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COMPARATIVE ANALYSIS OF THE USE OF CLASSIC AND LIGHT MATERIALS IN THE CONSTRUCTION OF ENERGY-ABSORBING STRUCTURES IN VEHICLES

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Abstract

This study investigates the performance of steel and aluminum alloys in the construction of energy–absorbing elements used in front collision management systems, essential for enhancing vehicle safety during frontal impacts. These systems are designed to absorb and dissipate impact energy while minimizing the acceleration forces transmitted to vehicle occupants, which could lead to injury. The research evaluates the impact of material choice and geometric modifications on the performance of these absorbers, using Finite Element Method (FEM) simulations.

Steel absorbers, known for their high strength, effectively absorb energy through plastic deformation while maintaining structural integrity. On the other hand, aluminum absorbers, with their lower density, offer notable advantages in reducing the overall mass of the vehicle, thus improving fuel efficiency and performance. However, a comprehensive analysis of the current state of knowledge on these materials in energy absorption applications is necessary. Previous studies, such as those by Bhardawaj et al. [1] and Hussain et al. [2], have explored similar aspects using simulation techniques, providing a foundation for further development in this field. Additionally, material properties and their impact on structural performance have been examined, offering insights into lightweight design optimization [3].

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This study also explores two geometric modifications—perforations and indentations—designed to optimize the absorber's acceleration profile and enhance energy dissipation. While these modifications have been analyzed in prior research, their combined impact with material selection in crash absorbers remains insufficiently examined. Therefore, this work builds on existing findings to further investigate the effectiveness of these geometric features, integrating insights from recent studies.

The results provide valuable insights into how material selection and geometric optimization can be combined to design efficient, lightweight, and high-performing energy-absorbing elements in collision management systems. Additionally, this study highlights gaps in the literature and suggests future directions for optimizing energy dissipation in automotive crash absorbers, ensuring a well-grounded contribution to the current state of knowledge.

Keywords: passive-safety; energy absorption; FEA; crash test; crash box

1. Introduction

In vehicle construction, one of the key aspects of ensuring passenger safety is the design of controlled crumple zones, whose primary function is to absorb and dissipate energy in the event of a collision. Depending on how stress is distributed throughout the vehicle's structural frame, as illustrated in Figure 1, the body is divided into several zones, each serving a different purpose. In the case of a frontal impact, the load is transferred from the front bumper to the crash boxes and then to the longitudinal beams. The main objective of the zone that includes these elements is to disperse the impact energy, so that as little as possible is transmitted to the rigid passenger cell [4].

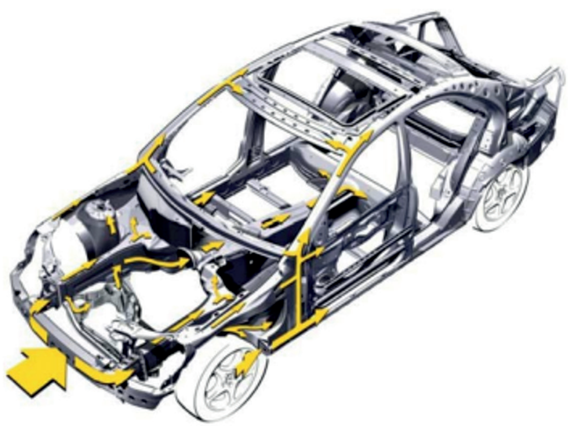

Fig. 1. Dissipation of energy in the vehicle due to a frontal impact [4]

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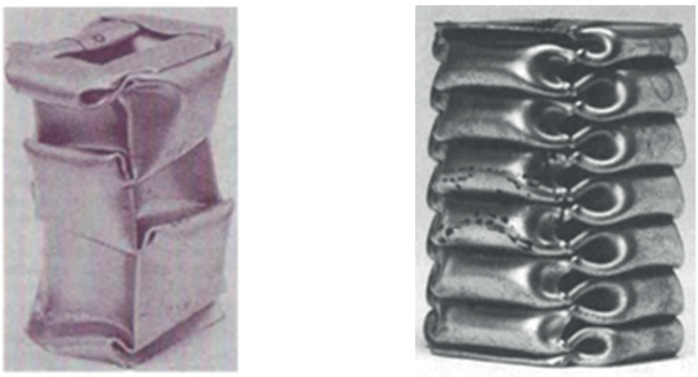
The primary materials used in constructing these structures include HSS and AHSS, known for their excellent strength properties and plastic characteristics. However, lightweight metal alloys such as aluminum and magnesium are increasingly utilized to reduce vehicle weight [5]. This weight reduction contributes not only to improved fuel efficiency but also enhances overall vehicle performance. It is emphasized that material selection should take mechanical properties into account to optimize energy absorption while minimizing mass, aligning with trends toward lightweight vehicle design [3].

