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Comparative study of the mechanical behavior a materials plates subjected to external force impact

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Abstract

The objective of this study is to analyze the dynamic response of aircraft structural components subjected to rapid mechanical shocks, with the aim of enhancing resistance to projectile impact. The investigation focuses on the influence of projectile geometry, mass, material properties, and impact velocity on the mechanisms of damage initiation and perforation. To this end, a square 2024-T3 aluminum plate with dimensions of 150 × 150 × 1 mm³, representative of a typical aircraft wing element, was modeled and analyzed. The contact interaction between the projectile and the target plate was simulated using a penalty-based method with a reduced-slip formulation to accurately capture impact behavior.

The results demonstrate that cylindrical projectiles with conical tips induce perforation damage within the aluminum structure, whereas flattening of the projectile nose significantly reduces the likelihood of catastrophic failure by promoting reversible, primarily elastic deformations. What we found from this research is that a number of projectile properties including shape, mass, material and velocity act in concert to govern the way thin aluminum aircraft panels respond to an impact. Changing one of these parameters has an impact on the others, and stress waves and kinetic energy are transferred differently in the structure. Over all, deformation and total damage are usually more severe with increased projectile weight or speed. The geometry of the penetrator is also very important, being it determines how local or extensive becomes the stress distribution upon impact. On the other hand, energy dissipation by material and how crack initiates and propagates is controlled by material composition. These effects combine to influence the overall ability of a structure to absorb an impact and maintain mechanical integrity.

Keywords: Plastic zone, Impact, Deformation, MEF, Resistance, Damage, Stresses, Velocity

Introduction

There are many problems in front of modern engineering on the way to creating high-performance structures of civil purpose, as well as military and aerospace applications. This is largely due to the specifics of the behavior of many materials in a condition of large deformation or with high rates of strain. For this reason, during normal operation, as well as during various hazardous impacts, structural elements are exposed to strong shock effects probability, generating a complex distribution of stresses, fraught with high pressure, as well as noticeable plastic deformation. For solving the issue, engineers, and scientists need to study thoroughly the behavior of materials subject to static and dynamic loads. This process involves various fields of science and is the object of increasing interdisciplinary interest [1–3].

Finally, in the field of transportation, there are many lines of work aimed at predicting and reducing damage to structures inflicted by vehicle impact or crash. Even in an aircraft body, the study of how micrometeoroids hit satellites and other orbital structures are still applicable as a measure to enhance the reliability, durability, and efficiency of running systems. Moreover, in defense, scientific discoveries about the behavior of materials under ballistic load are used to design innovative protective gear and projectile materials. To address all these industrial and scientific problems, one must know what it constitutionally looks like, and this information refers to the constitutive response of metallic materials. Here, the stress-strain behavior and the study of the mechanisms of fracture, deformation, and energy absorption under extreme conditions of a structural member are considered.

These data contribute to the creation of both physically stronger and more secure structure and passive protection systems designed to save both lives and essential equipment and structures subject to accidental or environmental hazards [4,5].

Traditional metallic structures benefit from repair procedures that are well established and thoroughly optimized. On the other hand, the increasing use of composite materials in critical components, for instance, the fuselages of airplanes, presents an increasingly pressing technical challenge. Despite their efficiency in terms of strength-to-weight ratios, composites tend to have more sensitivity to dynamic load and distinct types of damage that can undermine the integrity of the entire structure. As such, one of the urgent tasks is adapting the existing frameworksed of repair and maintenance in order to account for the distinct properties of composite materials. In subsequent years, one of the key challenges would be the development of maintenance frameworks for composite-based aeronautical structures, which would enable the reduction of the overall lifecycle and maintenance costs, while ensuring the highest standards of safety and reliability [6].

Impact loading is considered one of the most severe in terms of stress conditions, responsible for the behavior of the structural systems made of composite materials. From the mid-1980s, their use has gradually expanded to the most significant frames of aeronautical structures. Among the first used solutions is the integration of composites into the principles and horizontal stabilizers of the ailerons of aircraft, among which stands out AIRBUS A310, A300/600, A320, A340. Similarly, composites were used to build the wing box of the French RAFALE military aircraft. In the case of the ATR 72 regional plane, composite materials account for about 22.6% of the total structural mass. It is specific in that the number of central panel parts is rather small, and composite materials are heavily used in the external wing boxes approximately 8.5 m in length each, part of the external cowling bundles [7,8]. The growing usage of these materials follows the fact that they exhibit enhanced specify strength with respect to common metallic alloys and an outstanding potential of energy dissipation. Nevertheless, the actual exploitation of the aforementioned properties in practice remains highly contingent on solving a number of tough issues that arise from ensuring adequate conversion of the experimental, analytical and numerical methods. The most critical part of it is linked with the need to investigate how various structures respond to dynamic loading associated with high strain rates. Progress in this field is required to better the energy absorption and make the features of passive safety better but also help enhance the structural endurance against high-energy impacts and natural disasters [9]. Despite the comprehensive efforts already made to investigate behavior of composite materials under various forms of a high-speed impact (HIS) and related mechanical and dynamic processes, the progress in utilizing new materials and techniques is far bigger than the accumulated knowledge. Many aspects of the influence of such materials on the global structural performance are not well understood, including damage delivery and evolution mechanisms in high-velocity impacts, which makes it impossible or impractical to build the proper material-based models. Hence, the engineering application of composites requires deep expertise about their static and dynamic behavior that is achieved mainly based on the correctness of numerical modeling. At present, even the most advanced computational approaches tend to overcalibrate to achieve the balance between predictability and validity on a particular test case. As a result, the actual use of composites becomes over-conservative which negates their potential advantage in weight over alternative materials and enhanced functional capabilities [10].

One of the most efficient methods overcoming these difficulties by predicting residual mechanical performance in the structures after the impact is numerical simulation. It can be described as follows: a direct simulation of the impact is conducted, and the damage distribution in the damaged area is obtained. The results of the simulations are inserted in models computing remaining strength as well as stiffness. There are three current models made based on the previous concept, among which two are considered as scale models. The first one was presented by Lammerant and Verpoest and was improved by Ilyas et al.. The model works on the idea on discrete representation of damage, where cracking is a local material separation. The strategy assumes that the material can be divided between volume elements and degradation links: springs, cohesive interfaces, constitutive interaction laws [12-15].

Properties of the Materials used

Tables 1, 2 and 3 show the mechanical and physical characteristics of the projectile and the target used in this study.

Table 1: Characteristics of 2024-T3 aluminum alloy [16,17].

Parameters	Symbol	Value	Unit
Young's modulus	E	73000	MPa
Modulus of rigidity	G	27400	MPa
Poisson's ratio	υ	0.33	-
Specific heat	C_p	874	J kg^{-1} K^{-1}
Coefficient of thermal expansion	α	23.1	µm m^{-1} K^{-1}
Density	ρ	2770	kg m^{-3}

Table 2: Characteristics of S235 steel [18,19].

Parameters	Symbol	Value	Unit
Young's modulus	E	210000	MPa
Modulus of rigidity	G	81 000	MPa
Poisson's ratio	υ	0.3	-
Specific heat	C_p	470	J kg^{-1} K^{-1}
Coefficient of thermal expansion	α	12	µm m^{-1} K^{-1}
Density	ρ	7800	kg m^{-3}

Table 3: Characteristics of polyester [20,21].

Parameters	Symbol	Value	Unit
Young's modulus	E	4000	MPa
Modulus of rigidity	G	1550	MPa
Poisson's ratio	υ	0.37	-
Specific heat	C_p	202	J kg^{-1} K^{-1}
Coefficient of thermal expansion	α	23.5	µm m^{-1} K^{-1}
Density	ρ	1200	kg m^{-3}

Model Definition

The principal goal is to advance our current knowledge and instrumentation to enable more accurate observation of material responses to dynamic mechanical loading. More specifically, we need a deeper understanding of the initiation and growth of damage at high loading rates and the mechanisms controlling the dissipation of energy, which are critical for the functioning and safety of aviation, marine, and road transportation systems, where lives and structural integrity are at stake. In some investigations, I wanted to understand the basic processes of energy dissipation and fracture during high-energy impact and classic perforation phenomena. It remains very sophisticated work and involves the creation of novel experimental techniques and formulations of reliable numerical models that could reproduce and predict the progression of these rapidly changing events properly. However, many important and advanced papers on the subject already exist. Among them, the pioneering work by the already mentioned Goldsmith stands out for its comprehensive contribution to understanding the penetration and perforation mechanics [22].

The conducted study has been completed within this framework, as it is aimed to investigate the projectile impacts on the components of an aircraft to ascertain their resistance to instantaneous mechanical loads. The analysis conducted serves the purpose of predicting the structural behavior in cases of a dynamic nature of shock, such as high-speed impacts. The selected case scenario was a state-of-the-art representative of powder metallurgy manufacturing, utilizing aluminum plate. For the illustrative purpose of this work, an example of the alloy composition 2024-T3 has been chosen, known for its Young's modulus of 73,000 MPa and Poisson's ratio of 0.33. The plate tool has been designed with measurements of 150mm by 150mm in quadratic form and 1mm in thickness; such dimensions have been adequate for the validity of computational simulation purposes. The geometry and size of the plate render the conformation dimension of the plate that demonstrated the segment removed from the wing of the Concorde supersonic aircraft that is investigated throughout the study in this simulation.

