the impact with the bullet 7.62 mm caliber.

The following can be listed among the specific objectives of this paper:

- the systematization and presentation in an accessible form of a study related to the structure of the IAR 330 Puma Socat helicopter, the main materials of its construction, the ballistic threats and the characteristics of the ammunition used against them, as well as the requirements and current ballistic protection solutions;
- the presentation of new methods and models of analysis and numerical simulation, studying with these methods the impact between a projectile and a plate in different configurations and comparing the results;
- studying the ricochet phenomenon at the projectile-plate impact and determining the conditions under which it occurs;
- designing, manufacturing and range testing of a ballistic protection system, performing the numerical analysis of the impact, comparing the numerical results with the experimental ones and validating the numerical model;
- the presentation of new constructive variants of ballistic protection and the performance of their related numerical analysis.

2.3. Conclusions

In the conditions of the current military tensions in the vicinity of the country, emphasis is placed on the renewal of military equipment and the development of effective protection systems, both for land and air vehicles.

From the above, it can be seen that increasing the protection factor for military helicopters is of great interest, both to the military and to the civilian side.

The organization of the doctoral thesis, the theoretical and experimental study carried out - with the current means of scientific investigation - led to the complete fulfillment of the assumed objectives, to the improvement of professional and personal training and the identification of new approaches to scientific research in the field.

CHAPTER III
NUMERICAL RESEARCH ON PROJECTILE - PLATE IMPACT

The numerical analysis of continuous media and the simulation of their behavior under certain conditions experienced an explosive development after the 2000s, being by far the most used means of investigation in the practice of design, optimization or scientific research, in general.

3.1. Fundamentals of the numerical methods used

Current material strength calculations, although applied to classical problems belonging to the theory of elasticity or plasticity, are impossible without the use of numerical methods and material models. This situation is the direct result of the evolution in the field of computers, both on the hardware side and on the software side.

It must be remembered that the impact analysis problems represent an analysis in a dynamic regime, taking into account the non-linearities of the material.

FEM - The Finite Element Method was developed in the second half of the 20th century, in response to the need for the numerical solution of complex physical phenomena, which are described by different differential equations, with difficult solutions. The versatility and wide applicability of this technique introduced it to the scientific world, and the development of computer technology facilitated its popularization and widespread use [35].

The Element Free Galerkin Method is based on a series of equations of the theory of elasticity, used in the special conditions of numerical approximation, by the moving least squares method.

The desire for new and increased efficiency led to the appearance of new methods of analysis and numerical simulation, known as meshfree particle methods, or particle-based methods, or meshfree methods.

These methods use nodes to approximate the field variables, as is the case with methods such as: the EFG (Element Free Galerkin) method, the SPH (Smoothed Particle Hydrodynamics) method, the RKPM (Reproducing Kernel Particle Method), the MLPG (Meshless Local Petrov method - Galerkin), the PIM method (Point Interpolation Method) and the FPM method (Finite Point Method). All methods of this type are also called meshfree methods or meshless methods [50].

The SPH method is a relatively new method, used for the approximate integration of partial differential equations. It is also a meshless method, in a Lagrangian approach, which uses pseudo-particles (attached in nodes), based on which an interpolation method is defined for the calculation of smoothed field variables.

Each of the two methods (MEF and SPH) has advantages and disadvantages, difficult to present, but easy to notice in the practice of their use. Ideally it would be to combine the advantages, so as to reduce the disadvantages as much as possible, coupling the two methods. Currently it is possible to model a structure in which one part is modeled with finite elements and another part with SPH.

Moreover, this coupling of the two methods leads to the solution of fluid-structure interaction problems, through a unique approach, in default automatic mode, which describes both the characteristics of the fluid flow, as well as the effects that appear in the structures with which they interact.

Today, there are almost no engineering papers, from graduation papers, especially master's and Phd papers, to large foundation or design studies, without calling for the use of numerical calculation methods and the simulation of the studied phenomena.

The field of numerical analysis of structures has been revolutionized, simply, by the new architecture of processors and their working frequency, by the storage capacity on hard disks, as well as by the increase in RAM memory.

To the above are added the dynamic allocation of memory, the improvement of procedures for solving systems of large algebraic equations, the parallel work of several computers and processors, etc.

Two very important aspects of the progress in the numerical calculation of structures are noted: the emergence of material models - which include the achievement of material rupture and the refinement of the description of the contact between materials.

3.2. Numerical models of impact analysis

Projectile-plate impact research must answer several questions from the designer or warfighter, the most important of which would be:

- if the bullet penetrates or perforates?
- if speed after perforating ensures lethal effect on personnel?
- under what conditions does the ricochet occur?
- what is the absorption capacity of the protective plates?

Of course, the most accurate answer to the above questions can be provided by experimental research, but it must be taken into account that numerical analysis can prepare the way for experimental investigation, leading to time and material savings.

In the following, the numerical analysis will be presented in the case of a projectile represented by the bullet 7.62 mm caliber, in interaction with a plate having different constructive versions (homogeneous and isotropic plate, multilayer plate and multilayer plate with honeycomb core). The numerical research carried out took into account the projectile-plate interaction, both under normal and oblique impact conditions, at different impact velocities.

The numerical research performed is based on the use of the Ansys LS Dyna program, considering several material models within the program's material library. All material models used describe both the impact stress and the phenomenon of breaking the material at the projectile-plate interaction. The most used material models which have been given special attention are: the plastic kinematic model and the Johnson Cook model. There are currently over three hundred material models. The advantage of the Johnson Cook model is the consideration of temperature, and the disadvantage is that more material constants must be determined/known. Considering the recommendations of specialists in numerical impact analysis, confirmed by their experimental validation, the kinematic plastic model was chosen.

3.2.1. Normal impact of projectile-homogeneous and isotropic plate

The FEM model - normal impact

For the investigation of the normal projectile-plate impact, it started with the study of a homogeneous and isotropic aluminum plate, with dimensions of 100 mm x 100 mm x 5 mm.

The impact with the bullet 7.62 mm x 39 mm caliber was a normal one, with a speed of 500 m/s, and the duration of the numerical analysis was $9 \cdot 10^{-5}$ seconds.

Special attention was given to the plate, therefore it was considered a rigid material for the bullet. Also, no angular velocity was applied to the bullet, as this rotational motion around the axis was found not to influence the perforating ability during the numerical analysis. The use of these assumptions covers the calculation results and a time saving occurs in running the program.

The finite element model (plate) was made with 61206 nodes and 50000 solid elements, having a uniform discretization, the size of the sides being 1 mm (figure 3.1).

Of course, the most economical solution would have been to use a simplified model (1/4), the structure having two axes of symmetry, but we opted for a whole model, in order to be able to follow the results of the graphic post-processing, which will also be in normally, symmetrical.

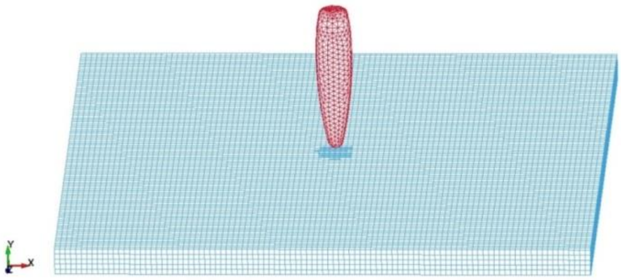
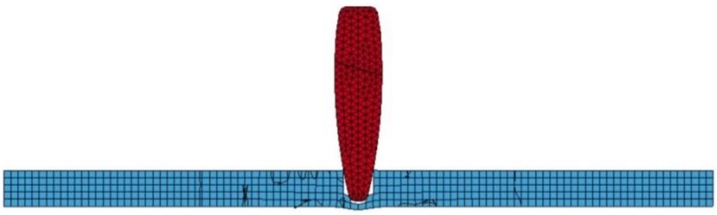
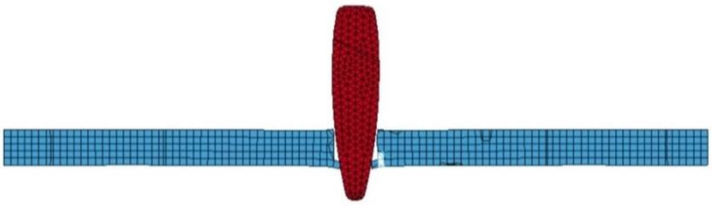


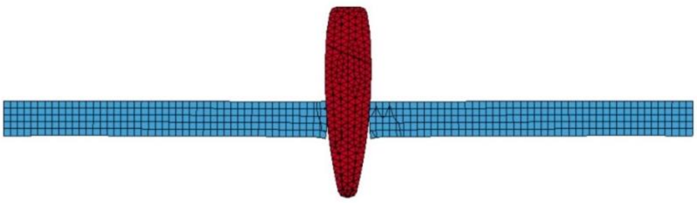
Fig. 3.1 The finite element model at normal impact



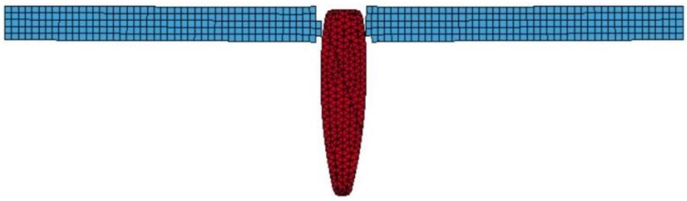
t = 10 µs



t = 20 µs



t = 30 µs

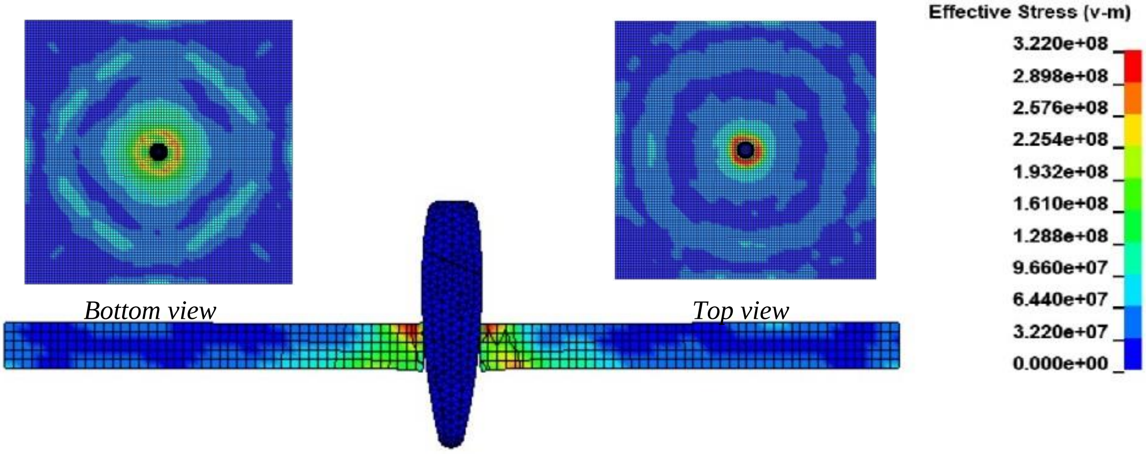


t = 60 μs

Fig. 3.2 Time evolution of the normal impact - FEM

Figure 3.2 shows the evolution of the impact, with its effects (deformation with perforation of the plate), by presenting the deformed state during the analysis of 60 microseconds.

