Design and Analysis of Automotive Crash Box Using the Composite Material

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Abstract. This study analyze the crashworthiness and design of car crash boxes made of composite and mild steel materials. The behaviour of square, circular, and hexagonal crash boxes under axial impact at a velocity of 4.167 m/s was examined using finite element analysis (FEA). The examination looked at a variety of performance variables, including energy absorption, equivalent stress, and deformation. With simply 7.46 mm of deformation and 3697.3 J of energy absorbed, the square crash box performed better than the other two designs. Lower energy values of 1328.2 J and 1132.4 J were absorbed by the hexagonal and circular models. The crash boxes were reinforced with composite materials including Carbon Fiber and Glass Fiber to assist enhance crash performance. The carbon fiber reinforced square crash box performed the best after reinforcing. Compared to the conventional mild steel square crash box, CFR crash box absorbed up to 4496.7 J of energy, or 21.6% more than the mild steel square crash box. Additionally, the model underwent reduced stress concentration during impact loading and maintained regulated deformation of about 8.67 mm. Stable progressive folding and continuous energy absorption during the loading process were demonstrated by experimental compression testing, which corroborated the computer results. According to the study, composite reinforcement can greatly increase crashworthiness and aid in the design of lightweight vehicles. The CFRP-reinforced square crash box was determined to be the best option for upcoming automotive safety applications out of all the tested configurations.

Keywords - Material Change, Crash Box, Composite Material, FEA.

1 Introduction

Today's automotive sector places a high priority on vehicle safety. Although automakers are working to make cars lighter and more fuel-efficient, crash protection remains crucial. One of the primary tools for enhancing collision safety is a crash box. It is situated in the space between the bumper and the car frame. The crash box bends and deforms in a controlled way

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to absorb impact energy in the case of an accident. This lessens damage to crucial vehicle components and lessens the force applied to the occupants. Passenger safety is enhanced in this way, and subsequent repairs are simpler and less expensive.

Because they were simple to construct and strong enough to provide impact protection, early crash boxes were typically constructed from thin-walled metal tubes. The requirement for crash boxes with better energy absorption grew as industries shifted to lighter, more fuel-efficient designs. Researchers have investigated several novel methods to improve crash performance, including as the use of geometric triggers, multi-cell designs, auxetic and origami-inspired structures, and foam-filled or hybrid materials. At once, advances in numerical analysis techniques and simulation tools have made it simple to analyze how these structures deform under impact. This has made it possible for engineers to create crash boxes that are more functional and suitable for various applications.

The main goal of this work is to design and analyze automotive crash boxes for improving their crashworthiness behaviour. The study that takes into account various factors like material selection, geometry design and simulation analysis. The goal is to discover a crash box structure that is proficient of absorbing more impact energy as maintaining a low weight and manufacturability of the design. The information gathered aids in the development of safer and more efficient impact-mitigation technology for cars of the future.

Increasing energy absorption (EA), specific energy absorption (SEA), and lowering peak force through advances in geometry, material, and manufacturing are the main goals of recent crash-box design studies. Abdullah et al. noticed the increasing trend toward composite and additive manufacturing solutions and emphasized the significance of unified experimental–numerical frameworks [1]. Designs based on additive manufacturing, including graded and tapered wall crash boxes, exhibit better progressive folding and fewer force spikes, although they have issues with scalability and anisotropy [2]. Higher SEA and stable deformation are shown by advanced geometries, such as auxetic and reentrant structures, when compared to designs [3].

Although controlled deformation and smoother force-displacement responses are made possible by origami-inspired composite crash boxes, their effectiveness is highly dependent on manufacturing accuracy [4]. Multi-cell and triggered geometries greatly improve energy absorption and stop global buckling, according to comparative FEA studies [5]. To improve crushing performance, trigger features such as dimples and notches are often introduced in sandwich structures so that collapse starts in a controlled and stable manner [6]. Some current studies found that topology optimization can create crash-box shapes that suggests different from traditional designs but can perform better under impact loading [7]. Researchers noticed that increasing Specific Energy Absorption alone is not enough for better passenger safety if the crash pulse is not effectively managed [8].

In electric vehicles, foam-filled crash boxes and structures improved for impacts from different directions have shown effective results during oblique collisions [9]. Some current studies have used alternate modelling methods like Gaussian Process Regression to improve the design of multi-corner crash boxes. These methods help researchers to reduce the overall weight of the structure whereas also improving its Specific Energy Absorption capability [10]. Researchers are now concentrating more on combining advanced materials, new geometric concepts, and improving techniques to develop the crash absorbers with better performance.

Novelty of Work - The Crash box is design and analyse to absorb more impact energy and remain lightweight and simple to build which is primary goal of the study. Unlike the previous studies which were focused on only one performance but this study focuses on several performance. It focuses on mainly three targets that are increasing energy absorption, lowering peak impact force and managing total weight. Realistic mounting and boundary conditions were also introduced to make the crash behaviour more similar to real car collision situations. Furthermore, different hybrid designs like multi-cell and tapered structures filled with foam or composite materials were investigated to improve progressive deformation and reduce sudden impact loads. The study also investigated oblique impact conditions, which are often seen in electric vehicles and also considered the effects of manufacturing variations on crash performance. Surrogate-based optimization techniques were employed to explore different design possibilities to improve the speed and efficiency of the design process. Some improved crash-box models were also tested experimentally to verify the simulation results and better understand the influence of the component behaviour on the safety of passengers during collisions.