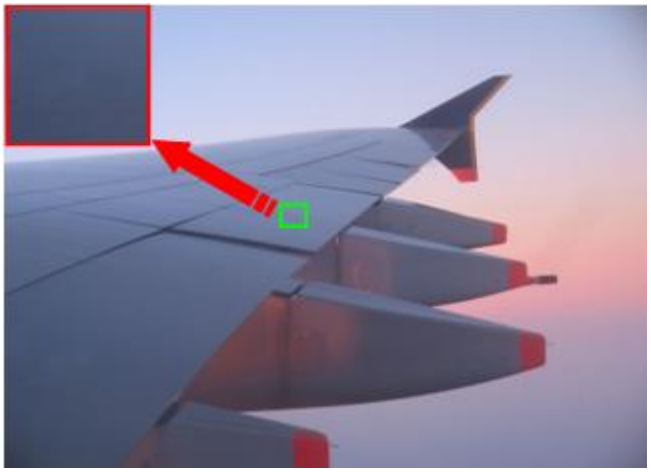


Figure 1 : Concorde supersonic aircraft wing.

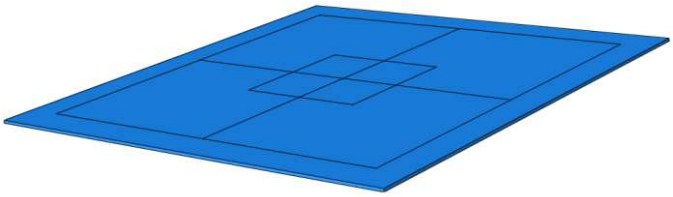


Figure 2 : Al 2024T3 plate analyzed.

The present paper attempts to conduct a systematic study on the impact that different aspects of the projectile's geometry, material composition, mass, and impact velocity have on the mechanical response of the target structure. Ideally, the outcomes gained through the analysis will facilitate better comprehension of the damage mechanisms responsible for the behavior of the structure under high-rate static loading. The configuration in question is demonstrated in Figure 3. The essential boundary conditions for the target plate simulate the fully clamped system, which restricts all translational and rotational degrees of freedom along the three principal axes. In contrast, projectile's translational degree of freedom is only restricted to move along z-axis, which is shown in Figure 4.

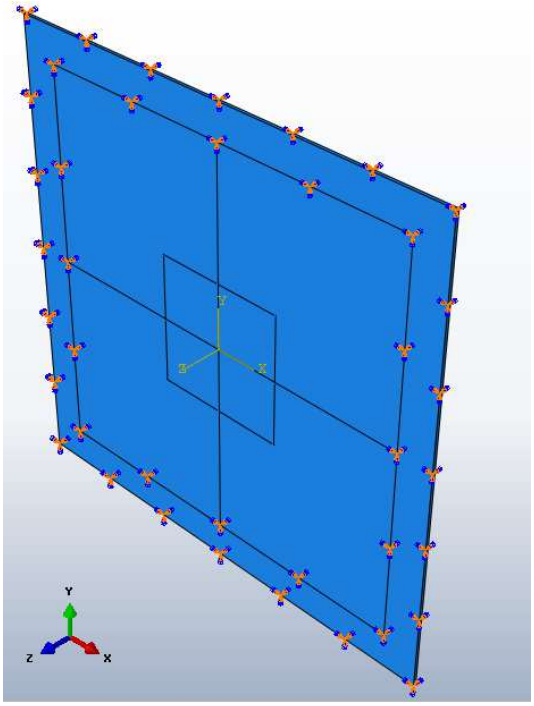


Figure 3 : Boundary conditions of the plate.

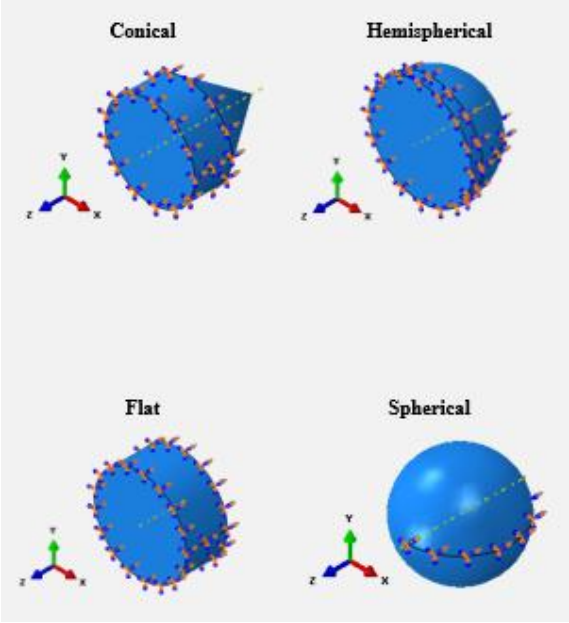


Figure 4 : Boundary conditions of the projectile.

Elemment finis

The finite element simulation developed for this specific research allows for authentic three-dimensional simulation of impact and perforation phenomena. The goal is to delicately predict the damage mechanisms following the interaction. As the overall deformation of the plate following an un-yield event applied symmetrically from two opposing sides is not inherently symmetric, the entire structure was modeled without using any symmetry conditions. The projectile and the target plate were discretized using eight-node hexahedral elements. The latter is considered excellent at capturing large deformations and correlated localized failure mechanisms. Mesh in the central impact zone of the element was finely refined, and mesh element size varied depending on the minimum feature size in the model. The total plate mesh included 498,322 elements, as shown in Figure 5. Different discretization assemblies can be seen in the mesh generated in the projectile-target models depending on the projectile-type element density. The choice of element density was made to ensure a realistic representation of the projectile-target interaction, and projectile target interactions were discretized with fewer elements. The view is shown in Figure 6.

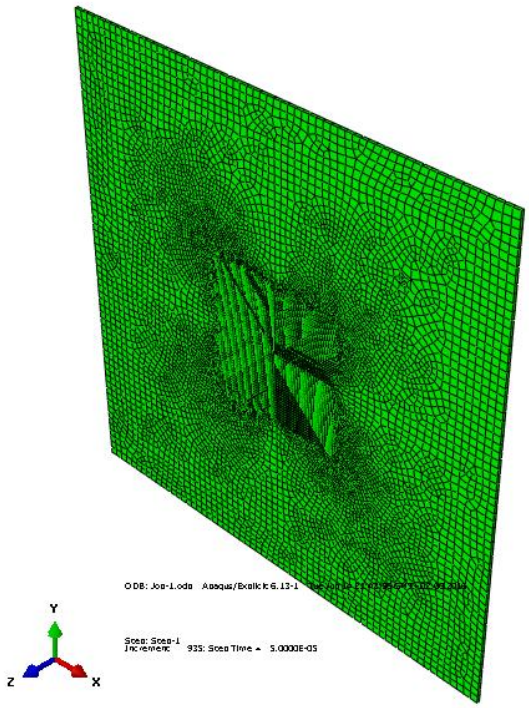


Figure 5 : Mesh of the analyzed structure.

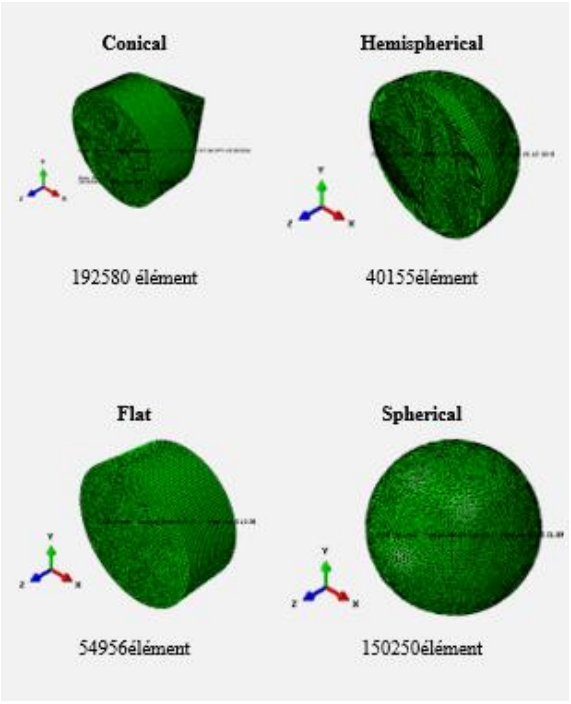


Figure 6 : Projectile mesh.

In this work, both the projectile and the target plate were considered to be deformable three-dimensional bodies, in a manner to appropriately model their mechanical interaction upon impact. The contact interface between the two was defined with the use of the penalty method, and a reduced-slip solution approach was used to enhance the robustness of contact constraint enforcement mechanisms under dynamic loading. Various strategies for creating the spatial discretization of the computational domain were tested to achieve a balance of computational efficiency, solution accuracy, and element geometry, prior to making a final selection. Fig. 3 presents the final layout of the mesh design for the plate. The plate's geometry was divided into two major zones: 1) a central square area, visualized in Fig. 3 and symbolizing the part of the plate exposed to the direct impact of the projectile. 2) An outer region of the plate forming the outside geometry throughout the simulation. In Fig. 7, the inner region is presented with the maximum level of detail; attention was given to stress concentrations and other damage patterns forming localized zones of high and low strain.