Figure 3.3 shows the values and appearance of the von Mises equivalent stress field for the plate at time t = 30 μs (viewed laterally, through a section halfway through the plate and viewed in the direction of impact, bottom and top view).



t = 30 μs

Fig. 3.3 Field of von Mises equivalent stresses at normal impact - FEM

Also, the time variation of the total energy of the plate, the time variation of the kinetic energy of the bullet, as well as the time variation of the bullet speed during the penetration and perforation processes were presented. The results were noted and compared later.

The EFG model - normal impact

The Element Free Galerkin model (plate) was made with 61206 nodes and 50000 solid elements, having a uniform discretization with 1 mm side size and is represented in figure 3.4.

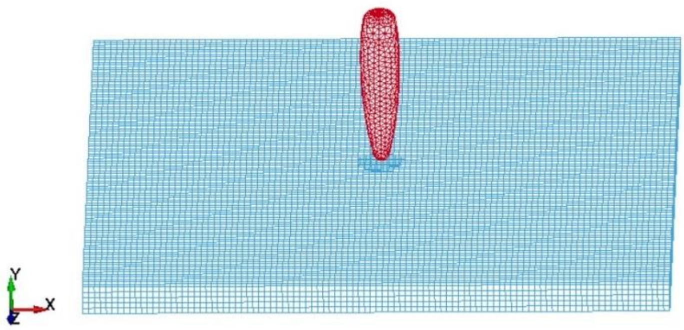


Fig. 3.4 The EFG model at normal impact

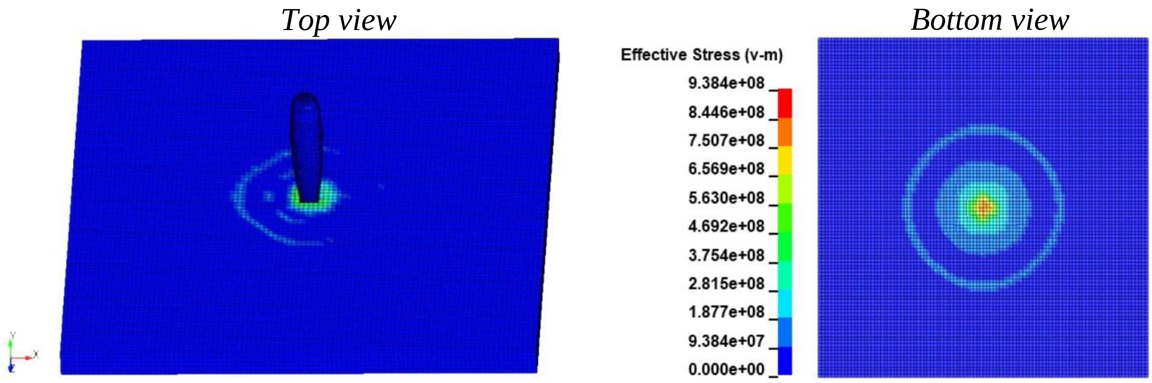


Fig. 3.5 Field of von Mises equivalent stresses at t = 10 μs at normal impact - EFG

From the analysis of the von Mises equivalent stress field or the pressure along the impact direction in figure 3.5, the strong local character of the impact can be found, as well as the symmetry of the stresses.

The SPH model - normal impact

The SPH model was made with 50000 nodes and 50000 solid elements with an internodal distance of 1 mm and is represented in figure 3.6.

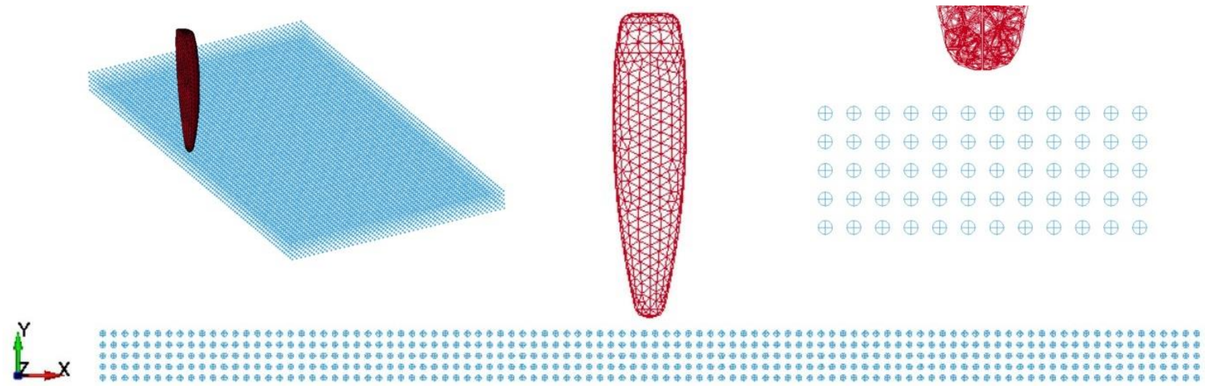
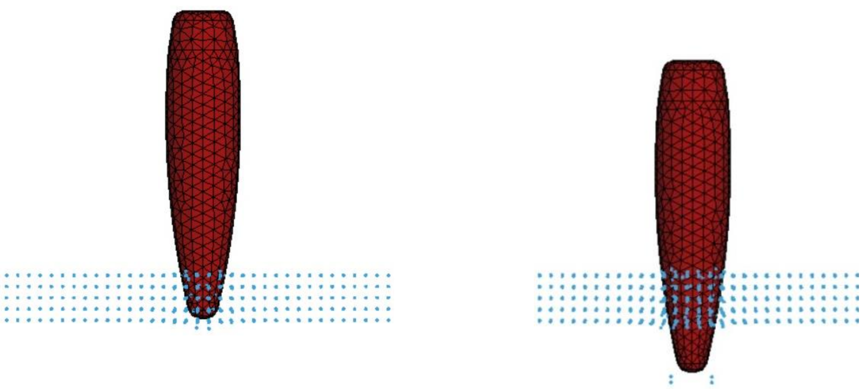


Fig. 3.6 The SPH model at normal impact



t = 10 μs *t = 20 μs*

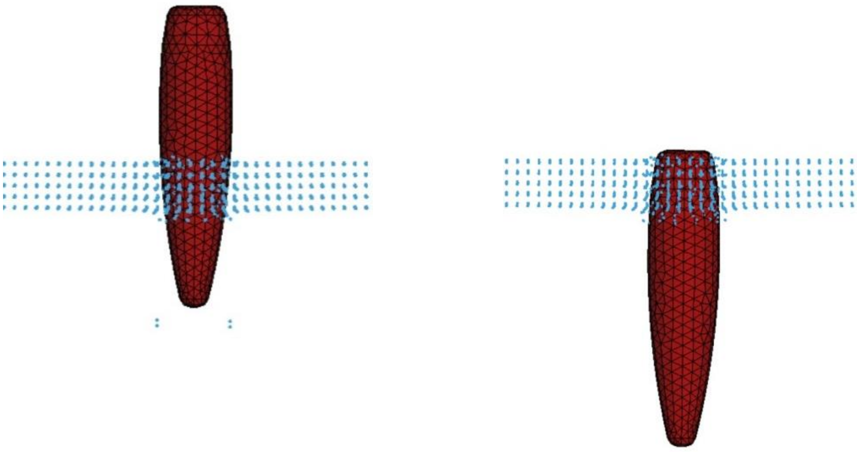


Fig. 3.7 The evolution of the plate perforation process at normal impact - SPH

From the analysis of the images in figure 3.7, the phenomenon of penetration of the aluminum plate can be seen, but also the phenomenon of yielding of the material through fragmentation and the movement of particles both in the direction of the perforation and in the opposite direction.

Observing the von Mises equivalent stress field in figure 3.8, can be observed both the strong local character of the impact and the symmetry of the stresses appearing in the plate.

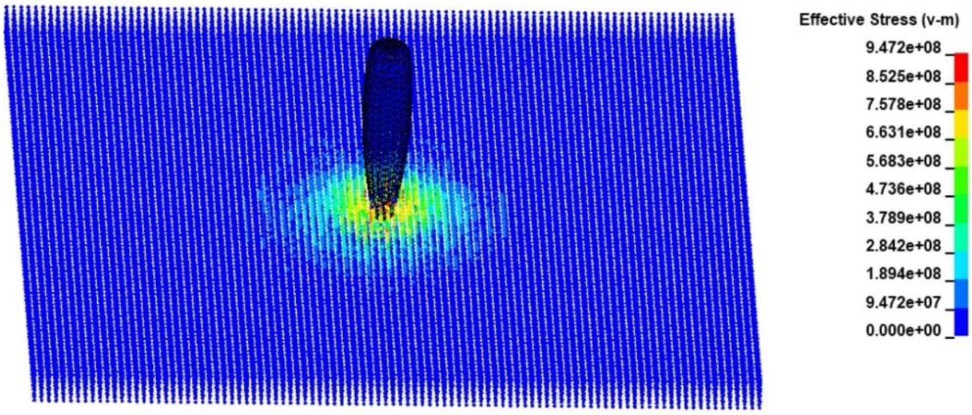


Fig. 3.8 Field of von Mises equivalent stresses at t = 10 μs at normal impact - SPH

The appearance of the stress field is natural, as expected, in that the normal impact represents an axially symmetric stress, and the stress field exhibits this symmetry with respect to the normal. The maximum stress values appear at the point of impact and they propagate as elastic waves throughout the material, respecting the symmetrical aspect of the stress.

