Evaluation of energy absorption performance of cylindrical crash boxes with layered geometric modifications

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Abstract. The growing demand for transportation has resulted in an increase in vehicle production, thereby raising the risk of traffic accidents. Enhancing passive safety systems, such as crash boxes, is crucial to reducing the severity of collisions and safeguarding both passengers and critical vehicle components. This study examines the crashworthiness performance of four cylindrical crash box configurations: (a) base model, (b) cross-section reinforced, (c) single-layer, and (d) double-layer. A research and development approach was employed, involving the design, characterization, and simulation of each configuration using AA6061-T6 aluminum alloy. The evaluation was performed through numerical simulations under frontal impact conditions in accordance with NCAP standards. The key crashworthiness parameters assessed include energy absorption (EA), specific energy absorption (SEA), initial peak force (IPF), mean crushing force (MCF), and crush force efficiency (CFE). The results demonstrate that the double-layer configuration outperforms the other designs, achieving an EA of 5.102 kJ and a SEA of 15.22 kJ/kg, representing a 368.74% improvement in structural energy absorption compared to the base model. These findings underscore the effectiveness of layered geometric modifications in enhancing the crash performance of cylindrical crash boxes.

1 Introduction

As technological advancements continue, the need for enhanced safety mechanisms in transportation has become increasingly critical, driven by the growing dependence on vehicles for daily mobility. Road accidents remain a significant challenge, prompting automotive manufacturers, particularly in the four-wheeler sector, to incorporate advanced safety solutions aimed at reducing collision risks for both drivers and passengers. Among these innovations is the crash box, a passive safety component within the crashworthy system, designed to mitigate injury severity and protect vital vehicle components, such as the engine, during frontal impacts [1]. Positioned strategically between the bumper and the front frame, the crash box serves as the primary energy-absorbing structure in frontal collisions. Its design facilitates controlled deformation upon impact, effectively dissipating kinetic energy before it reaches the vehicle's cabin or chassis, thus minimizing potential damage [2] [3].

A study by Velmurugan and Muralikannan (2009) evaluated the energy absorption efficiency of crash boxes by testing different cross-sectional profiles circular, square, and rectangular under static loading conditions, with consistent material thickness. The results indicated that circular designs exhibited superior specific energy absorption compared to square and rectangular profiles, while square profiles outperformed rectangular ones in terms of energy dissipation efficiency. This research aims to design and assess a crash box with a circular cross-section and a multi-layered structure [4].

Thin-walled tubes are frequently utilized as energy-absorbing components in crash boxes because they can effectively absorb a considerable amount of impact energy through plastic deformation and maintain a relatively constant load via progressive folding during axial compression [5] [6]. Numerous studies have focused on optimizing material properties, cross-sectional configurations, wall thickness, and multi-sided designs of thin-walled columns [7] [8]. Additionally, several enhancement methods have been employed on thin-walled tubes to boost their crash resistance, including foam filling and multi-cell structures [9]. Aluminum foam, a lightweight cellular material known for its outstanding compressive energy absorption capabilities, has been extensively used as a filler in thin-walled structures aimed at crash protection [10] [11] [12]. Foam-filled tubes can significantly improve energy absorption due to the interaction between the foam filler and the wall of the column [13]. Furthermore, a double foam-filled tube design can further enhance specific energy absorption [14]. However, the high cost

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of aluminum foam-filled designs limits their widespread adoption by manufacturers. Consequently, a design strategy incorporating partial filling is necessary to reduce material costs without compromising safety performance.

Building on the gaps identified in the literature, this study aims to design and evaluate a crash box with a circular cross-section and multi-layered structure to enhance energy absorption efficiency during frontal collisions. The central hypothesis of this research is that combining a multi-layered structure with a circular cross-section will yield superior energy absorption performance compared to traditional designs that rely on a single layer or alternative cross-sectional shapes. Additionally, by adopting a partial structural approach within the multi-layered tube design, this study seeks to reduce material costs without compromising the crash box's safety performance. Ultimately, this research aims to contribute to a deeper understanding of crash box design optimization, with the goal of developing safer, more efficient, and cost-effective vehicle safety solutions.

