Automotive Experiences

Vol. 8 No. 3 (2025) pp. 726-740

p-ISSN: 2615-6202 e-ISSN: 2615-6636

Research Paper

The Influence of Aluminum Thickness on Energy Absorption and Stability of Circular Crash Box Performance Under Axial Load

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https://doi.org/10.31603/ae.15149

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang

Article Info
Submitted: 28/10/2025
Revised: 08/12/2025
Accepted: 15/12/2025
Online first: 27/122025

Abstract

The need for improved vehicle safety, particularly in the face of rising road traffic accidents, makes the optimization of crash box designs crucial. This study addresses the impact performance of circular cross-section crash boxes, focusing on how variations in aluminum thickness affect energy absorption and deformation behavior under axial impact loading. A combination of numerical simulations and experimental tests was used to evaluate the crash box performance across different aluminum thicknesses ranging from 1 mm to 3 mm. The results show that increasing thickness improves energy absorption, with the 3 mm thick specimen absorbing the highest energy of 7.3089 kJ, while the 1 mm specimen absorbed only 1.1018 kJ. However, thicker specimens exhibited higher peak forces and force fluctuations, suggesting potential instability after the peak load, while intermediate thicknesses 1.5 mm and 2 mm provided a better balance of energy absorption and structural stability. This research contributes to the development of more efficient crash box designs by providing insights into the optimal material thickness for crashworthiness, with a recommended thickness range of 1.5 mm to 2 mm.

Keywords: Crash box; Aluminum thickness; Energy absorption; Axial impact loading; Deformation behavior; Structural stability

1. Introduction

The global transportation system plays a crucial role in facilitating the movement of goods and people, which in turn supports economic growth and societal development. With the expansion of urban populations and advancements in economic growth, the demand for transportation has increased significantly, leading to a surge in vehicle ownership worldwide [1]. In Indonesia, for example, a population exceeding 230 million has driven the growth of vehicle production and consumption, further stimulating the rapid development of the automotive sector and infrastructure [2]. While this phenomenon has contributed to economic prosperity, it has also resulted in worsening traffic congestion and road accidents. As a consequence, the automotive industry faces an urgent need to improve vehicle safety standards in order to mitigate the impact of these accidents [3].

Vehicle safety is a major issue in automotive engineering, particularly when considering global statistics on road traffic accidents. Over 1.2 million deaths and approximately 10 million injuries are reported annually as a result of road accidents worldwide [4]. These alarming figures underscore the importance of efforts to improve vehicle safety measures. Among the passive safety systems designed to protect passengers and critical vehicle components during collisions, the crash box represents a significant innovation. Positioned between the vehicle's bumper and the main frame, the crash box is designed to absorb impact energy, thereby reducing the collision's effects on passengers and key components [5]. The deformation behavior of the crash box during a collision plays a pivotal role in energy dissipation, ensuring that forces are not transmitted to the vehicle's primary structure. The primary function of the crash box is to undergo progressive deformation under axial load during a collision, absorbing a substantial amount of kinetic energy [6]. This process helps minimize damage to the vehicle's main frame and improves the safety chances for passengers. However, to ensure that the crash box is optimized for energy absorption, understanding how various design parameters such as material thickness, cross-sectional shape, and the use of fillers affect crash box performance is essential [7].

Thin-walled aluminum tube designs are widely used as energy absorbers due to their ability to undergo significant plastic deformation and maintain stable axial compression through progressive folding [8]. The most commonly studied deformation modes for tubes include diamond mode, concertina mode and dynamic plastic buckling mode [9]. Among these modes, progressive buckling or axial concertina mode results in maximum energy absorption by allowing the tube to deform in folds [10]. However, this deformation mode is not always naturally achieved in all cases. This issue can be addressed by making geometric modifications to the tube surface, such as dimples, corrugations, grooves, reinforcements, multi-cell structures, and cutouts [11]. These modifications act as deformation triggers. Research has also shown that introducing cutouts can reduce the peak load transmitted [12]. A lower peak load ensures that a uniform average force is transmitted to the rear end of the crash frame. Subsequently, this reduces the potential for shock experienced by the vehicle occupants during a crash. Otherwise, such shocks could cause severe neck injuries and fatalities in car accidents.

Extensive research has been conducted to optimize thin-walled structures through variations in material properties, cross-sectional shapes, and wall thicknesses [13]. Additional strategies, such as foam filling, multi-cell designs, and honeycomb structures, have been applied to further enhance energy absorption [14], [15]. For instance, aluminum foam, known for its excellent compressive energy absorption and lightweight properties, is frequently used as a filler in thin-walled crash box systems [16]. While various foam-filled crash box designs and double-tube systems offer superior energy absorption, the high cost limits their application in mass production [17]. Aside from the cost, the peak force values may trigger severe injuries and fatalities in car accidents. Therefore, optimizing energy absorption improvements in conventional tubes is a focus of this study.

Numerous researchers and scientists have applied their ideas to modify the structure of thin-walled tubes used in vehicle crash frames. These thin-walled tubes are primarily used to absorb axial loads during frontal collisions. The tube absorbs impact energy by deforming into folds. The amount of energy absorbed can be increased by controlling the deformation of the tube. The most studied deformation modes for tubes are Euler buckling, diamond mode and concertina mode [9]. Among these modes, progressive buckling or axial concertina mode provides maximum energy absorption by allowing the tube to deform in folds [18]. However, this deformation mode is not always achieved in every case. This issue can be addressed by making geometric modifications to the tube surface, such as dimples, corrugations, grooves, reinforcements, multi-cell structures, and cutouts [19], [20]. These modifications serve as triggers for the folding phenomenon [21], [22]. Research has also demonstrated that by introducing cutouts, the peak load transmitted can be reduced.

Therefore, this study investigates the axial impact performance of circular-section aluminum crash boxes, with particular emphasis on how variations in wall thickness influence the folding mechanism and the stability of crashworthiness under axial impact loading. Although previous studies have examined the effects of geometric modifications, fillers, and cross-sectional designs, relatively few have provided a detailed comparison of deformation modes and energy-absorption efficiency across a range of wall thicknesses in cylindrical aluminum tubes. Moreover, many studies still rely on conventional aluminum tubes to enhance energy absorption by modifying the geometry and adding additional materials; however, this approach can increase the IPFC and reduce the SEA value, which may remain unsafe during a collision. Addressing these gaps, the present study aims to explore the effect of wall thickness in conventional tubes on the integration of energy absorption, deformation stability, and impact force characteristics. The optimal material thickness identified in this study is expected to serve as a reference standard for developing conventional tubes into hybrid configurations, thereby improving passive safety systems capable of absorbing higher levels of impact energy.