3.2.2. Oblique impact of the projectile-homogeneous and isotropic plate

For the projectile-plate oblique impact research, the study continued on the previously presented plate. Thus, the input data were kept and an angle of inclination α=30º was applied to the projectile with respect to the longitudinal axis.

The projectile-plate oblique impact was simulated by MEF, the finite element model (plate) was made with 61,206 nodes and 50,000 solid elements, presenting a uniform mesh, having the size of the sides of 1 mm (figure 3.9).

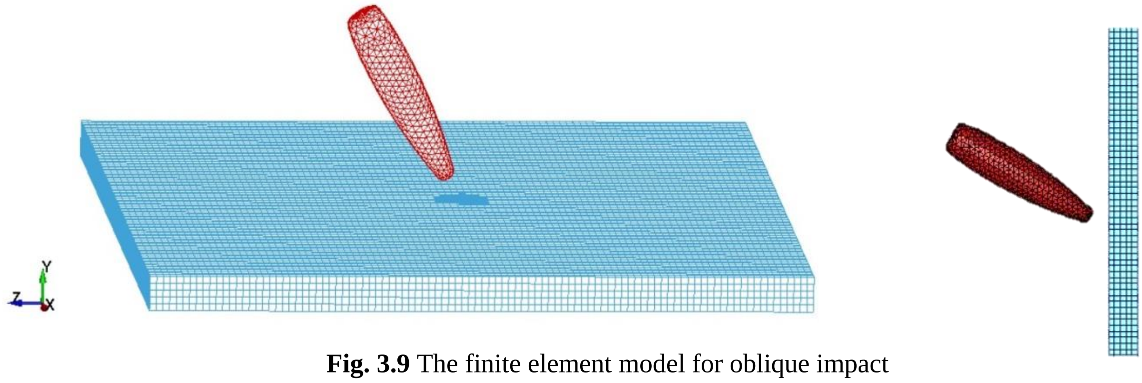


Fig. 3.9 The finite element model for oblique impact

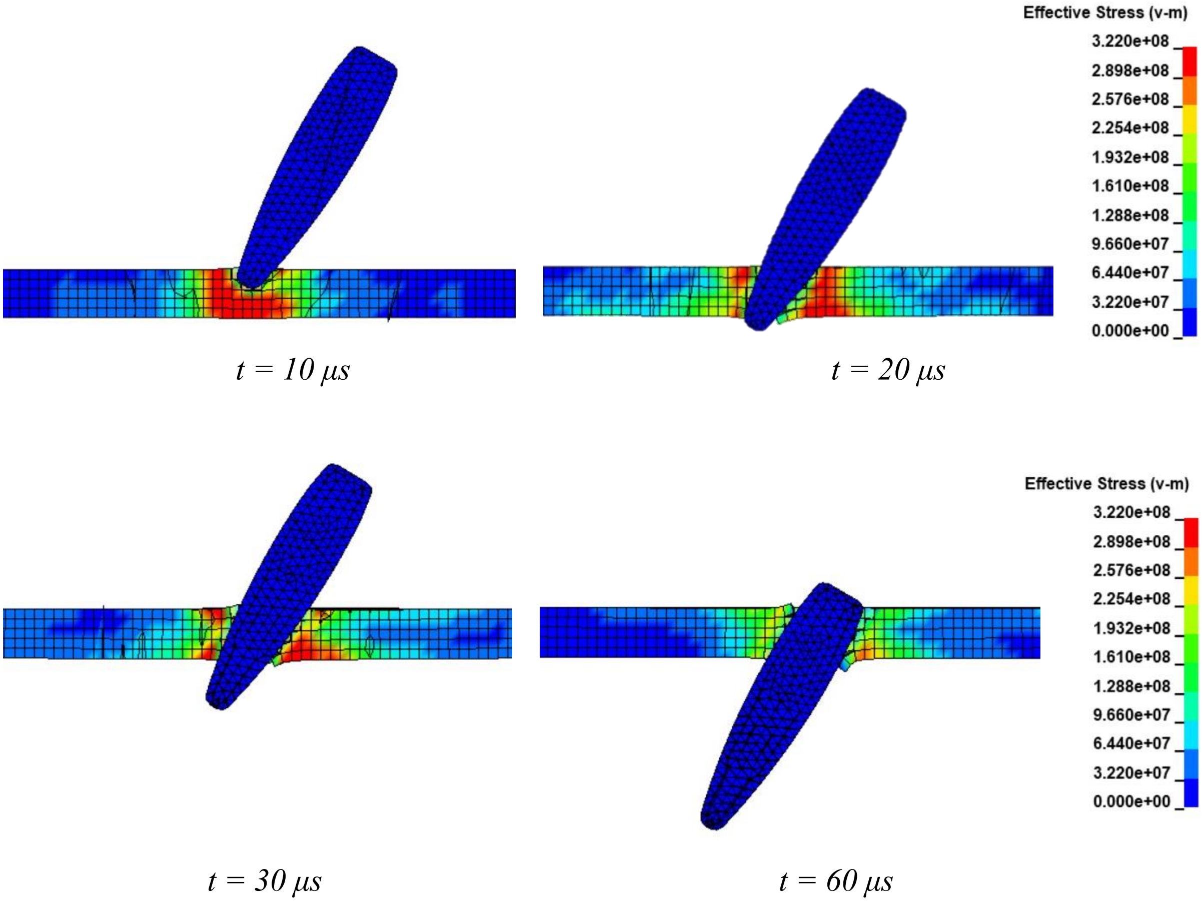


Fig. 3.10 Field of von Mises equivalent stresses at oblique impact - FEM

Figure 3.10 shows, independently as a post-processing, the values and appearance of the von Mises equivalent stress field for the plate modeled with finite elements (seen laterally, through a section halfway through the plate).

Modeling the ricochet phenomenon

In studying the projectile-plate oblique impact, the ricochet phenomenon must also be taken into account. Thus, the study was continued on the previously presented plate, aluminum plate, dimensions 100 mm x 100 mm x 5 mm, subjected to an oblique impact, the speed of the bullet being 500 m/s. If previously the oblique impact was presented, the bullet having an angle of inclination α=30º (figure 3.11), in this subchapter the angle at which the ricochet started was determined, the angle α=50º.

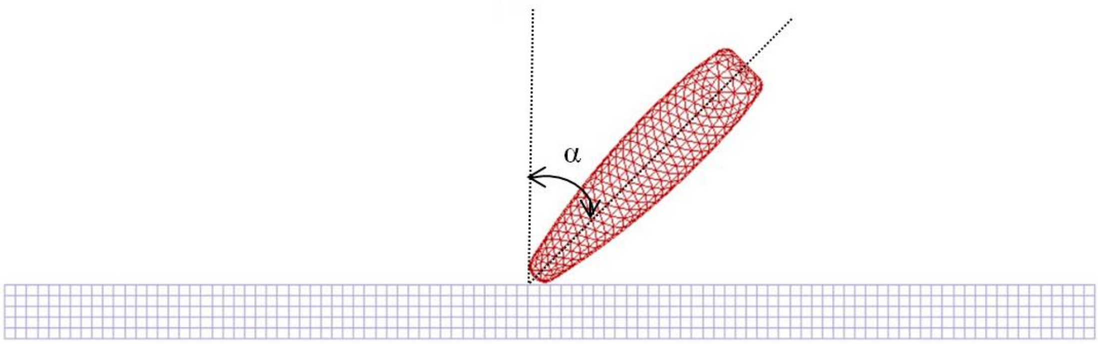
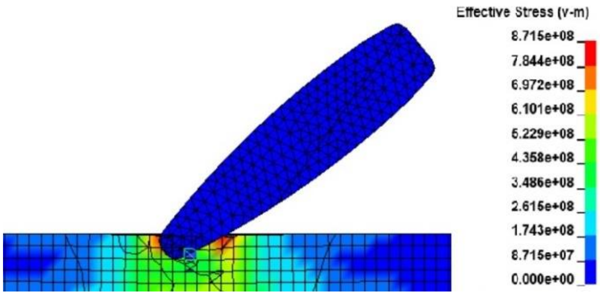
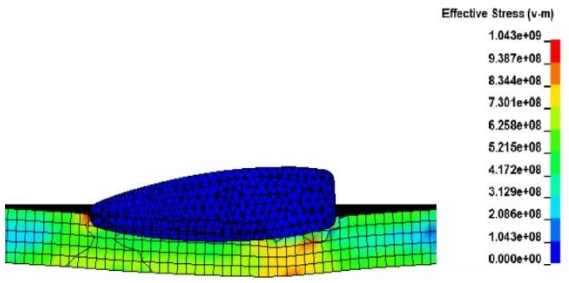