2 Research method

This research investigates the geometric optimization of crash box structures by implementing dimensional and configurational modifications to enhance energy absorption efficiency, as depicted in Fig. 1. The study focuses on a cylindrical energy absorber with the following specifications: an external diameter of 100 mm, an axial length of 160 mm, and a wall thickness of 1 mm. The crash box is constructed from AA6061-T6 aluminum alloy, chosen for its favorable combination of specific strength and energy dissipation properties.

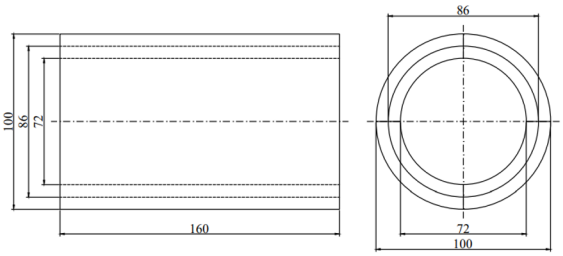

Fig. 1. Hierarchical shell structure dimensions (mm).

Geometric configuration, dimensional parameters, crash bead patterns, and material selection are critical factors that influence the energy absorption performance of crash boxes during impact events. This study develops four crash box models based on a baseline cylindrical design, with structural modifications introduced through layered configurations: (1) Base Cylinder, (2) Cross-Section Reinforced Cylinder, (3) Single-Layer Cylinder, and (4) Double-Layer Cylinder, as shown in Figs. 2 and 3.

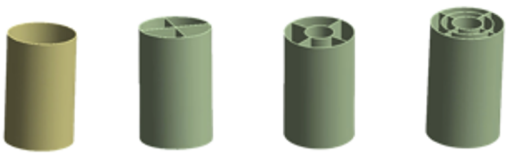

Fig 2. 3D Crash Box Designs. (a) Base Cylinder, (b) Cross-Section Reinforced Cylinder, (c) Single-Layer Cylinder, (d) Double-Layer Cylinder.

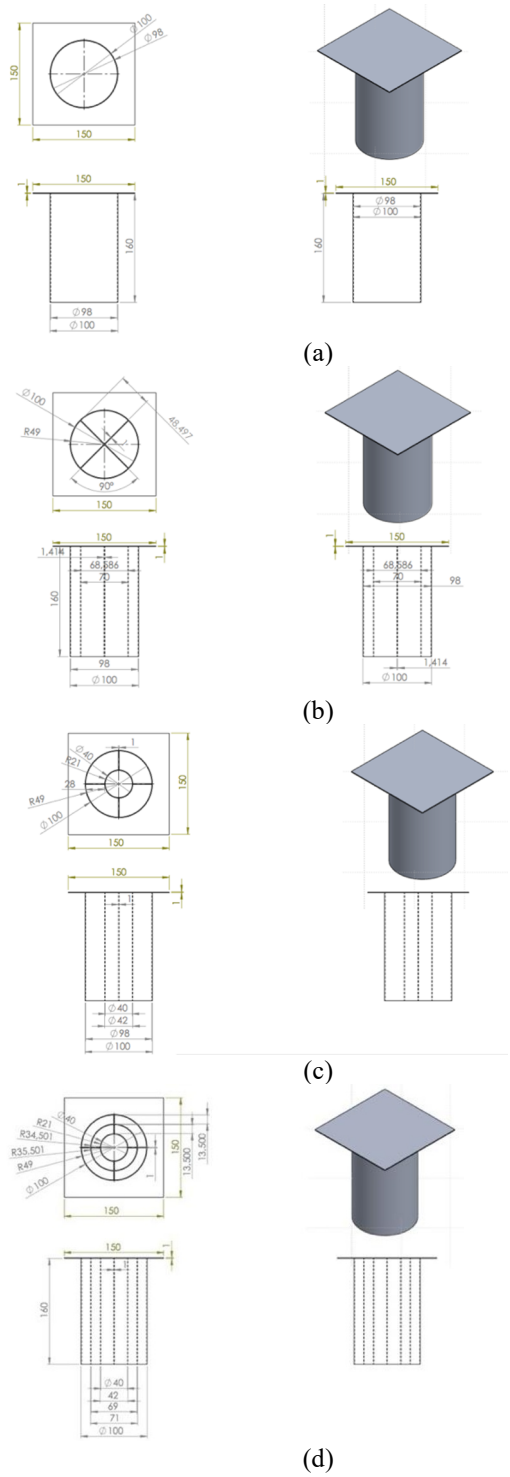

Fig. 3. 2D Crash Box Designs. (a) Base Cylinder, (b) Cross-Section Reinforced Cylinder, (c) Single-Layer Cylinder, (d) Double-Layer Cylinder.