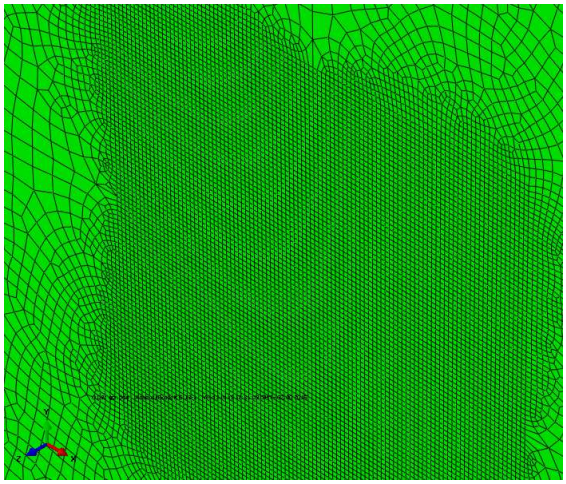


Figure 7 : Mesh of the central square part.

Analysis of numerical Results

Shape Effect

The current section discusses the influence of the projectile geometry on the mechanical response of the plate impacted at the high velocity. More specifically, the thorough investigation of the stress distribution and the stress intensity generated in the target material is presented. In the present research, the projectile, consisting of E360 steel material with mass 2.65 g, was launched with a velocity 18 $m \cdot s^{-1}$ to the aluminum plate, composed of 2024-T3 alloy material. The following four forms of the projectile geometry are defined: flat-ended cylinder, a spherical-nosed cylinder, a conical-nosed cone, and a fully spherical as provided in the schematic image of Figure 6.

Stress distribution within the area of the impact is illustrated in Figure 8. According to the simulation outcomes, in the target material, the stress concentrations are significantly higher if the projectile has a steeper geometry. The plates themselves undergo extensive deformation under the considered loading conditions, with the conical nose causing the most substantive reaction. This severe behavior is illustrated in the fact that the stress value exceeds the failure criterion of the 2024-T3 aluminum plate; hence, this material has exhausted its structural resource, and all the major failure modes are initiated. This pronounced localization is shown in Figure 8d.

The comparison of the fully spherical and spherical-nosed projectiles depicted in Figures 8b and 8c indicates that the effect of these configurations on the target structure is very much the same. These two setups produce almost equally strong magnitudes and patterns of stress in the area of impact. In those zones, pressure values exceed the yield strength of the aluminum plate, and the material behaves elastically at first, then cavitation and plastic flow occur due to the summation of the stress magnitudes. As a result, a share of the kinetic energy of the projectile is spent within the material and dissipate into the material in the form of irreversible plastic deformation, or residual stress.

The analysis depicted by Figures 8b and 8c indicates that the shape of the tip of the projectile plays crucial role in determining the stress distribution in the hitting material and its mechanical response upon high-velocity impact. On the other hand, the cylindrical projectile with a flat tip shown in Figure 8a generates less stress which is lower than the yield strength of the material. Therefore, the plate does not reach yield point and there is no noticeable instability degradation.

The results of the current analysis affirm that the cross-sectional geometry of the projectile determines the extent of the stress concentrations and, hence the behavior of impact on the 2024-T3 aluminum plate. In particular, the sharpness of the nose results in the strength of the stress concentration and the size of the plastic deformation area, affecting either the localized plastic deformation or, in the worst-case scenario, perforation of the target. The regions of plastic deformation corresponding to the projectile geometries are displayed in Figure 9. It is indicated that the size of the plastic convergence zone generated by the spherical-cone projectile is double that formed through the impact of the purely conical impactor. Furthermore, the impactor with the sharp-pointed head

shapes the stress fields more strongly across the general norm, resulting in the narrower, yet substantially more pensive plastic zone, with local stresses possibly surpassing the failure strength of the material.

For three types of projectiles, so characterized by the inscriptions, the dimensions plastify the zone has the same order of magnitude. In the first two cases, there is a very rapid exchange of momentum in a very small time, which causes the appearance of permanent plastic damage. The distribution of the von Mises equivalent stress in the deformed zone is shown in Fig. This diagram is similar to the presented above in Figs. 8 and 9. In all cases, it was a geometric sweep generalized to insignificant implantation from the nose of the projectile. This figure confirms the expressed opinion of the high concentration of localized stress of the projectile with the pointed noses in a small area with a high degree of load, and the projectile with the curved nose – more widely distributed pressure fields. It should be noted that for a flat-nosed projectile between the maximum in the zone do not have a point of the drawing, and the distribution is almost linear with almost linear dependence and the lining is always a factor below the allowed values.

In general terms, the outcomes show that the geometry of the projectile significantly determines the mechanical response of the aluminum plate in the case of an unanticipated impact. The sharper the projectile tip, the more likely it is to cause perforation, which is a form of irreversible structural failure; conversely, the milder and shorter the tip, the less it contributes to significant elastic deformation and structural failure.

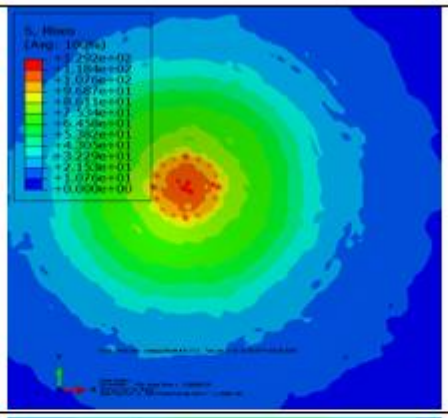
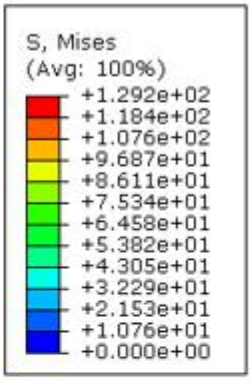
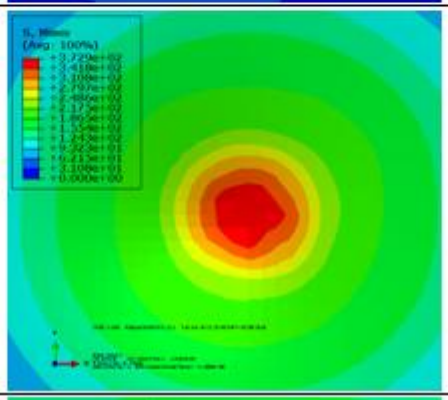
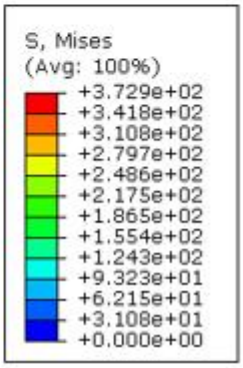
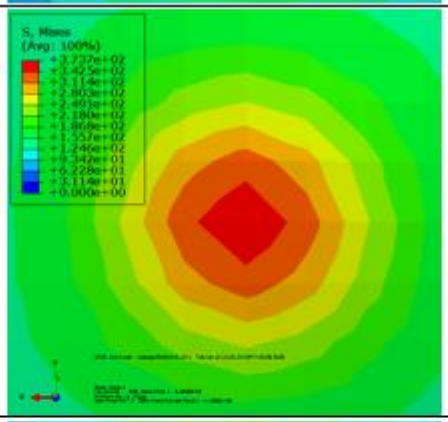
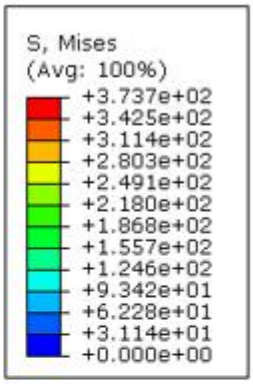
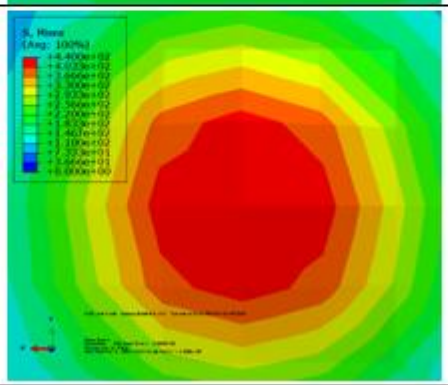
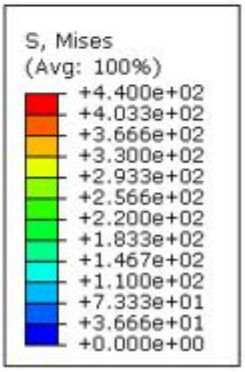
Tests	Shape	Stress distribution	Stress levels
a	Flat		
b	Spherical		
c	Hemispherical		
d	Conical		

Figure 8 : Influence of projectile shape on the distribution of von Mises stresses in the plate.

