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RESEARCH OF THE RICOCHET PHENOMENON APPEARING AT THE IMPACT BETWEEN A KINETIC PROJECTILE AND A PLATE

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Ballistic protection systems are used in areas of transport or combat to avoid or reduce damage caused 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 done in the context of destruction mechanisms, by types of threats and levels of protection.

In order to study and design a ballistic protection system, it is necessary to first perform the numerical analysis, in order to save time and materials. Also, all the factors that influence the degree of protection must be taken into account: the material of the plate, the thickness of the plate, the shooting distance, the projectile caliber, the velocity of the bullet, as well as the degree of incidence of the bullet. The curent paper presents the numerical analysis of an aluminum homogeneous and isotropic plate in interaction with a projectile represented by the 7.62 mm caliber perforating bullet. Starting from the normal impact, the ricochet angle was determined. Studying the ricochet angle of a bullet can help researchers to understand how different types of materials and designs perform under different conditions.

Keywords: projectile-plate impact, normal impact, ricochet phenomenon

1. Introduction

Projectile-plate impact research should answer a number of questions from the designer or fighter, the most important of which should be if the bullet penetrates or perforates, if the speed after the perforation ensures a lethal effect on the personnel, under what conditions the ricochet is produced and what is the absorption capacity of the protection plates etc. [1].

Of course, the most accurate answer to the questions about the impact of the projectile-plate is given by experimental research, but it must be noted that numerical analysis can pave the way for experimental investigation, leading to time and material savings. If we add to this the wealth of information provided by modern methods of numerical analysis, we can appreciate that numerical research on the impact of projectile-plate is extremely useful and necessary [2].

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Significant research has been conducted on the behavior of different impact materials. Hou et al. [3] investigated the impact ballistic performance of aluminum foam sandwich metal structures and presented the effects of several key parameters, such as impact velocity, layer thickness, foam core density, and energy absorption of panels during impact. Cheng et al. [4] developed a model for the high-velocity impact on thick-layer composites to study the target's response to impact.

A numerical study by Zukas and Scheffler [5] shows that 31.8 mm thick monolithic steel targets have a higher strength than targets with several layers of equal thickness when those are hited by 65 mm projectile, with an initial velocity of 1164 m/s. Almohandes et al. [6] showed that monolithic steel plates are more efficient than multilayer plates of the same total thickness when hit by a 7.62 mm projectile with an initial velocity of 826 m/s. An investigation by Dey et al. [7] into the ballistic strength of Weldox 700E steel shows that the 12 mm monolithic plate has better ballistic performance against projectiles compared to two-layer plates of the same thickness. Borvik et al. [8] studied the same plate configurations, using Weldox 700E steel, against 7.62 mm projectiles. They discovered that the ballistic limit of monolithic and two-layer plates were identical. However, the 12 mm monolithic plate performed slightly better for impact velocity of over 850 m/s. A recent investigation by Teng et al. [9, 10] into the ballistic performance of monolithic and two-layer steel plates showed that ballistic strength depends on several factors, including projectile shape, projectile mass, impact velocity, plate configuration and material properties.

The above references show that the process of projectile impact is a complex issue, which has not been fully understood. For design purposes, several of the factors mentioned above need to be considered in order to obtain optimal protection structures.

The current paper presents the numerical analysis of a homogeneous and isotropic plate in interaction with a projectile represented by the 7.62 mm caliber perforating bullet. Numerical research has taken into account the projectile-plate interaction, both in terms of normal and oblique impact, at different bullet velocity. This numerical analysis has not been validated, but it is important to note that numerical analysis can be a faster and more cost-effective way to study the behavior of a system compared to experimental methods and can provide accurate and detailed predictions of the behavior of a system based on a wide range of input conditions, helping to identify potential issues or to optimize performance.

2. Materials and methods

The purpose of this paper is to evaluate the performance of an aluminum homogeneous and isotropic plate, on normal and oblique impact with a 7.62 mm projectile and to determine the angle from which the ricochet phenomenon appears, at a certain velocity of impact.

