ENHANCING CRUSH BOX ENERGY ABSORPTION CAPACITY: A NUMERICAL INVESTIGATION UNDER QUASI-STATIC AXIAL CRUSHING

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The growing number of passenger vehicles has led to an increase in road accidents, emphasizing the need for improved safety and energy absorption systems. The crush box is an essential component located at the front end of the car frame. Its purpose is to collapse and absorb crash energy, effectively minimizing damage to the main cabin frame and ensuring the safety of the passengers. For the design of the crush box, various shapes and material combinations are considered and numerically analyzed using LS-DYNA software to investigate the energy absorption capability of various crush boxes. For all these analyses, preprocessing is done using ANSA and post-processing using HyperView. The crush box is subjected to nonlinear, quasi-static, and axial crushing loads during finite element analysis. Extensive analysis has been conducted to examine the impact of material properties, wall thickness, and shape of the crush box on energy absorption. The findings reveal that a rectangular crush box with alternate beads demonstrates superior energy absorption efficiency compared to conventional designs.

Keywords: Energy absorption; crash box; crashworthiness; crushing

1. Introduction

For the purpose of addressing the growing concerns over the safety of passengers and the requirement for transportation solutions that are more energy efficient, governments all over the world have implemented stringent laws on vehicle safety requirements [1]–[3]. In order to fulfil these standards for safety and energy efficiency, automobile manufacturers have been pushed to continually innovate in order to avoid compromising the quality of their products. Because of this, it has become necessary to improve crashworthiness, which refers to the ability of a vehicle to protect its occupants in the event of an accident [4]–[6].

Alarming statistics regarding road accidents are provided by the World Health Organization (WHO), which draws attention to the significance of the

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subject of vehicle safety. Every year, road traffic accidents cause a large number of deaths and serious injuries worldwide [7]. The data that was recently collected from the United States by the National Highway Traffic Safety Administration (NHTSA) indicates that the situation is extremely serious [8]. Despite the fact that significant progress has been made in terms of passenger safety since the establishment of federal motor vehicle regulations in 1966, new challenges continue to emerge as a result of the growing desire for environmentally friendly and fuel-efficient automobiles [9].

Advancements in vehicle safety have been driven by a deep understanding of crashworthiness principles. This knowledge has paved the way for the creation of innovative engineering solutions that aim to reduce the impact of collisions on car occupants. Essential to these endeavours is the enhancement of automobile crash boxes, which play a critical role in absorbing and dispersing energy during frontal and rear collisions, thus mitigating harm to passengers. An investigation has been conducted to examine the influence of material properties and wall thickness on the energy absorption of the crash box. A recent study by Ma et al. [10] revealed that aluminium-composite hybrid tubes exhibit superior crashworthiness characteristics compared to bare aluminium tubes. Specifically, these hybrid tubes demonstrate higher levels of crushing force consistency and specific energy absorption. Previous studies have shown that incorporating auxetic foam in thicker tubes can enhance energy absorption but may reduce crushing efficiency. These observations highlight the significance of selecting appropriate material properties and wall thickness to optimize crash box performance. Furthermore, the complete diamond collapse mode has been reported to improve energy absorption while reducing peak crushing force compared to conventional designs [11]. In addition, the origami crash box, which produces a diamond-shaped mode, showcases a decrease in the initial peak force and a notable enhancement in energy absorption when compared to traditional hexagonal tubes [12]. Furthermore, studies have shown that foam-filled tri-tubes exhibit superior energy absorption compared to other tube configurations. Recent innovations, such as diamond and origami crash box designs, significantly improve energy absorption and overall crashworthiness. Numerical and experimental results confirm that these advanced designs are highly effective as energy absorbers in automotive applications [13]. These findings have practical implications and can be directly applied to improve the safety and crashworthiness of automotive vehicles. Although previous studies have yielded valuable findings regarding the enhancement of crash box designs and materials for impact protection and occupant safety, there remain several areas that require additional exploration. For example, further investigation is needed to understand how different cross-sections and materials, including magnesium, aluminium, and advanced high-strength steels, impact the crash performance of thin-walled energy absorbers [14]. In addition, upcoming studies should prioritize the advancement of novel materials and bionic designs that draw inspiration from cattails and bamboo structures. These innovations have the potential to significantly improve the specific energy absorption of automotive bumpers, as demonstrated by previous research [15]. The crash boxes are strategically placed in the front and back of automobiles, and they also absorb the energy that is generated by collisions. In the event that there is an impact on the back or front end of a vehicle, the crash boxes are designed in such a way that they collapse, so maximizing the amount of energy that is absorbed before the forces are transmitted to the main cabin. This ensures that the occupants are exposed to the least amount of risk possible. In this attractive field, experimental and theoretical studies [16]–[20] have examined square and circular tubes under static and dynamic loads. Several indicators have been proposed to evaluate the crashing characteristics and energy absorption capabilities of various structures [21]–[24].

