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Crashworthiness Analysis of Hierarchical Multi-Cell Circular Structures Made of Recycled Aa6061 Aluminium Alloys for Sustainable Automotive Crash Box

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Abstract

The crashworthiness of automotive structures is crucial for vehicle safety, particularly in reducing impact forces during collisions. Hierarchical multi-cell (HMC) crash box designs, made from recycled AA6061 aluminium alloys, offer superior energy absorption and lightweight properties. However, many existing designs lack thorough evaluation under axial impact conditions, which may affect energy dissipation and structural integrity. This study analyzes stress distribution, deformation behavior, and key metrics such as Specific Energy Absorption (SEA) and Peak Crushing Force (PCF) in both traditional and HMC crash boxes under axial impact. The methodology includes 3D modeling using ANSYS Workbench and Finite Element Analysis (FEA) simulations. Results showed that the conventional crash box design recorded a peak deformation of 31.302mm and a peak crushing force (PCF) of 4.246 kN, while the HMC design achieved a peak deformation of 22.479mm and a PCF of 3.418 kN. This indicated that the HMC design absorbed impact energy more efficiently, resulting in 6.7% less deformation and a lower peak crushing force. Additionally, the HMC crash box demonstrated a higher Specific Energy Absorption (SEA) of 6.963 kJ/kg, compared to 5.612 kJ/kg for the conventional crash box, further proving that the HMC design provides better energy dissipation and enhanced crashworthiness. This research highlighted an innovative HMC crash box design from recycled AA6061 aluminium alloys, enhancing energy dissipation, material efficiency, and structural resilience for safer, sustainable automotive components.

1. Introduction

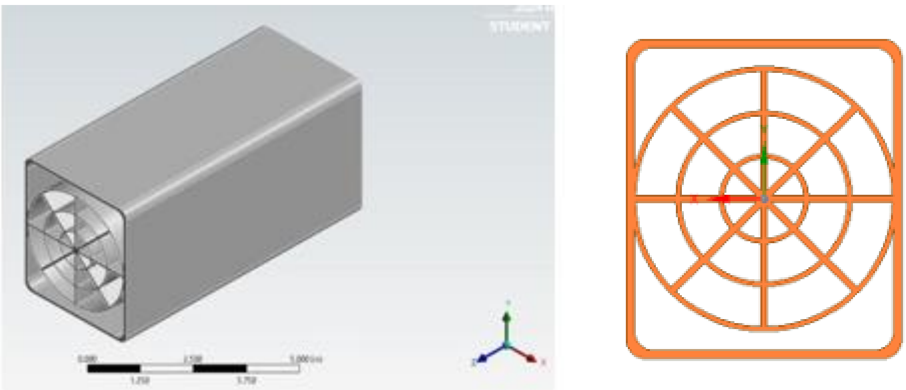
Crashworthiness is crucial for vehicle safety, specifically in absorbing impact energy and protecting occupants during collisions. Crash boxes are vital components that deform upon impact to dissipate energy and minimize damage to the vehicle structure [1]. Traditional designs, such as cylindrical tubes, offer limited energy absorption under complex high-velocity impacts [2]. Recent innovations in crash box designs, like hierarchical multi-cell (HMC) structures, improve energy absorption by distributing impact forces across multiple cells, enhancing crashworthiness while maintaining lightweight properties [3][4]. Aluminium alloys, particularly AA6061, are commonly used in crash boxes due to their high strength-to-weight ratio and recyclability [5][6]. Recycled AA6061 alloys offer environmental benefits by reducing energy consumption and carbon emissions during production [7]. While conventional crash box designs are effective, they often do not perform optimally under complex collision scenarios, particularly with high-velocity impacts. The potential of HMC structures made from recycled AA6061 alloys is underexplored, especially in their ability to improve crashworthiness and sustainability [8][9]. This research aims to fill this gap by evaluating the performance of HMC crash boxes compared to traditional designs. This study aims to: 1) analyze the crashworthiness of HMC crash box designs made from recycled AA6061 alloys using FEA, 2) compare the performance of HMC and conventional crash box designs in terms of energy absorption, deformation, and impact resistance, and 3) assess the environmental benefits of using recycled AA6061 alloys in crash boxes [10]. The study will focus on evaluating the performance of HMC crash boxes under axial impact conditions, comparing crash boxes made from recycled and primary AA6061 alloys, and analyzing energy absorption, deformation behavior, and performance metrics such as Specific Energy Absorption (SEA) and Peak Crushing Force (PCF) [10].