2. Methods

This study employed a quasi-experimental approach to investigate the crash performance of circular cross-section crash boxes, focusing particularly on analyzing the impact of variations in aluminum thickness on energy absorption and deformation behavior. A combination of numerical simulations and experimental testing was used to provide a comprehensive analysis of the crash box's behavior.

2.1. Material and Crash Box Design

The crash box used in this study is made from 6063-T5 aluminum, a material commonly chosen in automotive applications due to its favorable combination of lightweight properties, strength, and excellent energy absorption characteristics. The specific properties of 6063-T5 aluminum are detailed in **Table 1** and **Figure 1**. The crash box has a cylindrical design with an outer diameter of 63 mm and a length of 150 mm, as shown in **Figure 2**. To investigate the effect of material thickness on the performance of the crash box, variations in wall thickness were considered as independent variables, with thicknesses of 1 mm, 1.5 mm, 2 mm, 2.5 mm, and 3 mm. These variations allow for a comprehensive evaluation of how different wall thicknesses influence the energy absorption and deformation behavior of the crash box under impact conditions.

2.2. Quasi Static Simulation Model

A numerical investigation was conducted using ANSYS Workbench 18.1. The finite element model was divided into three primary components: the impactor tube, the crash box, and the fixed support, as shown in **Figure 3**. The crash box tube was modeled using 6063-T5 aluminum, with bilinear isotropic hardening applied to the material properties.

In this study, the crash box was discretized using 2 mm square elements and positioned between the impactor die and the fixed support. The impactor was modeled using solid hexahedral elements with a size of 300 mm. Both the impactor and the fixed support were treated as rigid bodies to ensure they remained undeformed during the impact. The tube was subjected to a collision with the impactor, which was assumed to have a mass of 103 kg. The impactor was constrained to move along the y-axis at a constant velocity of 10 mm/s. To reduce computational time in the numerical simulation, a mesh size of 3 mm was selected for the rigid bodies. The von Mises criterion was used to define the failure condition, with stress calculated as the equivalent von Mises stress during the solution step.

2.3. Experimental Validation

The validation of this study was carried out by comparing the results of the finite element model with experimental data obtained from compression tests. The experimental specimens had an outer diameter of 63 mm, a length of 150 mm, and a wall thickness of 1.5 mm, selected based on material availability. Compression tests were performed using a hydraulic Universal Testing Machine (UTM) manufactured by Instron, with a maximum capacity of 300 kN, as shown in **Figure 4**. The comparison revealed that the discrepancy between the force–displacement curves obtained from the numerical simulation and the experimental data was less than 15%. Therefore, the developed finite element model is considered to have an acceptable level of accuracy and is suitable for further investigations into the behavior of the crash box.

Table 1. Material properties

Material Properties	Aluminium 6063-T5
Density	2700 kg/m^3
Young’s Modulus	69000 Mpa
Poisson’s Ratio	0,33
Yield Strength	180 Mpa
Tangen Modulus	580 Mpa