This study focuses on improving crash box design to enhance energy absorption and occupant safety. Simulations are carried out using LS-DYNA, with preprocessing in ANSA and postprocessing in HyperView. The analysis investigates the effects of material properties, wall thickness, and geometric configuration under nonlinear, quasi-static, and axial loading conditions. The outcomes aim to provide a better understanding of the factors influencing energy absorption in automotive crash boxes.

2. Finite element modelling

For this investigation, we utilized advanced computational simulations through the implementation of Computer-Aided Engineering (CAE) software. The process is depicted in Figure 1, representing the sequential steps involved in constructing the numerical model. Nonlinear analysis is essential for understanding the behaviour of physical structures comprehensively. Nevertheless, in numerous instances, the behaviour of a structure can be estimated as linear if its deformation or motion remains minimal. As an example, a study on the behaviour of a structure takes into account the variations in its stiffness as it undergoes deformation. This requires the calculation of equilibrium. There are three main types of nonlinearities in structural analysis: geometrical, material, and boundary. These categories help to classify and understand the different factors that can affect the behaviour of structures. Significant deformations are involved in geometrical nonlinearity, while the elastic and plastic behaviour of materials is accounted for by material nonlinearity. Analysts must manage convergence, contact mechanics, and material issues with such complexity. As a result, predicting and getting reliable solutions from nonlinear simulations is difficult.

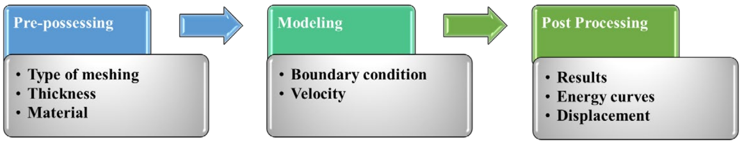

Fig. 1. The procedure for constructing the numerical model.

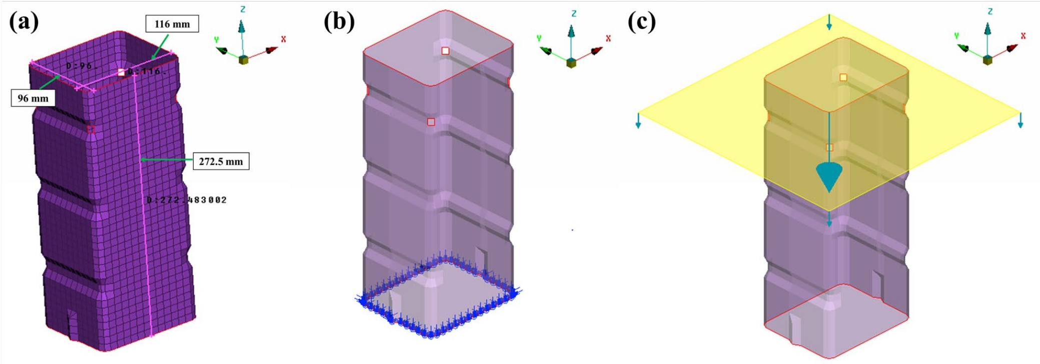

Fig. 2. Finite element (FE) model of the crush box structure (a) mesh model, (b) Boundary conditions, and (c) loading conditions (mass with initial velocity).

In the present work, LS-DYNA finite element software is used to design and simulate crush box deformation under compression load. Preprocessing is carried out using ANSA, while post-processing is performed using Hyper View for all these analyses. Originally designed for complex and dynamic simulations, it utilizes an explicit time marching scheme for solutions. It has the ability to deal with a wide range of engineering problems, including both simple and complex scenarios, and can handle various types of analyses and tasks. During a crash test, the vehicle undergoes a controlled impact with a solid wall at a specific speed. For the European New Car Assessment Programme (ENCAP) rigid wall front impact test, the velocity is set at 54 km/h. The goal is for the entire vehicle structure to achieve this speed upon impact and then come to a stop by the end of the crash. In order to accurately simulate any model in CAE software, it is crucial to specify the appropriate boundary conditions that closely resemble the real-world conditions. This is essential for obtaining accurate results in the analysis. This pertains to the practical applications of the model.