2. Methodology

This section describes the methodology for analyzing the crashworthiness of hierarchical multi-cell (HMC) crash boxes made from recycled AA6061 aluminium alloys using finite element analysis (FEA). The study evaluates energy absorption, peak crushing force (PCF), and deformation behavior under axial impacts, comparing HMC designs with traditional single-cell crash boxes. The crash box geometry, featuring concentric circular cells, is modeled in CAD and imported into ANSYS Workbench. Material properties for recycled AA6061 were defined, and meshing was applied to critical regions. Simulations were carried out to assess performance under various impact speeds, measuring specific energy absorption (SEA) and PCF and then it was compared between the HMC structures and conventional designs.

2.1 Geometry

The geometry of the HMC crash box was designed in ANSYS Workbench, utilizing its advanced tools for seamless integration with the simulation process. The crash box's outer dimensions are 100 mm x 86 mm x 200 mm, with a wall thickness of 2.6 mm, providing a robust external framework designed to withstand axial impacts. The internal structure incorporates concentric circular cells with diameters of 83 mm, 55 mm, and 25 mm, arranged to enhance energy dissipation during impact. The arrangement is reinforced by intersecting lines and an "X" structure at the center to improve deformation resistance and maintain structural integrity under high-stress conditions [3][4]. The internal elements, including the circular cells and reinforcement lines, have a thickness of 1.5 mm, optimizing the balance between strength and deformability as shown in Fig. 1. This hierarchical cell design and reinforcement promote progressive crushing behavior, essential for efficient energy absorption.



(a) (b)

Fig. 1 *Geometry for HMC Crash Box Design*

2.2 Geometry Model Meshing

Meshing in ANSYS Workbench is a critical step in preparing the finite element model for dynamic simulations of the HMC crash box. The mesh subdivides the geometry into smaller finite elements, enabling accurate modelling of complex behaviours during axial impact loading. ANSYS Workbench provides advanced meshing tools that ensure the geometry is represented with precision, which is essential for reliable simulation results. For the HMC crash box, a high-quality mesh was generated as shown in Fig. 2, with finer elements applied to critical regions such as the junctions of concentric circular cells, reinforcement lines, and areas prone to stress concentration.

Skewness, a key quality parameter, was carefully monitored to ensure that the mesh met the required quality standards. By maintaining low skewness values, the mesh quality was optimized to enhance the accuracy of the simulation results and ensure numerical stability during the analysis. A mesh independence study was conducted to confirm that the results were not sensitive to changes in mesh density. This involved running simulations with progressively finer meshes and comparing key performance metrics such as Specific Energy Absorption (SEA) and Peak Crushing Force (PCF). The final mesh configuration was selected to balance computational efficiency and accuracy, ensuring reliable, precise results for the crashworthiness analysis.

Details of "Mesh"	
Quality	
Check Mesh Qua...	Yes, Errors and Warnings
Target Elemen...	Default (0.2)
Target Charac...	Default (8.6639e-004 m)
Target Aspect ...	Default (5.0)
Smoothing	High
Mesh Metric	Skewness
Min	1.3057e-010
Max	0.86635
Average	0.24632
Standard Devi...	0.29759
Inflation	
Advanced	

Fig. 2 *Mesh Quality*

2.3 Material Properties

The material selected for the study was recycled AA6061 aluminum alloy, known for its excellent mechanical properties, including a high strength-to-weight ratio, good ductility, and resistance to corrosion. These properties make it an ideal candidate for use in crash box applications, where energy absorption and material performance under impact conditions are critical. The material properties of the recycled AA6061 alloy were defined in ANSYS Workbench using data from literature [2][7]. Key material properties were assigned to the recycled AA6061 aluminum alloy is illustrated in Fig. 3, including its strength, ductility, and corrosion resistance, all of which play crucial roles in the crashworthiness of the structure.