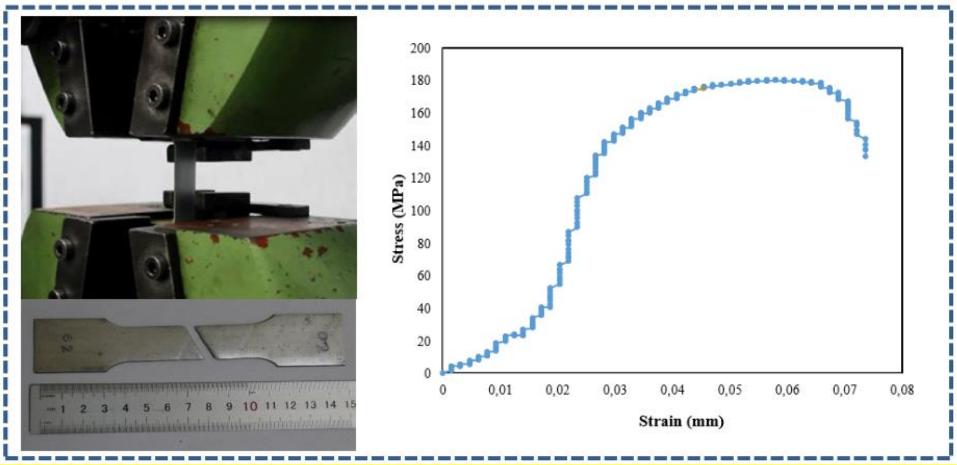

Figure 1. Engineering stress-strain Aluminium 6063-T5 tensile test result

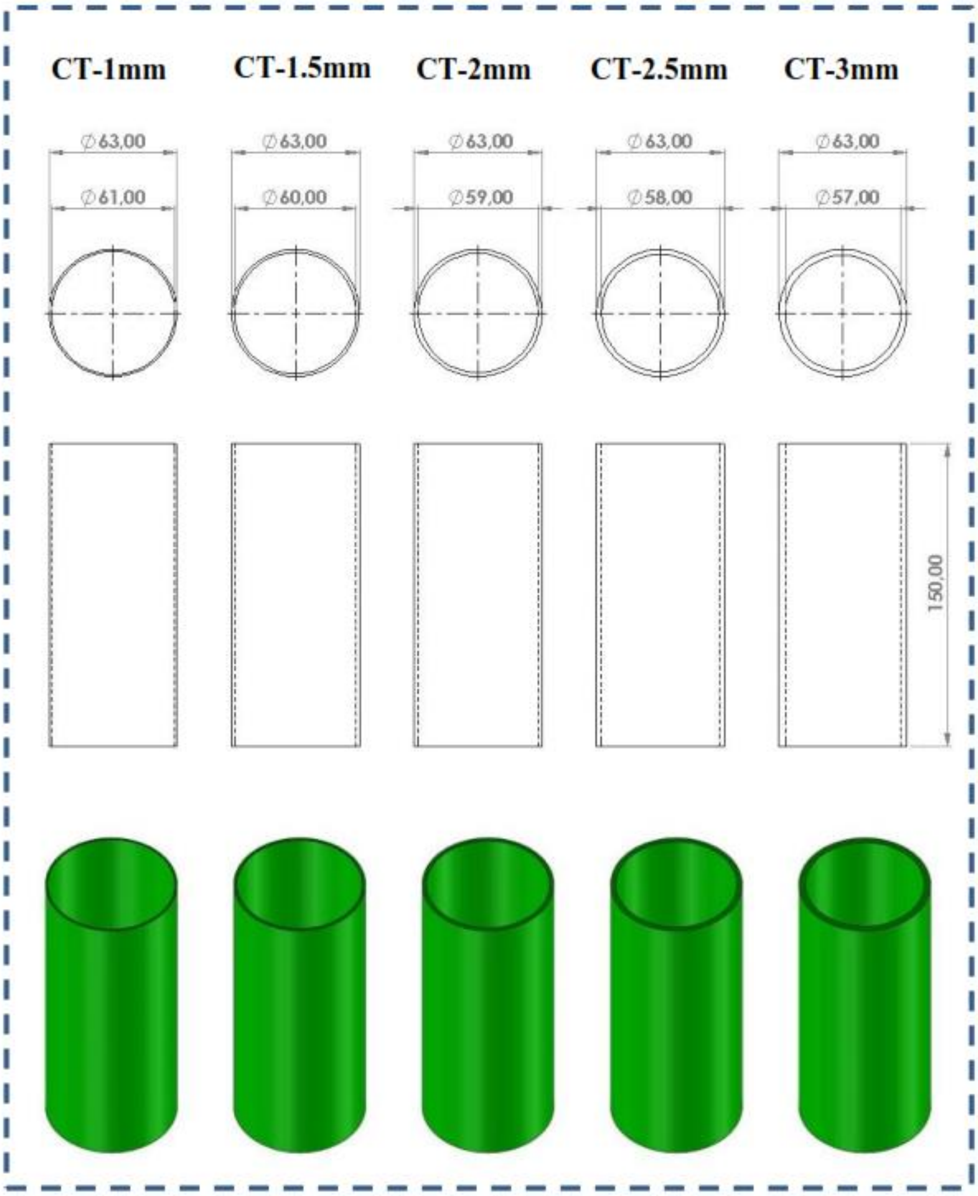

Figure 2. Crash box design

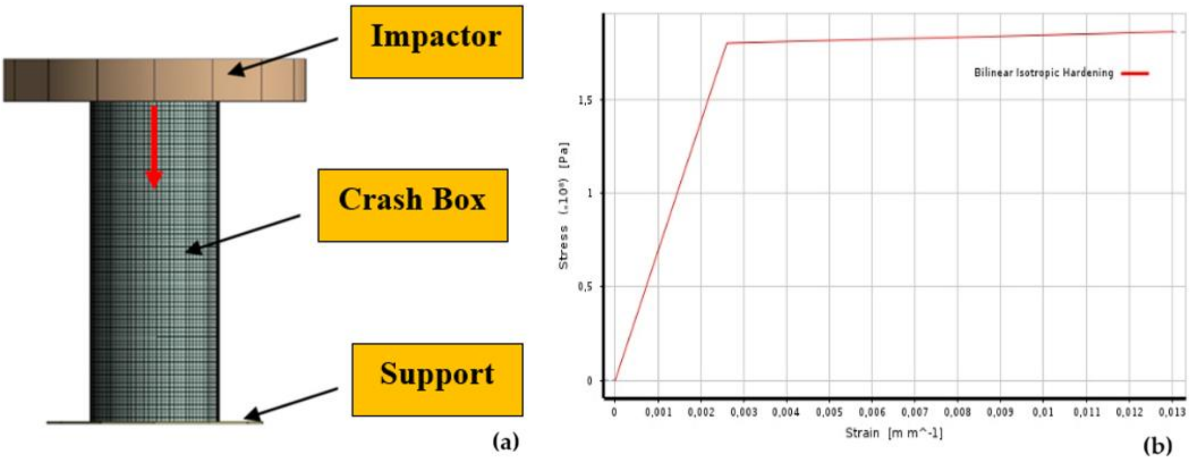

Figure 3. (a) Illustration of crash box simulation, and (b) bilinear isotropic hardening material properties

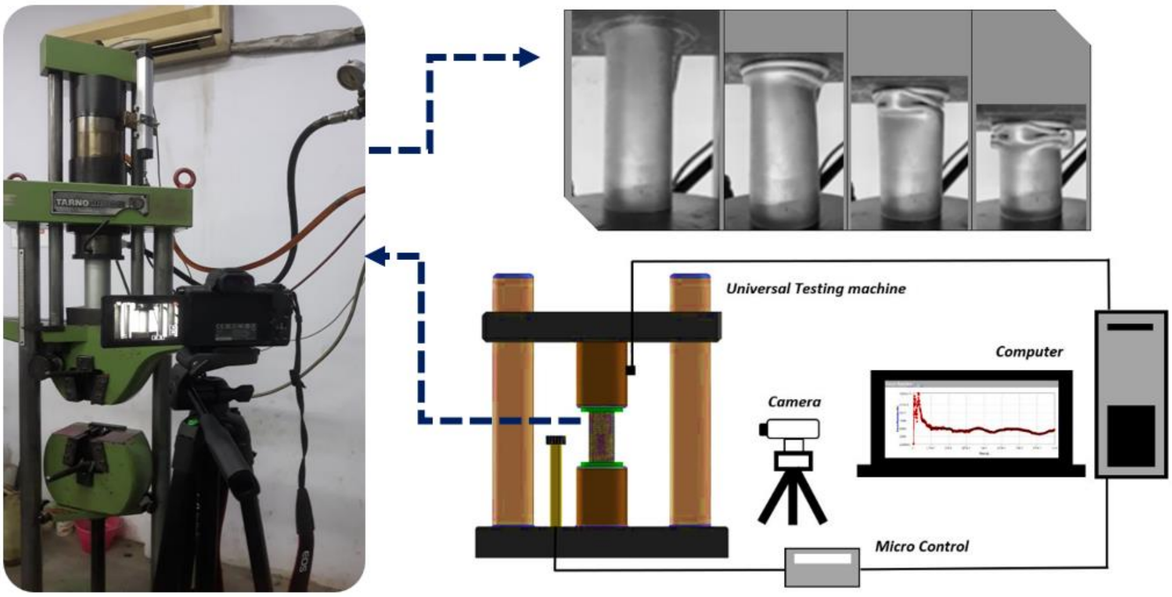

Figure 4. Experiment test

2.4. Crash Box Performance Analysis

The criteria used to evaluate impact efficiency include Energy Absorption (EA), Mean Force (MF), Initial Peak Force (IPFC), Crush Force Efficiency (CFE), and Specific Energy Absorption (SEA). These metrics are essential for assessing the crash box's ability to effectively absorb energy during a collision and how forces are distributed across the structure. By analyzing these parameters, the performance of the crash box can be better understood in terms of energy dissipation, structural integrity, and overall crashworthiness.

Energy Absorption (EA) refers to the total energy absorbed during the impact event, which is calculated by determining the area under the load-displacement curve. This can be expressed mathematically as:

$$EA = \int_0^d f(\delta)d\delta \quad (1)$$

F(δ) is the force-displacement function, and δ represents the displacement.