Fig. 3.11 Projectile inclination angle α

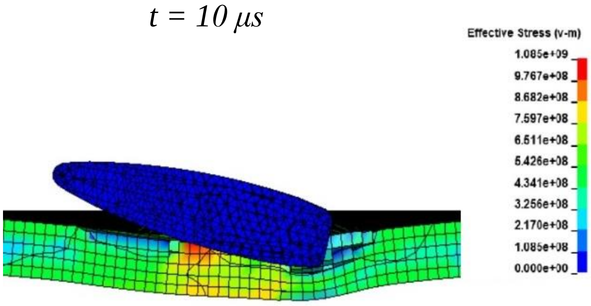
a) Angle α=50º



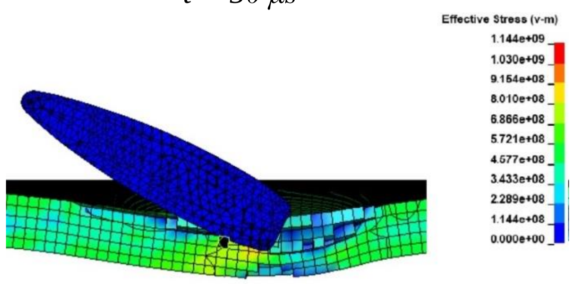
t = 10 µs



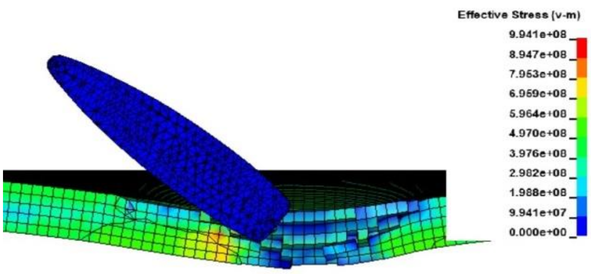
t = 50 µs



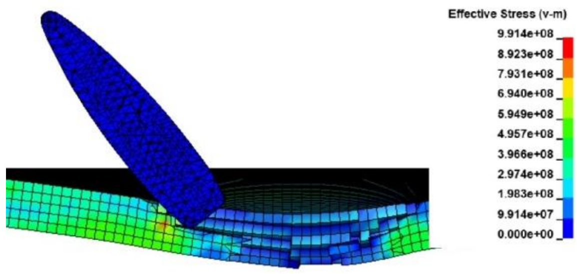
t = 60 µs



t = 70 µs



t = 80 µs



t = 100 µs

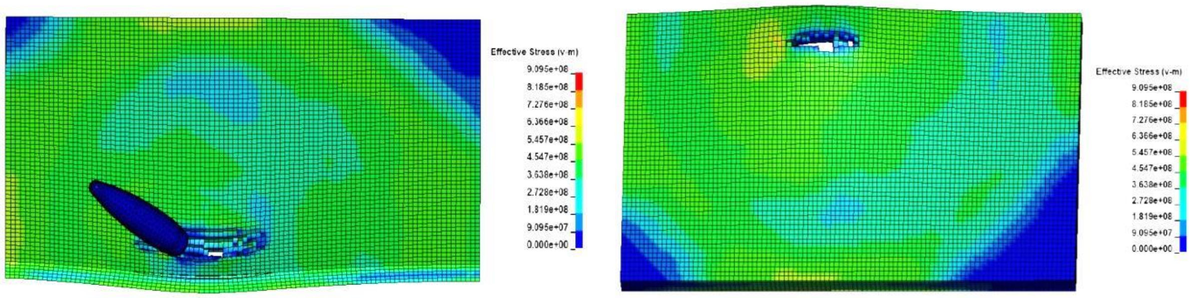
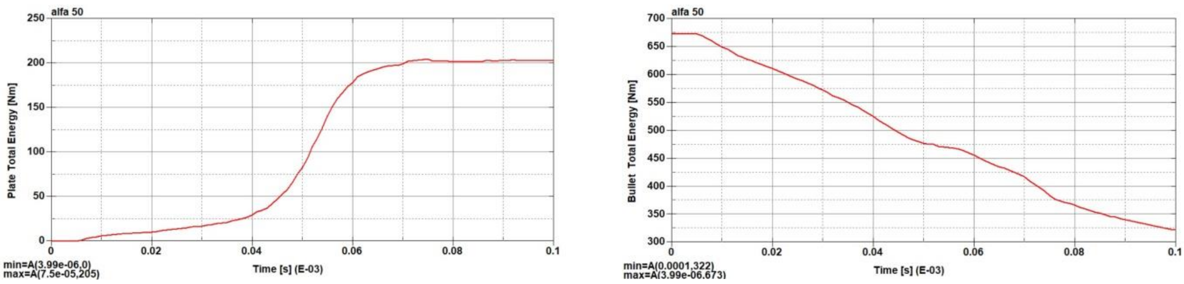


Fig. 3.12 The von Mises equivalent stress field for α=50º



a) b)

Fig. 3.13 Total energy of plate (a) and bullet (b) for α=50º

Figure 3.12 shows the variation of the von Mises equivalent stresses at an angle of inclination of the projectile α=50º. It is observed that, at this angle of inclination, the phenomenon of ricochet occurs, and at the same time the projectile succeeds in perforating the plate.

In figure 3.13, the strong local character of the impact can be observed and it is found that the total energy absorbed by the plate has increased considerably, up to the value of 205 Nm, compared to the value of 32.8 Nm, at an angle of inclination α=45º.

This calculation methodology can be used to find the ricochet angle for any problem, except that due to differences in material and bullet speed, it will be different for each case.

3.2.3. The impact between a projectile and a multilayer composite plate

Next, the numerical analysis is presented in the case of a projectile represented by the bullet 7.62 mm caliber, in interaction with a plate made of composite material, in two constructive versions: multilayer plate with homogeneous and isotropic layers and multilayer plate with a honeycomb core.

For the projectile impact research - multilayer plate, it started with the study of a plate with two homogeneous and isotropic layers, an aluminum layer, with dimensions of 100 mm x 100 mm x 5 mm and a steel layer, with dimensions of 100 mm x 100 mm x 2 mm (figure 3.14). The impact was a normal one with varying speed, increasing from 200 m/s, when the bullet just penetrates the plate, to a speed where the bullet penetrates and perforates the plate.

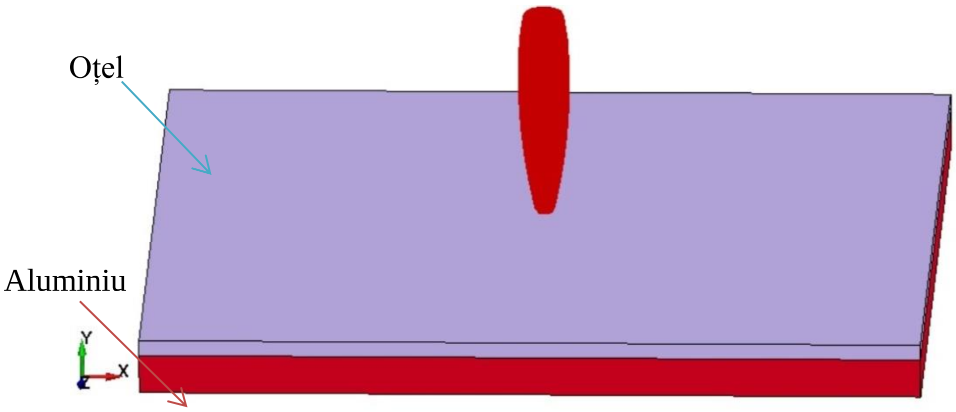


Fig. 3.14 Model 3D impact glonț - placă multistrat

The two constructive versions of the plates were also presented, when they are solidarized (coupled) / non-solidarized (uncoupled). In addition, the kinetic energies of the bullet and the plates were compared, as well as the velocity of the bullet at which it stopped piercing the plate.

Multilayer plate with honeycomb core

Next, the numerical analysis is presented in the case of a projectile represented by the bullet 7.62 mm caliber, in interaction with a composite plate, in two constructive versions: multilayer plate with homogeneous and isotropic layers and multilayer plate with a honeycomb core.

Projectile impact - multilayer plate with honeycomb core, the example to be presented, refers to the normal impact of a rigid bullet, with a velocity of 500 m/s, previously used velocity, with a multilayer plate consisting of two aluminum plates, dimensions 100 mm x 100 mm x 2 mm, united by an aluminum honeycomb core, dimensions 100 mm x 100 mm x 5 mm.

The material models used for the plate were non-linear, inelastic with kinematic plastic, and a rigid material was used for the bullet.

The projectile-plate impact was simulated by FEM, the finite element model is presented in figure 3.15.