This numerical research is based on the use of the Ansys LS Dyna program, taking into account several material models in the program's material library. All the material models used describe both the impact stress and the phenomenon of the material breaking at the projectile-plate interaction. The most used model of material and to which we have given a special attention is the plastic kinematic model. According to the specialized literature [11, 12], this model of material gives very good results which agree with the experimental results.

The plastic kinematic hardening (P-K) material model is useful for simulating the dynamic behavior and accurately predicting the strain rates of materials under moderate velocity impact. It is particularly effective at modeling material properties using a combination of kinematic and isotropic hardening and the maximum strain failure criterion. Using plastic kinematic model material in Ansys/LS-DYNA can improve the accuracy and efficiency of simulations involving plastic deformation and failure of materials

For the beginning, a normal impact was considered, with an impact velocity of 500 m/s and the analyses time of $9\cdot10^{-5}$ s. For the theoretical study, the aluminum plate had the following mechanical characteristics:

- Dimension: 100 mm x 100 mm x 5 mm;
- Material model: plastic-kinematic;
- Density: ρ = 2700 kg/m^3;
- Young's modulus: E = 0.690e11 Pa;
- Poisson's ratio: ν = 0.33;
- Yield stress: σ_c = 315e6 Pa.

The projectile-plate impact was simulated using the finite element method in Ansys/LS-Dyna, a software package that is commonly used to simulate dynamic events such as impacts and explosions. The plate, presented in figure 1, was made with 61,206 nodes and 50,000 elements, having a uniform and symmetrical mesh, with finite element size of 0.001 m.

Increasing the number of elements in a finite element model can improve the accuracy of the results, as it allows for a more detailed representation of the geometry and behavior of the system. However, there is a trade-off between accuracy and computational efficiency. As the number of elements increases, the computation time and memory requirements of the model also increase. Also, the nodes belonging to the four sides have all degrees of freedom blocked.

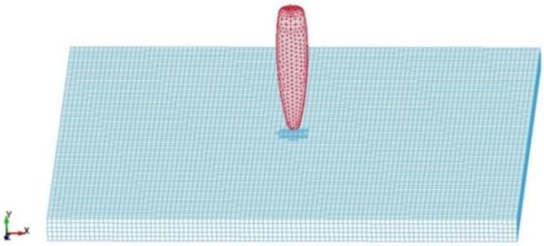


Fig. 1 Finite element model

The focus of the study was on the behavior of the plate, so it was assumed to be a rigid material for the bullet. This assumption allowed for more efficient calculations and saved computational time, while still providing meaningful results regarding the plate's response to the impact.

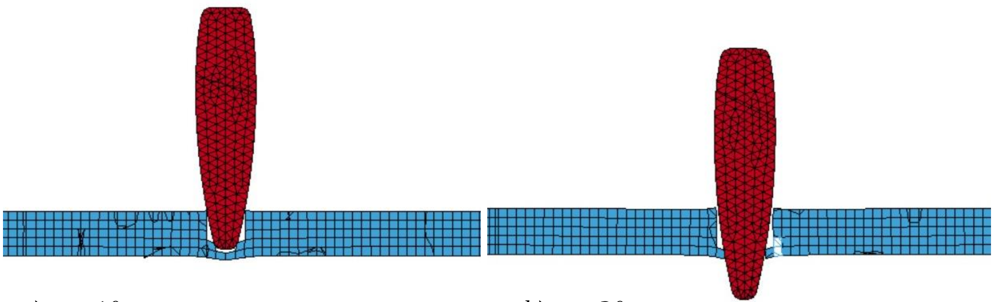
The characteristics of the bullet are the following:

- Caliber = 7.62 mm;
- Density: ρ = 7850 kg/m^3;
- Impact velocity = 500 m/s;
- Mass = 0.00538 kg;
- Elements (SOLID168) = 3860;
- Nodes = 6046.