The Mean Force (MF) is the average load experienced by the energy absorber as it transitions to a stable form. It is defined by the following equation:

$$MF = \frac{1}{d}\int_0^d f(\delta)d\delta \quad (2)$$

Crush Force Efficiency (CFE) is the average ratio of the destructive force, calculated by dividing the mean force (MF) by the initial peak force (IPFC):

$$\text{CFE} = \frac{MF}{IPFC} x\ 100 \qquad (3)$$

Specific Energy Absorption (SEA) is a criterion used to measure the energy absorbed per unit mass. It is an important indicator of a structure's ability to absorb energy. SEA can be calculated using the following equation:

$$\text{SEA} = \frac{EA}{m} \qquad (4)$$

where m represents the mass of the energy absorber.

3. Result and Discussion

3.1. Characteristics of Circular Tube (CT) Crash Boxes with Various Aluminum Thicknesses

This study aims to assess the impact of variations in aluminum thickness on the deformation response characteristics of crash box structures under quasi-static loading conditions. This testing is essential for understanding the mechanical behavior of materials in structural applications that require both mass efficiency and high energy absorption capacity. One of the key parameters influencing the performance of the crash box structure is thickness, as it directly affects load-bearing capacity, stiffness, and failure mechanisms [23]. Therefore, characterizing performance through simulation methods for different thicknesses is crucial for developing an optimal design [24]. The simulation results for various aluminum thicknesses, in terms of their load-displacement response, can be analyzed through the load-displacement curves shown in **Figure 5**.

Figure 5 illustrates the relationship between load and displacement for various circular tube (CT) thicknesses, ranging from 1 mm to 3 mm. Each curve highlights significant differences in peak load capacity and load retention time. Generally, increasing the CT thickness enhances both peak load capacity and the duration of deformation before load reduction occurs. The specimen with a CT thickness of 3 mm (CT-3) demonstrates the highest load capacity and the longest deformation time, while the CT-1 specimen exhibits the lowest load capacity and the shortest load retention time. This suggests that material thickness has a substantial effect on the strength and resistance of the structure under compressive load [25].

Additionally, specimens with larger thicknesses, such as CT-2.5 mm and CT-3 mm, show force fluctuations after the peak load, indicating the presence of plastic deformation or progressive damage mechanisms. This implies that greater thickness may compromise structural strength due to excessive local stresses. In contrast, specimens with thinner thicknesses, such as CT-1 mm and CT-1.5 mm, exhibit more stable responses, with a more moderate load reduction and minimal force fluctuations following the peak. This suggests that thinner thicknesses may help maintain structural stability for a longer period before significant damage occurs [26].

In general, increasing CT thickness improves both load capacity and load retention time, as thicker tubes enhance the structure's ability to withstand loads for a longer period before failure [27], [28]. This is particularly evident in the CT-3 specimen, which can withstand the load for a longer time and exhibits increased strength before a drastic decline. However, the force fluctuations observed in the CT-2.5 mm and CT-3 mm specimens indicate the potential for further damage, such as local buckling or cracking of the material [29]. These fluctuations suggest that although greater thickness increases load capacity, it also leads to greater structural instability after the peak load. In other words, structures with greater thickness may be more susceptible to damage after the peak load due to excessive pressure at local points [30].

For specimens with intermediate thicknesses, such as CT-1.5 mm and CT-2 mm, the curves demonstrate a transition from elastic to plastic behavior, with more stable force amplitudes after the peak load. This indicates that intermediate thicknesses strike a balance between strength and energy absorption capacity [31]. Intermediate thicknesses offer a better combination of strength and damage resistance, with more controlled force fluctuations after the peak load. This suggests that intermediate thicknesses may be more effective at absorbing energy without significantly increasing the risk of post-peak instability (Wirawan et al. 2025). Thus, while thicker materials increase energy absorption capacity and strength, the findings of this study suggest that excessive thickness can lead to higher structural instability after reaching the maximum load. Therefore, the optimal thickness appears to be in the range of 1.5 mm to 2 mm, offering the best balance between strength and structural stability.

Figure 6 presents the load-deflection curves for specimens with varying circular tube (CT) thicknesses, emphasizing significant differences in the material's deformation response under quasi-static loading. Increasing the CT thickness markedly enhances the energy absorption capacity, with the CT-3 mm specimen absorbing the highest energy at 7.3089 kJ, followed by CT-2.5 mm (5.5683 kJ), CT-2 mm (3.6873 kJ), CT-1.5 mm (2.2735 kJ), and CT-1 mm (1.1018 kJ). This trend indicates that thicker materials enable the structure to absorb more energy before failure. The increase in thickness contributes to a more uniform stress distribution, which prolongs plastic deformation and improves the material's ability to withstand load over an extended period [29].

However, although greater thickness enhances energy absorption capacity, the force fluctuations observed in the CT-2.5 mm and CT-3 mm following the peak load, such as local buckling or more complex cracking mechanisms. In contrast, thinner specimens, such as the CT-1 mm, exhibit more stable responses but with lower energy absorption capacity. While thicker materials improve energy absorption, it is essential to carefully balance strength and structural stability in design, particularly in applications requiring high energy absorption without compromising post-peak stability. Therefore, the optimal thickness, offering the best balance between strength, energy absorption, and structural stability, lies within the range of 1.5 mm to 2 mm.

Figure 7 illustrates the measurement results for various parameters at different material thicknesses, including Initial Peak Force (IPFC), Mean Force (MF), Specific Energy Absorption (SEA), and Crush Force Efficiency (CFE). Overall, the results for each parameter demonstrate that material thickness plays a significant role in influencing the material's performance in terms of energy absorption and resistance to applied forces. An increase in material thickness, such as with the CT-3 mm specimen, enhances performance, although greater fluctuations in force are observed in thicker materials. These findings are particularly relevant for industrial applications, especially in the selection of materials for structural components that require optimal force resistance and energy absorption properties.

As shown in **Table 2**, the Initial Peak Force (IPFC) increases with material thickness. The CT-3 mm specimen demonstrates the highest IPFC, exceeding 120 kN, while the CT-1 mm specimen exhibits the lowest IPFC, just above 40 kN. This increase in IPFC indicates that material thickness plays a critical role in enhancing energy absorption during the initial impact. However, it also leads to greater damage during the collision, as thicker materials are less prone to deformation, which may pose safety risks risks [27], [28].

