

Design and Structural Analysis of an Automotive Crash Box Using Advanced Hybrid Composite Materials and Optimized Polygonal Geometry

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Abstract

The crash box is a critical energy-absorbing component of the vehicle crumple zone, designed to protect occupants during frontal collisions by reducing the impact force transmitted to the passenger compartment. With the increasing demand for lightweight vehicle design, improved crashworthiness, and stringent safety regulations, the evaluation of advanced materials and optimized crash box geometries has become increasingly important. This study presents a structural analysis of conventional rectangular and optimized polygonal crash box designs using advanced aluminium-based hybrid composites, namely Al + SiC + Graphene and Al + Al₂O₃ + CNT. The study involves CAD modelling, finite element mesh generation, and explicit dynamic crash simulations using Finite Element Analysis (FEA). The crashworthiness performance of the developed designs is evaluated and compared in terms of equivalent stress, total deformation, equivalent elastic strain, and energy absorption to identify an effective lightweight crash box configuration for enhanced automotive safety.

Keywords: Automotive Crash Box; Polygonal Geometry; Hybrid Composite Materials; Crashworthiness; Explicit Dynamic Analysis; Finite Element Analysis (FEA).

1. Introduction

Road transportation has become an integral part of modern society, providing mobility and contributing significantly to economic growth worldwide. However, the increasing number of vehicles on roads has also resulted in a rise in traffic accidents, leading to substantial human and economic losses. According to global road safety reports, millions of people are injured or killed every year due to road traffic collisions, making vehicle safety a major concern for researchers and automobile manufacturers [1], [2], [17]. Therefore, improving vehicle crashworthiness has become a key focus in modern automotive engineering.

A crash box is a sacrificial structural component positioned between the bumper and the main chassis of a vehicle. During a collision, the crash box absorbs a significant portion of the impact energy through controlled plastic deformation, thereby reducing the force transmitted to the passenger compartment. The efficiency of a crash box primarily depends on its geometry, material properties, and energy absorption capability [3]–[5].

In recent years, advancements in material science have enabled the development of lightweight hybrid composites and high-strength alloys that offer superior crashworthiness characteristics compared to conventional metallic materials. Furthermore, innovative

structural configurations such as polygonal sections, multi-cell structures, reinforced designs, and honeycomb geometries have been introduced to improve load distribution and progressive collapse behaviour during impact events [6]–[8]. These developments have contributed significantly to the design of lightweight and safer automotive structures. Recent studies have also highlighted the importance of optimized material selection in improving the structural efficiency of automotive components [16]. Therefore, this study aims to evaluate the structural performance of rectangular and optimized polygonal crash box designs using advanced aluminium hybrid composites under identical crash conditions.

2. Literature Review

A comprehensive review of the literature reveals that considerable research has been conducted on automotive crashworthiness, energy-absorbing structures, thin-walled crash boxes, and advanced lightweight composite materials. Researchers have investigated various crash box geometries, including square, circular, hexagonal, and multi-cell configurations, to improve impact energy absorption while reducing peak crushing forces [1]–[5]. Several studies have also explored the use of lightweight materials such as aluminium alloys, carbon fiber-reinforced composites, graphene-reinforced composites, and ceramic particle-reinforced metal matrix composites to enhance vehicle safety while reducing structural weight [6]–[10].

Despite these advancements, limited research has focused on the comparative crashworthiness performance of conventional rectangular crash boxes and optimized polygonal crash box configurations using advanced aluminium-based hybrid composites. While numerous studies have examined either innovative structural geometries or advanced materials independently, the combined influence of optimized polygonal geometry and lightweight hybrid composite materials under identical impact conditions remains relatively unexplored [11]–[14].

Therefore, the present study addresses this research gap by developing and analysing two crash box configurations: a conventional rectangular crash box and an optimized polygonal crash box. Both designs are evaluated using two advanced hybrid composite materials, Al + SiC + Graphene and Al + Al₂O₃ + CNT. Explicit dynamic finite element analysis (FEA) is performed to compare their crashworthiness performance in terms of equivalent stress, total deformation, equivalent elastic strain, and energy absorption under identical impact conditions. The findings of this study are expected to contribute to the development of lightweight, high-performance crash box designs for improved vehicle occupant safety while supporting weight reduction in modern automotive structures [15], [16].