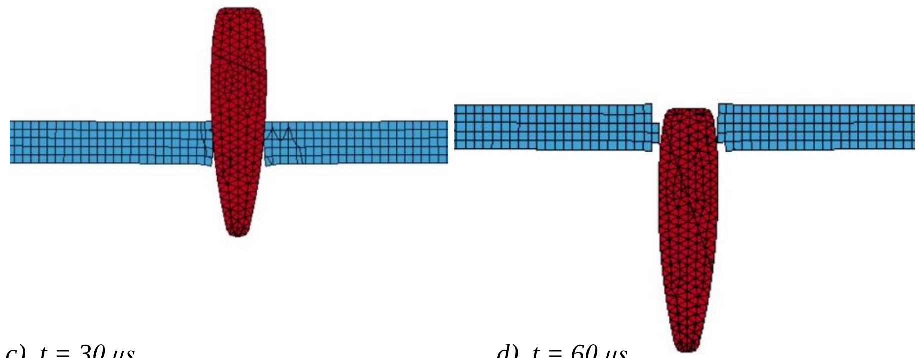
A very important thing in obtaining a result as close to reality is defining the contact between the bullet and the perforated plate. Thus, was used *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE, a recommended contact between a rigid and a solid finite element. This contact represents the positioning of the two primitives, the bullet and the plate, and the analysis is done at the surface level, finite element with finite element, with or without erosion.

3. Normal impact

In figure 2 is shown the evolution of the normal impact, with its effects (deformation with perforation of the plate), by presenting the deformed state during the analysis of first 60 microseconds.



a) t = 10 μs *b) t = 20 μs*



c) t = 30 μs *d) t = 60 μs*

Fig. 2 The evolution of the impact

The evolution of the energy absorbed by the plate is presented in figure 3. It can be seen that the maximum value it reaches is 9.89 J. Letter A in figure 3 is the designation for the minimum and maximum point, consisting of the x-axis and y-axis. The first value is on the x-axis, and the other value is on the y-axis. The notation “Time[s] (E-03)” refers to the units of the x-axis on a graphic. The “Time[s]” part indicates that the x-axis represents time, with the units given in seconds. The “(E-03)” part indicates that the x-axis is plotted on a logarithmic scale, with the base of the logarithm being 10. The “E-03” part stands for 10-3. This means that each tick mark on the x-axis is separated by a factor of 0.001 times the previous tick mark.

The energy absorbed by a plate on impact is the energy that is dissipated as the plate deforms and fractures under the applied load. This energy can be calculated by measuring the change in kinetic energy of the projectile as it impacts the plate, or by measuring the energy dissipated through deformation and failure of the plate itself.

The evolution of the energy absorbed by the plate on impact refers to the way in which this absorbed energy changes over time during the impact event. This can be influenced by a number of factors, including the material properties of the plate, the velocity and angle of the projectile, the size and shape of the plate, and the type of impact (blunt or perforating).

Understanding the evolution of the energy absorbed by the plate on impact can provide valuable insights into the mechanics of the impact event and the response of the plate to the applied load. It can also be useful in designing structures that are able to withstand such impacts, such as armor plating or vehicle components.

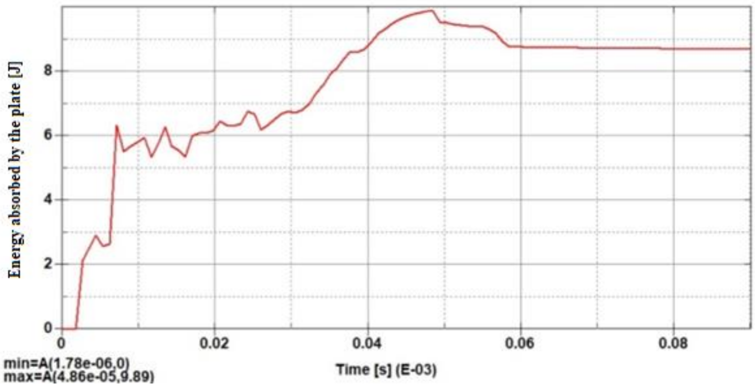


Fig. 3 Evolution of the energy absorbed by the plate for norml impact

4. Modeling the ricochet phenomenon

The ricochet phenomenon, also known as incidence or rebound angle, refers to the behavior of a projectile after it impacts a surface. When a projectile impacts a surface at an oblique angle, it may bounce off the surface rather than coming to a stop or penetrating it. The angle at which the projectile rebounds off the surface is known as the ricochet angle.