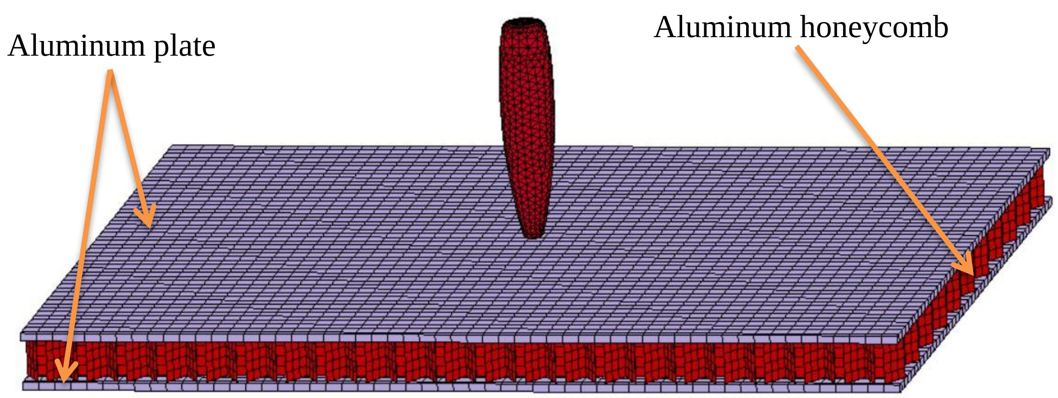


Fig. 3.15 The finite element model of multilayer plate with a honeycomb core

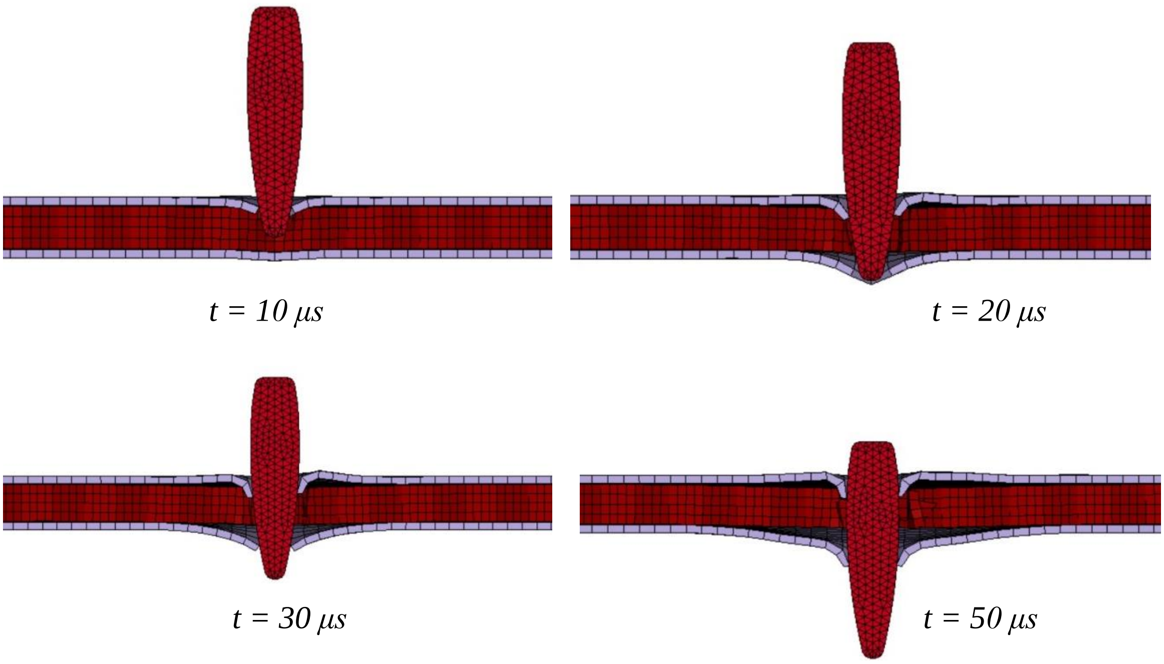


Fig. 3.16 Time evolution of projectile impact - honeycomb core multilayer plate

Figure 3.16 shows the evolution of the impact, with its effects (deformation with perforation of the plate), by presenting the deformed state during the analysis of 50 microseconds.

This method allows to obtain an armor that resists the impact and that can be adapted to any requirements, by changing the materials and by increasing/decreasing the thickness, thus reaching a saving of time and resources.

3.3. Conclusions

Even if applied to classical problems of elasticity or plasticity theory, modern calculations of material strength are inconceivable without the use of numerical methods and material models. This is a direct result of technological and software advancements made in the field of computers.

The most commonly used method for numerical analysis and for modeling the behavior of continuous media is the finite element method. The performance of the finite element method is closely related to the performance of programs and computers. The size of the problem is no longer an insurmountable obstacle because today's software analysis products offer high performance.

In order to describe the phenomena as close as possible to reality, new methods of numerical analysis and simulation have appeared.

A new approximate method is the SPH method, being used for the approximate integration of partial differential equations. This falls under the category of mesh free methods, which use pseudoparticles.

The Element Free Galerkin method is based on a series of equations of the theory of elasticity, used in the special conditions of numerical approximation by the moving least squares method.

In this chapter, the numerical analysis was presented in the case of a projectile represented by the bullet 7.62 mm caliber, in interaction with a plate with different constructive versions (homogeneous and isotropic plate, multilayer plate and multilayer plate with honeycomb core). The numerical research carried out took into account the projectile-plate interaction, both under normal and oblique impact conditions, at different impact velocities.

The numerical research performed was based on the use of the Ansys LS Dyna program, considering several material models within the program library.

The impact study of a projectile with a homogeneous and isotropic aluminum plate, dimensions 100 x 100 x 5 mm, with a bullet speed of 500 m/s, simulated by MEF, the EFG method and the SPH method, was presented. The results obtained by the three methods were close, with relatively small errors, below 5%, this representing a very good agreement of the obtained values, implicitly a proper analysis.

The study was continued by simulating, also through the three methods (MEF, EFG and SPH), the projectile impact - homogeneous and isotropic aluminum plate, with a projectile to which an angle of inclination was applied. And in this case close values were obtained, with errors below 5%. By increasing the angle of inclination of the projectile, it was determined that, after the angle $\alpha=50^o$, in the case of the studied model, the phenomenon of ricochet appears.

This chapter presents a series of concrete cases and numerical analysis models under different conditions. The conclusions are useful, both in terms of modeling, running the calculation, and in interpreting the results. Results obtained in the numerical calculation show the validity and usefulness of mesh free methods, compared to the finite element method.

Through the study and through the simulations presented in this chapter, it should be noted that post-processing and results interpretation models are offered, which can be enriched and customized for other similar or less similar situations.

CHAPTER IV
RESEARCH ON THE IMPROVEMENT OF BALLISTIC PROTECTION OF THE IAR 330 HELICOPTER

4.1. Introduction

Ballistic protection systems are used in the transportation or combat domains to avoid or reduce damage created by enemy fire. They are subject to different dynamic demands depending on the types of threats in the theaters of operations. Thus, the design of ballistic protection systems must be carried out in the context of destruction mechanisms, by types of threats and by levels of protection.

The experimental research to be presented in this chapter aims to validate the numerical model, which can be enriched and customized for other situations, similar or less similar. By default, the way to find a quick answer to certain questions is made available.

The experimental research considered the projectile-plate interaction under normal impact conditions, the projectile being represented by the bullet 7.62 mm x 39 mm caliber, in interaction with the following protective plates:

- steel plate - aluminum alloy - aluminum honeycomb core - aluminum alloy (figure 4.1);

Fig. 4.1 Ol-Al-Al Honeycomb-Ol plate

- steel plate - aluminum alloy - aluminum honeycomb core - aluminum alloy (figure 4.1);

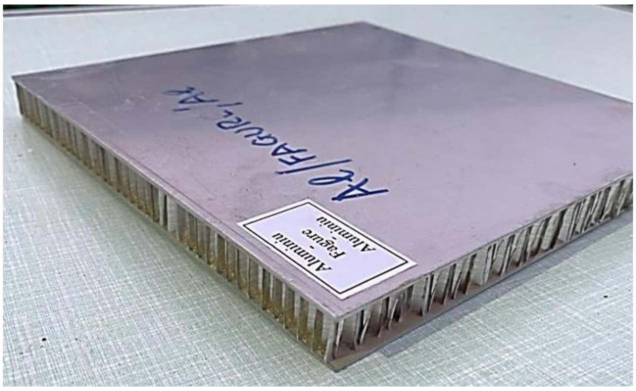


Fig. 4.2 Al-Al Honeycomb-Al plate

- steel plate - aluminum honeycomb core - steel (figure 4.3).

Fig. 4.3 Ol-Al Honeycomb-Ol plate

During the execution of the experimental tests, the plates were inserted into a testing support designed by me and created specifically for this test plan (figure 4.4). The test stand has four removable legs and can be adjusted in height.

To provide additional stability, the soles of the legs have a hole through which a fastener can be inserted into the ground (auger/thorn).

The plate support, arranged at the top, provides embedment on all sides for the inserted plates. Four angles of incidence can also be applied to it: 0º, 15º, 30º și 45º.

Fig. 4.4 Plate support for testing in the polygon

4.2. Experimental impact analysis

The purpose of the experimental research to be presented in this chapter is to follow the evaluation of the ballistic capabilities for certain experimental configurations of materials and to validate the numerical model, implicitly the method and the results of the numerical research, a numerical model that can be enriched and customized for other situations.

In order to validate the numerical model, both the effects and the dynamic parameters of the impact were analyzed (impact velocity, velocity remaining after the impact - residual velocity, hole diameter, hole appearance).

The experimental research activity was carried out in an approved military training ground, which ensured the necessary safety and performance conditions. Devices, installations and equipment from the Ferdinand I Military Technical Academy were used to implement the tests.

Representatives of the ”Ferdinand I” Military Technical Academy and trained staff, with the duties provided for in the operational procedures, have participated in the experimental tests.

Fig. 4.5 Experiment organization

First, the test area (shooting range) was prepared, the test stand was placed, and the shooting distance was set to 10 m, as can be seen in figure 4.5.

The video camera was placed on the left side, at a distance of 15 m from the test site, with the lens centered on the test stand.

The test-evaluation program consisted in researching the projectile-plate impact, by performing two shots with the bullet 7.62 mm x 39 mm caliber and one shot with the bullet 5.56 mm x 45 mm caliber NATO, in the plates consisting of the following covers (layers):

- steel - aluminum - aluminum honeycomb - aluminum (two plates);
- aluminum - aluminum honeycomb - aluminum (two plates);
- steel - aluminum honeycomb - steel (two plates).

The first set of tests was carried out on the plates formed from the steel - aluminum - aluminum honeycomb - aluminum layers. In figures 4.6 and 4.7 you can see the two plates (front view and back view), where was fired the bullet 7.62mm x 39mm cal., the bullet succeeding in perforating them.

Fig. 4.6 Ol-Al-F-Al plates - 2 x 7.62 mm - impacted front view

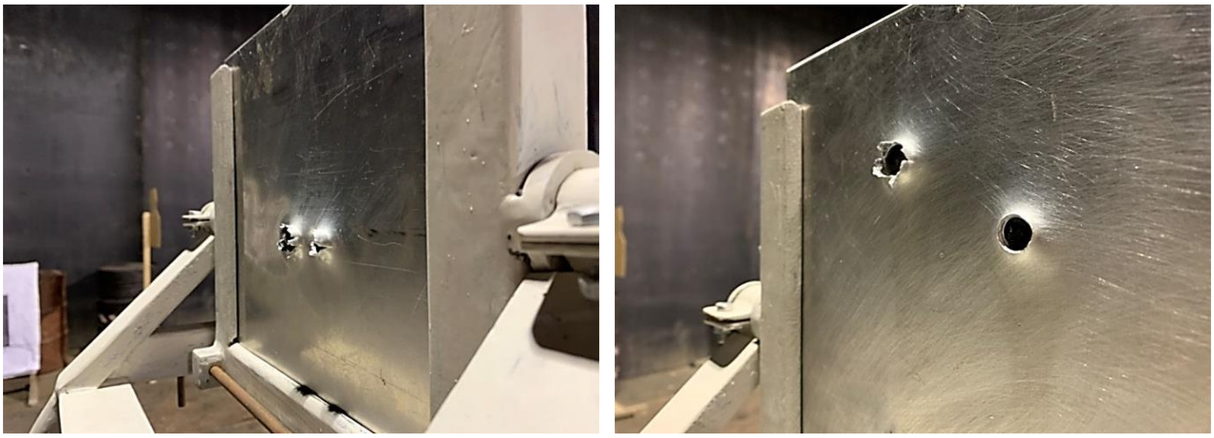


Fig. 4.7 Ol-Al-F-Al plates - 2 x 7.62 mm - rear view

In this experimental testing, the velocity of the bullet before impact, as well as the velocity remaining after perforation, were determined for each set of plates. The hole diameter of the perforated plates was also measured. The results were compared.