The desired deformation mechanism for energy absorbers is crushing, achieved through a series of local buckling (symmetric or asymmetric), resulting in stable energy absorption along the entire length of the crush. However, global buckling of the absorber may occur, leading to a drastic reduction in its energy absorption capacity. A comparison of these deformation mechanisms is shown in Figure 2.



(a) **(b)**

Fig. 2. Comparison of the crushing mechanisms of the absorber: global buckling (a), series of local bucklings (b) [6]

The studies by Bhardawaj et al. [1] demonstrated that the use of numerical methods, such as ANSYS, enables accurate modeling of frontal collision characteristics. Hussain et al. [2] analyzed the impact of notches on the energy absorption capacity of composite elements, highlighting the importance of geometric modifications for optimizing collision management systems. Ferdynus et al. [7] conducted research on the influence of indentations on the energy absorption capacity of thin-walled prismatic tubes. Podkowski and Okruch [8] explored fatigue properties of steel, providing complementary insights into material behavior under repeated loading that can inform energy dissipation strategies. The results of these studies suggest that proper deformation geometry is crucial for effective energy absorption.

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In the work presented in [9], numerical simulations were conducted on aluminum profiles with cylindrical dents located on the side edges. The study focused on investigating how the location and depth of these cylindrical dents affected the energy absorption properties of the profiles. A similar issue was addressed in [7], where both numerical and experimental analyses were used to explore the influence of geometric modifications on energy absorption. These studies highlight the significant role that dent characteristics play in the overall crashworthiness of aluminum structures.

It is well known that deacceleration has massive impact on human body and its internal organs. Even without serious external damage of the tissue, internal injuries can be deadly. The maximum allowable deceleration [10] for a serious injury but not life-threatening injury is 20 g. The clear conclusion is the significant impact that shape modifications have on acceleration levels [11].

The buckling mechanism was described in the works of Wierzbicki and Abramowicz [12], who adopted a rigid-perfectly plastic material model to simulate the behavior of thin-walled profiles under axial loading. In this model, deformation occurs in layers, as shown in Figure 3, and the dissipated energy can be described by equations (1) or (2) [4].

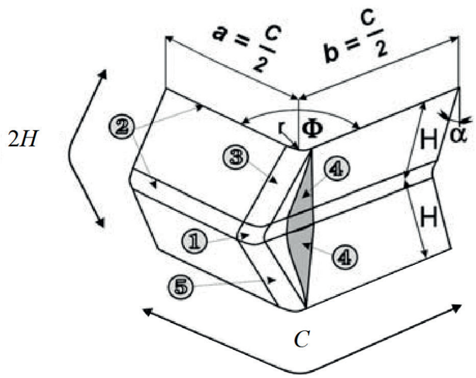

Fig. 3. The model of asymmetric deformation of thin-walled structure [4]

$$E_I = \frac{\sigma_0 t^2}{4}\left(16HA_1\frac{r}{t} + 2\pi(a+b) + 4A_3\frac{H^2}{r}\right) \quad (1)$$

$$E_I = \frac{\sigma_0 t^2}{4}\left(2\pi\frac{H^2}{t} + 2\pi(a+b) + \pi H\right) \quad (2)$$

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σ_0 – Stress in the plastic deformation zone, MPa,
t – Wall thickness, mm,
H – Distance between adjacent plastic hinges, mm,
A_1, A_2 – Geometric coefficients of the deformed plastic element,
r – Radius of the toroidal surface, mm.

The behavior of thin-walled energy absorbers, such as crashboxes, under axial loading has been elucidated in the work of Baroutaji, Sajjia, and Olabi [13]. In their study, "On the crashworthiness performance of thin-walled energy absorbers: Recent advances and future developments", the authors explore the progressive buckling mechanism of these structures. They describe how deformation unfolds through controlled plastic folding, where the thin-walled profile collapses in a series of predictable folds, dissipating energy efficiently. This process, illustrated in their analysis of various tube configurations, relies on the material's plastic properties and geometric design, with energy dissipation quantifiable through metrics like specific energy absorption (SEA) and crush force efficiency (CFE) [13].