The ricochet phenomenon is important to consider in the study of projectile-plate oblique impacts because it can affect the trajectory of the projectile and the amount of energy absorbed by the surface. For example, if a projectile bounces off a surface at a high ricochet angle, it may travel a longer distance than if it had come to a stop or penetrated the surface. This can have significant implications for the design of structures or materials that are intended to absorb the impact energy of a projectile, as the ricochet angle can affect the amount of energy that is absorbed.

Thus, we continued the study on the same plate presented above and it was determined the angle of incidence (figure 4), step by step, at wich the ricochet appeared.

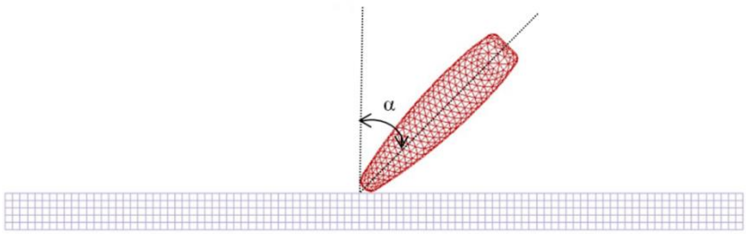


Fig. 4 The angle of incidence α of the projectile

a) The angle α = 45º:

In the figure 5 are presented the von Mises equivalent stress field at an angle α = 45º for two particular time values. It is observed that the projectile continues its trajectory, perforates the plate and there is a deviation of the angle of incidence, due to the resistance force encountered.

For a given angle α, the von Mises equivalent stress field can be calculated at different time values, for example, at two particular time values t_1 and t_2. The equivalent stress field at t_1 and t_2 represents the stress distribution within the material at those specific times, and it can be used to evaluate the material's response to the applied loads or deformations. The equivalent stress field at t_1 and t_2 can be visualized as a plot or map, with the equivalent stress values represented by different colors or contour lines.

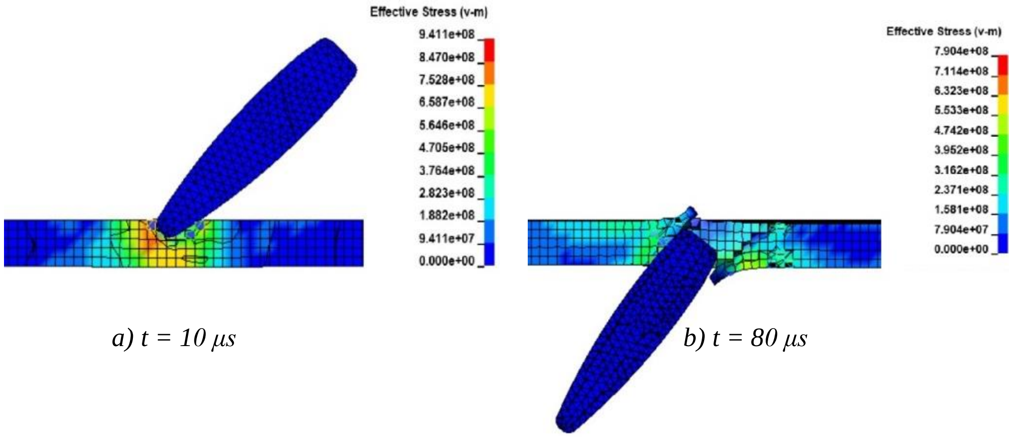


Fig. 5 Time evolution of the von Mises equivalent stresses at α = 45º

In the figure 6 is presented the energy absorbed by the plate for the angle α = 45º. The energy absorbed by the plate has a maximum value of 32.8 J.