In this study, the crash box has overall dimensions of 116 mm length, 96 mm width, and 272.5 mm height, with a wall thickness of 2 mm as shown in Figure 2(a). The FE model was generated using a mixed mesh, predominantly with four-node Belytschko–Tsay shell elements, with an average element size of 7 mm. The element formulation adopted was ELFORM 16 (shell) with five through-thickness integration points (NIP = 5). In Figure 2(b), the boundary conditions are depicted, where six degrees of freedom are constrained at the bottom of the crash box, with one end being free and the other fixed due to a stay plate. Figure 2(c) represents a mass with an initial velocity loading condition, having a specified velocity of 15 m/s and a mass of 800 kg, resulting in a total impact energy of 90,000 J. Contact interactions were defined using the automatic single surface contact algorithm. During subsequent processing, the initial input file was given material properties and geometries in order to generate a coupled input file based on the information contained within the file. After that, the task was sent for analysis, and energy absorption capability and maximum displacement were obtained for further analysis.

Table 1.

Material properties

Material	Material Property			
	Density (kg/m^3)	Yield Strength (MPa)	Modulus of Elasticity (GPa)	Poisson's Ratio
Mild Steel	7830	235	200	0.3
Aluminium	2810	231	71.1	0.33
AlMgSi (B52)	2700	120	70	0.33

Table 1 provides the properties of the materials selected for analysis, including mild steel, aluminium, and aluminium alloy (AlMgSi - B52). FEM simulations inherently involve numerical errors due to discretization, material modelling, and boundary condition assumptions. Error in the present FEM simulations is less than 8%, which is within the acceptable range for crashworthiness analysis. In the present study, these three materials are considered for evaluating the crash box performance. Future investigations can be extended to additional materials to further broaden the scope and applicability of the analysis.

3. Results and discussion

3.1 Deformation analysis of crush box for various materials

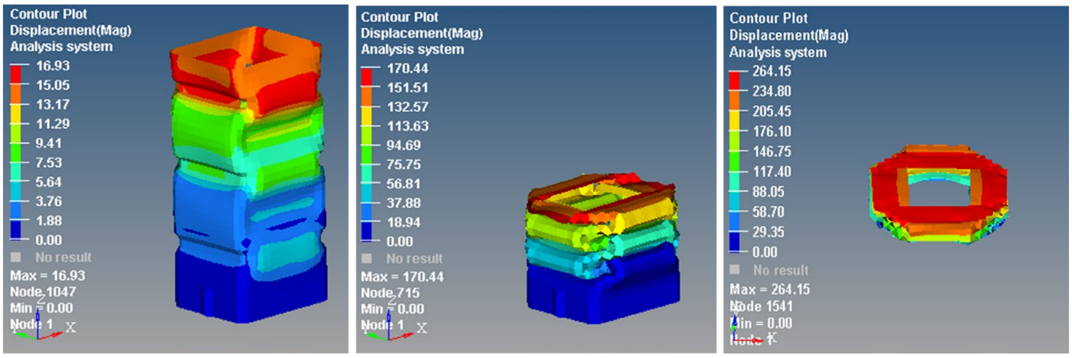

Fig. 3. Deformed shape of the square cross-section crush box of mild steel.

The crush tests carried out on mild steel, aluminium, and AlMgSi (B52) square cross-section crush boxes offer important insights into their mechanical behaviour under compressive loads. Figure 3 demonstrates the distorted form of the mild steel crush box, showing a maximum deformation of 264.15 mm. The axial behaviour can be observed in three distinct stages, representing elastic, plastic, and ultimate failure stages. On the other hand, Figure 4 illustrates the distorted form of the aluminium crush box, exhibiting surprising non-axial behaviour in spite of a maximum deformation of 267.41 mm, thereby requiring additional research into the deformation properties of the material. The deformed shape of the AlMgSi (B52) crush box is shown in Figure 5, with a maximum deformation of 265.13 mm. Its axial behaviour is similar to that of mild steel, although it exhibits slightly different deformation characteristics. This indicates a good balance between strength and ductility.