2 Material and Method

The behaviour of crash boxes under axial impact loading was investigated using finite element analysis in this study. Three shapes i.e. square, circular and hexagonal were generated using mild steel material properties. To obtain accurate stress and deformation results during the simulation, a mesh size of 10 mm was selected. According to RCAR standards, one end of the model was fixed and an impact velocity of 4.167 m/s was applied at the other end to study crash response of each geometry. Large deformation behaviour was simulated using nonlinear transient structural analysis. The square shape was covered with 1 mm thick GFRP and CFRP layers to create composite combinations. To track energy absorption and crushing reaction, contact interactions and energy probes were established. In order to verify simulation results, a prototype was also built and tested experimentally using a Universal Testing Machine (UTM).

2.1 FEA of Crash boxes

2.2.1 Square Crash box

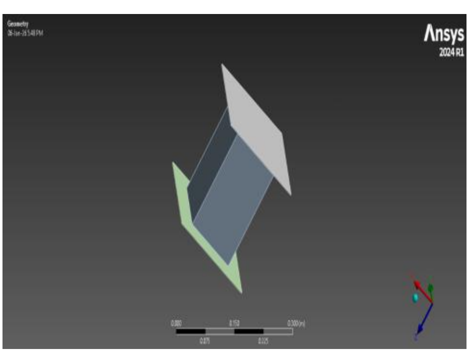


Fig. 1. Geometry of Square Crash box

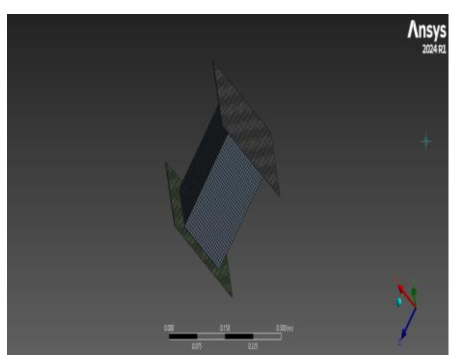


Fig. 2. Meshing of Square Crash box (Element size – 10.0 mm, Nodes- 13760, Elements- 6786)

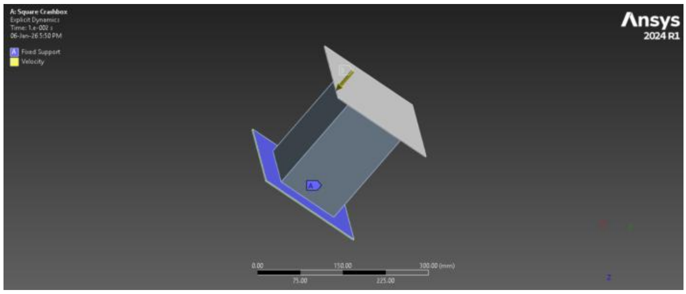


Fig. 3. Boundary conditions for Square Crash box

Standard measurements were used to represent the square crash box geometry, and mild steel material properties were applied. The deformation behaviour was accurately captured using a tiny mesh with an appropriate element size. The crash box had axial impact loading applied at one end and one end fixed. In order to replicate actual crushing behaviour during impact, appropriate contact definitions were incorporated. Large deformations and material response might now be taken into consideration using nonlinear analysis. The simulation was run with transient structural analysis parameters.
The initial impact velocity was calculated by converting the usual RCAR crash test speed of 15 km/h to 4166.7 mm/s (4.167 m/s). The moving crash box was given this speed, and the other end stayed stationary. Energy absorption was tracked throughout time using energy probes. All things considered, these circumstances guaranteed accurate simulation of crash performance and deformation characteristics.

2.2.2 Circular Crash box

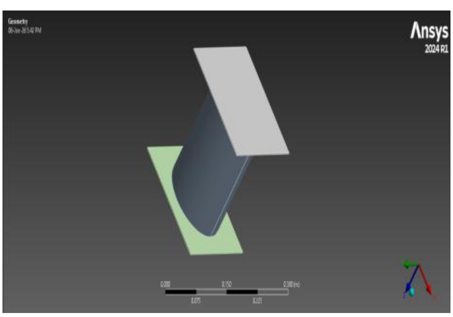


Fig. 4. Geometry of Circular Crash box

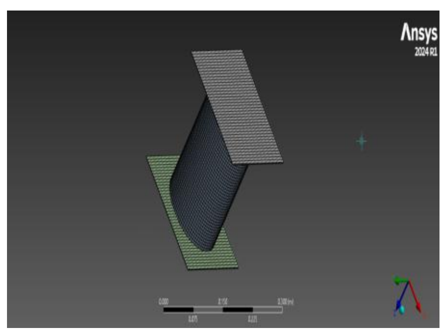


Fig. 5. Meshing of Circular Crash box (Element size - 10.0 mm, Nodes - 13411, Elements - 6522)