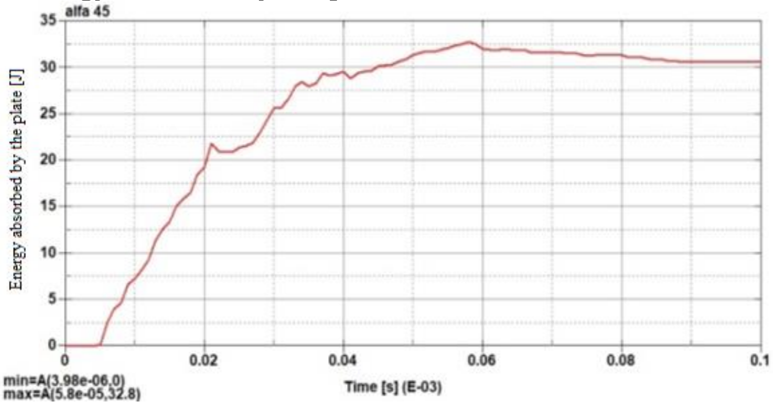
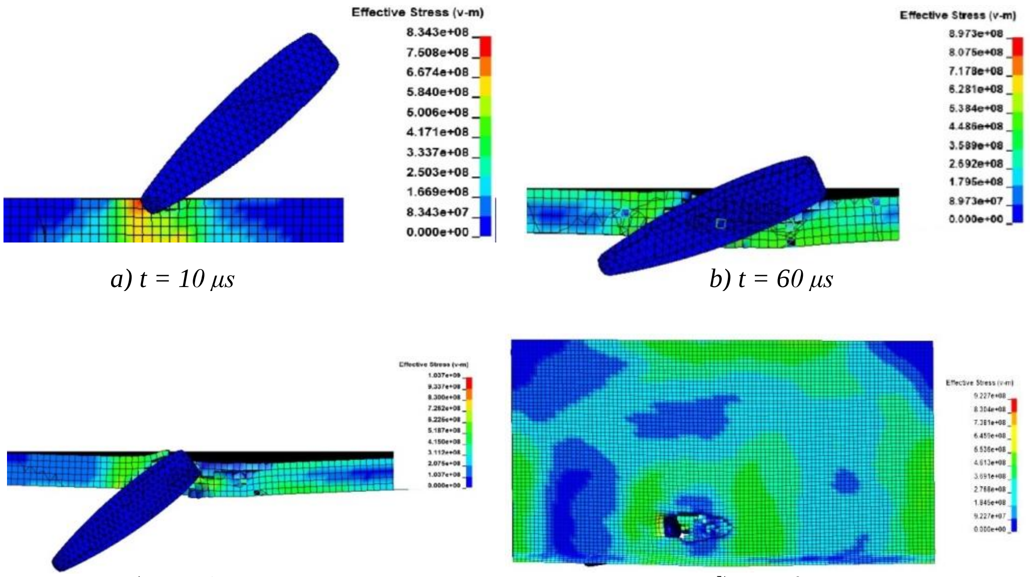


Fig. 6 Energy absorbed by the plate for α = 45º

b) The angle α = 48º:

In the figure 7 are presented the von Mises equivalent stress field at an angle α = 48º for three particular time values. Can be observed that the projectile continues its trajectory, perforates the plate and there is a deviation of the angle of incidence greater than the previous case.



a) t = 10 μs *b) t = 60 μs*

c) t = 90 μs *d) t = 90 μs*

Fig. 7 Time evolution of the von Mises equivalent stresses at α = 48º

In the figure 8 is presented the energy absorbed by the plate for the angle α = 48º. The energy absorbed by the plate increased considerably, to the value of 76.3 J, compared to the previous case, where the maximum value was 32.8 J.