As can be seen, the above described deformation phenomenon is a non-linear issue, although as the authors of the publication [14, 15] note, due to the limitations of computing power of computers, a linear approach was used in the CRASH3 method, used to determine the speed and deformation of vehicles during a collision. The non-linear approach proposed by them using tensor calculus allowed for a more accurate determination of EES, but the use of the Finite Element Method should allow for obtaining even more accurate results.

2. FEA model description

In the application phase, computer simulations using the Finite Element Method were utilized to investigate the behavior of all design variants under dynamic loading. A simulation was prepared according to the scheme presented in Figure 4, where the tested absorber, labeled as number 2, is attached to a rigid plate with a mass of 350 kg, labeled as number 1, and then collides with a rigid plate, labeled as number 3, at a speed of 24 km/h. Boundary conditions were applied as in standard test prepared by Automotive Industry Institute. In results of these assumptions it let to compare the results with other tests [16]. Preprocessing was carried out using HyperWorks software, and the calculations were performed using the LS-Dyna r13 solver.

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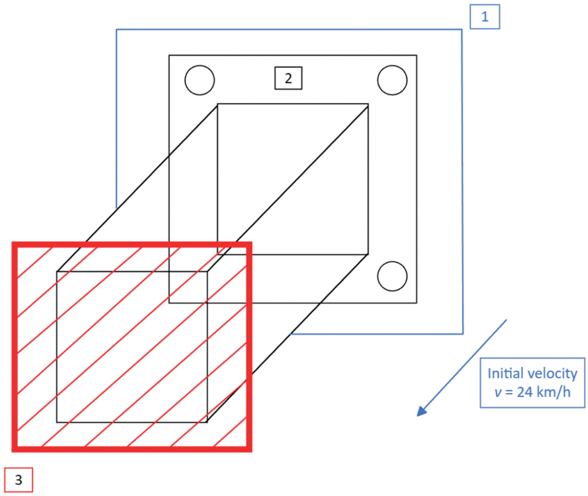

Fig. 4. Schematic of the conditions for numerical analysis to study crash boxes

Due to the fact that the construction of the crash box consists of thin-walled elements, shell elements were chosen for the discretization of the geometric model. SHELL elements were used with ELFORM16, the scheme of which is shown in Figure 5. This is a fully integrated element with 4 integration points on the surface and 5 integration points through the thickness. It has 5 degrees of freedom at each node (3 translations and 2 rotations) [17].

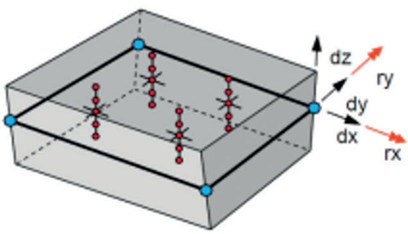

Fig. 5. Schematic of the SHELL element with the ELFORM16 definition [17]

For the elements describing the wall and plate represented by trolley with mass equal to 350 kg, MAT20 RIGID was assigned, which is characterized by the absence of deformability. The defined Young's modulus and Poisson's ratio for this material model are used to address contact issues [7].

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For the elements describing the deformable parts such as crashbox, front and rear base, MAT24 was assigned, for which plasticity hardening curves were added (see Figure 6).

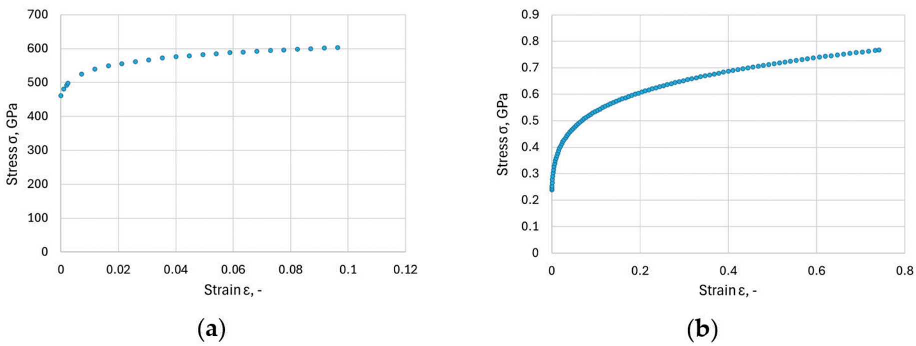

Fig. 6. Applied plasticity hardening curves: (a) structural steel S235, (b) aluminum alloy 7075

3. Basic CrashBox model

The baseline model of the absorber was a rectangular profile with dimensions of 126x66x1 mm and a height of 140 mm, connected to two bases. The CAD model is shown in Figure 8. Based on this, the FEM model was prepared, as shown in Figure 7.