Properties of Outline Row 3: Recycled Aluminum Alloy NL

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	2770	kg m^-3		
4	Isotropic Elasticity				
5	Derive from	Young's Modulus and Poisson...			
6	Young's Modulus	6.36E+10	Pa		
7	Poisson's Ratio	0.33			
8	Bulk Modulus	6.2353E+10	Pa		
9	Shear Modulus	2.391E+10	Pa		
10	Bilinear Isotropic Hardening				
11	Active Table	Total			
12	Yield Strength	2.2672E+08	Pa		
13	Tangent Modulus	1.5E+09	Pa		
14	Specific Heat Constant Pressure, C_p	875	J kg^-1 C^-1		

Fig. 3 *Material Properties Crash Box HMC design*

The selection of recycled AA6061 aluminum alloy is a pivotal aspect of the study, as it ensures that the crash box design performs effectively in terms of crashworthiness while supporting the sustainability goals of the project. By using recycled materials, the study emphasizes environmental responsibility, ensuring that the material maintains the structural integrity required for effective crash energy dissipation [1][6].

2.4 Boundary Condition

In the dynamic simulation of the HMC crash box, boundary conditions were implemented to replicate a realistic crash scenario where the structure moves and impacts a rigid wall. The rigid wall was modeled as a fixed, immovable surface, accurately representing a real-world collision scenario. The crash box was assigned an initial velocity, causing it to move axially toward the rigid wall, simulating the conditions of a frontal crash. To ensure accurate interaction between the crash box and the rigid wall, a frictionless contact condition was defined at the interface. This setup allowed the crash box to deform and dissipate energy upon impact without unnecessary friction from the surface. The rigid wall was assigned as a reference surface with zero degrees of freedom, while the crash box was set as a dynamic body capable of deformation under impact forces.

The initial velocity of the crash box was specified to align with the target impact speed, ensuring that the simulation captured the energy dissipation and deformation behavior accurately. These boundary conditions effectively modeled the progressive crushing behavior and energy absorption characteristics of the HMC crash box during axial impact.

2.5 Loading Condition

In the dynamic simulation of the HMC crash box, loading conditions were applied to simulate a collision with a rigid wall. A velocity-controlled method was used, assigning an initial velocity to the crash box to mimic real-world crash conditions. This velocity was selected to represent typical crash speeds, ensuring accurate simulation of energy absorption and deformation behaviour. The crash box was moved toward the rigid, immovable wall, which provided the opposing reaction force to induce progressive crushing in the HMC structure. The initial velocity ensured consistent energy input to the system, allowing detailed analysis of the crash box's performance under high-impact loading. These loading conditions ensured a realistic representation of the axial impact, providing reliable data on crashworthiness metrics, such as Specific Energy Absorption (SEA) and Peak Crushing Force (PCF).

2.6 Postprocessing and Results Analysis

The HMC crash box simulation was performed using the Explicit Dynamics module in ANSYS Workbench, selected for handling high-speed, nonlinear dynamic simulations. Time step control adjusted automatically based on the smallest element size, ensuring stability during rapid deformation. The explicit solver managed the time dependent behaviour of the crash box under impact, while reduced integration elements minimized computational time. The simulation ended when the crash box reached a predetermined displacement or when energy absorption stabilized.

Key output parameters, including Specific Energy Absorption (SEA) and Peak Crushing Force (PCF), were monitored to assess the crashworthiness of the HMC crash box. Deformation behavior and stress distribution, especially Von Mises stress, were visualized to identify failure points. Kinetic and internal energy were recorded to evaluate the energy absorption and dissipation efficiency.

3. Simulation Results

Impact simulations were conducted for two crash box designs: a conventional single-cell design made from standard aluminum and a hierarchical multi-cell (HMC) design made from recycled AA6061 aluminum alloys. The analysis focused on deformation, elastic strain, von-Mises stress, Specific Energy Absorption (SEA), and Peak Crushing Force (PCF) to assess energy absorption and impact distribution.