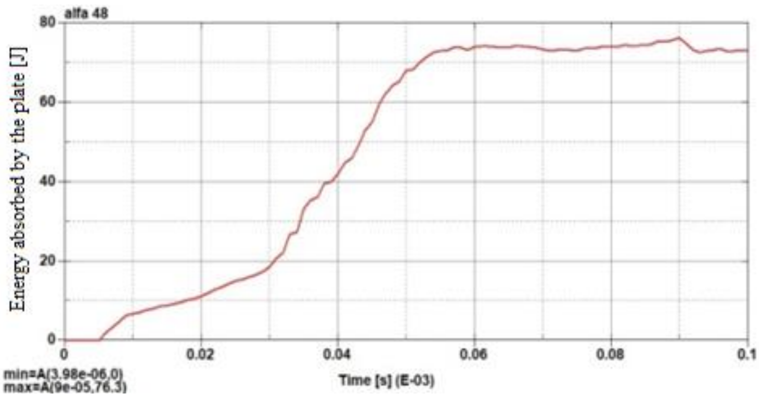
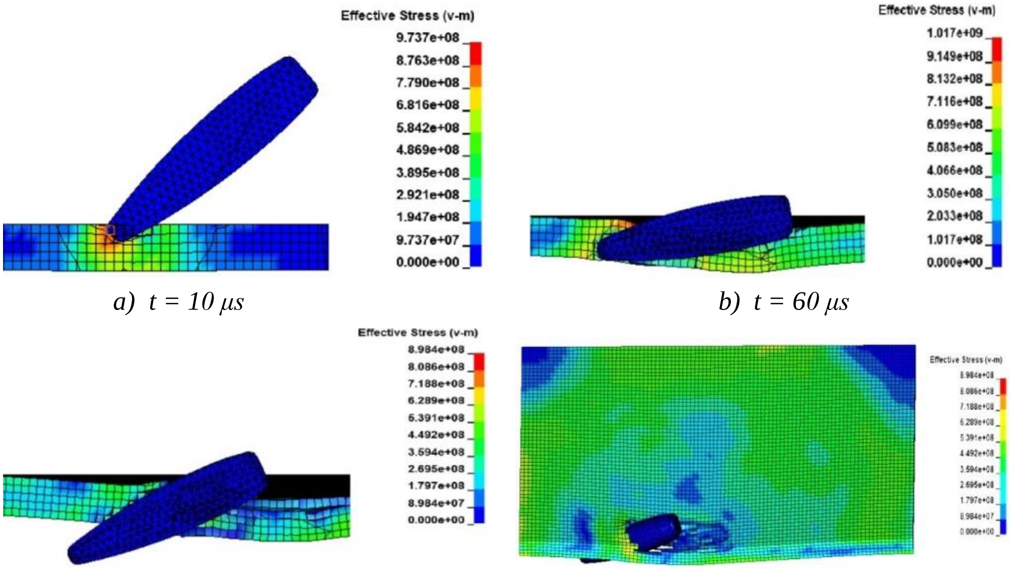


Fig. 8 Energy absorbed by the plate for α = 48º

c) *The angle α = 49º:*

Figure 9 shows the von Mises equivalent stresses at an angle α = 49º for three particular time values. It is observed that, until the time t = 60 μs, the projectile perforates the plate, having a trajectory almost parallel to it, which means that we are approaching the ricochet angle.



a) t = 10 μs *b) t = 60 μs*

c) t = 90 μs *d) t = 90 μs*

Fig. 9 Time evolution of the von Mises equivalent stresses α = 49º

The strong local character of the impact is also observed in figure 10, where can be observed that the energy absorbed by the plate has increased considerably to the value of 146 J.