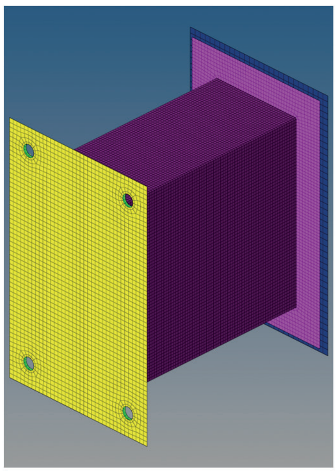

Fig. 7. FEA model of the baseline crash box

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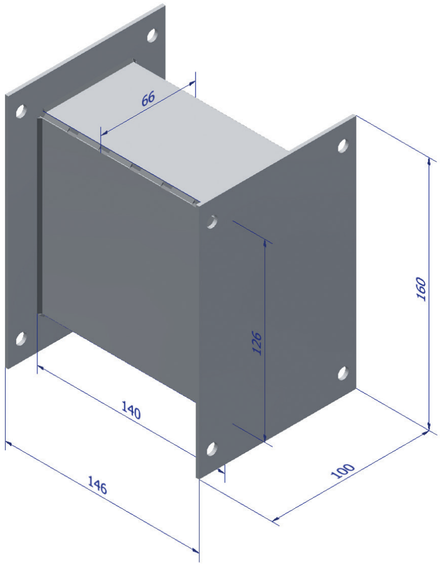

Fig. 8. CAD model of the baseline crash box

Simulations of a frontal collision at a speed of 24 km/h were conducted, with the primary metric for comparison being the time history of acceleration profile during the impact. According to the assumptions, the absorber should absorb the impact energy before crushing, while the resulting acceleration must not be excessive for passenger safety. A threshold acceleration value of 40 g was adopted based on crash box tests available on the market. Figure 9 shows the deformation profile of the absorber, while Figure 10 illustrates results of time history of acceleration during the impact. The energy balance in the simulation, presented in Figure 11, does not show any anomalies, such as an hourglass effect or unexplained increases in energy within the system.