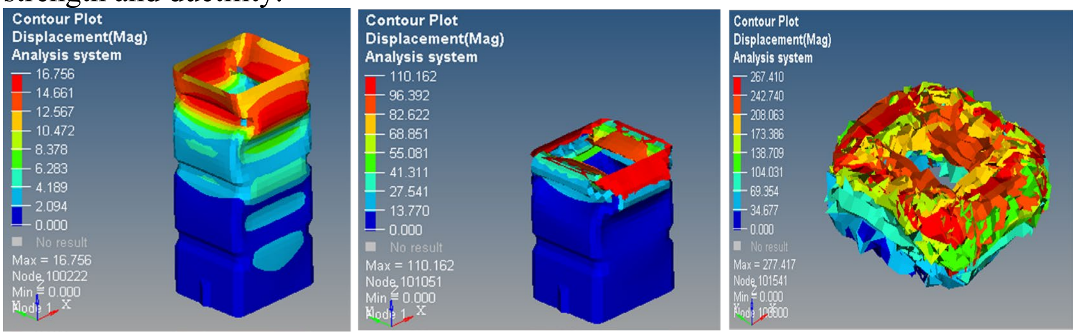

Fig. 4. Deformed shape of the square cross-section crush box of aluminium.

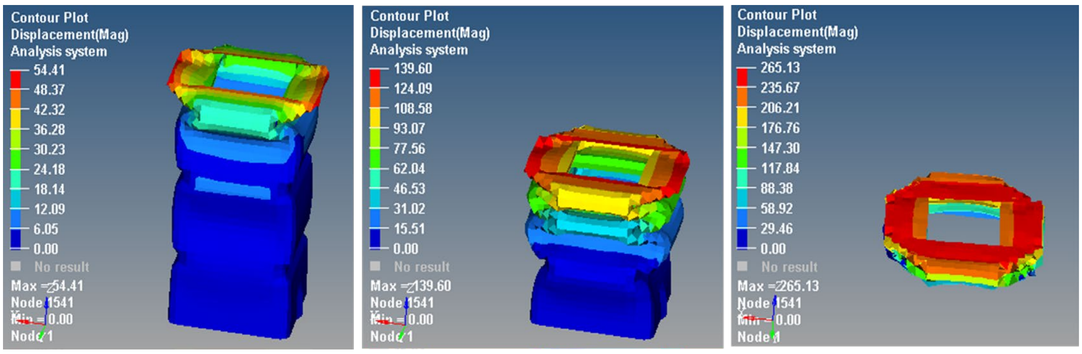

Fig. 5. Deformed shape of the square cross-section crush box of AlMgSi (B52).

3.2 Energy absorption analysis of crush box for various materials

Figure 6 illustrates the energy curves for the crush tests conducted on the mild steel, aluminium, and AlMgSi (B52) square cross-section crush boxes. Figure 6(a) illustrates the energy balance of the dynamic test conducted on the mild steel crush box. As kinetic energy decreases, there is a corresponding increase in internal energy. In addition, the sliding interface and hourglass energy levels remain at a low level, indicating effective energy absorption within the crush box. In contrast, Figure 6(b) displays the energy balance of the dynamic test conducted on the aluminium crush box. In line with the findings for mild steel, the decrease in kinetic energy is observed as the internal energy increases. Nevertheless, the sliding interface and hourglass energy exhibit significant levels, suggesting possible inefficiencies or obstacles in energy absorption within the aluminium crush box. On the other hand, Figure 6(c) shows the energy balance of the dynamic test conducted on the AlMgSi (B52) crush box. It is again observed that an increase in internal energy leads to a decrease in kinetic energy. It is worth mentioning that the sliding interface and hourglass energy levels exhibit a consistently low level, indicating a highly effective energy absorption mechanism comparable to that of the mild steel crush box. The observations highlight the variations in energy absorption properties among the materials that were tested. AlMgSi (B52) demonstrates superior energy absorption efficiency compared to aluminium. These findings could have significant implications for the design and effectiveness of crashworthy structures.