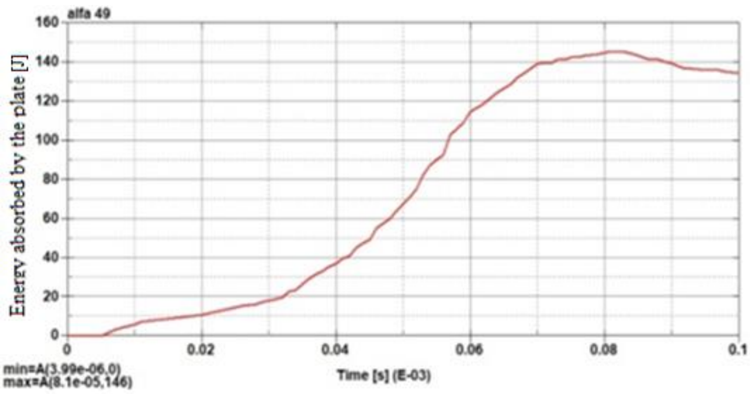
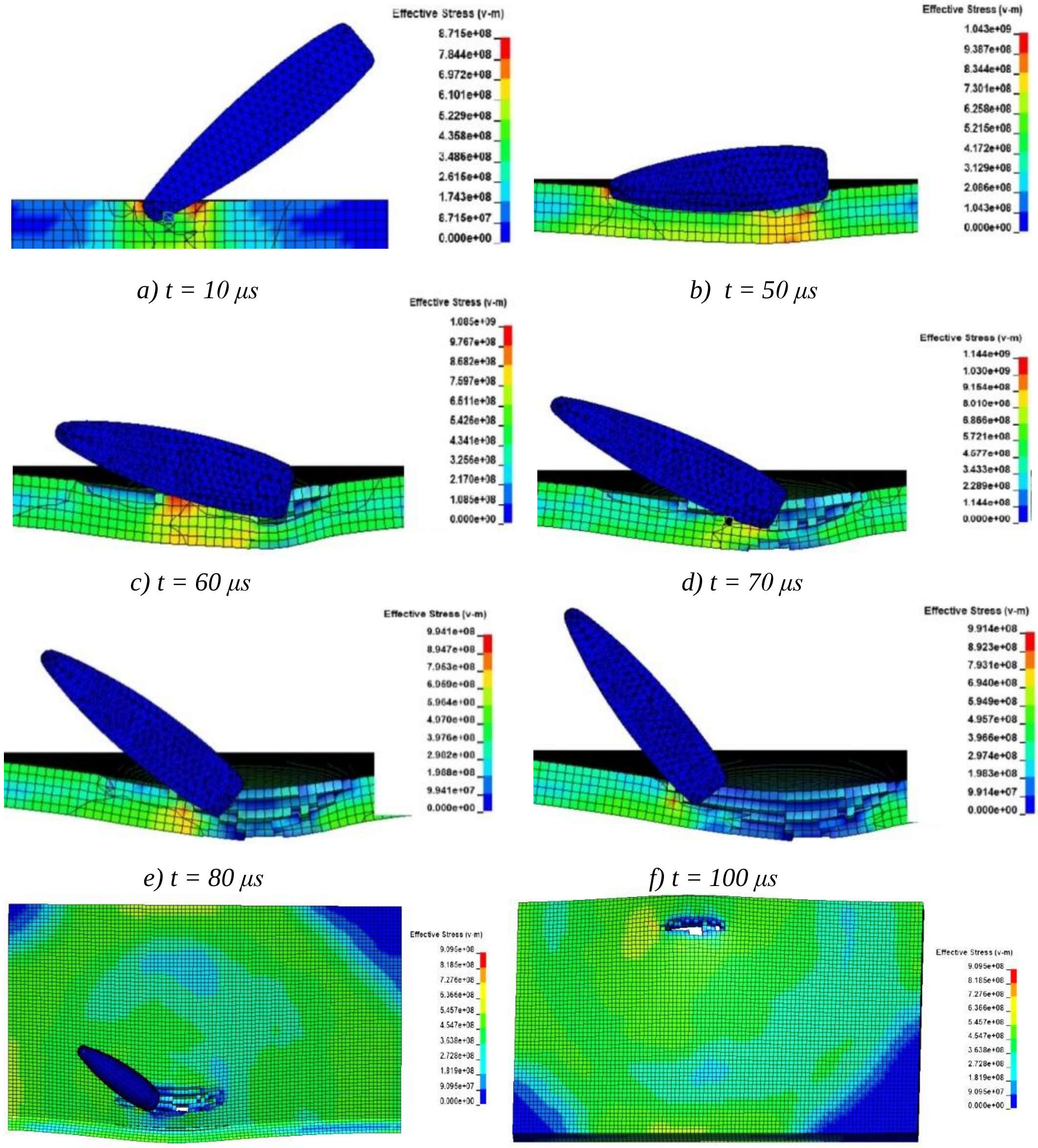