As expected, the steel-honeycomb aluminum-steel plates provide the greatest protection in the event of a projectile impact. A very good yield, similar to the first one, is presented by the plate formed from the steel - aluminum - aluminum honeycomb - aluminum layers.

4.3. Numerical impact analysis

Projectile - plate impact is a complex phenomenon, which is analyzed by analytical methods, based on simplifying assumptions. In addition to the use of empirical laws, these aspects of the projectile-plate interaction and the effects on the structure are studied using numerical methods.

The purpose of this subchapter is to study the interaction process of a projectile with certain plates, in different configurations.

The finite element method was used for the numerical analysis and simulations. Starting from the configurations of the experimental tests carried out in the range, numerical simulations were carried out that faithfully follow the experimental research.

The definition of the basic conditions, necessary for the dynamic analysis with finite elements, was carried out following the impact protocol used in the experimental part of this work.

The numerical research carried out is based on the use of the Ansys LS Dyna program, considering several material models within the program's material library. All the material models used describe both the impact stress and the phenomenon of breaking the material, at the projectile-plate interaction. Material models that have received special attention are Johnson Cook and kinematic plastic. Following the numerical analyses, it was found that the kinematic plastic material model agrees better with reality.

The geometric model faithfully follows the model made for experimental testing. Thus, the geometric model was designed for each individual plate, at the actual dimensions of 250 mm x 250 mm.

The impact was a normal one, with different bullet velocity for each individual case, and the duration of the numerical analysis was 10^{-5} seconds.

In order to faithfully follow the experiment, each case was analyzed separately. The speed of the bullet was different with each shot, with small differences. The velocities were measured in subsection 4.2 and entered as initial data in the numerical simulations presented below.

The normal projectile impact - plate made of layers of steel - aluminum - honeycomb aluminum - aluminum was simulated by MEF (figure 4.8), using as initial data the values presented above, and the initial velocity of the bullet was 737 m/s, velocity previously measured.

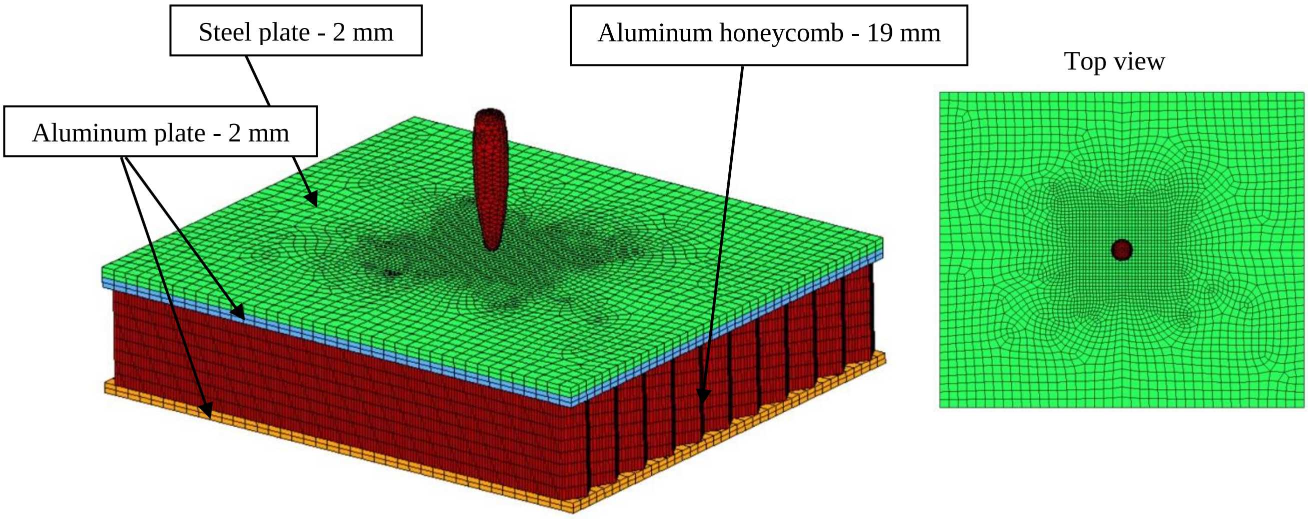


Fig. 4.8 The Ol-Al-F-Al plate finite element model

Figure 4.9 shows the evolution of the impact, with its effects (deformation with perforation of the plate), by presenting the deformed state during the analysis of 90 microseconds. The picture explains the mechanism of the destruction of the protective plate, in which the appearance of a local phenomenon, damage in certain directions and a shearing of the material is observed. Also, a removal of the plates occurs due to the fact that they are not solidarized.

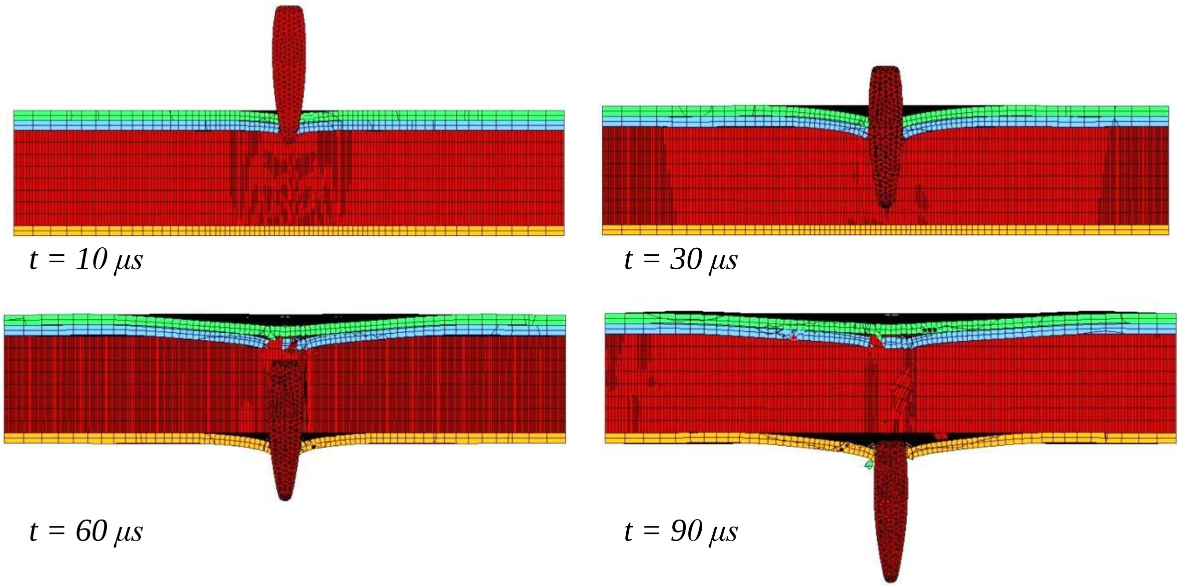


Fig. 4.9 Time evolution of the impact - Ol-Al-F-Al plate

The following aspects were determined and presented for each protection plate:

- the evolution of the impact, with its effects (deformation with perforation of the plate);
- the values and appearance of the von Mises equivalent stress field for the plate (viewed laterally, through a section halfway through the plate and viewed in the direction of impact, bottom and top view);
- the variation in time of the kinetic energy of the bullet and the variation in time of the total energy of the plate;
- the variation in time of the velocity of the bullet.

4.4. Numerical model validation

In order to highlight the experimental and numerical results, their comparative analysis was carried out, for each individual plate. Thus, the following results obtained by the two study methods were compared:

- the initial velocity of the bullet;
- the residual velocity of the bullet;
- the mass of the plates tested experimentally and those analyzed numerically;
- diameter and appearance of the hole after drilling.The first observations following the experimental and numerical tests refer to the protective plate formed by the steel - aluminum - aluminum honeycomb - aluminum layers.

Residual bullet velocities, diameter of the hole after impact, and plate mass have close values with a maximum error of 3.54%. This signifies a good design of the geometric model and at the same time a validation of the numerical model for that plate.

The appearance of the holes after impact was examined, shown in Figures 4.10 and 4.11. The similarity between the two models is noticeable. Ductile material failure, combined with petaling failure, also occurs.

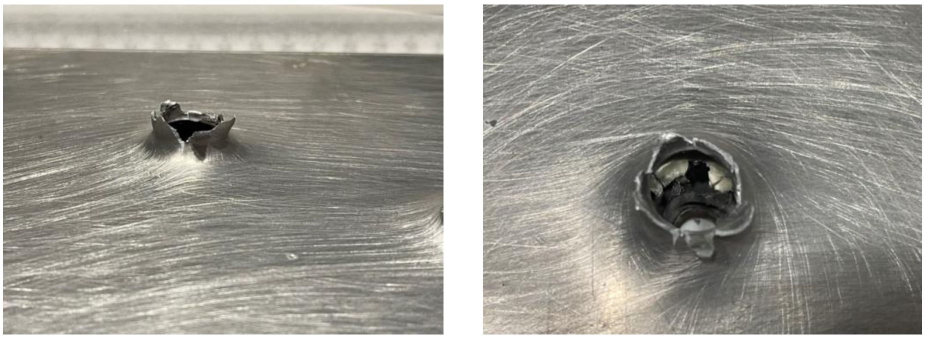


Fig. 4.10 Appearance of the hole after impact Ol-Al-F-Al plate - experimental testing

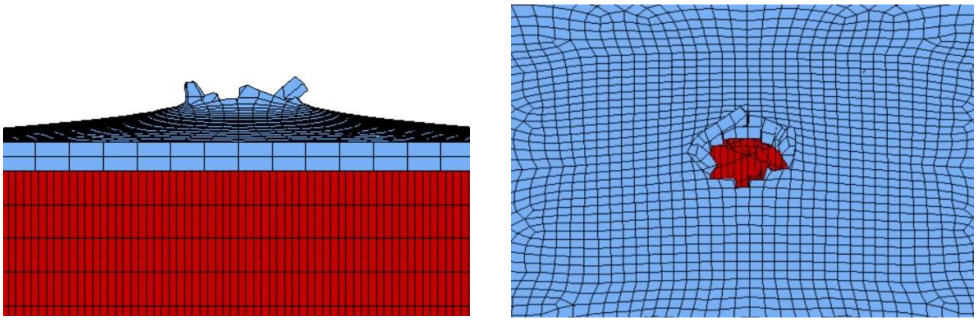


Fig. 4.11 Appearance of the hole after impact Ol-Al-F-Al plate – numerical simulation

4.5. Conclusions

After carrying out the comparative analyzes between the experimental and numerical results, it was found that the plate formed from the layers of steel - aluminum honeycomb - steel presents the best protection factor, compared to the other two types of plates but, at the same time, presents a higher mass by about 13% compared to the steel - aluminum honeycomb - aluminium plate.