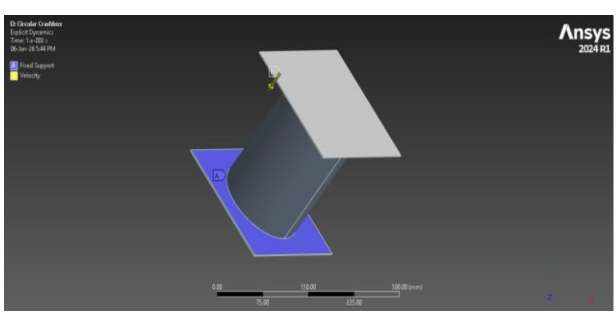


Fig. 6. Boundary conditions for Circular Crash box

Mild steel material properties were assigned to the circular crash box model with a uniform cross-section. A structured mesh was created to achieve better accuracy along the curved regions of the geometry. One end of the crash box was fixed, while an impact velocity of 4166.7 mm/s was applied at the opposite end. Contact definitions were included to capture the deformation behaviour during impact. The analysis also considered large deformation effects and nonlinear material characteristics. Transient analysis settings were applied to study the response over time, and probes were used to monitor the amount of energy absorbed during the simulation.

2.2.3 Hexagonal Crash box

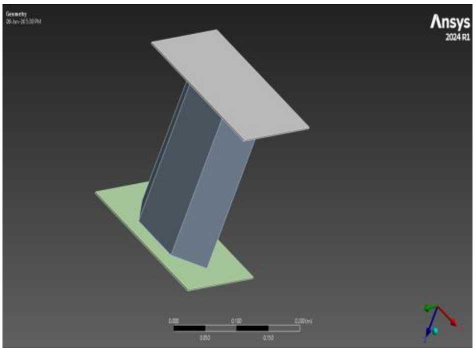


Fig. 7. Geometry of Hexagonal Crash box

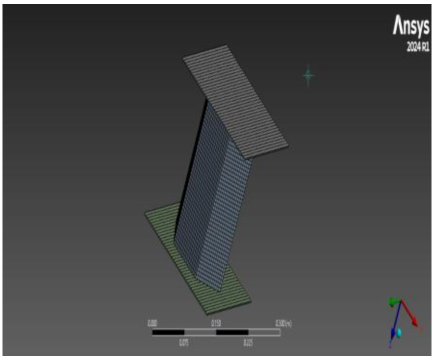


Fig. 8. Meshing of Hexagonal Crash box (Element size - 10.0 mm, Nodes - 13042, Elements - 6402)

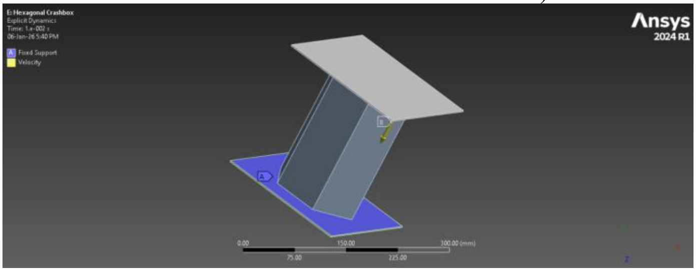


Fig. 9. Boundary conditions for Hexagonal Crash box

Six-sided geometry was used to model the hexagonal crash box, and mild steel characteristics were assigned. The mesh was improved to clearly examine stress distribution and edge-related effects. One end had fixed support, and the other end had an impact velocity of 4166.7 mm/s. Nonlinear analysis settings were enabled to capture realistic deformation during the impact simulation. Proper contact regions were assigned between the interacting surfaces to ensure accurate results. The crash behavior was analyzed using transient solver settings under impact loading conditions. In addition, energy probes were included throughout the simulation to observe the energy absorption response during deformation.

2.2.4 Glass Fiber Reinforced Crash box

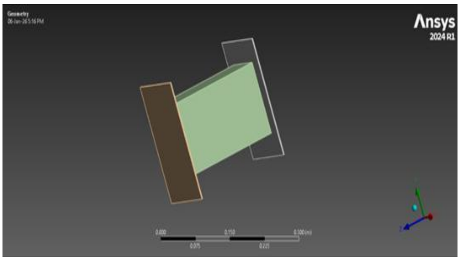


Fig. 10. Geometry of GFR Square Crash box.