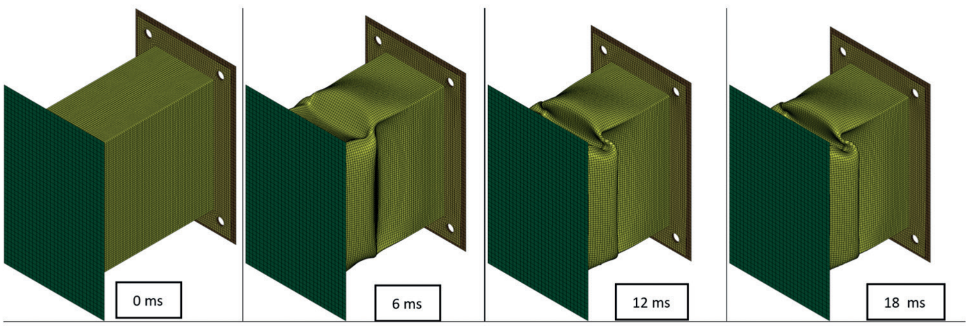

Fig. 9. Simulation results for the baseline absorber

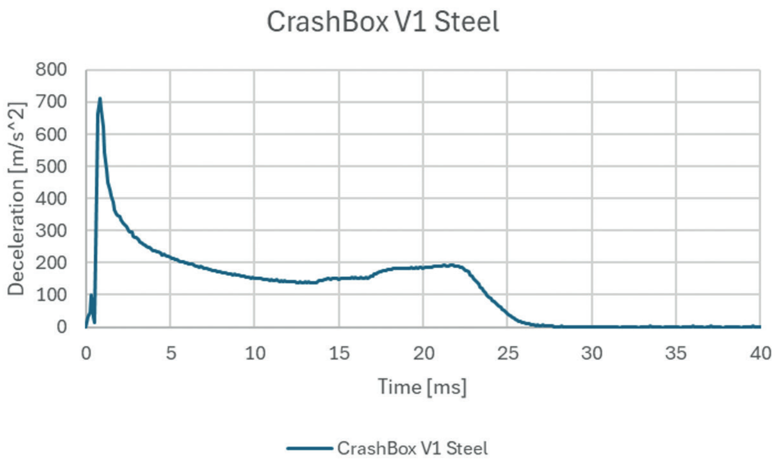

Fig. 10. The time history of acceleration during the impact

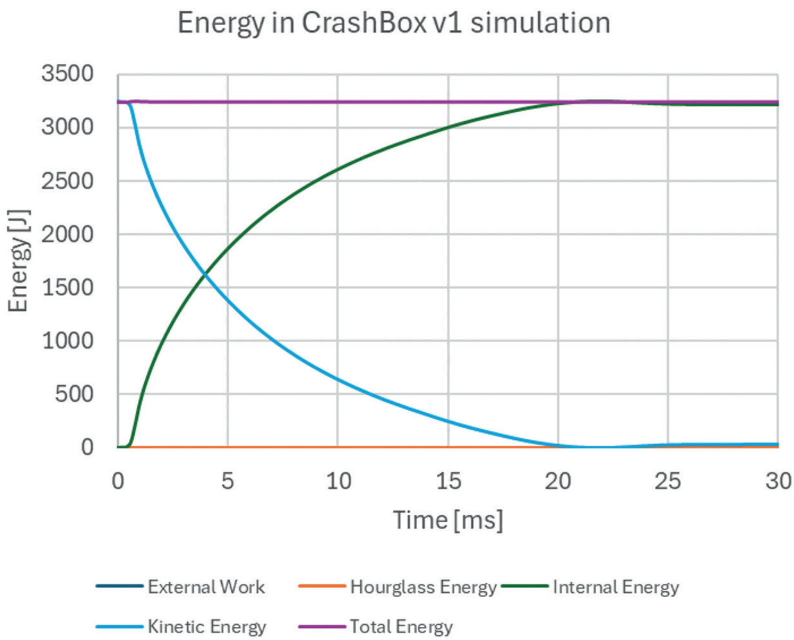

Fig. 11. Energy balance in the simulation for the baseline absorber

The obtained peak of acceleration during the initial contact exceeded 69 g. To reduce this value, changes were made to the geometry of the crash box.

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4. First improvement of geometry

In the first iteration, initiators were added to the structure in the form of notches in the corners, visible in Figure 12, aimed at reducing the stiffness of the structure. The results of the simulations are presented in Figures 13 and 14.