3. Objectives

- I. To design and develop different vehicle crash box structures using various metallic and composite materials.
- II. To perform explicit dynamic crash analysis using Finite Element Analysis (FEA) and compare the crashworthiness performance of the developed crash box designs based on their mechanical properties, including equivalent stress, total deformation, equivalent elastic strain, and energy absorption.

4. Methodology

4.1. Geometry and Material Specification

Material selection is one of the most important stages in the design of crashworthy structures, as the crash box must provide high energy absorption while maintaining low weight and adequate structural integrity. The selected material should possess high strength, excellent toughness, good impact resistance, low density, high specific energy absorption, as well as good manufacturability and cost-effectiveness. To identify the most suitable material for the proposed crash box application, a systematic material selection process was carried out using the Pugh Matrix Method [2].

In the present study, AA6061 Aluminium Alloy was selected as the reference material owing to its widespread application in automotive crash structures. Six candidate materials were evaluated based on their suitability for crash box applications, considering their mechanical performance, weight, and practical applicability.

Below Candidate Materials Considered,

- I. AA6061 Aluminum Alloy (Reference Material)
- II. Al + SiC + Graphene Composite
- III. Al + Al₂O₃ + CNT Composite
- IV. Carbon Fiber Reinforced Polymer (CFRP)
- V. Magnesium Alloy AZ91
- VI. Inconel 718 Superalloy

The candidate materials were systematically evaluated and ranked using the Pugh Matrix Method. The comparative scores obtained for each material are presented in **Table 1**.

Table 1: Material Ranking

Rank	Material	Scores
1	Al + SiC + Graphene	+8
2	Al + Al ₂ O ₃ + CNT	+7
3	CFRP	+5
4	Inconel 718	+2
5	AZ91 Magnesium Alloy	0
6	AA6061 Aluminium Alloy	0

The Pugh Matrix results indicate that Al + SiC + Graphene and Al + Al₂O₃ + CNT achieved the highest overall scores among all the candidate materials. The Al + SiC + Graphene composite demonstrated excellent specific strength, stiffness, impact resistance, and energy absorption capability while maintaining relatively low weight. The incorporation of silicon carbide (SiC) particles enhances hardness and wear resistance, whereas graphene improves tensile strength, crack resistance, and load transfer efficiency.

The Al + Al₂O₃ + CNT composite ranked second and exhibited a balanced combination of strength, toughness, stiffness, and impact resistance. Carbon nanotubes (CNTs) improve load transfer and crack arrest behaviour, while aluminium oxide (Al₂O₃) particles enhance hardness and compressive strength. Consequently, this composite offers favourable lightweight characteristics together with improved crashworthiness performance.

Although Carbon Fiber Reinforced Polymer (CFRP) possesses high specific strength and low density, its brittle failure behaviour and relatively high manufacturing cost limit its suitability for crash box applications. Similarly, Magnesium Alloy AZ91 provides significant weight reduction but exhibits comparatively lower impact resistance and fatigue strength. Inconel 718 offers excellent mechanical properties; however, its high density and manufacturing cost make it less suitable for lightweight automotive crash structures.

Based on the Pugh Matrix evaluation, mechanical performance requirements, crashworthiness characteristics, and lightweight design considerations, the following materials were selected for detailed explicit dynamic finite element analysis (FEA):

- I. Aluminum + Silicon Carbide + Graphene (Al + SiC + Graphene)
- II. Aluminum + Aluminum Oxide + Carbon Nanotube (Al + Al₂O₃ + CNT)

4.2. Crash Box Thickness Design

For the preliminary design of the crash box, the wall thickness was estimated using the mean crushing force method. The impact energy absorbed during a frontal collision is calculated using the kinetic energy equation:

$$E = \frac{1}{2}mv^2 \quad (1)$$

where:

E = Impact energy (J)
 m = Vehicle mass (kg)
 v = Impact velocity (m/s)