Fig. 10 Energy absorbed by the plate for α = 49º

d) The angle α = 50º:

In the figure 11 is presented time evolution of the von Mises equivalent stresses at an angle α = 50º for six particular time values. It is observed that, at this angle of incidence, the phenomenon of ricochet appears, but, at the same time, the projectile manages to perforate the plate.



a) $t = 10\ \mu s$ b) $t = 50\ \mu s$

c) $t = 60\ \mu s$ d) $t = 70\ \mu s$

e) $t = 80\ \mu s$ f) $t = 100\ \mu s$

g) $t = 100\ \mu s$ - top view h) $t = 100\ \mu s$ - bottom view

Fig. 11 Time evolution of the von Mises equivalent stresses $\alpha = 50^{\circ}$

The strong local character of the impact is also observed in figure 12, where it is found that the energy absorbed by the plate has increased considerably, to the value of 205 J, compared to the value of 32.8 J, at an angle $\alpha = 45^{\circ}$.

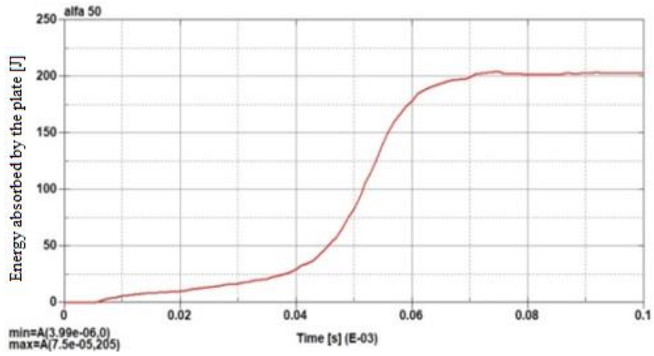


Fig. 12 Energy absorbed by the plate for α = 50º

5. Conclusions

The purpose of this paper was to evaluate the performance of an aluminum homogeneous and isotropic plate, on normal and oblique impact with a 7.62 mm projectile and to determine the angle from which the ricochet phenomenon appears.

The numerical research conducted was based on the use of the Ansys LS Dyna program, taking into account several material models from the program's material library.

For the beginning, the normal impact was presented with an initial bullet velocity of 500 m/s. The next step was to discover the incidence angle from which the ricochet phenomenon appears. Thus, the value of the angle of incidence was gradually increased to the value of α = 50º, where the ricochet phenomenon occurs. This angle is influenced by the initial velocity of the bullet, as well as by the material and thickness of the impacted plate.

It was analyzed under what conditions the ricochet could appear and what could be the consequences. Additionally, the ricochet phenomenon can also affect the safety of individuals or structures in the vicinity of an impact. For example, if a projectile ricochets off a surface at a high angle, it may pose a greater risk to nearby individuals or structures than if it had come to a stop or penetrated the surface.

Overall, it is important to consider the ricochet phenomenon in the study of projectile-plate oblique impacts in order to accurately predict the behavior of the projectile and the impact energy absorbed by the surface, and to ensure the safety of individuals and structures in the vicinity of the impact.

If the mesh the plate model analyzed above is refined, it is possible that the same angle of ricochet on impact with a rigid bullet could be obtained. However, if the material, thickness of the plate, or other parameters are changed, it is likely that the angle of ricochet will not be the same.

The angle of ricochet is determined by a number of factors, including the elastic and plastic properties of the material, the thickness and geometry of the plate, the impact velocity and angle of the bullet, and the type of loading and deformation that occurs during the impact. Any changes to these factors will affect the angle of ricochet.

In general, it is important to carefully consider the appropriate level of mesh refinement for a given analysis in order to strike a balance between accuracy and computational efficiency. In some cases, it may be necessary to perform a sensitivity analysis to understand how changes in material properties or other parameters affect the angle of ricochet.

The purpose of the study has been achieved and this brings to those interested a model and a valid calculation methodology for studying such phenomena.

Through the study and simulations presented in this paper, it should be noted that post-processing models and interpretation of results are offered, but which can be enriched and customized for other situations.

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