While the conventional crash box uses standard aluminum, the HMC design, made from recycled AA6061, offers environmental benefits with reduced production energy. Simulations used a rigid head form, modeling aluminum alloys and excluding structural steel to ensure a lightweight, realistic simulation. The key results such as total deformation, von-Mises stress, elastic strain, energy absorption and peak force were illustrated in the following section.

Research Progress in Mechanical and Manufacturing Engineering Vol. 6 No. 2 (2025) p. 217-227

3.1 Total Deformation

Fig. 4 and Fig. 5 shows the total deformation of the conventional and HMC crash boxes, respectively. The contour plot image shows the progressive crushing during the impact simulations. The total deformation during axial impact was measured at different time steps. This shows that, at the early stage of impact, the crash box structure undergoes significant deformation at the point of impact.

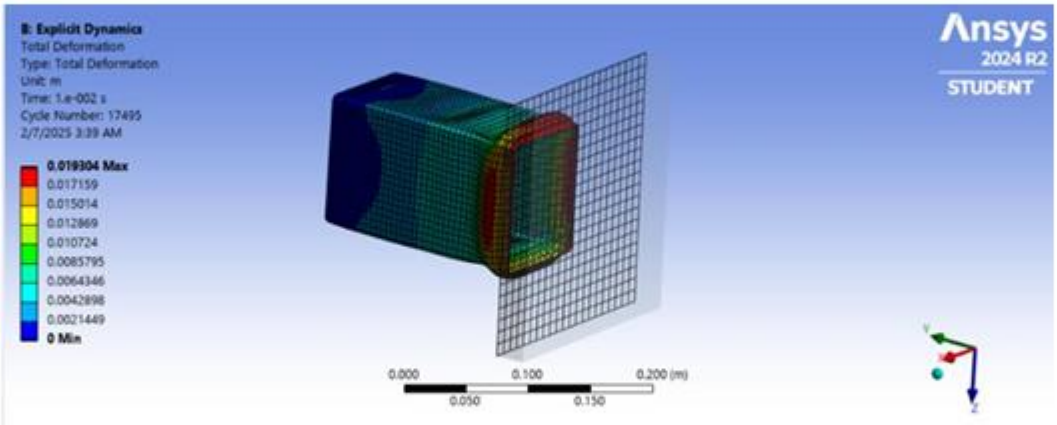


Fig. 4 *Total Deformation Conventional Crash Box Design*

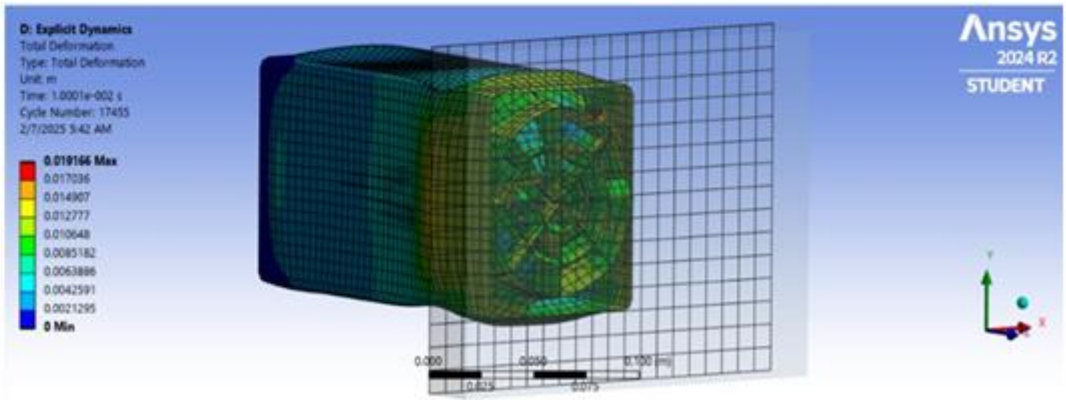


Fig. 5 *Total Deformation HMC Crash Box Design*

Fig. 6 shows that the peak deformation for the HMC Crash Box is 0.022479 meters, while the conventional crash box reaches 0.031302 meters. This indicates that the HMC Crash Box experiences less deformation, suggesting more efficient energy absorption and distribution, likely due to its hierarchical multi-cell structure, which enhances energy dissipation compared to the conventional design.