Despite this, material thickness positively influences the Mean Force (MF), meaning that after the collision event, energy can be dissipated more efficiently. The CT-3 mm specimen generates the highest average force, approaching 80 kN, while the CT-1 mm specimen produces the lowest average force, around 20 kN. The increase in average force with greater material thickness suggests that thicker materials offer higher resis-

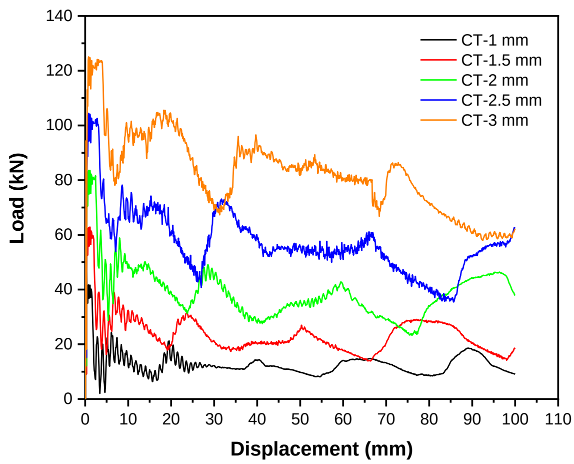

Figure 5. Load-displacement

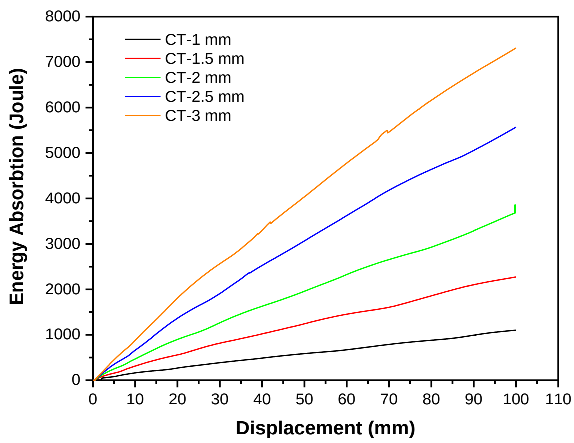

Figure 6. Energy absorbtion

tance to applied forces. However, larger fluctuations in force are observed with thicker materials, indicating greater variability in the material's response.

Subsequently, the Specific Energy Absorption (SEA) and Crush Force Efficiency (CFE) increase with the material thickness, with the highest SEA value observed at CT-3 mm, reaching nearly 30 kJ, and CFE at 0.7%. Although thicker materials demonstrate improved energy absorption and resistance, they may also experience more complex failure mechanisms. For instance, the material could undergo local buckling or cracking, especially under high-stress conditions, which may reduce the overall integrity of the material during deformation. Thicker materials tend to be stiffer, which can lead to less progressive deformation patterns, resulting in sudden structural failure once the peak load is reached. This contrasts with thinner materials, which may experience more progressive deformation and absorb energy over a longer period, thereby reducing the risk of sudden failure. Therefore, while thicker materials enhance energy absorption and structural performance, they also introduce a higher risk of failure due to excessive

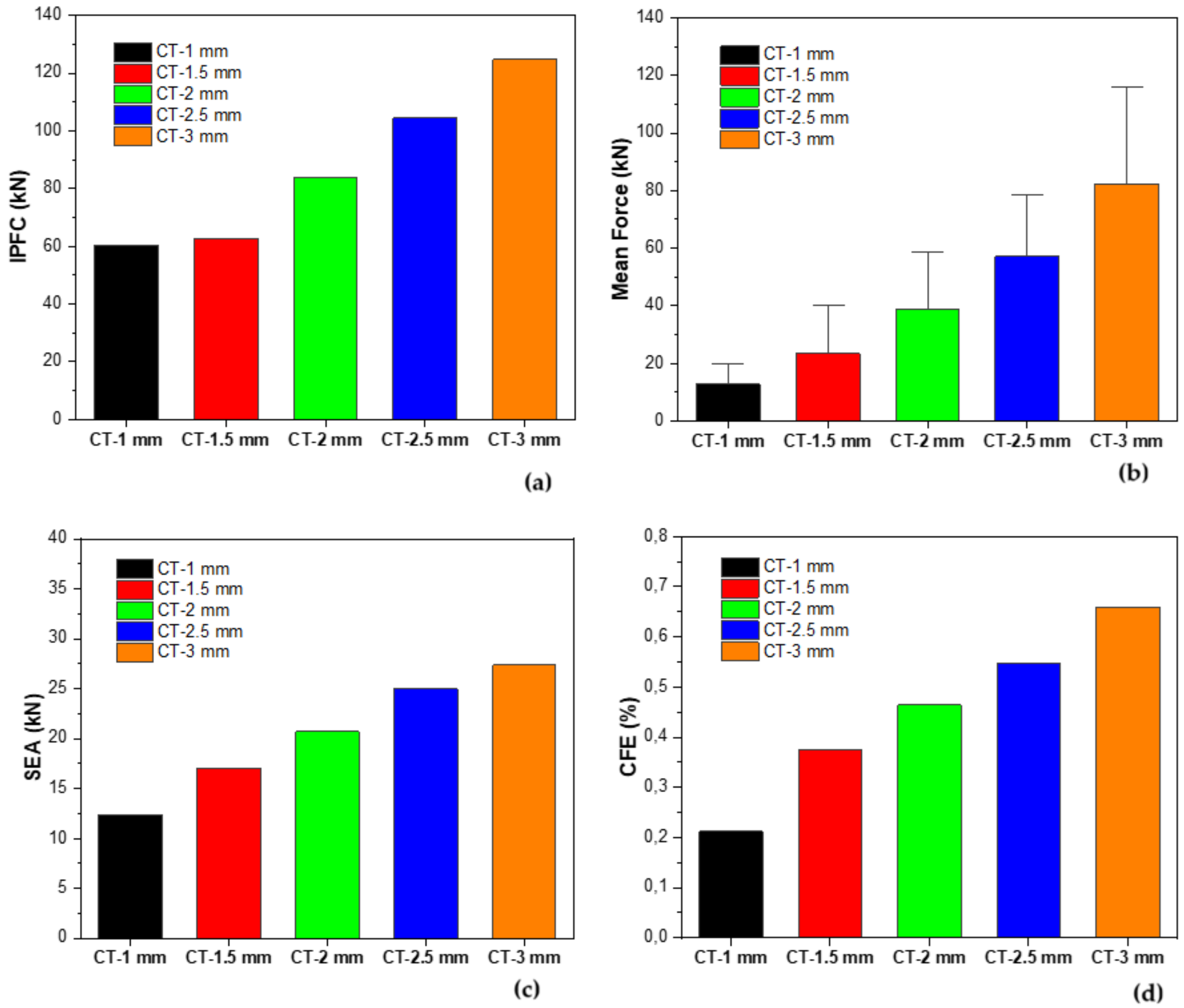

Figure 7. Initial Peak Force (IPFC) (b) Mean Force (MF) (c) Specific Energy Absorption (SEA) (d) Crush Force

Table 2. Measurement results of crash box characteristics with various material thicknesses

Model	Total Mass (kg)	EA (kJ)	SEA (kJ/kg)	IPFC (kN)	MF (kN)
CT-1 mm	0.089064	1.1018	12.37088	60.293	12.76594
CT-1,5 mm	0.1336	2.2735	17.01722	62.675	23.4371
CT-2 mm	0.17813	3.6873	20.70005	83.606	38.81455
CT-2,5 mm	0.22266	5.5683	25.00808	104.41	57.02634
CT-3 mm	0.26719	7.3089	27.35469	124.78	82.25062

local stress. Based on this study, a 2 mm geometry is recommended as the optimal configuration for crashworthiness.