Although each protective plate has been perforated, both in the case of experimental testing and in the case of numerical simulation, it cannot be said that they do not provide protection. It can be noted that each of these provides some protection, only that this factor is influenced by the distance from which it is fired.

Of course, the degree of protection of the presented plates can be improved by different processes, depending on the desired objective, in relation to the added mass and production costs. Thus, among the improvement proposals are gradually increasing the thickness of the steel shell, increasing the thickness of the honeycomb, filling the spaces of the honeycomb structure with plastic or composite materials, as well as changing the protective plates with other systems made of new composite materials, specially created in this purpose (titanium, ceramics, Dyneema, Tensylon, carbon nanotubes).

The comparative analysis of the two data sets shows a very good correlation between the experimental and numerically determined values for the analyzed parameters. It can be stated that the numerical model has been validated, because the differences between the experimentally and numerically obtained data are small, with errors below 5%.

CHAPTER V
ANALYSIS OF SOME NEW CONFIGURATIONS OF BALLISTIC PROTECTION PLATES

The field of ballistic protection is in continuous development, through the optimization of protective materials and structures and through the discovery of new materials, in order to achieve a balance between the variety of threats in theaters of operations and the protection against them. The aim is to increase the degree of protection and, at the same time, to reduce the mass of the protection system.

These systems have seen considerable progress over the years, especially in military applications. However, the high costs as well as the changing landscape of materials found the need for a deeper understanding of the impact mechanism as well as new permutations in the development of the design strategy [55].

Titanium Ti6Al4V

Titanium alloy Ti6Al4V, also known as Ti64, Grade 5 or TC4 is an alloy that exhibits high specific strength, low density, high fracture toughness, excellent corrosion resistance and superior biocompatibility [56].

Recognized as the most popular titanium alloy, Ti6Al4V occupies almost half of the market share of titanium products used in the world today. It is considered to be one of the most popular titanium alloys, being used in various applications where it is necessary for the material to have a low density and, at the same time, an increased resistance to corrosion. Thus, it is used in fields such as: the aerospace industry, biomechanical applications (implants and prostheses), the naval industry, the chemical industry.

In the following, new constructive variants of ballistic protection are proposed, variants that will be analyzed numerically for the impact with the bullet 7.62 mm x 39 mm caliber, the results are then compared and analyzed.

5.1. Ti-F-Ti protective plate

As mentioned in the previous chapter, numerical analysis helps you save time and financial resources when it comes to developing a ballistic protection system and more.

In order to improve the protection factor offered by the previously presented protection plates, the steel plates were replaced with Ti6Al4V alloy plates. Thus, the model with finite elements presented in figure 5.1 was obtained. The plate projectile impact was simulated by the finite element method, the duration of the numerical analysis was 10^{-5} seconds, and the initial velocity of the bullet was 741 m/s and gradually decreased to determine the residual velocity. In order to closely follow the model presented in chapter four, the same conditions regarding the types of contacts between elements were used, as well as the same boundary conditions. The Ti6Al4V alloy plates are 2 mm thick and the honeycomb 19 mm.

The material model used for the plate was, again in this case, plastic-kinematic, and for the bullet a rigid material was considered.

Using thin plates, high impact speed, short execution time and unreliable thermal effect, this material model is the most suitable in our case. According to the specialized literature [60, 61], the finite element analysis of the Ti6Al4V alloy, in which the plastic-kinematic material model is used, at ballistic impact, shows very good results, which agree with the experimental results.

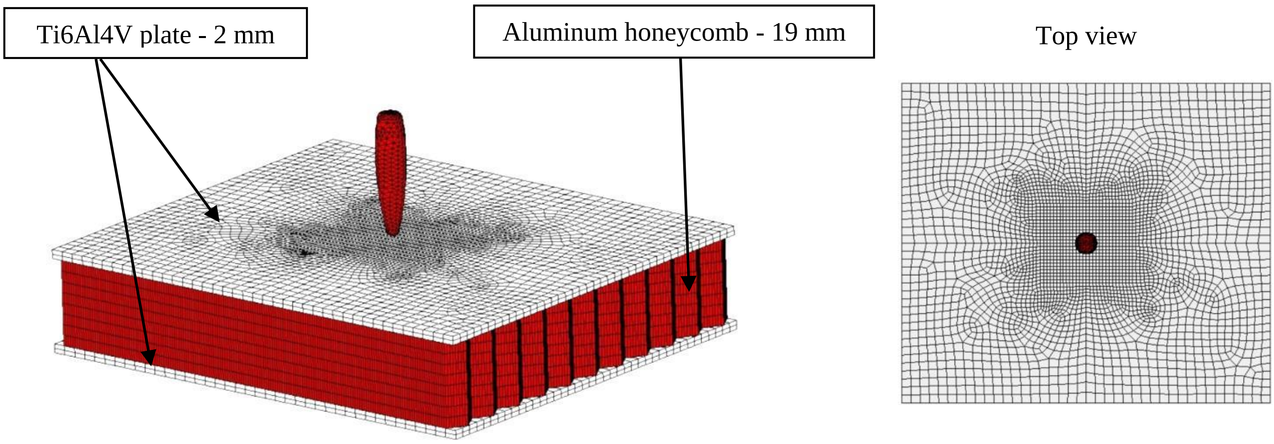


Fig. 5.1 The Ti-F-Ti plate finite element model

It was observed that, in this case, the velocity of the bullet decreased from the initial value of 741 m/s to a minimum value of 254 m/s, which represents the residual velocity.

To determine the velocity of the bullet at which it no longer perforates the plate, the initial velocity was gradually decreased, this representing firing from a greater distance.

Using the methodology for determining the firing distance presented in chapter four, the initial velocity was reduced. Thus, it was found that the protective plate formed by the layers of titanium - aluminum honeycomb - titanium will no longer be perforated by the bullet when it will have an initial velocity lower than 665 m/s, this velocity corresponding to shooting from a distance of about 41 m.

5.2. Ti-Ti-F-Ti protective plate

In an attempt to increase this protection factor, a 2 mm thick titanium alloy plate was also added to the top. Thus, the new protective plate configuration consists of the following layers: titanium - titanium - aluminum honeycomb - titanium, the geometric model being shown in figure 5.2. In this configuration, the plate is not perforated by the bullet.

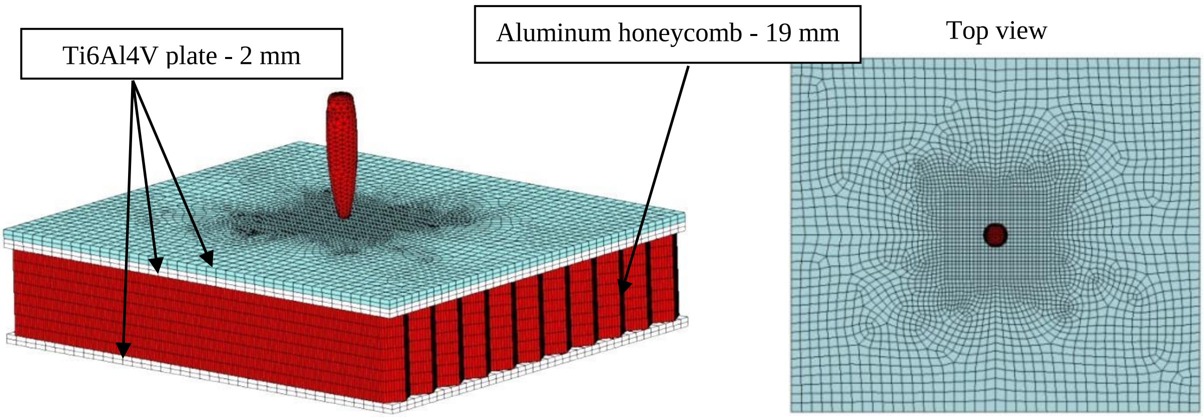


Fig. 5.2 The Ti-Ti-F-Ti plate finite element model

5.3. Ti-Ti protective plate

We noticed that the two-layer titanium alloy protection plate on the top provides the best protection, and the titanium layer on the bottom does not get penetrated, then, the aluminum honeycomb and the aluminum plate have been removed. Below, the geometric model being made up of only two titanium alloy plates, each 2 mm thick, respecting the same conditions. Thus, the model with finite elements in figure 5.3 was obtained.

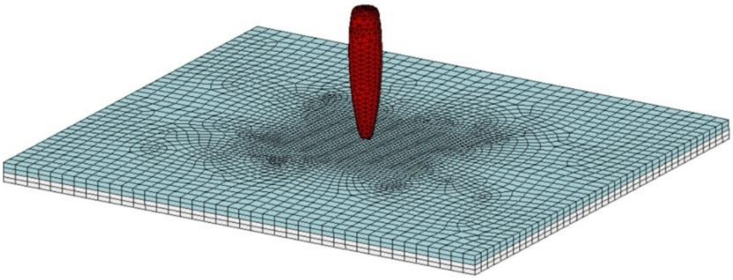


Fig. 5.3 Ti-Ti plate finite element model

In this case, it was observed that the protective plate consisting of two layers of Ti6Al4V alloy is perforated by the bullet, and the residual velocity is 312 m/s. The initial velocity was gradually reduced and it was noted that the Ti6Al4V bilayer shield would no longer be pierced by the bullet when the initial velocity was less than 660 m/s, which corresponds to the firing from a distance of about 40 m.