For the present study,

$$m = 300 \text{ kg}, v = 13.89 \text{ m/s}$$

Substituting the above values into Eq. (1),

$$E = \frac{1}{2} \times 300 \times (13.89)^2$$

$$E = 28,947 \text{ J}$$

For a rectangular crash box, the wall thickness can be estimated using the following simplified relation:

$$t = \frac{E}{\sigma_y \times P \times L} \quad (2)$$

where:

t = Wall thickness (mm)
 E = Impact energy (N·mm)
 σ_y = Yield strength (MPa)
 P = Perimeter of crash box section (mm)
 L = Crush length (mm)

The perimeter of the rectangular crash box is calculated as

$$P = 2(60 + 90) = 300 \text{ mm}$$

The impact energy is converted into N·mm as

$$E = 28,947 \times 1000$$

$$E = 2.8947 \times 10^7 \text{ N·mm}$$

I. Al + SiC + Graphene

Assumed yield strength:

$$\sigma_y = 280 \text{ MPa}$$

Substituting the values into Eq. (2),

$$t = \frac{2.8947 \times 10^7}{280 \times 300 \times 350}$$

$$t = 0.985 \text{ mm}$$

Considering manufacturing feasibility, buckling resistance, and an appropriate crash safety factor, the recommended wall thickness was selected as 3 mm for subsequent finite element analysis,

$$t \approx 3 \text{ mm}$$

II. Al + Al₂O₃ + CNT

Assumed yield strength:

$$\sigma_y = 320 \text{ MPa}$$

Substituting the values into Eq. (2),

$$t = \frac{2.8947 \times 10^7}{320 \times 300 \times 350}$$

$$t = 0.86 \text{ mm}$$

Considering manufacturing feasibility, buckling resistance, and an appropriate crash safety factor, the recommended wall thickness was selected as 3 mm for subsequent finite element analysis.

$$t \approx 3 \text{ mm}$$

Table 2 : Calculated and Recommended Crash Box Thickness

Material	Calculated Thickness	Recommended Thickness
Al + SiC + Graphene	0.99 mm	3 mm
Al + Al ₂ O ₃ + CNT	0.86 mm	3 mm

4.3. Design of Crash Box

The Below CAD models of the crash box designs were developed using CATIA V5.