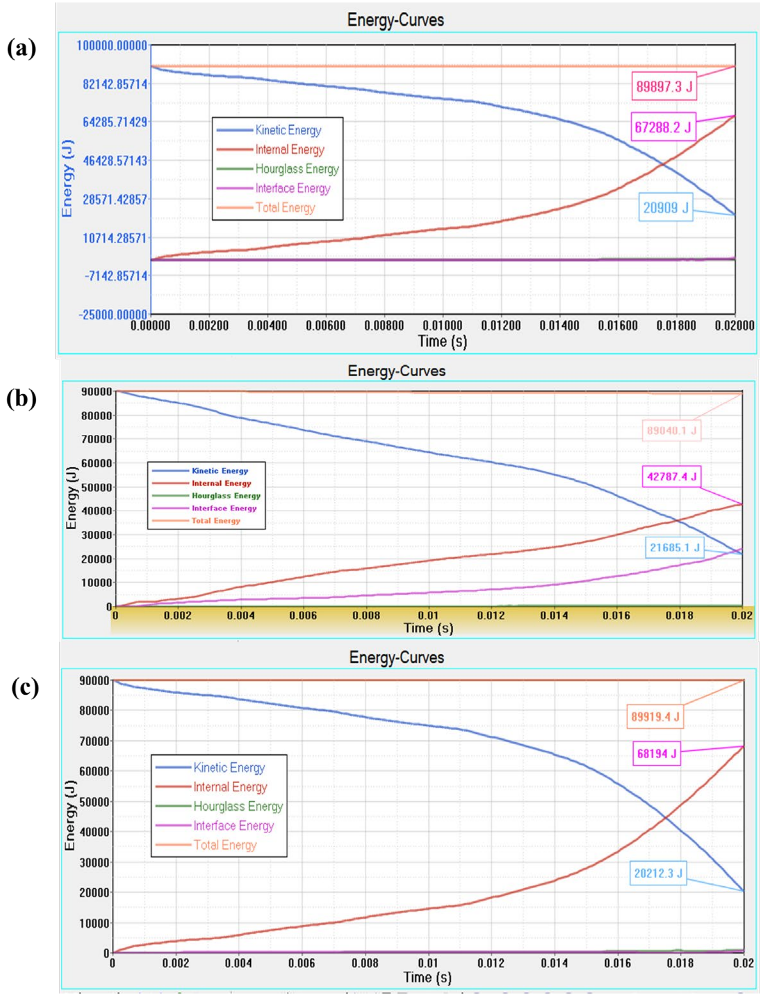

Fig. 6. Energy curves (a) mild steel, (b) aluminium and (c) AlMgSi (B52).

3.3 Deformation analysis of square and hexagonal crush boxes with alternate-bead AlMgSi (B52) configurations

In this study, we investigate the impact of alternative geometries on the crashworthiness of crush boxes. Specifically, we focus on configurations with hexagonal cross-sections and alternate beads. Earlier section findings have shown that AlMgSi (B52) is superior to mild steel and aluminium in terms of crash performance. The present study aims to determine how these alternative configurations affect the energy absorption capabilities and structural integrity of the crush boxes. The distorted form of the square cross-section crush box with alternate beads composed of AlMgSi (B52) is illustrated in Figure 7. The crush box had significant deformation, with a maximum deformation of 243.94 mm, demonstrating the impact of the applied load. In addition, the crush box displayed moderate deformation characteristics in terms of axial behaviour.

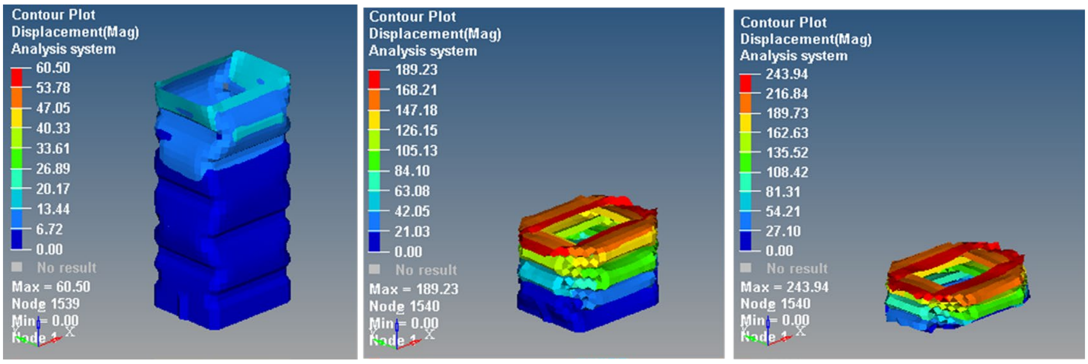

Fig. 7. Deformed shape of square cross-section with alternate beads crush box of AlMgSi (B52).