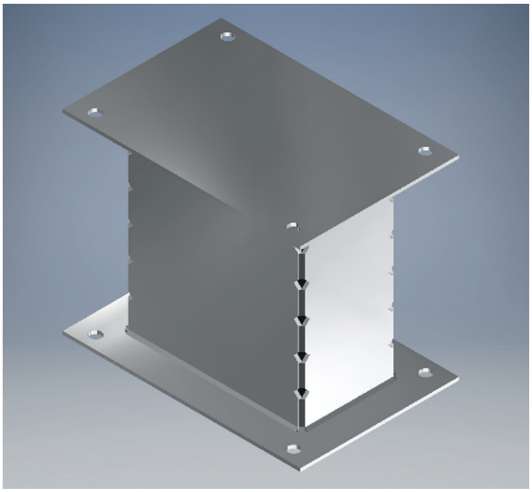

Fig. 12. Model after the first optimization of the absorber

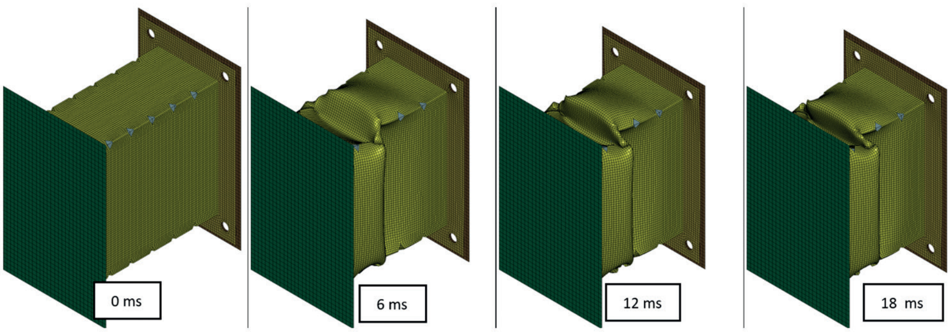

Fig. 13. Simulation results after the first optimization of the absorber

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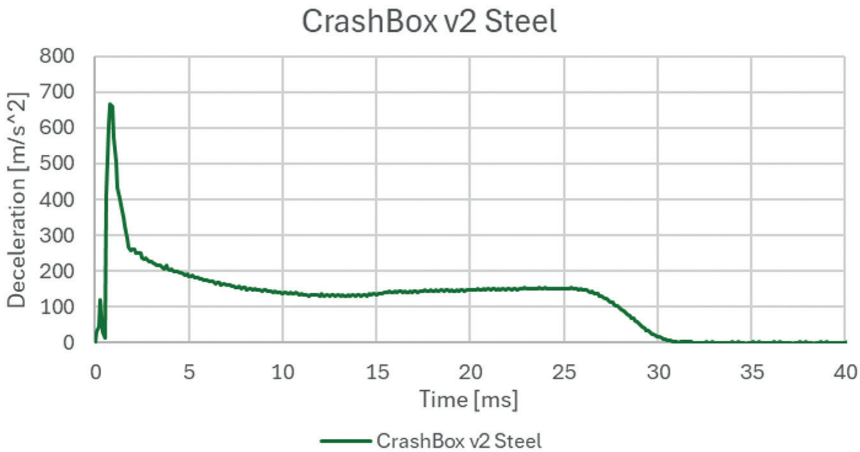

Fig. 14. Deceleration profile obtained for the first optimization of the absorber

The application of geometric changes did not yield the expected results, as the simulation produced an deceleration of around 68 g.

5. Second improvement of geometry

The next step was to add horizontal indentations, visible in Figure 15, which were intended to induce controlled folding of the absorber. The simulation results are presented in Figures 16 and 17.

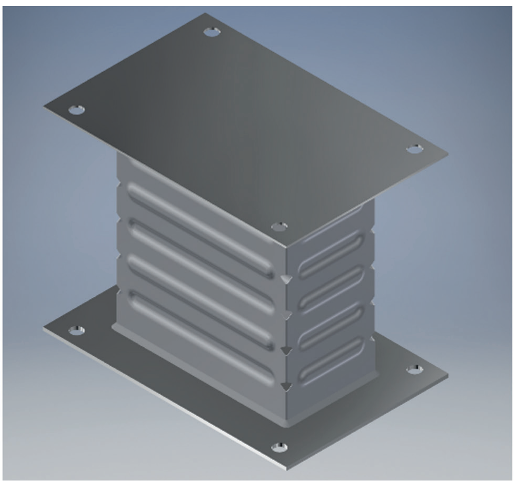

Fig. 15. Model after the second optimization of the absorber

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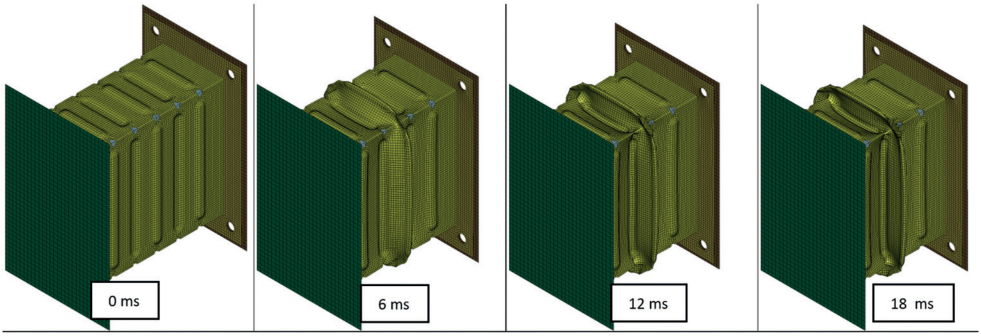

Fig. 16. Simulation results after the second optimization of the absorber

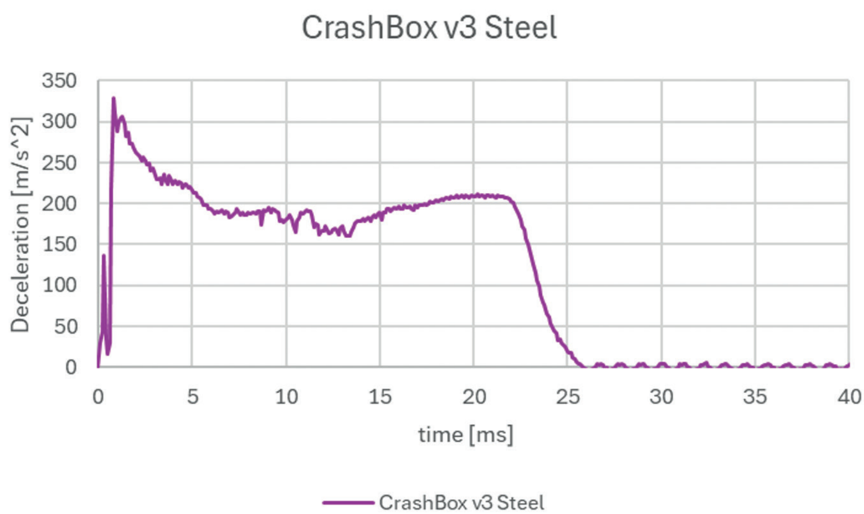

Fig. 17. The time history of acceleration during the impact

The introduction of geometric changes resulted in an acceleration of approximately 33 g.