Numerical simulations were performed using the explicit finite element solver LS-Dyna. The crash box was modeled as a deformable body to examine its structural response to impact excitation, while both the impactor and base plate were modeled as rigid bodies. The crash box structure was discretized into quadrilateral shell elements with a mesh size of 2 mm, selected based on mesh sensitivity analysis to achieve a balance between computational accuracy and efficiency.

The model was subjected to three boundary conditions: prescribed velocity, fixed support, and standard gravitational acceleration, as illustrated in Fig. 4. A rigid impactor with a mass of 275 kg was assigned an initial velocity of 56 km/h (15.56 m/s) to simulate frontal impact conditions, in accordance with NCAP testing standards.

Crashworthiness performance was evaluated using five key indicators: energy absorption (EA), mean crushing force (MCF), initial peak force (IPF), crush force efficiency (CFE), and specific energy absorption (SEA) [15]. These parameters provide a comprehensive assessment of the structure's energy absorption capacity, deformation behavior, and distribution of impact loads.

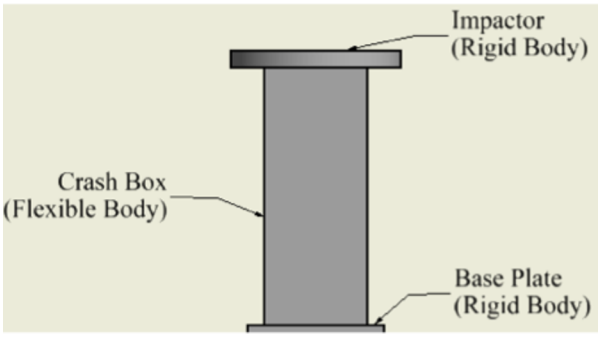

Fig 4. Numerical simulation setup of the crash box model.

3 Results and discussion

Energy absorption (EA) defines a structure's ability to take in energy during an impact incident. As a key metric for assessing crashworthiness performance, EA clearly reflects how effectively a structure reduces collision forces. As a primary parameter for evaluating crashworthiness performance, EA directly reflects how effectively a structure mitigates collision forces.

Specific energy absorption (SEA) is derived by normalizing the energy absorption based on the structural mass. An energy absorption analysis was conducted for each crash box model design.

Table 1 summarizes the numerical simulation results for both energy absorption and specific energy absorption across the different crash box configurations. The numerical results indicate that the double-layer circular base configuration exhibits superior energy absorption characteristics, with values of 5.1018 kJ (EA) and 15.22 kJ/kg (SEA). This suggests that the addition of layers strikes a balance between structural strength and energy absorption capacity. These findings are consistent with the research by Fengxiang Xu (2022) [16].

Table 1. Numerical simulation of EA and SEA in crash box models.

Crash Box Type	Mass (Kg)	Energy Absorption (KJ)	Specific Energy Absorption (KJ)
Circular base	0.13436	1.0884	8.100625186
Cross section circular base	0.2199	2.2283	10.13324238
Single layer circular base	0.24012	3.0019	12.50166583
Double layer circular base	0.33512	5.1018	15.22380043

As shown in Fig. 5, the double-layer circular base model demonstrates superior structural energy absorption within the observed 0.003-second time interval. These results indicate that the double-layer configuration enhances crashworthiness performance in terms of both energy absorption (EA) and specific energy absorption (SEA). The inclusion of an additional layer in the crash box design significantly improves its energy dissipation characteristics. Comparative analysis reveals that the double-layer circular base achieves a 368.7% increase in EA and an 87.93% improvement in SEA compared to the conventional single-layer circular base model. Furthermore, the shell thickness and core gradient within the structure were found to significantly influence the crash performance [17].