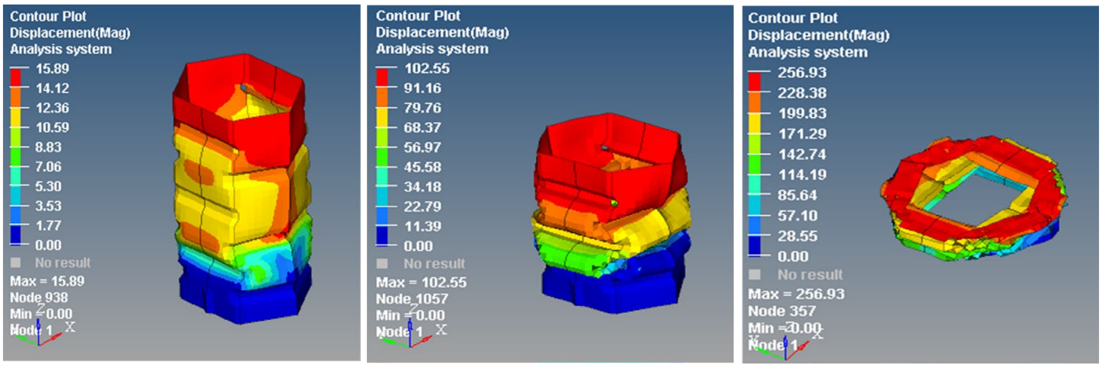

Fig. 8. Deformed shape of the hexagonal cross-section crush box with alternate beads of AlMgSi (B52).

Figure 8 presents the deformed shape of the hexagonal cross-section crush box with alternate beads of AlMgSi (B52). In this study, the crush box exhibited a significant displacement of 256.93 mm. Contrary to the square cross-section counterpart, the hexagonal crush box exhibited a non-axial behaviour. The observed deviation from axial behaviour suggests potential difficulties in the absorption and distribution of energy within the structure. The crush box with alternate beads in a square cross-section displayed moderate deformation and axial behaviour, indicating its effectiveness in absorbing energy. However, the hexagonal counterpart exhibited non-axial behaviour, indicating the need for improvement in energy absorption efficiency.

3.4. Energy absorption analysis of square and hexagonal crush boxes with alternate-bead AlMgSi (B52) configurations

Figure 9 displays the energy curves for crush boxes composed of AlMgSi (B52) with alternate beads, having square and hexagonal cross-sections. Figure 9(a) presents the energy balance of the dynamic test conducted on the square cross-section crush box with alternate beads of AlMgSi (B52). As the applied load decreases, there is a corresponding increase in internal energy. The observed behaviour suggests that there is a transfer of energy happening within the crush box. As the deformation takes place, the kinetic energy is converted into internal energy. Notably, the total energy remains constant, consistent with the principle of energy conservation. In addition, the sliding interface and hourglass energy levels remain low, indicating effective energy absorption and minimal energy losses caused by friction or deformation issues.

(a)

(b)

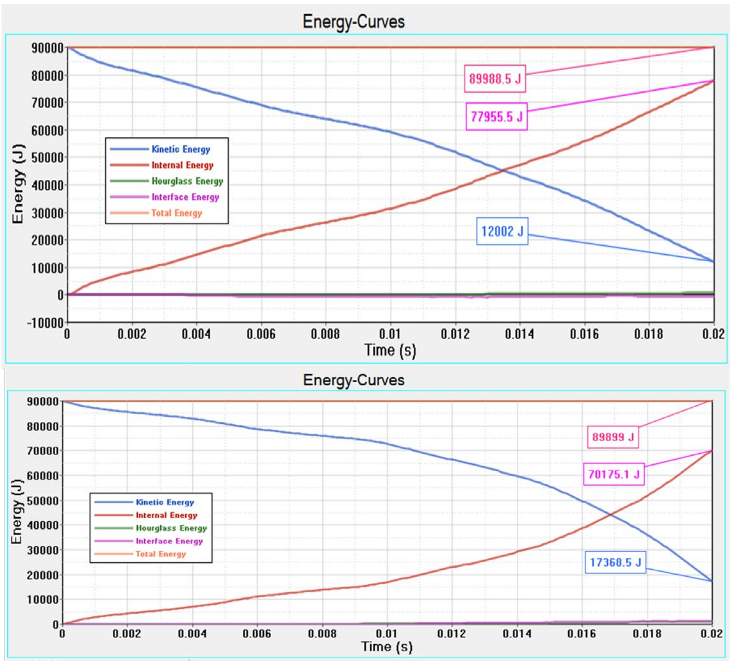

Fig. 9. Deformed shape of square cross-section with alternate beads crush box of AlMgSi (B52).