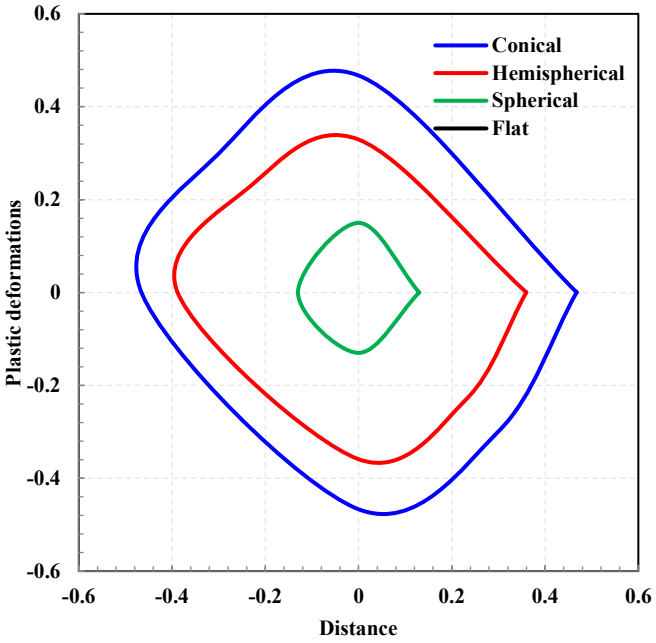


Figure 9 : Effect of the projectile shape on the size of the damaged area of the plate.

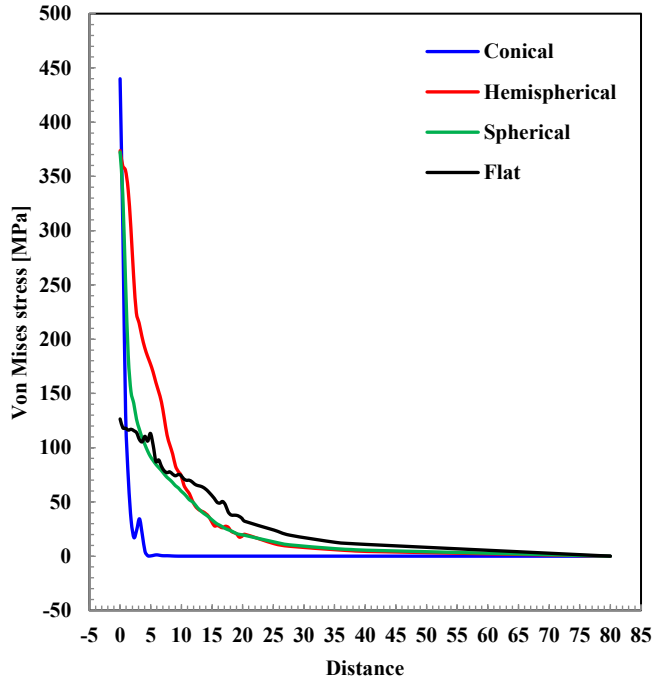


Figure 10 : Variation of the Von Mises stress along the damaged area of the plate under the effect of projectile shape.

Mass Effect

Such a geometry is adopted in the present stage of the analysis because the results of the previous studies, which demonstrate that when using a conical-tipped cylindrical projectile, perforation type damage is developed in the aluminum plates. The purpose of the study is to obtain an empirical dependence of the manifestation of the target material's dynamics in dynamics on variations in projectile masses. The response is investigated by analyzing the parameters and the uniform integral parameters of impact-induced stress fields in the target material.

In this case, two E360-grade steel projectiles with the same geometry and different masses were used to launch at the impact velocity of 11 $m \cdot s^{-1}$ towards aluminum alloy 2024-T3 plate. As a result, the corresponding stress fields induced by the impacts are represented in Figure 11(d). Specifically, the obtained results demonstrate that the increase in the projectile mass implies an evident rise inside the target plate stress intensity field. Furthermore, the result of the mass increase is characterized via expanding the influenced area, which also indicates the fact that heavier projectiles induce wider regions of plastic deformation and damage, reflected in Figure 12. Within those areas, the locally emerged stress concentrations, or peaks, exceed the aluminum alloy yield strength, resulting in a permanent plastic deformation. Moreover, in the situation of the relevantly high projectile masses, such generated stresses would overpass the strength of materials and enable the full-thickness plate penetration.

In order to explore the behavior of the target's stress response in further detail, it is possible to consider the changes in the von Mises- equivalent contour patterns above the impact region with the increase in the mass of the projectile, as described in Figure 13. As one can see, the stress fields are confined to relatively narrow areas, which is typical for the impacts of conical-nosed projectiles; yet, what is noticeable is that they increase in magnitude as one adds more mass to the projectile. This pattern serves to prove the high correlation between the mechanical response of the plate made of aluminum and the mass of the impacting object.

These results clearly reveal that the projectile's mass is a key factor influencing the outcome of how the structure responds to an impulsive load. When mass is added or increased, voluminous zones of plastic deformation form and grow laterally and on the plate's thickness, leading to an increase of the chance of perforation. Even at a moderate velocity, and when the mass is sufficient, a projectile can produce far-reaching plastic deformation or, if the plate is thin enough, shatter it entirely.

As a result, the projectile mass and the impact velocity can be considered as jointly related parameters that occur concomitantly and are responsible for the dynamic response exhibited by the thin metallic plate under impact loading conditions. Hence, the combined action of both these parameters must be well understood under the conditions established, particularly since the subsequent part will discuss how the accelerated projectile velocity affects the plate during the impact event.

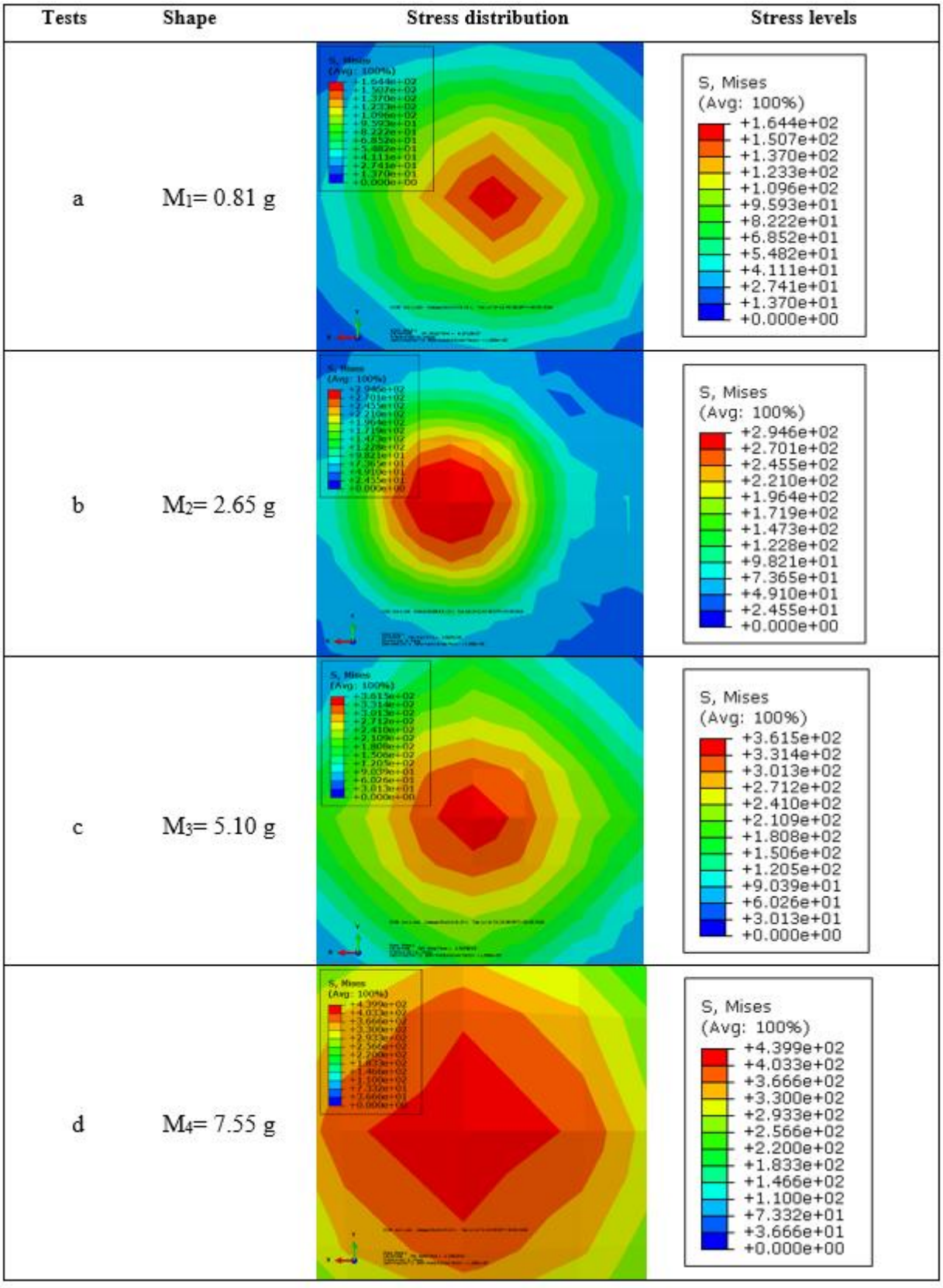


Figure 11 : Influence of projectile mass on the distribution of von Mises stresses in the plate.