3.2. Deformation Pattern with Variation of Aluminum Thickness

Figure 8 and Figure 9 shows the deformation patterns of the crash box with material thicknesses of 1 mm and 1.5 mm. The deformation patterns observed at these thicknesses are less ideal compared to the crash box with a 2 mm thick material. The 1 mm and 1.5 mm thicknesses exhibit uncontrolled deformation patterns, with the formation of concertina and diamond patterns at the bottom of the tube after the impactor first contacts the surface. At the 1.5 mm thickness, deformation occurs rapidly, and the crash box structure becomes more susceptible to buckling. This indicates that materials with thinner thicknesses are not strong enough to withstand large impact forces, leading to faster damage and a reduced ability to absorb energy. At a material thickness of 2 mm, the deformation pattern appears much better controlled. In this case, the deformation is more evenly distributed across the entire crash box, and the concertina pattern formed is less extreme. The structure with a 2 mm thickness is more effective at energy absorption, maintaining structural stability and slowing down the deformation process compared to thinner materials. The deformation is more controlled, without excessive damage, making the

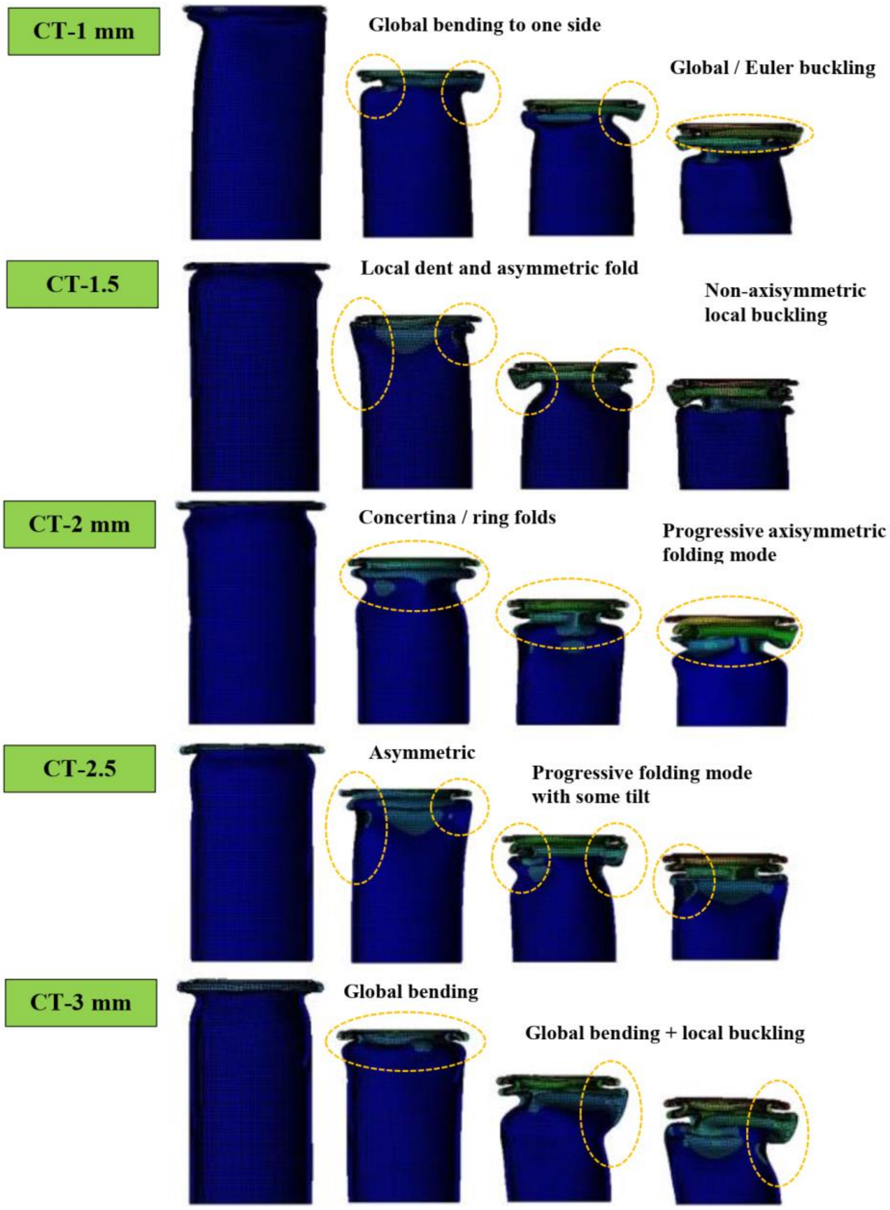

Figure 8. Deformation patterns of the crash box with varying loading test durations