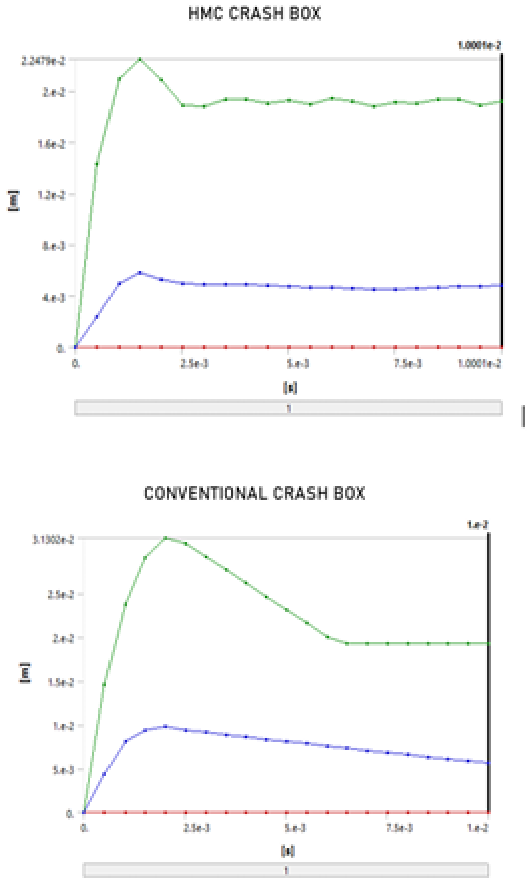


Fig. 6 *Comparison of Total Deformation vs. Time*

3.2 Equivalent (von-Mises) Stress

Fig. 7 and Fig. 8 show the contour plot images of equivalent (von-Mises) stress of the conventional and HMC crash boxes, respectively. Following that, Fig. 9 shows the stress comparison which indicated that the HMC Crash Box reaches a lower peak stress of 429.69 MPa, which quickly decreases and stabilizes, indicating efficient energy absorption and redistribution. In contrast, the conventional crash box peaks at 488.79 MPa and maintains a higher stress level, reflecting less efficient energy dissipation. The HMC design manages stress better, with minimal hourglass and contact stress, while the conventional design shows slower stress reduction, demonstrating the HMC Crash Box’s superior ability to absorb and dissipate impact forces.