Design 1: Rectangular Crash Box

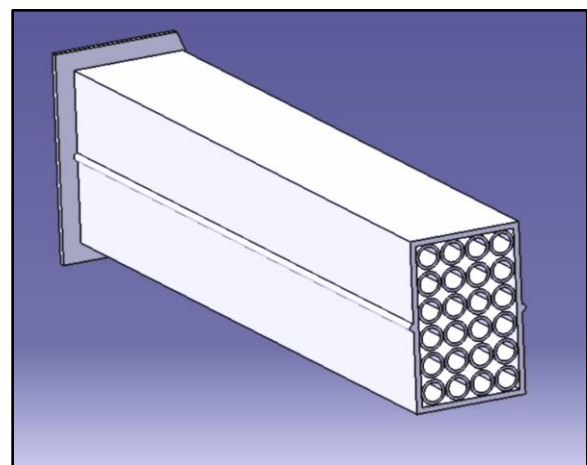


Figure 1: Rectangular Crash Box

Design 2: Optimized Polygonal Crash Box

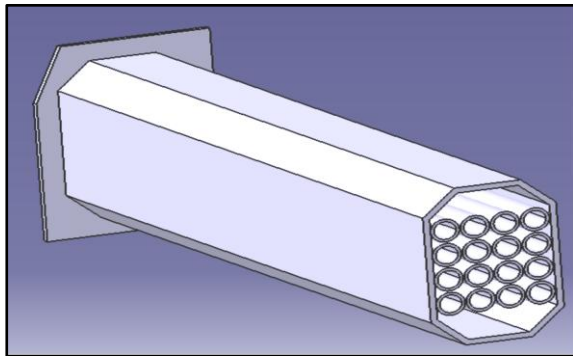


Figure 2: Optimized polygonal crash box

4.4. Analysis

A rectangular crash box and an optimized polygonal crash box, each with dimensions of $90 \times 60 \times 350$ mm, were designed using CATIA V5 and analyzed under explicit dynamic loading conditions. The models were evaluated using two advanced aluminum-based hybrid composite materials, Al + SiC + Graphene and Al + Al_2O_3 + CNT, to investigate their crashworthiness performance and lightweight characteristics. For the explicit dynamic analysis, each crash box was assigned an impact velocity of 13,888.89 mm/s (50 km/h) against a rigid concrete wall of 50 mm thickness. The finite element simulations were performed in ANSYS Workbench to evaluate the crash response of each design in terms of equivalent stress, total deformation, equivalent elastic strain, and energy absorption under identical impact conditions. The comparative analysis was carried out to identify the combination of crash box geometry and material that provides the most effective crashworthiness performance while maintaining a lightweight structure.

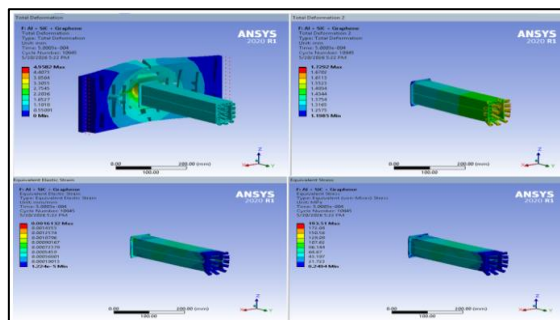


Figure 3: Analysis of Rectangular Crash Box using Al + SiC + Graphene

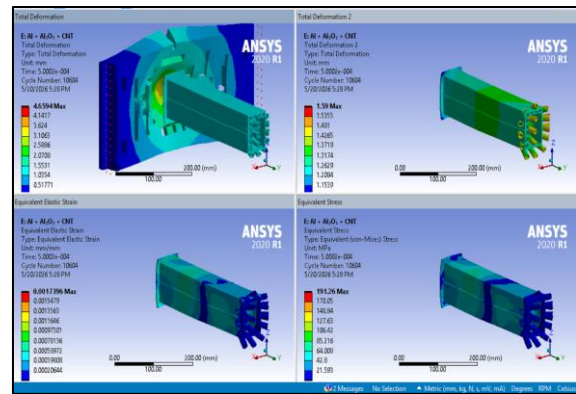


Figure 4: Analysis of Rectangular Crash Box using Al + Al_2O_3 + CNT

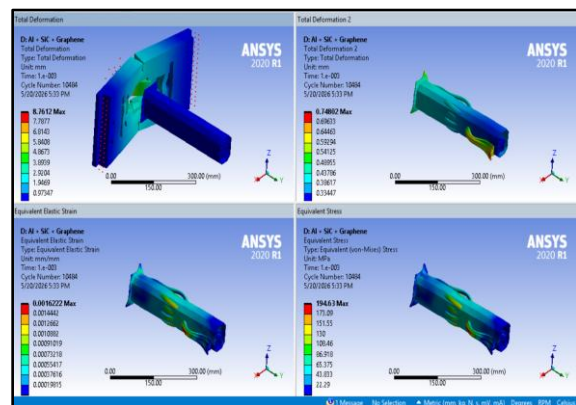


Figure 5: Analysis of Optimized Polygonal Crash Box using Al + SiC + Graphene

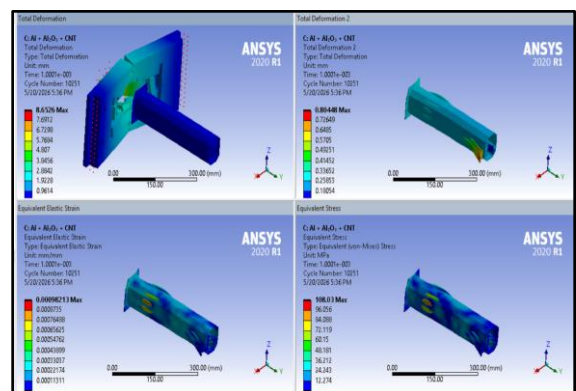


Figure 6: Analysis of Optimized Polygonal Crash Box using Al + Al_2O_3 + CNT

5. Results and Discussion

5.1. Results

Table 3 presents the crashworthiness performance of the conventional rectangular and optimized polygonal crash boxes fabricated using Al + SiC + Graphene and Al + Al_2O_3 + CNT

hybrid composite materials under identical explicit dynamic loading conditions.