The impact of shape design is well described already [18, 19]. The variable thickness of the sidewall is intended to trigger profile deformation in its thinnest cross-section. In addition, the wall thickness gradation allows more energy to be absorbed at a later stage of dynamic loading [20].

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6. Comparison with aluminium alloys

For the latest geometric model, a comparison was made for the absorber made from aluminum alloy 7075 to determine the potential benefits of using this material without reducing the absorber's energy absorption capacity. The comparison of the material hardening curves is presented in Figure 18.

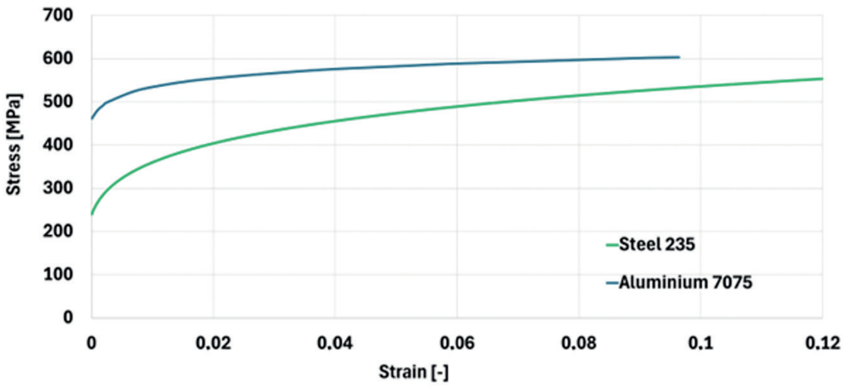

Fig. 18. Comparison of the material hardening curves for steel S235 and aluminum alloy 7075

The comparison of the acceleration profiles is shown in Figure 19. It can be observed that the values obtained in both cases are similar. Although the peak acceleration is 12% higher than that of the steel absorber, the resulting values are still within acceptable limits. The distribution of stresses and strains in the absorber is presented in Figure 20, while Table 1 provides a comparison of the weights of the absorbers.

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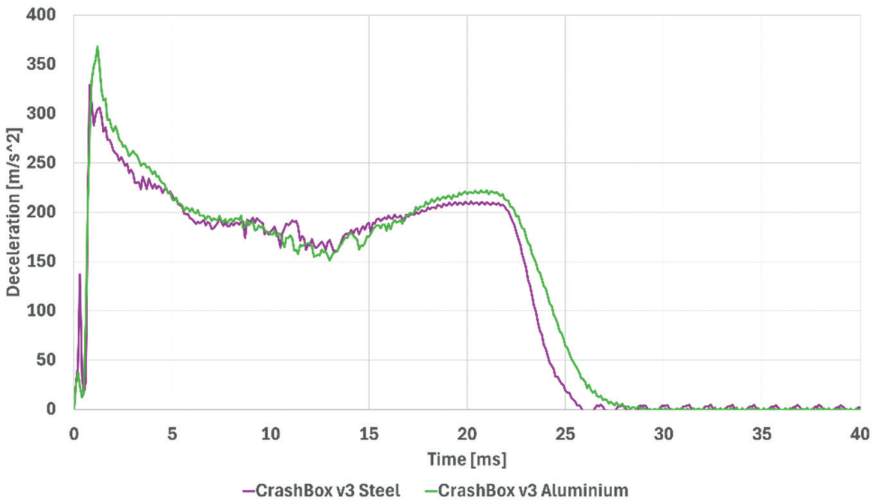

Fig. 19. Comparison of the deceleration profiles for steel and aluminum crash boxes

There are clearly visible parameters of the results, which have already been described [21]. The initial peak crush force should not be too high, to avoid causing any deformations that are unsafe for occupants, and not too low, so that it does not deform under low forces. Another main property is its energy absorption, which is the load as a function of displacement.