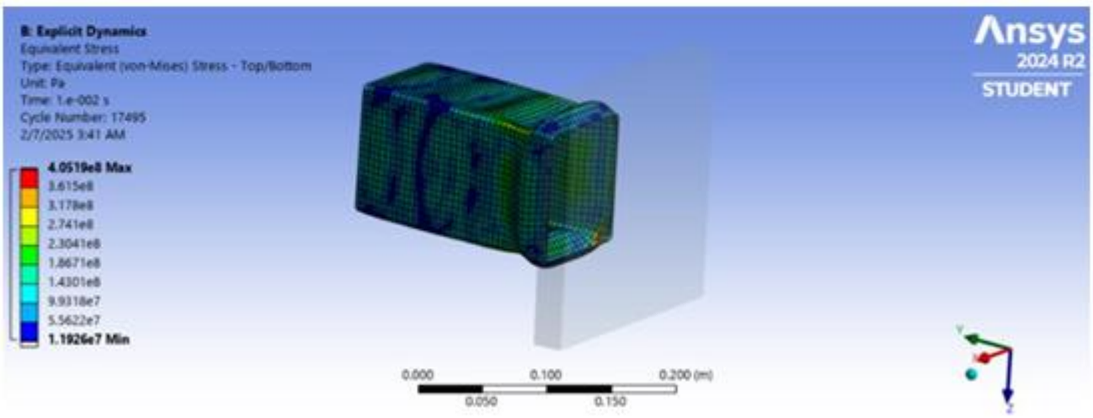


Fig. 7 *Equivalent (von-Mises) Stress Conventional Crash Box Design*

Penerbit UTHM

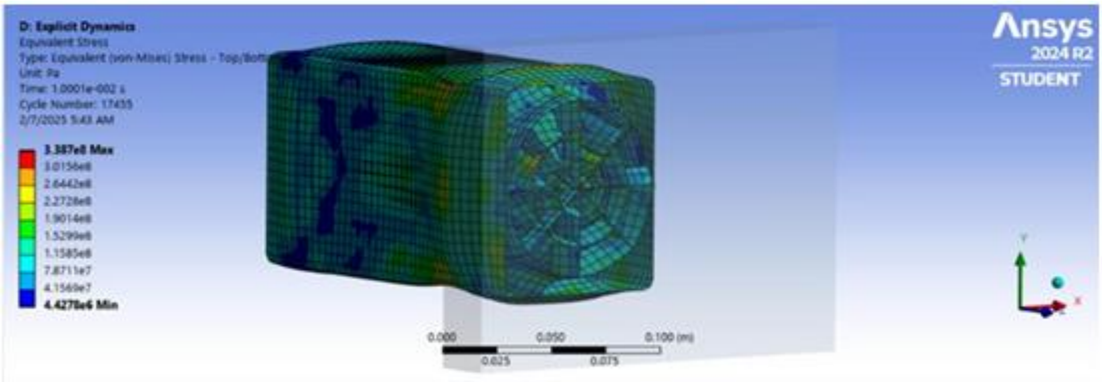


Fig. 8 *Equivalent von-Mises Stress HMC Crash Box Design*

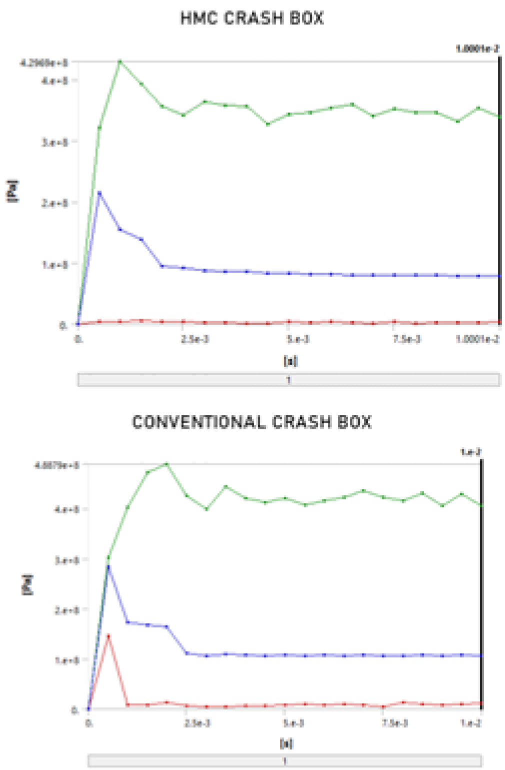


Fig. 9 *Comparison of Equivalent (von-Mises) Stress vs. Time*

3.3 Equivalent Elastic Strain

Fig. 10 and Fig. 11 showed the contour plot images of equivalent elastic strain of the conventional and HMC crash boxes, respectively. Following that, Fig. 12 shows the elastic strain in the conventional crash box exceeded 7.1755 x 10^{-3} m/m, while the HMC crash box remained below 6.9057 x 10^{-3} m/m. This difference highlights the variation in deformation behavior, with the conventional design showing higher localized strain. In contrast, the HMC crash box distributes strain more evenly through its hierarchical multi-cell structure, leading to better energy absorption and more controlled deformation.