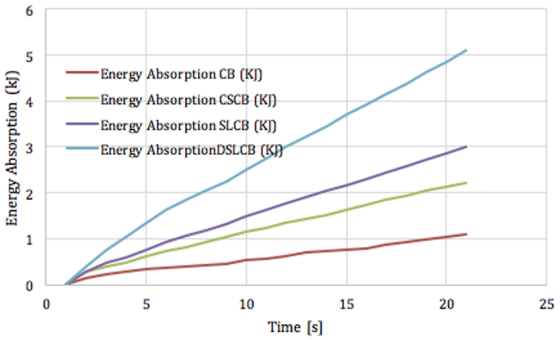

Fig 5. The energy absorption-time (EA-t) curve.

In addition to energy absorption capacity, the initial peak force (IPF) is a crucial parameter in evaluating crash box performance. An optimal crash box design should exhibit a relatively low initial peak force while maintaining high energy absorption capabilities. Table 1 below presents the initial peak force values obtained from the numerical simulations of the various crash box models.

As shown in Fig. 6, the double-layer circular base configuration demonstrates superior structural energy absorption performance within the 3-millisecond (0.003 s) observation window. These results confirm that the

double-layer design significantly improves both total energy absorption (EA) and mass-specific energy absorption (SEA). The strategic incorporation of an additional structural layer proves particularly effective, resulting in a 368.7% increase in total energy absorption capacity and an 87.93% improvement in specific energy absorption. Beyond energy absorption capacity, the initial peak force (IPF) is another critical parameter in evaluating crash box performance. The optimal design seeks to minimize the initial peak force while maximizing energy absorption—this dual objective enhances overall crashworthiness [16].

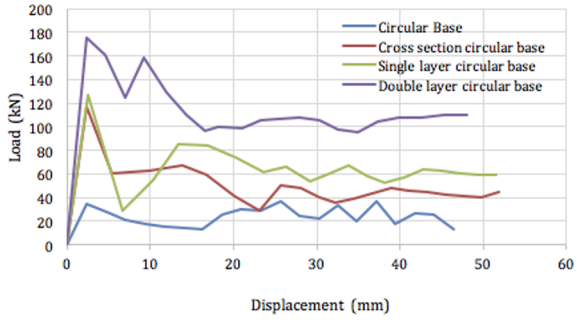

Fig 6. Load-displacement crash box.

Fig. 7 presents the numerically simulated initial peak force (IPF) values for the evaluated crash box configurations. The Force vs. Displacement graph in Fig. 6 illustrates the force response of four crash box types. The horizontal axis (X-axis) represents the displacement of the crash box from the initial state before the collision to the point of impact, while the vertical axis (Y-axis) shows the force in kilonewtons (kN). The interpretation of the graph reveals the force response to displacement for each structure. In the red circle, the IPF values are highlighted for each configuration. For the Circular Base model, the IPF occurs at 37 mm with a force of 37.182 kN. Cross-Section Circular Base model, the displacement change is 2.36 mm, with a force of 116.750 kN. Single-Layer Circular Base model, the displacement change is 2.51 mm, with a force of 127.270 kN. Double-Layer Circular Base model, the displacement change is 2.34 mm, with a force of 175.820 kN.

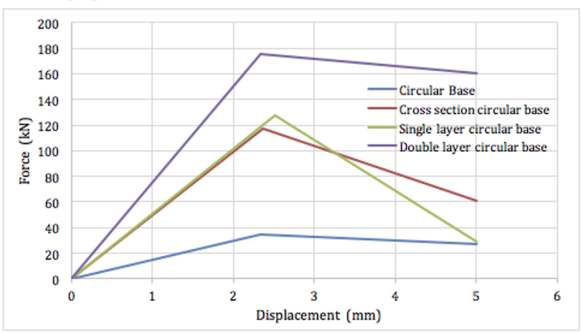

Fig 7. IPF under force-displacement.

The Double-Layer Circular Base model demonstrates a relatively stable force-displacement curve after reaching the IPF, indicating consistent energy absorption performance. In contrast, the Circular Base model exhibits a sharp decrease in force after reaching the IPF, suggesting that the structure collapses or buckles immediately upon reaching peak force. This rapid decrease in force indicates unstable deformation behavior, leading to less efficient energy absorption [18] [19] [20]. The Double-Layer Circular Base model shows a 368.74% increase in energy absorption and a 380.4% improvement in IPF compared to other configurations.