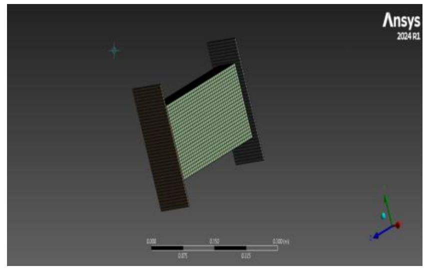


Fig. 11. Meshing of GFR Square Crash box. (Element size - 10.0 mm, Nodes - 16288, Elements - 7842)

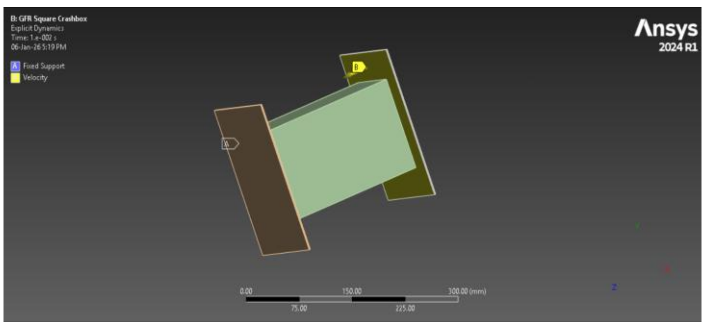


Fig. 12. Boundary conditions for GFR Square Crash box

Mild steel was used to model the square crash box, and its exterior was covered with a 1 mm coating of glass fiber. The GFR layer was applied on a Crash box to act as a composite material. To see exactly how the Crash box bends in high detail we used tiny mesh particles. The velocity of 4166.7mm/s was applied to hit at one end on Crash box while leaving another end is fixed. Nonlinear transient analysis and proper contact were observed. Energy absorption was monitored with energy probes. Overall performance and deformation control were enhanced by the GFR layer.

2.2.5 Carbon Fiber Reinforced Crash box

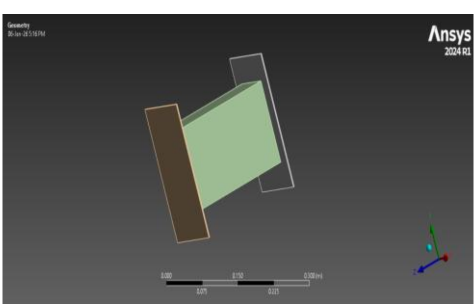


Fig. 13. Geometry of CFR Square Crash box

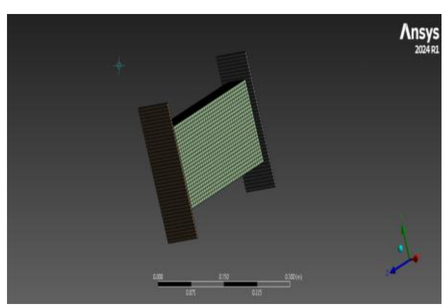


Fig. 14. Meshing of CFR Square Crash box (Element size - 10.0 mm, Nodes - 16288, Elements - 7842)

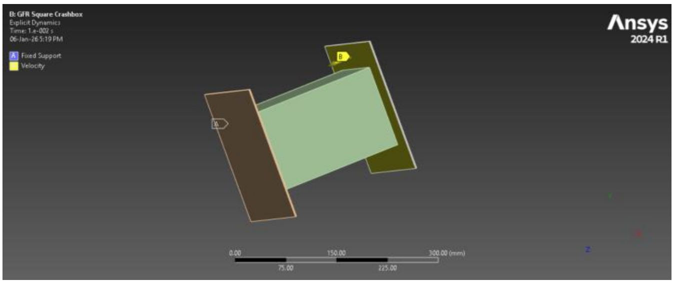


Fig. 15. Boundary condition of CFR Square crash box

A coating of 1 mm carbon fiber was placed over mild steel to fortify the square crash box. Higher strength and stiffness were offered by the characteristics of carbon fiber. Accurate stress and deformation findings were guaranteed by a revised mesh. Fixed support and an impact velocity of 4166.7 mm/s were the boundary conditions. Nonlinear transient analysis and contact were used. Throughout the simulation, energy absorption was tracked. The optimal configuration is the CFR model, which demonstrated greater energy absorption.

2.2.6 Manufacturing Method

Sheet metal forming and composite reinforcing techniques are used in the production of the square crash box. First, a mild steel (MS) sheet is chosen and cut in accordance with the design's specifications. To create a square cross-section, the sheet is then meticulously marked along bending lines. The material is plastically distorted along these lines using a bending machine to create a square shape with accurate dimensions. After shaping the sections, the edges were joined together to complete the crash box structure.

Fig. 16. Crash box after bending

First, the outer surface of the mild steel (MS) crash box was cleaned properly to remove dust, rust, and oxide particles so that good bonding could be achieved. The MS surface was cleaned and resin was applied on it. Then carbon fiber sheets were wrapped around the crash box and again resin was applied on it. By making the use of sanding and grinding, the extra resin and surface imperfections was removed. The exact size and structural stability of crash box were analyzed. This whole production process improved the structure's energy absorption capacity, stiffness and crashworthiness.

Fig. 17. Resin Solution Preparation

Fig. 18. Reinforced Part Using Carbon Fiber

3 Result and Discussion

The square crash box performed better than the circular and hexagonal forms in terms of energy absorption, according to the results. Its energy absorption of 3697.3 J suggests improved crashworthiness. Because of its high stiffness, the hexagonal model showed the least amount of deformation (3.19 mm), although it had a reduced capacity for absorbing energy. The circular geometry absorbed lower energy than the square model and had the higher deformation of 14.21 mm.