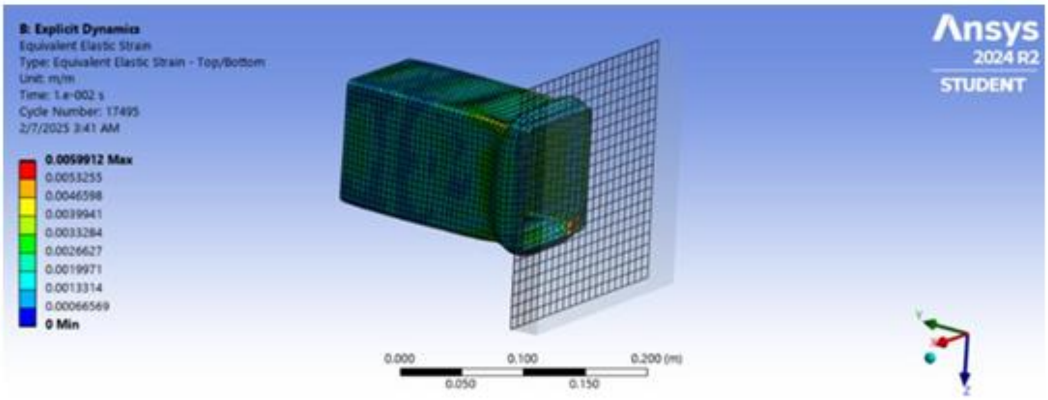


Fig. 10 *Equivalent Elastic Strain Conventional Crash Box Design*

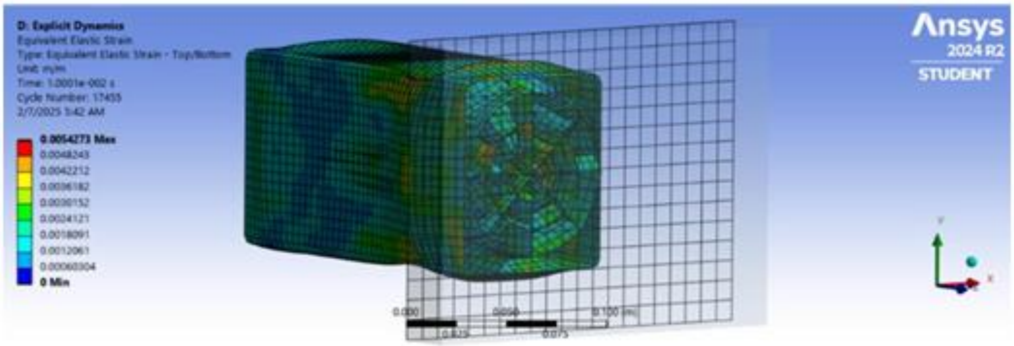


Fig. 11 *Comparison of Equivalent Elastic Strain vs. Time*

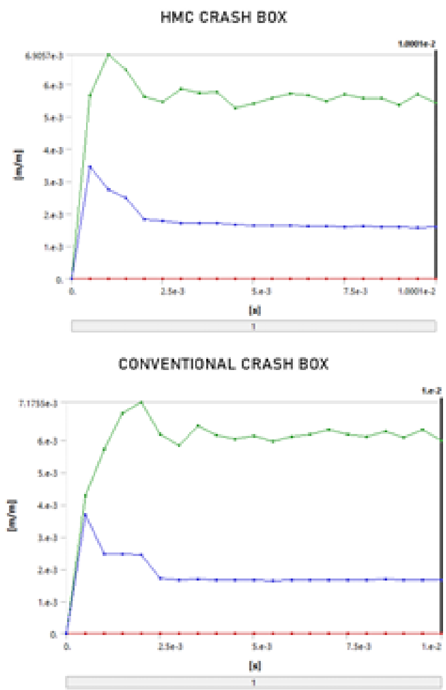


Fig. 12 *Comparison of Equivalent Elastic Strain vs. Time*

3.4 Specific Energy Absorption (SEA)

Fig. 13 indicating the SEA curves of that conventional and HMC crash boxes. This shows the difference in energy absorption between the conventional and HMC crash boxes. The conventional crash box retains more energy throughout the impact, transmitting more force to the vehicle's main structure. In contrast, the HMC crash box absorbs energy rapidly and stabilizes quickly, leading to more efficient energy dissipation, reduced peak forces, and better protection during the collision.