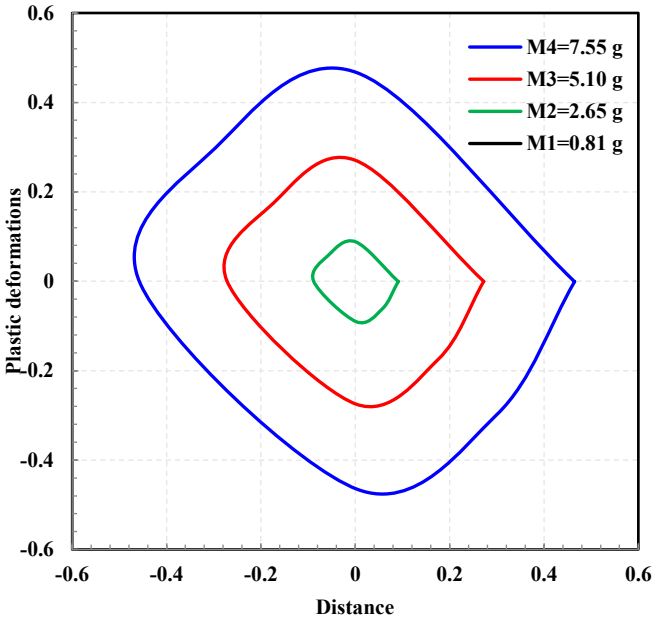


Figure 12 : Effect of the projectile mass on the size of the damaged area of the plate.

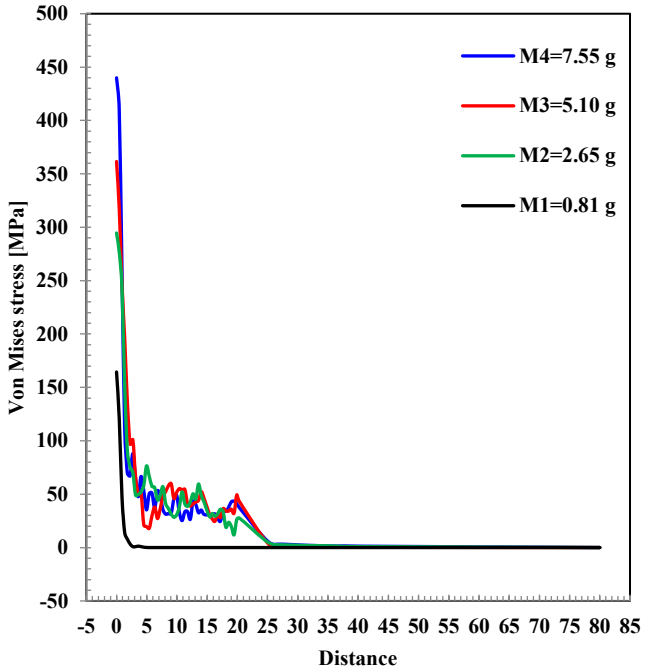


Figure 13 : Variation of the Von Mises stress along the damaged area of the plate under the effect of projectile mass.

Velocity Effect

A cylindrical projectile with a conical nose made of E360 steel was used in this study, and it had a mass of 2.65 g. However, it can be seen that the stress amplitude generated in the plate by this context is at the order of magnitude of the yield strength of the material, and such a level should not lead to permanent plastic deformation. This observation allows for the assessment of a critical velocity which might induce failure of the tested specimen. In turn, the following section investigates the influence of the projectile's velocity on the material's dynamic behavior when subjected to high-speed impact loading. Figure 14 displays the results which indicate the distribution and the value of the axial von Mises equivalent stress generated in the 2024-T3 aluminum plate for various loading velocities.

In the case of even higher impact velocities, the levels of generated stresses inside the target plate are significantly elevated. As presented in Figure 14(c), the peak stresses almost reach the levels measured in the central region due to the similarity in the impact force impact. This means that the defined conditions have the capacity to cause the initiation of material damage and, possibly, perforation. Finally, in the case of the lowest velocities, the levels of localized stresses are substantially reduced, remaining far below the macroscopic threshold of damage of about 2 GPa, which means that the material response remains within the elastic area, as shown in Figure 14(a).

After the projectile impacting the target at an intermediate velocity, the induced stresses are beyond the value that will start plastic deformation in the 2024-T3 aluminum alloy, as seen in Figure 14 b. The collision process places irreversible plastic effort between the target material that results in part of the projectile's kinetic energy. The trend is better defined in Figure 15, where the pressure distribution and the radial inflow velocity differ considerably with pavement range, respectively, and so does the liquid zone's weight. First, as explained earlier, these plastically twisted regions continue to be definitively very narrow sectors that differ only in power. The above scenario is illustrated in Figure 16.

The results of this section demonstrated that projectile velocity is a crucial parameter that affects the deformations of thin metallic structures under impulsive mechanical loading conditions. The impact velocity can contribute to both localized plastic deformation and catastrophic structural failure depending on its magnitude. The effects of a high-energy impact are shown to cause considerable material deterioration and plate perforation after total failure.

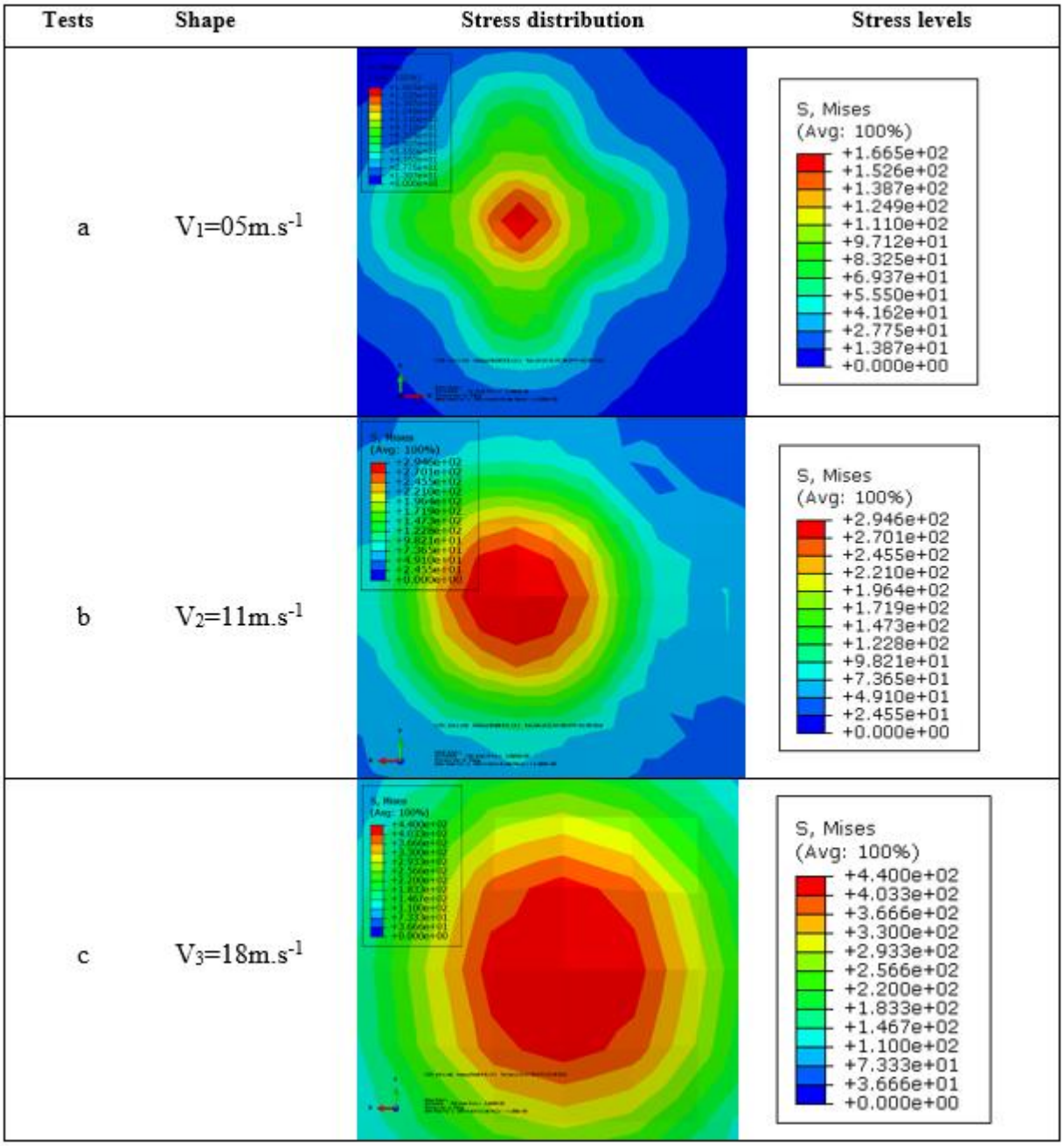


Figure 14 : Influence of projectile velocity on the distribution of von Mises stresses in the plate.