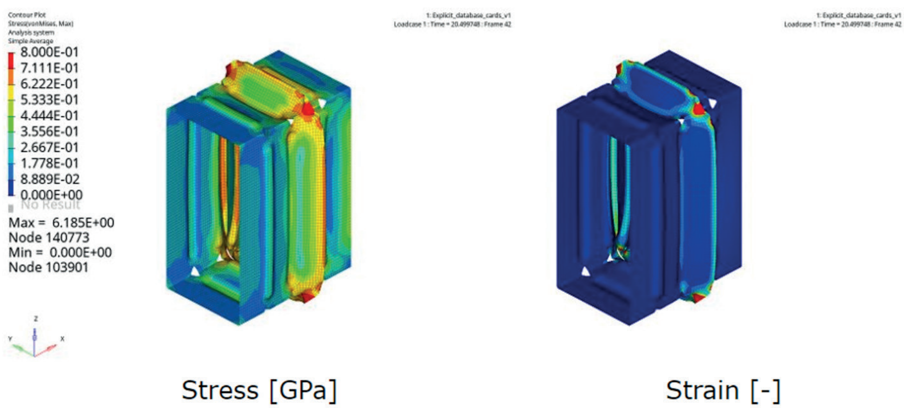

Fig. 20. Distribution of stresses and strains in the aluminum absorber in max deformation at function of time

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Tab. 1. Comparison of the weights of the absorbers [kg]

	Crashbox_V1	Crashbox_V2	Crashbox_V3
Aluminium 7075	0.292	0.287	0.294
Steel S235	0.845	0.835	0.855

In this case mass reduction of 35% was achieved.

The obtained acceleration values in the second variant (33 g) are comparable to the results obtained by Ferdynus et al. [7], who studied similar geometric modifications in thin-walled energy-absorbing structures. The advantage of the analyzed solution is the reduction in the absorber's dimensions, allowing it to be used in space-constrained locations.

7. Conclusions

The results of this study underscore the critical role that both material selection and geometric design play in optimizing the performance of energy-absorbing elements in front collision management systems. Steel, with its high strength and durability, is an excellent choice for absorbers that require a robust capacity to absorb significant amounts of energy. Steel absorbers effectively manage impact energy through both elastic and plastic deformation, ensuring the vehicle's structural integrity is maintained during high-load collisions. However, while steel offers high energy absorption, its heavier weight can be a disadvantage in terms of vehicle mass, fuel efficiency, and overall vehicle performance.

In contrast, aluminum alloys offer significant benefits in terms of mass reduction due to their lower density. By incorporating aluminum in the design of absorbers, manufacturers can reduce the overall weight of the vehicle, which positively impacts fuel efficiency and performance metrics. Although aluminum absorbers may not offer the same level of strength as steel, their ability to absorb energy efficiently through deformation, combined with their lightweight properties, makes them a suitable option for applications where reducing the overall vehicle weight is a priority [8].

A particularly significant aspect of the studied solution is the noticeable improvement in deceleration over a small displacement. Due to the compact size of the crash-box structure, it is possible to apply this or similar modifications in designs requiring limited overall dimensions. Additionally, the smooth acceleration profile with low deceleration values can significantly enhance the safety of passengers or other participants involved in an incident utilizing the proposed structural solution.

Furthermore, the study examined the impact of geometric modifications on the performance of the absorbers. Two modifications, perforations and indentations, were implemented in the

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absorber design to optimize the acceleration profile. These geometric changes proved to be effective in enhancing the energy absorption capabilities of the absorber by improving the distribution of impact forces and reducing the peak acceleration transmitted to the vehicle occupants. Perforations allowed for more controlled deformation, while indentations created localized zones for better energy dissipation.

Overall, the findings suggest that a balance between material properties and geometric design is crucial to achieving optimal performance in energy-absorbing elements. Both steel and aluminum alloys have distinct advantages that can be leveraged depending on the specific requirements of the vehicle design, such as strength, weight reduction, and energy efficiency. Geometric modifications further enhance the absorber's functionality, enabling more efficient energy dissipation and improving occupant protection during frontal collisions. The results of this study provide valuable insights for future vehicle design, highlighting the importance of integrating material and design innovations to improve vehicle safety and performance.

8. Acknowledgement

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The paper submitted for the first time for publication in our periodical will be treated as an original. After the peer reviews are received, all changes to the paper should only be made in the “Track changes” mode.

9. Nomenclature

EES Equivalent Energy Speed, m/s
HSS High Strength Steels
AHSS Advance High Strength Steels
FEA Finite Methode Analysis
CAD Computer Added Design
g Earth acceleration, m/s^2

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