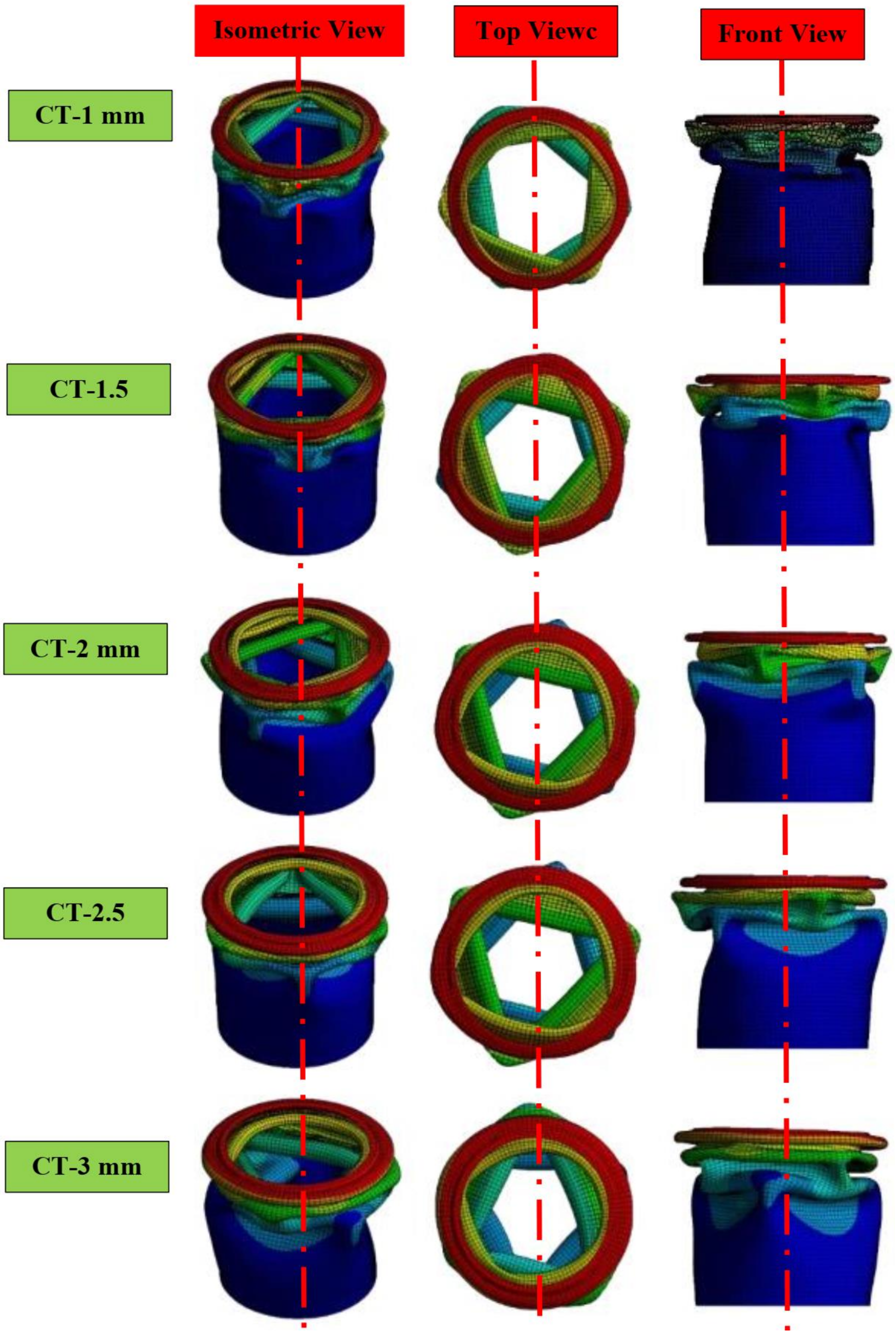

Figure 9. Final deformation crash box

material with this thickness offer a good balance between durability and efficiency in crash box applications. For material thicknesses of 2.5 mm and 3 mm, although the crash box with greater thickness appears to absorb higher energy, the resulting deformation is not as optimal as expected. The figure shows that at 2.5 mm and 3 mm thicknesses, buckling occurs in certain areas, which is undesirable. A thicker material causes a higher concentration of forces in smaller areas, leading to excessive local stress [33]. This results in uncontrolled plastic damage, where the structure no longer effectively distributes the forces or absorbs energy efficiently. The deformation patterns suggest that while thicker materials provide higher strength, they do not necessarily maintain structural stability in some specific applications. Overall, a thickness of 2 mm seems to be the optimal choice for crash box designs requiring a combination of resistance to external forces and effective energy absorption, while thicknesses greater than this may lead to increased structural instability [30] [34].

3.3. Validation of Circle Tube Crash Box Design with Various Aluminum Thicknesses

Figure 10 shows two graphs illustrating the relationship between reaction force (Load) and displacement (Displacement) in both experimental and simulation results for the crash box. The graph at the top of Figure 10a presents the experimental results, which display significant fluctuations in force as displacement changes. The reaction force fluctuates in accordance with the impact and deformation patterns, reflecting how the material absorbs energy and responds to external forces. Meanwhile, the graph at the bottom of Figure 10b presents the simulation results, which show a similar pattern but with smoother fluctuations. This difference indicates that while the simulation captures the general pattern of force versus displacement, the experimental results are more complex, exhibiting larger fluctuations. The deformation pattern observed is consistent, with the crash box showing significant deformation and the formation of clear buckling patterns, indicating how the material undergoes progressive damage due to the impact.

According to Table 3, the Energy Absorption (EA) value obtained from the experiments is 2.414 kJ, while the simulation results show a slightly lower value of 2.273 kJ, resulting in an error of 6.20%. Despite this minor difference, the simulation values are relatively close to the experimental results, indicating that the simulation model is generally accurate in representing the crash box's energy absorption capacity. The discrepancy could be attributed to variations in experimental conditions, simulation settings, or inaccuracies in the material model used. For the Initial Peak Force (IPFC) parameter, the experimental results show a value of 71.922 kN, while the simulation produces a value of 62.675 kN, yielding a larger error of 14.75%. This suggests that the simulation model requires revision to improve its accuracy in predicting the

Table 3. Validation Values of Simulation and Experimental Crash Box

Parameters	Experimental	Simulation	Eror (%)
Energy Absorbtion (kJ)	2.414	2.273	6.20
Initial Peak Force (kN)	71.922	62.675	14.75
Specific Energy Absorbtion (kJ)	15.091	17.017	11.31