Performance was also plainly impacted by the use of composite materials. At 4496.7 J, the CFR-reinforced square crash box had the maximum energy absorption 21.6% which more than mild steel. At 3349.3 J, GFR reinforcement verified a little reduced energy absorption, offering a more consistent stress distribution. Additionally, CFR kept stress levels reasonable at 4876.5 MPa while supporting in the maintenance of stable deformation behaviour. Progressive folding was verified by experimental observations without sudden failure. In terms of strength, deformation control, and energy absorption under impact loading, the CFR-based square geometry presented the best overall balance.

3.1 FEA Results of Crash boxes

3.1.1 Square Crash box

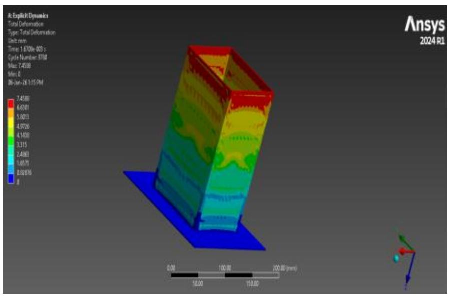


Fig. 19. Total Deformation of Square Crash box

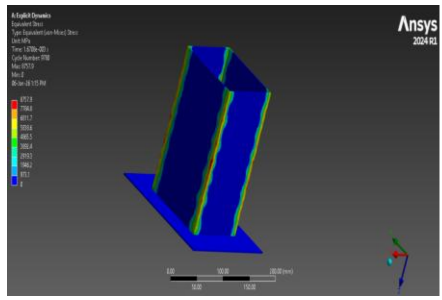


Fig. 20. b) Equivalent Stress of Square Crash box.

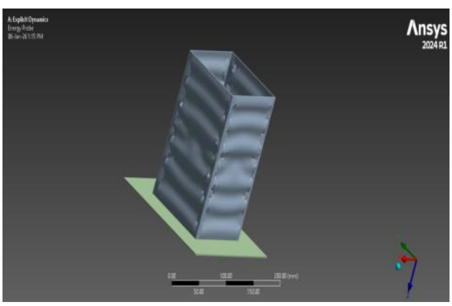
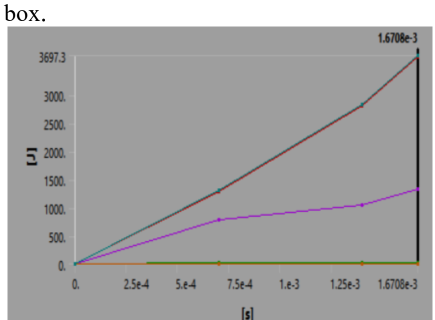


Fig. 21. Energy Probe



Maximum Value Over Time	
Internal	3684.1 J
Kinetic	13.143 J
Plastic Work	0. J
Hourglass	1328.1 J
Contact	0. J
Total	3697.3 J

Fig. 22. Energy Probe vs Time Graph

With a maximum total deformation of 7.4588 mm, the square crash box demonstrated a considerable degree of structural collapse. Higher stress produced at specific areas of the structure during impact, as shown by the model's equivalent stress value of 8757.9 MPa. With a collision energy absorption of 3697.3 J, it verified strong energy dissipation capabilities. Even so, the chance of structural failure may be increased in particular areas due to the concentration of stress. The structure's stability under impact loading remains concern, despite the overall energy absorption performance sufficient for the purpose.

3.1.2 Circular Crash box

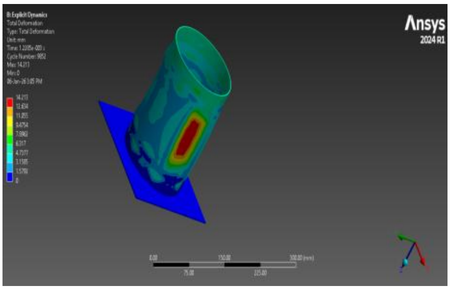


Fig. 23. Total Deformation of Circular Crash box

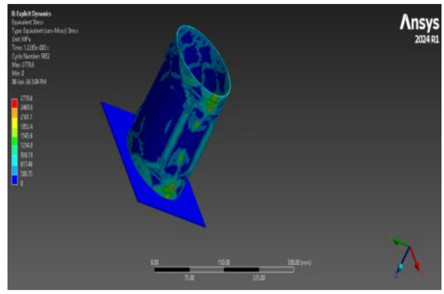


Fig. 24. Equivalent Stress of Circular Crash box.