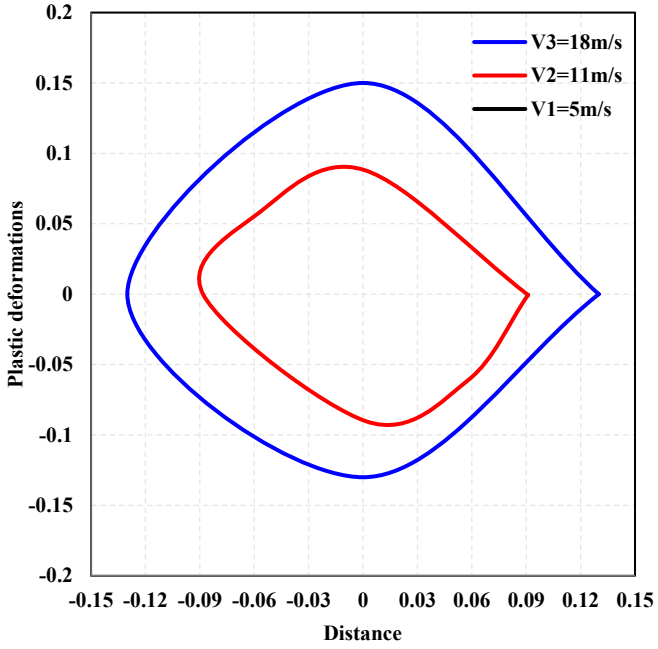


Figure 15 : Effect of the projectile velocity on the size of the damaged area of the plate.

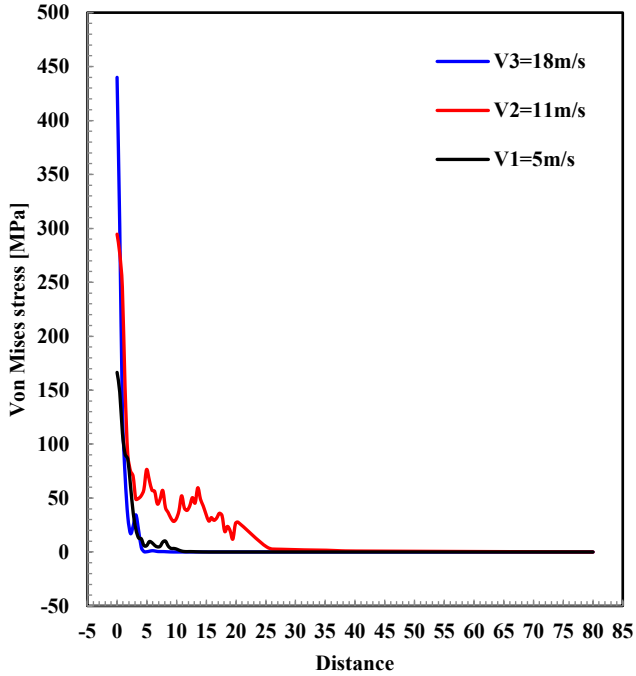


Figure 16 : Variation of the Von Mises stress along the damaged area of the plate under the effect of projectile velocity.

Nature Effect

To sum up, the current study aimed to investigate the influence of the projectil es material properties on the aluminum plate mechanical response to impact loading. For this purpose, the simulations were conducted for the 7.55 g cylindrical projectile with a conical n ose impact on the aluminum plate with the velocity of 11 m·s -1. The obtained stress fields demonstrated considerable differences in their intensity and the pattern of their propagation, mainly due to the projectil es distinctive material properties, which consisted of the Young's modulus. The goals correspondence results can be observed in Figure 17. As it can be seen, the plate reaction to sudden mechanical loading diminishes with the strengt h of the respective projectiles material. Precisely, the type of pr ojectile with the high Young's modulus strength results in a more pronounced structural response, as represe nted by Figure 17 c. Therefore, the high strength materials projectiles tested at the high volocities bring the risk of progressive material destruction shown in Figure 17 c, where the exceeding stress levels are above the rupture value.

When the projectile has an intermediate stiffness, substantial plastic deformation takes place in the impact zone, as the local equivalent von Mises stress surpasses the material's elastic limit. This explanation is illustrated in Figure 18, where it is shown that the size of the region that underwent plastic deformation decreases as the projectile's stiffness grows. More importantly, Figure 18 also shows that in the case when the impactor has low stiffness, there is little areas of plastic deformation in the plate — the rest of the deformation remains elastic.

Figure 19 shows the development of the von Mises stress distribution over the impacted region increases the projectile's stiffness. The simulation demonstrates that high levels of stress concentrate in a very narrow zone that shrinks when the projectile becomes harder, but expands when the material becomes more ductile. It can be concluded that the stiffness of the projectiles shapes the response of the target to an impact in an identifiable way.

In general, the results obtained suggest that the mechanical properties of the projectile as well as its elastic modulus, in particular, critically affect the stress level and distributions over the entire plate impacted. Thus, when high-modulus projectiles are used, structural perforation is possible. In contrast, low-modulus or relatively more ductile impactors show much lower levels of stress, as well as relatively lower contours, and create almost no damage or deformation of the 2024-T3 Al plate when comparing conditions of impact.

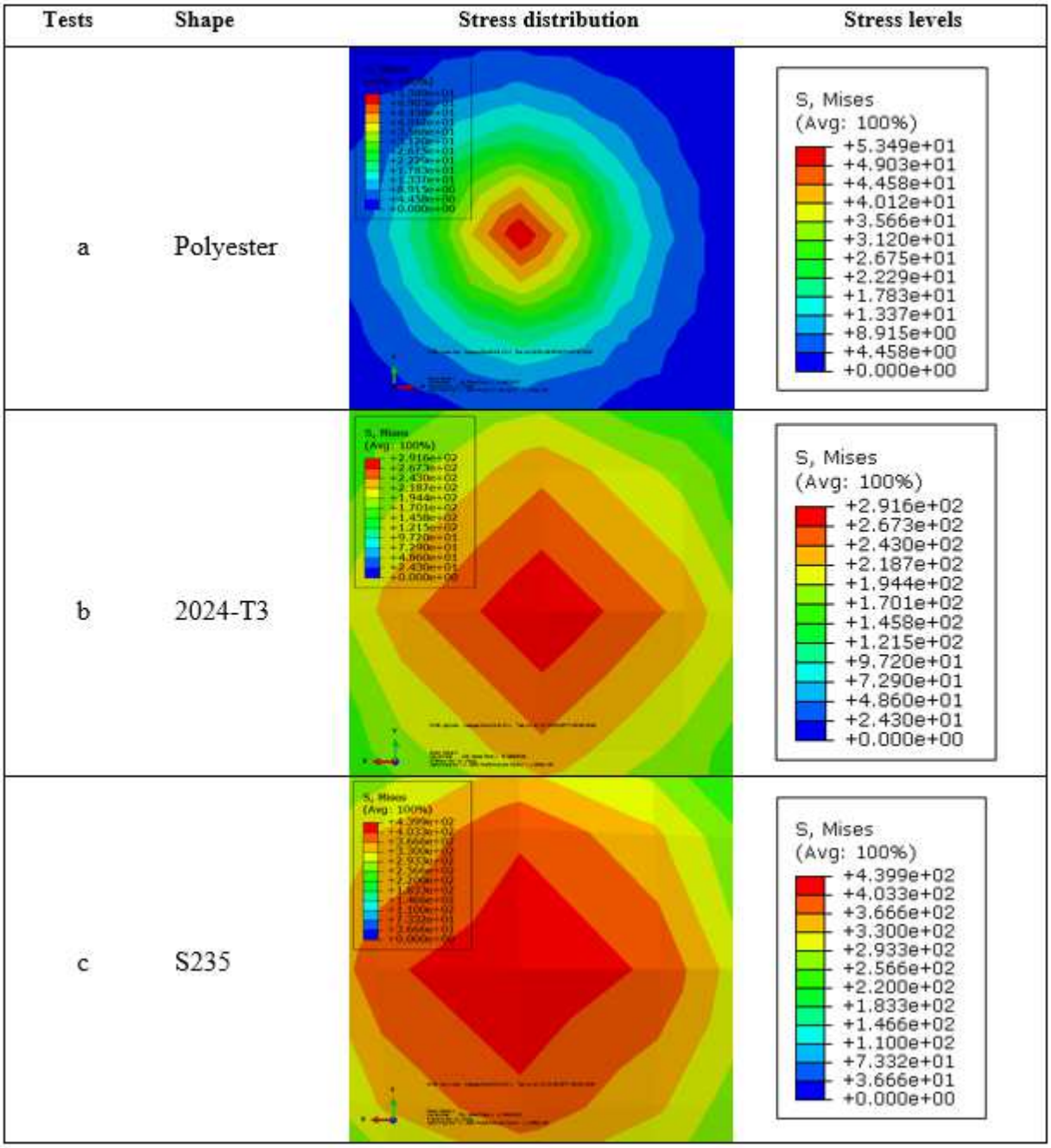


Figure 17 : Influence of projectile nature on the distribution of von Mises stresses in the plate.