Table 3: Results

Design & material	Deformation (mm)	Stress (Mpa)	Strain	Energy (mJ)
Design 1 Al + SiC + Graphene	1.7292	193.51	0.00161	2.181×10^5
Design 1 2Al+AlO ₃ +CNT	1.59	191.26	0.00173	2.144×10^5
Design 2 Al + SiC + Graphene	0.748	194.63	0.00162	1.6596×10^5
Design 2 2Al+AlO ₃ +CNT	0.804	108.03	0.00098	1.6315×10^5

For the rectangular crash box, the Al + SiC + Graphene composite exhibited a total deformation of 1.7292 mm, an equivalent stress of 193.51 MPa, an equivalent elastic strain of 0.0016132, and an energy absorption of 2.181×10^5 mJ. The Al + Al₂O₃ + CNT composite recorded a slightly lower deformation of 1.59 mm and an equivalent stress of 191.26 MPa, with an equivalent strain of 0.0017396 and an energy absorption of 2.144×10^5 mJ. The results indicate that both materials demonstrated comparable crashworthiness performance, while the Al + SiC + Graphene composite exhibited marginally higher energy absorption. For the optimized polygonal crash box, a significant reduction in total deformation was observed for both materials. The Al + SiC + Graphene composite recorded a deformation of 0.74802 mm, an equivalent stress of 194.63 MPa, an equivalent elastic strain of 0.0016222, and an energy absorption of 1.6596×10^5 mJ. In comparison, the Al + Al₂O₃ + CNT composite exhibited a deformation of 0.80448 mm, the lowest equivalent stress of 108.03 MPa, the lowest equivalent strain of 0.0009821, and an energy absorption of 1.6315×10^5 mJ.

Overall, the optimized polygonal crash box demonstrated superior deformation resistance compared with the conventional rectangular design, indicating improved structural stiffness and more efficient load distribution during impact. Among the investigated materials, the Al + SiC + Graphene composite consistently exhibited higher stress-carrying capability and greater energy absorption, whereas the Al + Al₂O₃ + CNT composite produced lower stress and strain values, suggesting a more uniform stress distribution. These findings indicate that the optimized polygonal crash box, combined

with advanced aluminium-based hybrid composites, offers improved crashworthiness while maintaining lightweight characteristics, making it a suitable candidate for automotive energy-absorbing structures.

5.2. Comparison

A comparative analysis was carried out to evaluate the crashworthiness performance of the developed crash box designs using **two** different hybrid composite materials. The comparison was based on key performance parameters, including total deformation, equivalent stress, equivalent elastic strain, and energy absorption, under identical impact loading conditions.

I. Deformation

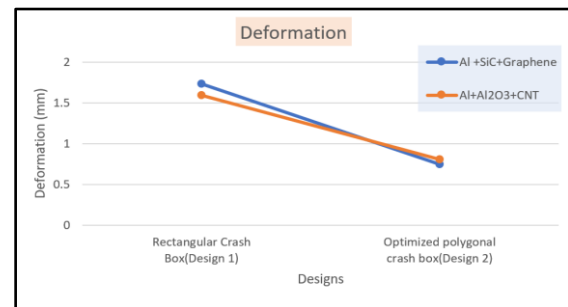


Figure 7: Deformation Comparison

The optimized polygonal crash box (Design 2) exhibited significantly lower deformation than the conventional rectangular crash box (Design 1) for both composite materials. The total deformation of the Al + SiC + Graphene composite decreased from 1.7292 mm to 0.74802 mm, while that of the Al + Al₂O₃ + CNT composite reduced from 1.59 mm to 0.80448 mm. This reduction in deformation indicates improved structural stiffness and enhanced crash resistance of the optimized polygonal design.