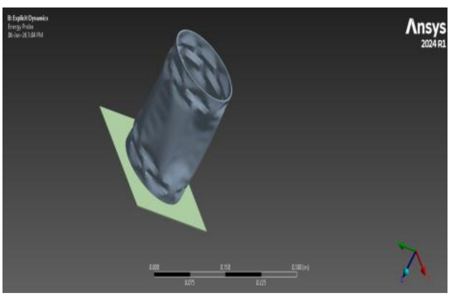
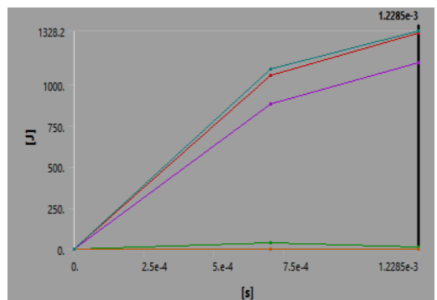


Fig. 25. Energy Probe



Maximum Value Over Time	
Internal	1317.3 J
Kinetic	39.052 J
Plastic Work	0. J
Hourglass	1135.8 J
Contact	0. J
Total	1328.2 J

Fig. 26. Energy Probe vs Time Graph

In comparison to other shapes, the circular crash box showed the greatest deformation of 14.213 mm, indicating inferior rigidity. With a balanced stress value of 2778.6 MPa, the circular model verified a more uniform distribution of stress than the square model. The measured directional deformation of 5.8659 mm show a smaller concentration of axial stress during impact. Even so, compared to the square model, the circular shape only absorbed 1328.2 J of energy. In spite of experiencing less stress, the structure's crash performance was inhibited by its increased deformation and decreased energy absorption. Therefore, the circular model may not be the best choice for applications where high impact resistance is required.

3.1.3 Hexagonal Crash box

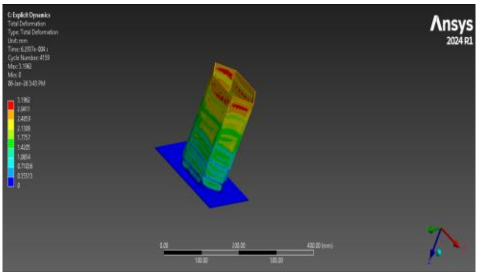


Fig. 27. Total Deformation of Hexagonal Crash box

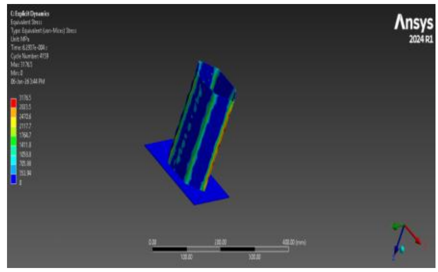


Fig. 28. Equivalent Stress of Hexagonal Crash box.

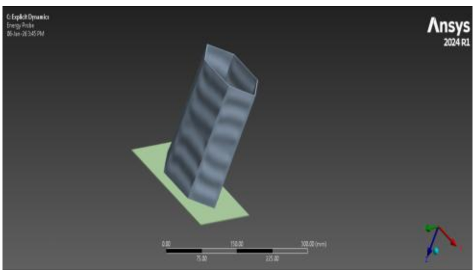
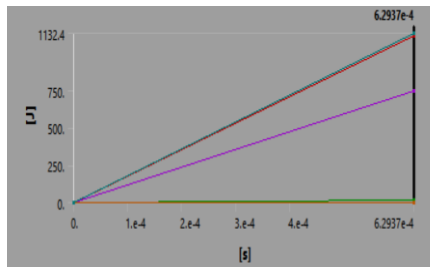


Fig. 29. Energy Probe



Maximum Value Over Time	
Internal	1118.8 J
Kinetic	13.642 J
Plastic Work	0. J
Hourglass	749.11 J
Contact	0. J
Total	1132.4 J

Fig. 30. Energy Probe vs Time Graph

With a deformation of only 3.1962 mm, the hexagonal crash box demonstrated the highest level of rigidity. The equivalent stress, which is modest and evenly distributed, was 3176.5 MPa. Out of all the geometries, the lowest energy absorption was 1132.4 J. This suggests a low dissipation of crash energy. It is less effective at absorbing impact energy even if it is structurally stable. It works well when energy absorption is not as important as stiffness.

3.1.4 Glass Fiber Reinforced Square Crash box

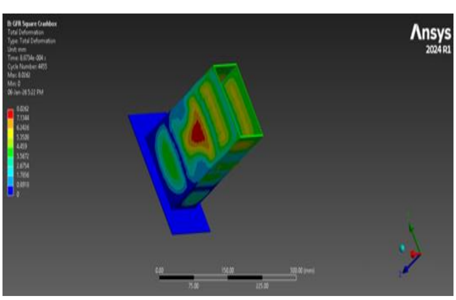


Fig. 31. Total Deformation of GFR Square Crash box

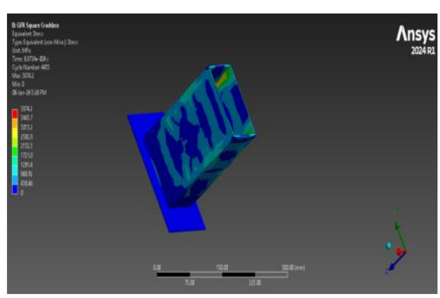


Fig. 32. Equivalent Stress of GFR Square Crash box.