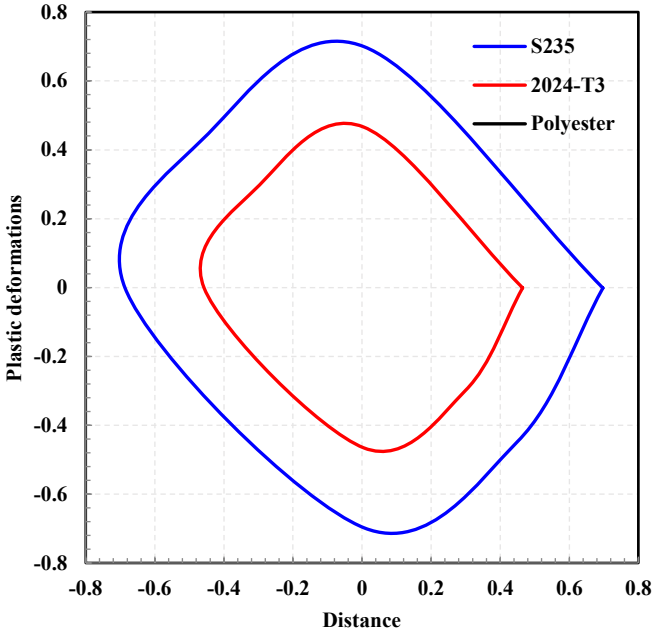


Figure 18 : Effect of the projectile nature on the size of the damaged area of the plate.

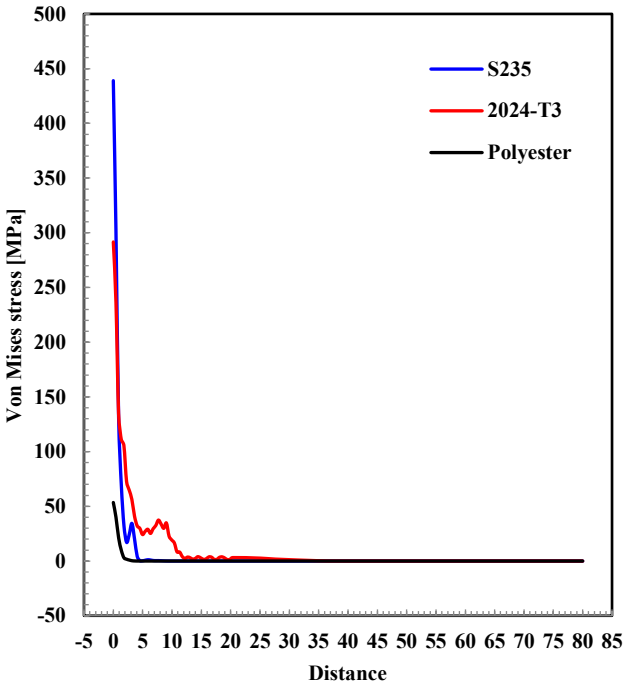


Figure 19 : Variation of the Von Mises stress along the damaged area of the plate under the effect of projectile nature.

Discussion

This study explores the dynamic behavior of a large, thin plate of 2024-T3 aluminum under striker normal impacts based on finite element method simulations. Projectile geometry, mass, velocity, and material stiffness influence the distribution of stress, size, and shape of the plastic strain fields and perforation resistance were examined. The numerical method uses an octic-based finite element solution based on three-dimensional hexahedral elements, which is graded after the squares in the effect zone to properly represent deformations. A penalty-based contact equation that will represent the continuous mechanical communication after the shooter on the target plate are all elastic loading and the marking will influence plastic consumption and possible structural failure through the rise of impact energy and sharpening of the marking. The results of simulations are good matches of the theoretical prediction for penetration mechanics and are correlating well with previously published simulations of recent experimental tests on the ballistics of plate targets [23,24].

It is evident that projectile's nose geometry is the most critical parameter determining local failure mechanisms. Conical-nosed projectiles produce highly concentrated contact pressures, which indicates extensive stress localization within the limited zone and facilitate shear plugging or tearing failure modes. Such damage localization reduces ballistic resistance as compared to that measured for blunt or javelin shaped impactors, while progressive or hemispherical fully spherical projectiles produce a more even distribution of stress over the target surface. These results in broader zones of deformation that require higher impact velocities for complete perforation. The observations made herein are in agreement with experimental findings made earlier for targets of comparable thickness made of steel and aluminum. Finally, flat-nosed projectiles result in high-intensity stresses developed in the continental areas but with moderate module effects, which usually do not exceed the plate's yield strength at moderate impact speeds. These trends of increasing gaussian penetration hierarchies indicate that conical and ogival projections are more efficient at inducing perforation when the projectile mass is held constant [25-27].

When increasing the velocity of a projectile at constant mass, it results in more intense stress concentrators and the level of plastic deformation in the target material. The same occurs when employing heavier projectiles, generating more momentum and kinetic energy during the impact. As a result, the structural response shifts from localized plastic deformation to complete perforation. This behaviour correlates with conventional outcomes of ballistic limit tests and theoretical analysis of energy–momentum balance models for a thin metallic plate with respect to an impulsive loading. The amplification with respect to mass of the stress-induced in the stress–distance distributions reveals a sharp elliptical nose in its DPMS. For stiff slender impactors, the dynamic plugging is very efficient, and the failure planes are vividly found in the stress-state map, concerned with the shear force and the normal stress predictors highly concentrated in the neighbourhood of the projectile's nose [28,29].

At the same time, the higher the impact velocity, the more significant the structural response of the plate displays specific transitional regions. In the low-velocity domain that includes $V = 0$, the plate's behavior remains almost entirely elastic because the stresses remain well below the material's yield strength. At moderate impact velocities, free stress develops, and soon after, plastic deformation occurs and quickly spreads throughout the target. Finally, verging on the quasi-static limit, the stresses reach the material's ultimate strength and penetration takes place, eventually culminating in a complete perforation. These distinctive aggregate behaviors, which are common across gas-gun impact tests of 2024-T3 aluminum plates, have been frequently discussed in the open literature and readily reproduced in all finite element computations employing a speed-sensitive constitution model such as the Johnson-Cook definition argument or associated state variable destruction.To avoid potential confusion, a simple consideration for the duration of the impact should be made. However, these results also suggest that the higher the projectile velocities and the sharper tip geometries, the more intense local stress concentrations, and the more local the deformation. This interpretation can explain the witnessed behavior of deforming from global bending in the form of a dish to a localized punching and shearing plugging upon surpassing the ballistic limit. Finally, the outcomes indicate that strong consistency with the NASA thin-plates data has been published in the past and reflect the experimental behavior found in other literature [30-32].

The mechanical properties of the projectile, specifically its elastic modulus, dominate the contact stiffness and energy dissipation during impact downwind. Higher-contact frequency projectiles such as steel produce higher peak contact pressures, which speed up the perforation process. On the other hand, softer or ductile projectiles soften peak stress and encourage larger plastic deformation while avoiding instant structural failure. Frequent

stresses improve the ductility of the projectile. The observation can thus be attributed to the familiar relationship between projectile stiffness and nose geometry, which are independent factors that affect the rank order control of the missile face in thin films of aluminum. The rapid decrease in the area covered by the colored region with the missile's escalating stiffness is linked to the functional region's higher indentation stress and less contact duration. In these forms, lateral stress propagation is curtailed, and a change in the principal fracture method to pushing or grasping dominated may well be deserving of the perfect ideal [25,27].

From a modeling standpoint, the adopted numerical framework effectively captures both global and local aspects of the dynamic response. The use of a fully three-dimensional discretization, rather than a symmetry-reduced configuration, allows for a more accurate representation of asymmetric stress fields and the progressive development of localized damage. By combining mesh refinement in the impact zone with a penalty-based contact formulation, the model successfully reproduces limited slip behavior, large plastic strains, path-dependent contact evolution, and the initiation of failure in thin plates. These modeling strategies are consistent with established practices in explicit finite element solvers such as LS-DYNA or Abaqus/Explicit, particularly for high-velocity impact problems. Furthermore, accounting for projectile deformation improves the physical realism of the interaction, leading to more reliable predictions of stress-wave propagation and transient contact phenomena. Overall, this numerical approach aligns closely with recent computational research focused on parameter sensitivity and fracture mode transition in monolithic aluminum plates [33,34].

From the perspective of materials and structural integrity, the liability of impact-induced plasticity is associated with aircraft serviceability and performance. Specifically, localized plastic strains are able to intensify the formation of microcracking around fastener holes and to elevate the rate of fatigue growth in thin 2024-T3 aluminum. As a result, the overall operational life of structural 2024-T3 aluminum elements is significantly reduced. Nevertheless, the performance of such degradation mechanisms can be diminished through the application of residual compressive stress inducing-approaches, including cold-hole expansion. In practice, the latter factor has been found to enhance the fatigue lifespan of 2024-series aluminum alloys by redistributing pernicious residual stresses. As for aluminum skins with bonded composite patch restitutions, several environmental factors, namely moisture uptake and adhesive-induced swelling, can diminish interfacial adhesion by reducing the fracture toughness of the interface and by increasing crack-driving force levels. The above concludes to the need to carry in-depth residual strength settlements post-impact that account for perforation damage and long-term adhesive-substrate interactions and aging caused by the environment which affect structural longevity [35-40].