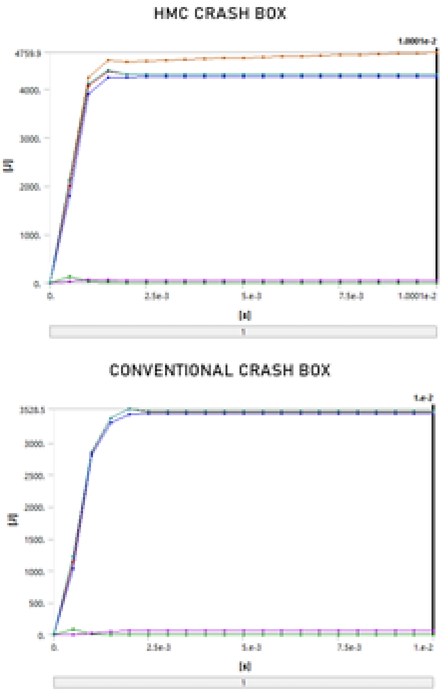


Fig. 13 *Comparison of Energy Probe vs. Time*

3.5 The Peak Crushing Force (PCF)

Fig. 14 highlights the PCF trends of that conventional and HMC crash boxes. The figure shows that the conventional crash box reached a peak deformation of 31.30mm, while the HMC crash box had a lower peak deformation of 22.479mm. This indicated that the HMC crash box experiences less deformation, reflecting its superior energy absorption and more efficient dissipation, offering better protection for the vehicle's structure.

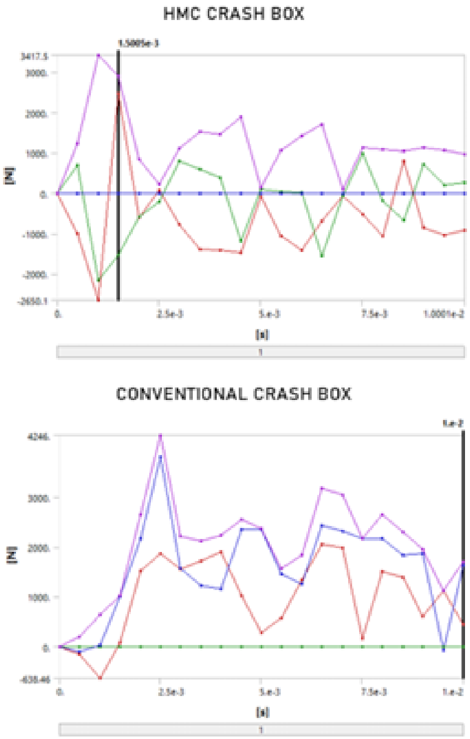


Fig. 14 *Comparison of Force Reaction vs. Time*

4. Conclusion

Through the comprehensive use of finite element analysis (FEA), this research demonstrated that the HMC Crash Box made from recycled AA6061 aluminium alloys significantly outperforms the conventional crash box in terms of energy absorption and crashworthiness. The study successfully analyzed the impact behaviour of both designs and developed comparative performance metrics. The HMC design shows a 25.9% reduction in peak deformation and a lower peak crushing force. Additionally, the HMC design exhibits enhanced energy absorption, with a higher Specific Energy Absorption (SEA) value of 6962.8 J/kg, compared to 5611.8 J/kg in the conventional crash box.

The HMC Crash Box's ability to distribute impact forces evenly, with lower peak stress and better strain control, demonstrates its effective management of impact energy. Unlike conventional design, the HMC design achieves faster stress dissipation and more efficient energy absorption due to its hierarchical multi-cell structure, which offers better load distribution and progressive deformation under impact.

In conclusion, the HMC Crash Box, made from recycled materials, offers a more sustainable and efficient solution for automotive safety. Its superior energy absorption, stress management, and deformation control make it a promising design for improving vehicle safety. This research highlights the potential of recycled materials to enhance both the performance and sustainability of automotive components, contributing to safer, more environmentally friendly vehicle designs.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design, data collection, analysis and interpretation of results and draft manuscript preparation.*** *All authors reviewed the results and approved the final version of the manuscript.*

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