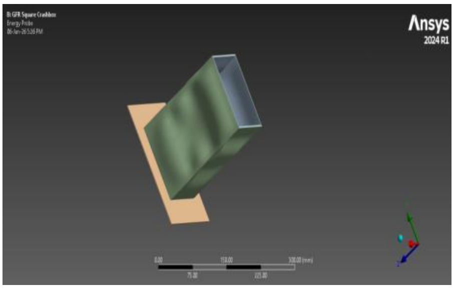
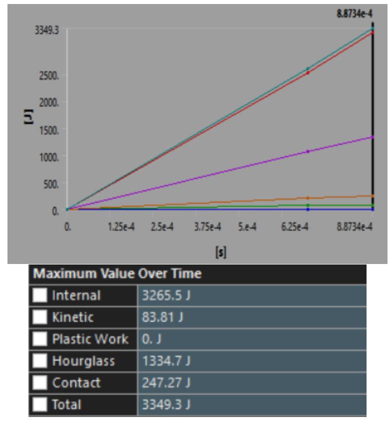


Fig. 33. Energy Probe



Maximum Value Over Time	
Internal	3265.5 J
Kinetic	83.81 J
Plastic Work	0. J
Hourglass	1334.7 J
Contact	247.27 J
Total	3349.3 J

Fig. 34. Energy Probe vs Time Graph

The deformation of the GFR crash box was 8.0262 mm, which was somewhat greater than that of mild steel. Better stress management was indicated by the equivalent stress dropping to 3874.2 MPa. The energy absorption was 3349.3 J, which was high but marginally less than that of steel. The composite material efficiently lessens the concentration of stress. It offers a harmony between energy absorption and deformation. In general, it distributes stress more effectively than steel.

3.1.5 Carban Fiber Reinforced Square Crash box

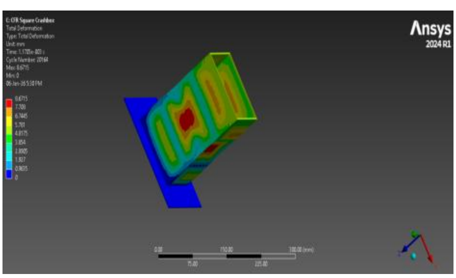


Fig. 35. Total Deformation of CFR Square Crash box

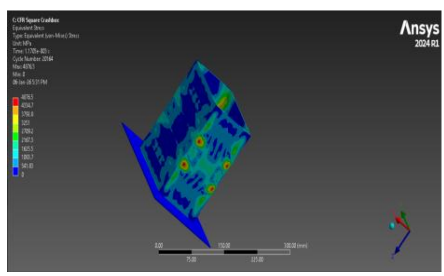


Fig. 36. Equivalent Stress of CFR Square Crash box.

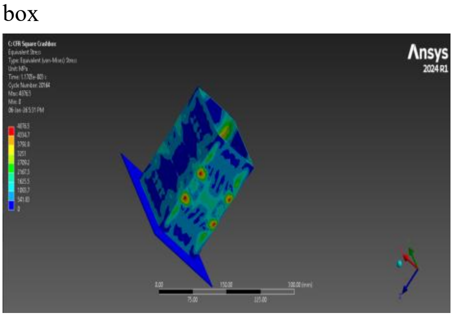
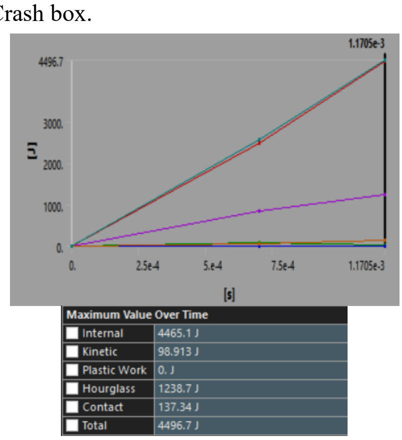


Fig. 37. Energy Probe



Maximum Value Over Time	
Internal	4465.1 J
Kinetic	98.913 J
Plastic Work	0. J
Hourglass	1238.7 J
Contact	137.34 J
Total	4496.7 J

Fig. 38. Energy Probe vs Time Graph

At 8.6715 mm, the CFR crash box had the most deformation of any composite. The equivalent stress was 4876.5 MPa, which was lower than steel but greater than GFR. With the highest energy absorption of 4496.7 J, it was the most effective absorber. It dissipates the most energy despite the greater deformation. Because of this, CFR is the most crash-worthy material. It provides the best possible ratio of energy absorption to strength.