II. Stress

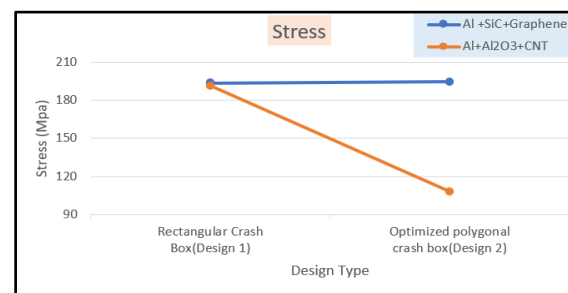


Figure 8: Stress Comparison

In terms of equivalent stress, the Al + SiC + Graphene composite exhibited comparable stress values in both designs (193.51 MPa and 194.63 MPa). In contrast, the Al + Al₂O₃ + CNT composite showed a substantial reduction in equivalent stress from 191.26 MPa in Design 1 to 108.03 MPa in Design 2, indicating a more uniform stress distribution in the optimized polygonal geometry.

III. Strain

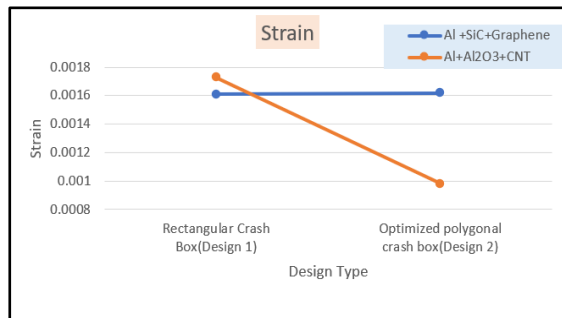


Figure 9: Strain Comparison

For equivalent elastic strain, the lowest value (0.0009821) was obtained for the optimized polygonal crash box (Design 2) fabricated with Al + Al₂O₃ + CNT, whereas the remaining cases exhibited strain values ranging from 0.00161 to 0.00174. This indicates a more uniform deformation behaviour and improved structural response of the optimized polygonal design under impact loading.

IV. Energy

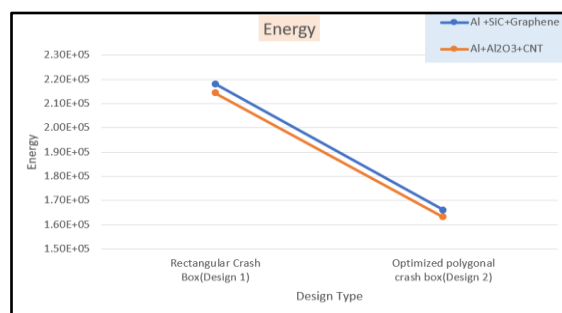


Figure 10: Energy Comparison

Regarding energy absorption, the conventional rectangular crash box (Design 1) absorbed slightly higher impact energy than the optimized polygonal crash box (Design 2). The maximum energy absorption of 2.181×10^5 mJ was recorded for the rectangular crash box fabricated with Al + SiC + Graphene, whereas the optimized polygonal design absorbed 1.6596×10^5 mJ and

1.6315×10^5 mJ for Al + SiC + Graphene and Al + Al₂O₃ + CNT, respectively. Although the rectangular configuration exhibited higher energy absorption, the optimized polygonal design demonstrated lower deformation and more favourable stress distribution, indicating improved overall structural performance under the applied impact loading.

6. Conclusion

The present study demonstrates that both crash box geometry and material selection significantly influence the crashworthiness performance of automotive energy-absorbing structures. Among the two crash box designs investigated, the optimized polygonal crash box exhibited superior structural performance by providing improved stress distribution and significantly reduced deformation compared with the conventional rectangular crash box. This improvement can be attributed to the optimized structural configuration, which enables more efficient transfer and distribution of impact loads.

In terms of material performance, the Al + SiC + Graphene composite demonstrated better overall crashworthiness characteristics, exhibiting higher stress-carrying capability, lower deformation, and greater energy absorption than the Al + Al₂O₃ + CNT composite. These characteristics indicate that the Al + SiC + Graphene composite possesses higher stiffness and improved impact resistance, making it a promising material for automotive crash box applications.

Overall, the combination of the optimized polygonal crash box and the Al + SiC + Graphene composite offers an effective balance between lightweight construction, structural integrity, and crashworthiness performance. Therefore, this combination is considered a suitable configuration for improving vehicle crashworthiness and enhancing passenger safety.

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