The force reaction graph for each crash box design with varying cross-sectional shapes is illustrated in Fig. 8. This graph shows that crash boxes featuring layered structures experience a greater initial peak force and a larger area beneath the curve when compared to the baseline model. A reduced initial peak force is preferable to lessen the impact forces that reach the vehicle's main compartment. Although the Circular Base model has a marginally lower IPF than the Double-Layer Circular Base, it falls short in energy absorption performance. Hence, in terms of the IPF parameter, the Double-Layer Circular Base model exceeds the performance of the other designs. The following diagram presents a comparison of energy absorption (EA) and IPF values for each model [21] [22] [23].

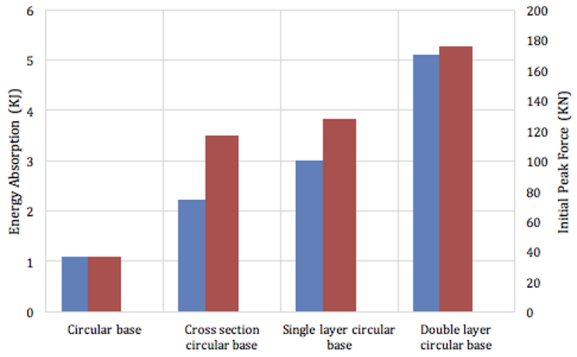

Fig 8. EA and IPF diagram of crash box model.

The mean crushing force (MCF) serves as an additional measure of a structure's capacity for energy absorption. It signifies the average value of all peak loads recorded on the force-displacement graph. The MCF and displacement values from the numerical simulations are shown in Fig 9.

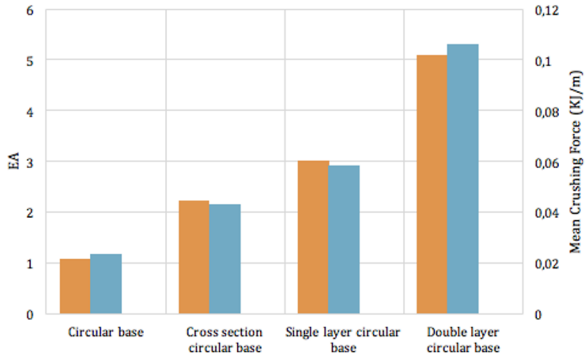

Fig 9. EA and MCF diagrams of the crash box models.

The deformation patterns for each crash box configuration are shown in Fig. 10**.** The Crush Force Efficiency (CFE) is the ratio of the MCF to the maximum peak force (Fmax), indicating the stability of

the structure during the crushing process. A structure with a higher MCF and a lower Fmax value will exhibit a better CFE. The Double-Layer Circular Base model has a superior CFE compared to the other configurations, as it demonstrates a higher MCF (106.2%) and a moderate Fmax value of 175.82 kN. The primary performance parameter for evaluating crash box structures is energy absorption. Figure 10 shows that the Double-Layer Circular Base model performs better in absorbing structural energy with a moderate initial peak force (Fmax) value. The numerical simulation results of the CFE for each crash box model are summarized in Table 2.

Table 2. Comparison value data between simulation and experiment.

Parameter	Simulation	Experiment
Energy absorption (J)	9891.2	9816.66
Crush Distance (mm)	34.5	36.5
Energy absorption Error (%)	0.75	
Crush Distance Error (%)	5.5	

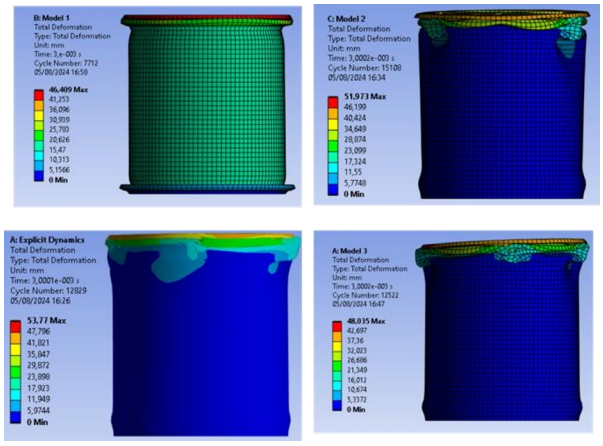

Fig 10. Deformation pattern of crash box model.