3.1.6 FEA Results

Table 1. Comparative Analysis of Maximum Deformation, Equivalent Stress, and Energy Absorption in Square, Circular, and Hexagonal Crash Boxes

Parameters	Square Geometry	Circular Geometry	Hexagonal Geometry
Max. Total Deformation (mm)	7.4588	14.213	3.1962
Max. Equivalent Stress (MPa)	8757.9	2778.6	3176.5
Max. Total energy absorption over time (J)	3697.3	1328.2	1132.4

According to the study, the square geometry has the largest energy absorption (3697.3 J), which is significantly more than that of the circular and hexagonal geometries, making it the most crashworthy. The highest equivalent stress (8757.9 MPa) indicates that, despite its moderate deformation, it efficiently uses material strength. The hexagonal geometry has low deformation and low energy absorption, whereas the circular geometry exhibits maximum deformation and low energy absorption. Therefore, the optimal ratio of strength to energy absorption is found in square geometry. As a result, glass fiber reinforced and carbon fiber reinforced configurations are chosen for further development.

Table 2. Comparative Analysis of Maximum Deformation, Equivalent Stress, and Energy Absorption in Mild Steel, Glass Fiber Reinforced (GFR), and Carbon Fiber Reinforced (CFR) Square Crash Boxes

Parameters	Square 5Geometry	GFR Square Geometry	CFR Square Geometry
Max. Total Deformation (mm)	7.4588	8.0262	8.6715
Max. Equivalent Stress (MPa)	8757.9	3874.2	4876.5
Max. Total energy absorption over time (J)	3697.3	3349.3	4496.7

Compared to mild steel and GFR, the CFR (Carbon Fiber Reinforced) square geometry has the highest energy absorption (4496.7 J), suggesting better crash performance. Despite this, its overall distortion is marginally greater. Additionally, the equivalent stress is balanced, demonstrating effective load distribution without undue stress concentration. Although GFR absorbs less energy than CFR, it controls deformation better than mild steel. Because of its excellent energy absorption and overall performance, CFR square geometry is the best option in the end and best suited for manufacturing.

3.2 Experimental Setup and Result

A Universal Testing Machine (UTM) compression test was used to conduct the experiment. The manufactured square crash box specimen was first prepared and examined for any obvious flaws and dimensional accuracy. In order to prevent eccentric loading, the specimen was then positioned vertically between the UTM's upper and lower platens. A constant displacement rate was applied while the machine was in compression mode. The load was progressively increased until the crash box began to noticeably bend and collapse. Force-displacement data was continually recorded for analysis throughout the test.

Fig. 39. Specimen under compression test using UTM.

Testing Graph

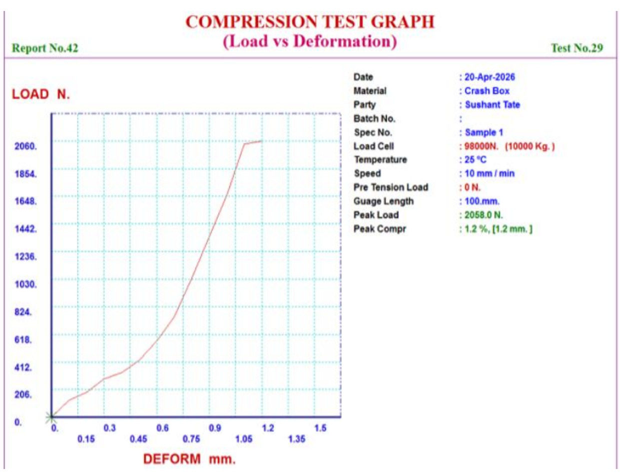


Fig. 40. Graph shows load vs deformation for the compression test. The Y-Axis represents the load in Newtons; the X-Axis represents the deformation of the specimen in mm.

The results show that the load-deformation graph shows an initial peak force followed by a gradual fall, indicating the start of progressive folding. While the impact test, the crash box showed steady deformation without any sudden failure, displaying good energy absorption capacity. The structure became more rigid and the buckling effect was delayed when the carbon fiber and resin composite layer was added. Hence, under axial loading conditions, the specimen showed improved crashworthiness performance, better structural strength, and controlled deformation.

4. Conclusion

In this research, different shapes and materials were examined to find a crash box design with preferable impact performance. The square crash box, which absorbed 3697.3 J of impact energy with only 7.4588 mm of deformation, had the best performance among the inspected models. The circular crash box absorbed lower energy at 1328.2 J and had the higher deformation of 14.213 mm. These findings demonstrated that the square geometry was more successful in withstanding impact loads. High stiffness but subpar crash performance was indicated by the hexagonal crash box, which showed the least deformation (3.1962 mm) and energy absorption (1132.4 J). A comparison of the materials reveals that the carbon fiber reinforced (CFR) crash box had the highest energy absorption of 4496.7 J, which is roughly 21.6% more than mild steel; the glass fiber reinforced (GFR) crash box absorbed 3349.3 J, which was marginally less than steel but had a significantly lower stress (3874.2 MPa vs. 8757.9 MPa) and the CFR also displayed moderate stress (4876.5 MPa) with better deformation characteristics (8.6715 mm). By combining high energy absorption, controlled deformation, and decreased stress concentration, the CFR square crash box offers the highest overall performance. The findings verify that, as compared to traditional steel designs, composite reinforcement increases crashworthiness by 20–25%. Therefore, the best configuration for lightweight and high-performance automotive applications is the optimized CFR square crash box.

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