5.4. Ti 4 mm protective plate

Observing that the two-layer titanium alloy protection plate shown above provides a high degree of protection, a 4 mm thick Ti6Al4V alloy plate was considered to see which configuration provides the best protection: two 2 mm thick plates or one 4 mm thick plate. Therefore, the finite element model of figure 5.3 was obtained.

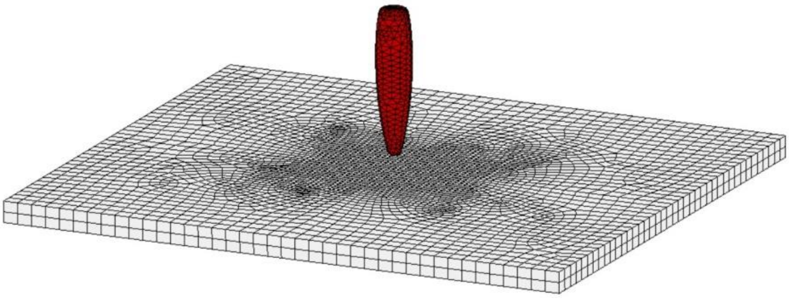


Fig. 5.3 The finite element model Ti 4 mm plate

From the impact analysis, it is observed that the Ti6Al4V alloy protective plate, 4 mm thick, is perforated by the bullet, and the residual velocity is 134 m/s. And in this case, the initial velocity was gradually reduced, and it should be noted that this plate will no longer be perforated by the bullet when it will have an initial velocity of less than 690 m/s, this velocity corresponding to firing from a distance of about 34 m.

5.5. Conclusions

In an attempt to develop a ballistic protection system capable of withstanding impact with a bullet 7.62 mm caliber, new constructive variants were proposed, which were analyzed numerically, the results being very good. Thus, the following plates were analyzed numerically, starting from the configurations presented later:

- protective plate with layers of titanium (2 mm) - aluminum honeycomb (19 mm) - titanium (2 mm);
- protective plate with layers of titanium (2 mm) - titanium (2 mm) - aluminum honeycomb (19mm) - titanium (2 mm);
- protective plate with layers of titanium (2 mm) - titanium (2 mm);
- 4 mm thick titanium protective plate.

The most widespread titanium alloy, Ti6Al4V, also known as Ti64, TC4 or ASTM Grade5, was used in the numerical analysis, being an alloy with: high specific strength, low density, high fracture toughness, excellent corrosion resistance and biocompatibility superior.

The four ballistic protection configurations were analyzed numerically and the following were found:

- the Ti-Ti-F-Ti plate offers the greatest protection but, at the same time, also presents the greatest mass, compared to the other three configurations;
- the aluminum honeycomb has an important role in the case of multilayer boards, and this has been proven;
- the plate made of two layers of titanium, 2 mm thick, shows a weaker behavior compared to the plate made of a single layer of Ti6Al4V alloy, 4 mm thick. In addition, it has the disadvantage of positioning the two layers in a support, involving additional costs.

The configurations presented in this chapter show very good impact behavior with the cal projectile. 7.62 mm x 39 mm, these are viable solutions for mounting on the IAR 330 Puma Socat helicopter.

CHAPTER VI
GENERAL CONCLUSIONS, PERSONAL CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS

6.1. General conclusions

Military helicopters play an important and integrated role in air, land and maritime operations and perform a number of critical missions. The spectrum of threats is represented by the air or ground strike components, more precisely, by the adversary's ability to detect, identify and engage helicopters.

Like any other aircraft, helicopters have critical areas, which can endanger the machine and the crew if they are hit by anti-aircraft defense systems or even individual infantry weapons. The main critical areas of the helicopter classify into two categories: the compartment of the power plant and mechanical assemblies and the cockpit and the cargo compartment.

Armor can be defined as a set of plates that have the role of protection against projectiles or shrapnel, and its classification is done according to different criteria. Thus, the following shields can be found, passive and reactive, depending on the impact behavior. Depending on the constructive solution, there are homogeneous and layered shields, and in relation to the place of installation, the shields can be: basic and removable.

Two very important aspects regarding the progress in the numerical calculation of structures can be noted: the appearance of new material models and the improvement of the description of the contact between materials.

In an attempt to develop a ballistic protection system able to provide a high degree of protection at minimum costs, in the fourth chapter, various multilayer protection plates were designed and manufactured, which were subsequently experimentally tested.

The experimental organization allowed the achievement of the proposed goal, that of following the evaluation of the ballistic capabilities for the proposed plates. Following the experimental testing of the projectile-plate impact, it is possible to identify the right material to provide high protection, the sizing and, last but not least, the validation of the numerical model, which will serve in future studies, without consuming resources for carrying out experimental tests.

It was found that the plate formed from the layers of steel - aluminum honeycomb - steel presents the best protection factor, compared to the other three types of plates but, at the same time, it has a higher mass by about 13% compared to the plate with layers steel - aluminum - aluminum honeycomb - aluminum.

Although each protective plate has been perforated, both in the case of experimental testing and in the case of numerical simulation, it cannot be said that they do not provide protection. It can be noted that each of these provides some protection, only that this factor is influenced by the distance from which the shooting takes place.

The experimental tests were performed under more rigorous conditions than in real cases of attack on the helicopter, since the chances of shooting a helicopter at a distance of 10 m, in a perpendicular direction, are very small. In addition, for there to be firing in a perpendicular direction, it would be necessary for the gunner to be positioned directly below the helicopter. This is a very difficult condition to fulfill, even ideal, and for the other cases, there is the possibility of the ricochet phenomenon, studied and presented previously.

The comparative analysis of the two data sets shows a very good correlation between the experimental values and the numerically determined ones, for the analyzed parameters. We can state that the numerical model has been validated, because the differences between the data obtained experimentally and those obtained numerically are small, with errors below 5%.

The correspondence of the results confirmed the validity of the test procedure, the material laws used and the model used and validated the numerical activity used in the development of appropriate numerical models, the obtained results representing the scientific basis for research directions that can be addressed later.

In the fifth chapter, different configurations of protective plates were proposed, starting from the configurations presented in the fourth chapter, having as the main material the Ti6Al4V titanium alloy, an alloy with high specific strength, low density, high fracture toughness and excellent corrosion resistance. These configurations were analyzed numerically and the results were very good.

After carrying out the numerical analyses, it was found that the best protection factor is presented by the plate made of layers of titanium - titanium - aluminum honeycomb - titanium, in which the bullet does not manage to perforate, but, at the same time, it also presents a higher mass compared to the other three configurations. Also, the 4 mm thick titanium alloy plate behaves very well, with a residual bullet velocity of 134 m/s, corresponding to firing from a distance of about 34 m. In addition, it has a low mass, compared to the other boards.

The theoretical and experimental studies carried out made it possible to identify the characteristic elements of the studied materials in terms of their impact behavior, to create a model that could be used to analyze the behavior of multilayer armors and to develop ways to capitalize on the results and further expand the research .

It can be concluded that this work has fulfilled its objectives, indicating that studying the impact behavior of materials requires a complex multi-criteria approach.

6.2. Personal contributions

Through the studies carried out and presented in this work, through the topic addressed, through the work methodology and through the results obtained, it can be noted that several original contributions have been made in this field.

Scientific reasoning, numerical simulations, theoretical and experimental studies carried out in the framework of the doctoral thesis led to the formulation of contributions to the improvement of ballistic protection systems for helicopters, among which the following are emphasized:

- the systematization of a bibliographic study regarding the structure of the IAR 330 Puma Socat helicopter and the main materials used in its construction;
- the analysis, systematization and presentation in an accessible form of ballistic threats to helicopters, the characteristics of the ammunition used against them, as well as the requirements and current ballistic protection solutions;

- the systematization and presentation in an accessible form of new methods of analysis and numerical simulation, known as meshfree methods, methods based on particles or methods with a free network;
- the presentation of concrete cases and numerical analysis models under different conditions, the conclusions being useful, both in terms of modeling, carrying out the calculation, and interpreting the results obtained in the numerical calculation, showing the validity and usefulness of the SPH and EFG methods, compared with the finite element method.
- performing the numerical analysis of the normal projectile impact - homogeneous and isotropic aluminum plate, dimensions 100 mm x 100 mm x 5 mm, with a bullet velocity of 500 m/s, simulated by MEF, by the EFG method and by the SPH method and comparing the results, obtaining close values, with errors below 5%;
- continuing the impact study by tilting the projectile, determining the conditions and studying the ricochet phenomenon;
- carrying out the experimental analysis, in the range, of some protective plates, made in different configurations, at the impact with the bullet 7.62 mm x 39 mm caliber, which allowed the determination of both the effects and the dynamic parameters of the impact (initial and residual velocity of the bullet, diameter and appearance of the hole);
- carrying out the numerical analysis of the impact through the finite element method, using the Ansys LS-Dyna software and comparing the numerical results with the experimental ones;
- confirmation of the validity of the test procedure, the material laws and the model used and the validation of the numerical model;
- proposing new configurations of ballistic protection plates, consisting of titanium alloy and carrying out the numerical analysis, the results being very good, they have a very good protection/mass/cost ratio.

6.3. Future research directions

Starting from the basic concept of this paper, which aimed to design, to test a ballistic protection system and to validate the numerical model, in order to develop an armor for military helicopters, capable of resisting the impact with the bullet 7.62 mm cal., the theme of the paper can easily be directed to the analysis of other constructive solutions, which include materials of the latest generation, such as Dyneema or Tensylon.

In addition to these classic ballistic protection systems, which present a very good protection/cost ratio, more advanced protection systems made of very hard polyethylene, called UHMWPE fibers (Ultra High Molecular Weight Polyethylene) have appeared.

At the same time, by using the finite element method, which has proven its effectiveness in impact analysis, new types of ballistic protection can be studied, designed and analyzed, leading to time and material savings.

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