The CFE is a key indicator of structural stability during the crushing process. The CFE value is influenced by both the MCF and Fmax values of the structure. Structures with a higher MCF and a lower Fmax will exhibit a better CFE. The Double-Layer Circular Base model achieves a better CFE due to its larger MCF. The EA and CFE diagrams in Fig. 11 show that the Double-Layer Circular Base model has a higher CFE and energy absorption value.

The simulation setup used in this study was based on numerical simulations conducted with models and parameters from previous tests and experiments by Velmurugan. Fig. 12 illustrates the dimensions of the test model used in Velmurugan's study. A comparison of simulation and experimental results, including deformation forms, is shown in Table 2 and Fig. 13. Based on the simulation and experimental results, the energy absorption values differ by 0.75%, and the crush distance differs by 5.5%. These differences are not significant, suggesting that the model setup used in this study can be relied upon for its accuracy [4] [24] [25] [26] [27].

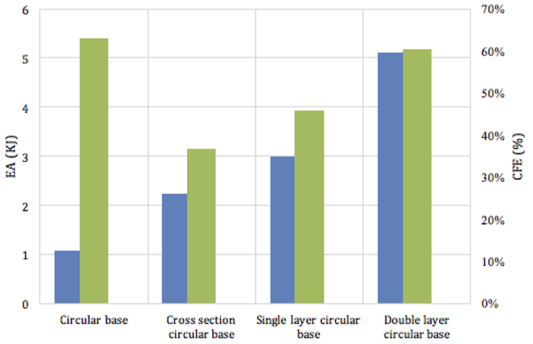

Fig 11. EA and CFE diagrams of the crash box model.

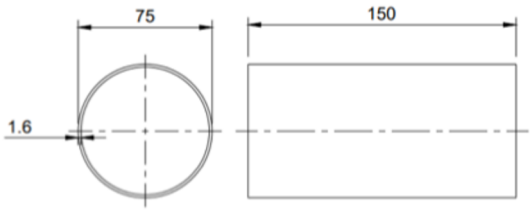

Fig 12. Test model dimensions.

Table 2 presents a comparison between the simulation and experimental results regarding energy absorption and crush distance for the crash box model. The simulation results show an energy absorption value of 9891.2 J, while the experimental results report an energy absorption of 9816.66 J. The difference in energy absorption between the simulation and experiment is only about 0.75%, indicating that the simulation model accurately reflects the energy absorption capability of the crash box under testing. On the other hand, for the crush distance, the simulation yields a value of 34.5 mm, while the experiment records 36.5 mm. The 5.5% difference in the crush distance is moderate but still falls within an acceptable tolerance range between the simulation and experimental results. Although a difference exists, these results suggest that the simulation model is sufficiently representative of the physical phenomena occurring during the crushing process. Overall, this comparison indicates that the simulations performed in this study have a high degree of accuracy and can be relied upon for further evaluation of crash box design and performance under real-world conditions [25] [27].

Fig 13. Experimental and simulated deformation forms.

4 Conclusion

This study aims to evaluate the crashworthiness performance of four cylindrical crash box configurations, with the primary goal of improving energy absorption efficiency during frontal impacts. The key finding of this research is that the double-layer circular base configuration achieved the highest energy absorption (EA) of 5.102 kJ and specific energy absorption (SEA) of 15.22 kJ/kg, representing a 368.74% increase in energy absorption capacity compared to the base model. This configuration also demonstrated superior performance in terms of initial peak force (IPF) and mean crushing force (MCF), positioning it as the optimal design for energy dissipation in crash boxes. The analysis of geometric variations, particularly the addition of layers to the crash box structure, proved effective in enhancing energy absorption capacity while maintaining structural stability during impact. These findings provide strong evidence that geometric modifications, such as the addition of layers, can significantly improve crash box performance, especially in terms of energy absorption efficiency and resistance to crushing forces.

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