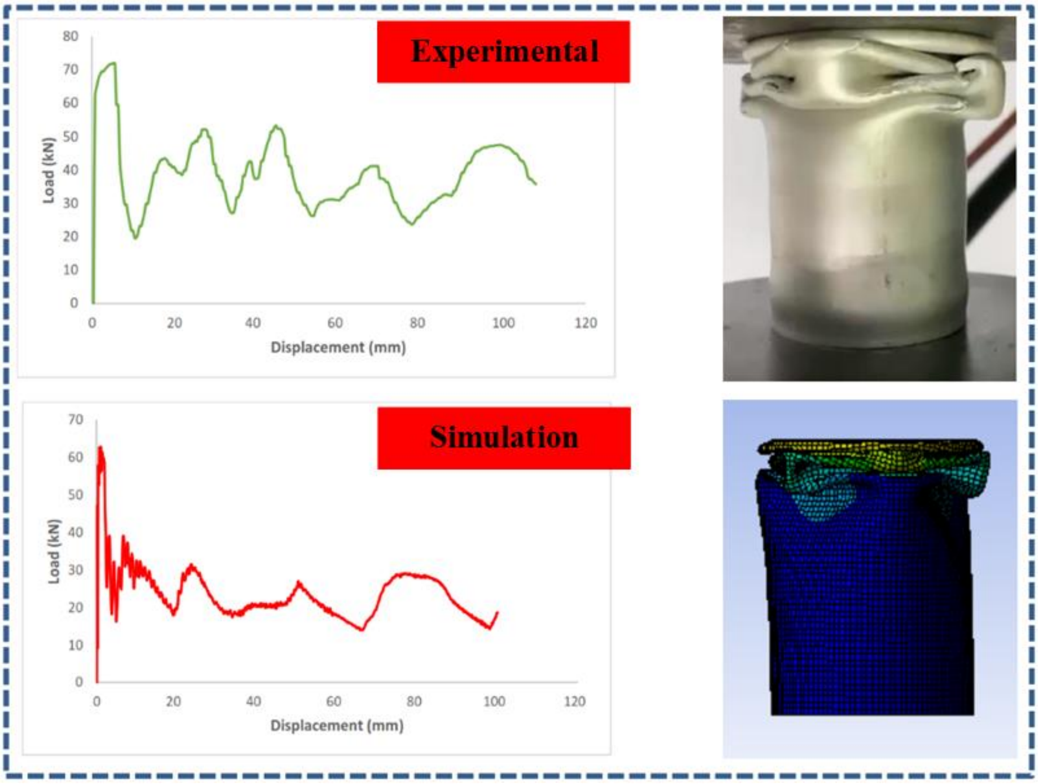

Figure 10. Experimental and simulation results

peak force during impact, with potential contributing factors including inaccuracies in impact modeling, boundary conditions, or variations in material properties. For Specific Energy Absorption (SEA), the experimental value is 15.091 kJ, while the simulation yields 17.017 kJ, resulting in an error of 11.31%, which, though higher than for EA, remains within an acceptable range. This difference may be due to variations in force distribution on the material during simulation versus the actual experiment. Nonetheless, the simulation appears to effectively reflect the energy absorption capacity per unit mass, with room for further improvement. Overall, while the comparison between experimental results and simulations reveals similarities in deformation patterns, the experimental results offer a more complex and realistic depiction of the crash box's behavior during under impact. In the experiments, deformation is more progressive, with increasing uncertainty at each stage, which is not fully captured by the simulations. This highlights that, while simulations provide greater predictability and structure, experiments better capture the inherent variability of real-world conditions, underscoring the need for simulation models that more accurately reflect the physical realities and material complexities involved.

Figure 11 illustrates the development of the deformation pattern of the crash box over time with the same material thickness, based on both experimental and simulation results. The figure shows that although the deformation patterns observed in the experiments and simulations are similar, the experimental results provide a more complex and realistic depiction of the crash box's behavior during impact. In the experiments, the deformation is more progressive, with increased uncertainty at each stage, which is not fully captured in the simulations [15]. This suggests that while simulations provide more structured and predictable results, experiments are better at capturing the variability that occurs under real-world conditions. The deformation in the experiments is well-controlled, with the formation

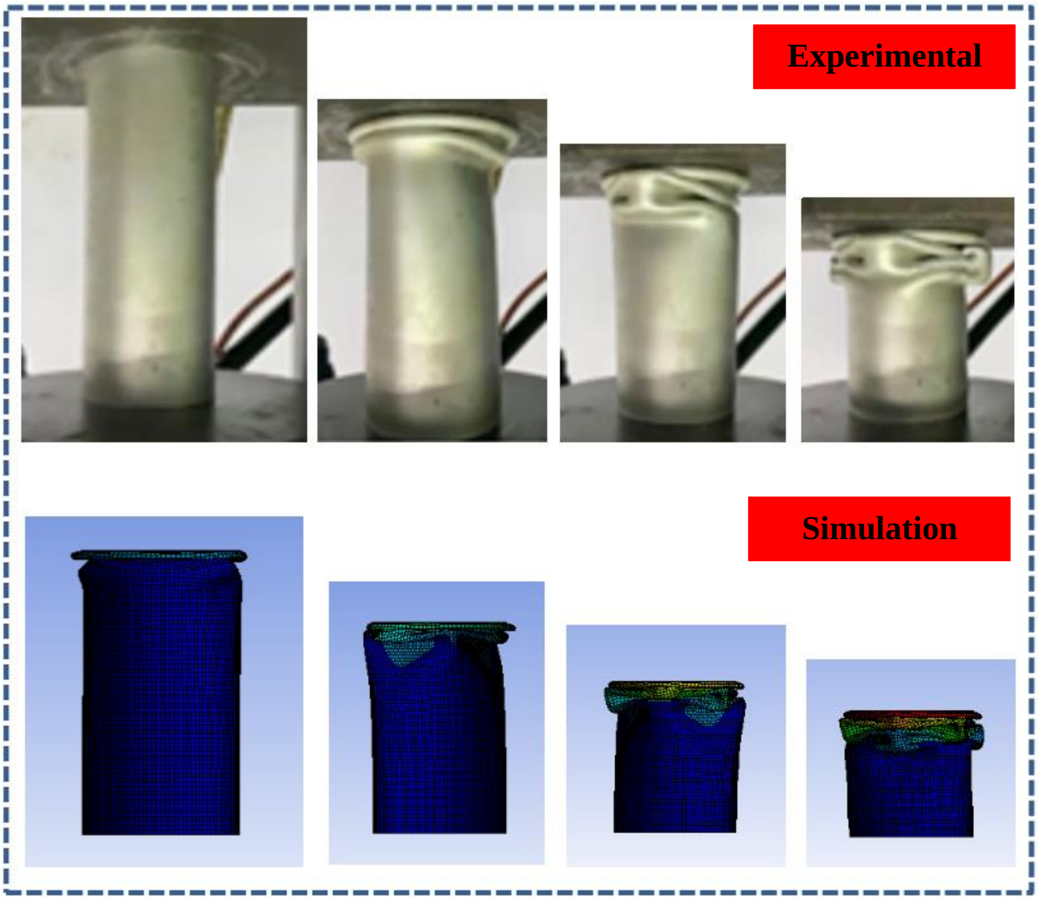

Figure 11. Stages of deformation patterns over time

of concertina and diamond patterns at the bottom of the tube after the impactor initially contacts the surface. This indicates that the material deforms in a more controlled manner, with the deformation more evenly distributed across the crash box, and the concertina pattern formed is not as extreme.

4. Conclusion

This study aims to assess the performance of circular crash boxes under axial impact loading by evaluating the effect of aluminum thickness variations on energy absorption and deformation behavior. The experimental results revealed that increasing the aluminum thickness enhanced energy absorption, with the CT-3 mm specimen absorbing the highest energy of 7.3089 kJ, while the CT-1 mm specimen absorbed only 1.1018 kJ. The study also highlighted that while thicker materials improved energy absorption, they introduced higher variability in the structural response, with peak forces and force fluctuations becoming more pronounced in thicker specimens. The optimal aluminum thickness for balancing energy absorption and structural stability was found to be between 1.5 mm and 2 mm, providing the best combination of strength and controlled deformation.

Aknowledgements

The authors would like to thank the colleagues, students and laboratory technicians of Institut Teknologi Sepuluh Nopember, and Universitas Negeri Surabaya, who have helped this research collaboration.

Author's declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

Funding

No funding information from the authors.

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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