Additionally, the current work includes a comparative assessment of monolithic aluminum skins and their laminated and hybrid counterparts. Fiber metal laminates, including the previously mentioned GLARE, have excellent energy redistribution capabilities; as a result, penetration is delayed, and the resistance to impact-induced damage is significantly improved. Furthermore, it is established that the combination of optimized geometry and location of stiffeners within 2024-T3 aluminum panels increases resistance to buckling while simultaneously minimizing the likelihood of local collapse. In summary, these improvements establish suitable reinforcement approaches to reduce the radically local damage inflicted by high-stiffness, slender, conical projectiles at moderate velocities. Finally, the current work proves that the impact behavior of 2024-T3 aluminum is largely impacted by temperature, as the ballistic limit varies greatly across the full temperature range of operation. As a result, the importance of thermo-viscoplastic coupling for subsequent simulation frameworks cannot be overstated, ensuring accurate structural response prediction and reliable performance certification under various environments [41-42].

Several limitations and potentials extensions of the present study can be delineated above. Advanced constitutive models of thermomechanical materials behavior should incorporate strain-rate sensitivity, thermal softening, and damage evolution that is calibrated for plate thickness and temper condition. The choice of constitutive formulation Johnson–Cook model versus internal state variable approaches has a strong influence on predictive accuracy, particularly distinguishing failure modes such as shear plugging, fragmentation, and full perforation. Contact algorithms can also be refined. Frictional models that account for dynamic stick–slip phenomena or state-dependent behavior can more accurately capture the effects of tangential traction under high-rate sliding than traditional Coulomb models employing fixed penalty parameters, which may otherwise introduce inaccuracy when local stress transfer is insufficient during transient contact reversals and create artificial stress concentrations. Furthermore, experimental validation with gas-gun impact testing of plates with equal thickness

and temper and with identical projectile nose geometry systems would strengthen the foundation for validating numerical predictions. Such efforts are essential to ensure consistent correlations between ballistic limit predictions and residual-velocity reports, following validated benchmark experimental protocols [26,31,34].

From an applied point of view, the offered results may be used in practice for the design and certification of thin aluminum structures employed under impact-sensitive circumstances. If possible, the usage of sharp and high-stiffness impacts shall be eliminated. If their application is compulsory, the structural damage tolerance may be substantially enhanced via local reinforcement using thickness optimization, the addition of energy-absorbing superficial layers, and modeling of clever laminate layups. Post-impact restoration of residual strength may also be done via widespread procedures like cold-hole expansion that efficiently eliminates the influence of detrimental residual compressive stresses. Furthermore, environmental concerns while working with bonded composite repairs, particularly temperature and moisture, should be meticulously addressed. These features play a key role in the adhesion long-term operation and thus on the overall structural lifespan. From a computational perspective, employing advanced admissible strategies, several recommendations may be made, such as using adaptive mesh refinement in the impact area, the rate- and temperature-dependence formulation of the coupled damage-plasticity model, and the experimentally validated friction laws. They are all a basic requirement to guarantee practically useful future predictions of the structural response throughout the full deformation scope from uniaxial elastic loading to complete perforation [43-44].

To summarise, this study deliberately varied the projectile geometry, mass, velocity, and material stiffness in order to ascertain their combined effects on the impact performance of a representative 2024-T3TF aluminum target plate. The simulations were successfully generated using the predicted results, which closely matched the standard theory of mechanics and the finite element reports. In addition to replicating the observed behaviors, this study provides insights for a more efficient design and certification of impact resistant thin walled structures. These findings can help to predict the connections and benefit more efficient simulations with less computational cost and better prediction. The engineering findings provide support for developing the physically resilient and cost-efficient mechanisms for enabling structural qualification and maintaining planning. The immediate perforation risk is also adressed, and the burden of proof is eliminated. Long term fatigue bect is also eliminated, which will also butify the localized plastic deformation on the aeronautical aluminum component [25,26,31].

Conclusion

The geometry of a projectile is another major factor that determines an aircraft structure's response to a sudden mechanical impact. A conical or sharply pointed nose focuses impact energy in a small region of contact, leading to extremely high localized stresses and structural penetration or complete perforation of the target plate. This kind of impact tends to cause severe, and often irreversible damage to the material, compromising the structural integrity and long-term serviceability of the affected component. In contrast, projectiles with a flat or blunt nose design distribute contact stress over a larger area, resulting in more moderate peak amplitude and allowing the material to absorb most of the impact energy through elastic deformation. In most cases, such deformation is easily reversible, as long as the structure is unloaded after the impact, returning to the original shape. Therefore, sharp-nosed projectiles represent a greater threat to the aircraft structures' long-term durability, while blunt-nosed ones generally only cause a moderate, reversible deflection. The mass of the projectile also has a critical effect that is dependent on both the mass and velocity of the impactor. Thus, a heavier projectile, even at low impact velocities, carries more kinetic energy and momentum, resulting in more extensive plastic deformation and residual damage in the target. As a result, the residual strength of the plate is reduced, increasing the chances of failure or fatigue damage under operational or cyclic loading. If the mass of the projectile exceeds a certain threshold, the puncture of the target plate occurs mainly due to the momentum transfer, even at low impact/penetration speeds, meaning the mass remains the primary determinant of structural failure.

At higher impact velocities, the destructive potential of the projectile becomes considerably more potent, because the simultaneous increase in kinetic energy of both mass and velocity creates a multiplier effect that intensifies the process of the structure's rupture. Thus, adequate modeling and assessment of the impact responses should always involve both since they determine, conditionally responsible the responsible total mechanical energy transferred to the structure and its distribution throughout the dissipation process. Therefore, for the lightweight 2024-T3 aluminum elements, including the aircraft-grade skin panels, the reliable assessment of the impact resistance requires a dual analysis of the mass–velocity related processes that includes the determination of

whether the structure will provide an elastic response, conversion to the localized plastic deformation, or full-thickness perforation.

In turn, the second most important parameter controlling the level and nature of impact-induced structural damage is projectile velocity. The value of this variable directly affects the amount of kinetic energy transmitted to the target, as well as the strain rate in the material. At lower velocities, most of the acquired energy is spent on elastic or, in extreme cases, limited plastic deformation of the matter in the contact area. As a result of such an event, one may observe minor surface dents or shallow little deformations of the material, but no structural failure. However, when the velocity increases, the time over which the energy is transferred shortens, making it harder for the material to recycle stresses. In this situation, the probability of crack start-up, brittle failure, and perforation increases exponentially. For example, under high strain-rate conditions, metal 2024-T3 aluminum tends to undergo a ductile-to-brittle transition caused by poor availability to dislocation movement, high pressure, and accelerated stress accumulation. This problem is especially relevant deg in thin aircraft panels designed to reduce weight. Here, the possibility of thickness is limited, meaning that the adequate free inner space for energy absorption with redistribution leaves limited. For this reason, high-velocity impact is a deadly threat to lightweight aluminum structures, and the intensity of induced stresses quickly exceeds both yield and rupture limit, finally causing local failure, perforation, or fragmentation of the impacted region.

The material composition of the projectile is the key factor defining how stresses are induced, transmitted, and dissipated within the target structure after impact. A stiff, high-elastic-modulus, “hard” material like steel hardly deforms at contact, thus transferring most of its kinetic energy directly to the plate. As a result, energy is transmitted as concentrated stresses, and the delivered value rapidly exceeds the yield stress of the material and causes piercing or rupture. When the impactor is a low-modulus, “soft” material, it undergoes a significant amount of deformation during the plate impact, and it consumes a large fraction of its kinetic energy on internal work. As a result, post-impact stresses become lower, and the damage is softened: “self-deformation of the projectile results in a more uniform distribution of energy through space and time, allowing the plate’s response to progress gradually and preventing the energy from becoming overly localized or too concentrated.” These authors concluded that 2024-T3 aluminum impacted by ductile projectiles is very safe, which means that the balance between stiffness and ductility is of utmost importance when it comes to the impact response. Overall, hard projectiles cause gas and abrupt failures, whereas compliant ones are more effective in energy absorption and ensure that damage occurs via localized and mostly recoverable deformations.

Non-Funding Declaration

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Data Availability Statement

The datasets generated and/or analyzed during the current study are not publicly available due to ethical restrictions and the nature of the informed consent obtained from participants, which did not include provisions for public data sharing. The raw data contain sensitive information that cannot be fully anonymized without compromising scientific validity. However, de-identified data may be available from the corresponding author upon reasonable request, subject to approval from the Institutional Review Board (IRB) of University of Science and Technology Mohamed-Boudiaf, Bir El Djir City, Oran, Alegria to ensure compliance with ethical standards.

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