In Figure 9(b), we present the energy balance of the dynamic test on the hexagonal cross-section crush box with alternate beads of AlMgSi (B52). Once more, the decrease in kinetic energy corresponds to an increase in internal energy, ensuring that the total energy remains constant throughout the experiment. The consistent total energy observed in our study suggests that the crush box successfully absorbs and dissipates energy as it undergoes deformation. In addition, the sliding interface and hourglass energy levels demonstrate a low value, indicating effective energy absorption and minimal energy dissipation within the crush box structure. The energy curves of the crush boxes with square and hexagonal cross-sections, containing alternate beads of AlMgSi (B52), exhibit impressive energy absorption capabilities. The findings indicate that the crush box configurations successfully dissipate energy, as evidenced by the consistent total energy and minimal levels of sliding interface and hourglass energy. The results of this study demonstrate the significant impact that AlMgSi (B52) crush boxes with alternate beads can have on crashworthiness, leading to enhanced vehicle safety and improved structural performance.

3.5. Comparison of crush box performance across different materials and configurations

According to the findings listed in the Table 2, it is clear that AlMgSi (B52) crush boxes, especially those with alternate beds, demonstrate superior performance when compared to both mild steel and aluminium counterparts. It is worth mentioning that the crush box made of AlMgSi (B52) with alternate beds, regardless of whether they are square or hexagonal in shape, exhibits considerably higher internal energy and total energy values in comparison to mild steel and aluminium. The findings suggest that the AlMgSi (B52) material has a higher ability to absorb and dissipate energy, which ultimately improves its crashworthiness. Also, the percentage change in energy and kinetic energy values also demonstrate AlMgSi (B52) crush boxes' superior performance, especially in configurations with alternate beds, demonstrating their potential as innovative crash-safety solutions.

The percentage change, or energy absorption efficiency, is calculated using equation (1) as follows:

$$\text{Energy Absorption Efficiency (\%)} = \frac{\text{Internal Energy}}{\text{Total Energy}} \times 100 \qquad (1)$$

This represents the fraction of total energy absorbed as internal deformation energy. Higher values indicate better energy absorption capability and enhanced crash performance.

Table 2.

Comparison of obtained results for crush box.

Material	**Shape**	**Thickness (mm)**	**Internal Energy (J)**	**Total Energy (J)**	**Energy Absorption Efficiency (%)**	**Kinetic Energy (J)**
Mild steel	Square	2	67288.2	89897	74.79	20909
Aluminium	Square	2	42787	89040.1	48.05	21685.1
AlMgSi (B52)	Square	2	68194	89919.4	75.83	20212.3
AlMgSi (B52)	Square - Alternate Beds	2	77995.5	89988.5	86.66	12002
AlMgSi (B52)	Hexagonal - Alternate Beds	2	70175.1	89899	78.04	17368.5

4. Conclusion

In the present work, a simulation-based examination of the impact performance of various crush boxes was carried out, focusing on their materials and configurations. By conducting dynamic tests and analyzing energy, we have obtained significant findings regarding the structural performance and ability of crush boxes to absorb energy during impact loading scenarios. The findings of our study emphasize the crucial role that material properties and geometrical configurations play in determining the crashworthiness of crush boxes. In particular, the material AlMgSi (B52) has shown great promise in scientific research, outperforming conventional materials like mild steel and aluminium. The square cross-section crush box made of AlMgSi (B52), especially those with alternate beds, demonstrated increased internal energy (77995.5 J), total energy (89988.5 J), and energy absorption efficiency (86.66%) in energy. The substantial increase in internal and total energy, along with the enhanced energy absorption efficiency, underscores its potential to improve automotive crash safety. The integration of such square AlMgSi (B52) crush boxes into vehicle safety systems can significantly enhance impact energy dissipation and occupant protection.

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