



# Crashworthiness Analysis of CFRP Crash Box by Finite Element Method

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**Abstract.** The crashworthiness of Carbon Fibre Reinforced Plastic (CFRP) crash box structure subjected to quasi-static axial loading was investigated by finite element method. Glass Fibre Reinforce Plastic (GFRP), ST37 mild steel and Aluminum 6061-T6 were analyzed for comparison. In this study, the influence of materials and cross-sectional shape, on Specific Energy Absorption (SEA) and deformation pattern were examined. Finite Element Analysis (FEA) by using ANSYS LS-DYNA software used to simulate the quasi-static axial crush. It was found that CFRP material has the highest Specific Energy Absorption (SEA) compared to metal material due to its strength and lightweight. In addition, the energy absorption on the hexagonal cross-sectional shape has the highest SEA value compared to rectangular and circular shape due to its stiffness.

**Keywords:** Crashworthiness · CFRP · Crash box · Finite Element Method

## 1 Introduction

Indonesia is a densely populated country, the number of individuals or groups having four-wheeled vehicles/passenger cars is not small. Based on data compiled from the Central Statistics Agency (BPS), in 2018 there were more than 14 million units, and not a few of them were involved in traffic accidents. Based on data compiled from BPS, the number of vehicles involved in the accident is more than 100 thousand. With the number of accidents that are not small, automotive manufacturers are increasingly pushing to make vehicles safer for the passengers inside. There are several parts that function as protectors for passengers both actively and passively, one part that functions as a protection against collisions on cars passively is the crash box. The crash box is part of the car frame which is located at the front of the car. The structure of the crash box could protect against accidents frontally. According to Frank et al. in 1992 [1] front collision accidents account for 64.1% of the total serious accidents involving cars.

In passenger vehicles, the ability to absorb impact energy and be sustained for passengers is called the crashworthiness of the structure. Crashworthiness relates to energy

absorption through controlled failure mechanisms and modes that allow maintaining gradual decay in the load profile during absorption.

To reduce overall weight and improve vehicle fuel economy, more and more metal parts are being replaced by polymer composite materials. In contrast to metals, especially in compression, most composite materials are generally characterized by a brittle response rather than a ductile response to loads. While metal structures collapse under crushing or impact by buckling and/or folding in a concertina mode involving extensive plastic deformation, composites fail through a series of fracture mechanisms involving fibre fracture, matrix crazing, cracking, fibre-matrix de-bonding, de-lamination, and separation between layers. The actual mechanism and the sequence of damage are highly dependent on the geometry of the structure, the orientation of the laminae, the type of trigger, and the speed of impact, all of which can be suitably designed to develop a high energy absorbing mechanism.

Several research on crash boxes using composite materials have been carried out. The research was carried out experimentally as well as numerically. Mamalis et al. [2] conducted a study on the crush response and compression properties of the CFRP material square-section tube structure using LS-DYNA3D software. The result is that the level of satisfaction between testing through experiments and numerical can be achieved. The use of composite materials in vehicle components is carried out to optimize vehicle components, such as reducing the total weight of the vehicle and the capacity to absorb greater energy through various failure modes.

When compared to metal alloys which are generally used in vehicle components, composite materials have a higher energy absorption. In 2017 Zhu et al. [3] conducted research on tube structures with the configuration of carbon fiber reinforced plastic (CFRP), aluminum, and CFRP hybrid materials, namely CFRP/aluminum. As a result, the tube with CFRP material has the highest specific energy absorption (SEA) value among all configurations tested axially.

In a previous study, Modak et al. [4] tested the composite panel structure to determine the effect of the layer orientation angle on the elastostatic response. The results show that the orientation angle and the type of loading have a significant effect. Then in this study, also said that the computational approach is a powerful enough tool to analyze the behaviour of composites on component structures. In 2009 Shokrieh et al. [5] also researched the crushing behaviour of tubes with composite materials using variations in orientation angles and cross-sectional shapes for energy absorption. The result is that a tube with a square cross-section absorbs less energy than a tube with a circular cross-section. The effect of orientation angle also affects energy absorption.

This study presents the crashworthiness analysis of the CFRP crash box using finite element method. The crash box subjected to the quasi-static axial loading. The energy absorption and the deformation of the crash box were examined. Aluminium, mild steel, and Glass Fiber Reinforce Plastic (GFRP) were examined for comparison. The effect of cross-sectional shape on the specific energy absorption was also studied.

## 2 Material Properties

The material commonly used in crash box structure is an iron based, such as aluminum and mild steel. In this study, ST37 mild steel and aluminum AL6061-T6 were used

**Table 1.** Mechanical properties for CFRP and GFRP

Properties	CFRP	GFRP
Young's modulus longitudinal direction ( $E_A$ )	61 GPa	37.9 GPa
Young's Modulus Transverse Direction ( $E_B$ )	58 GPa	11.5 GPa
Shear Modulus ( $G_{12}$ )	3.4 GPa	4.5 GPa
Density ( $\rho$ )	$1.8 \times 10^{-6} \text{ kg/mm}^3$	$2 \times 10^{-6} \text{ kg/mm}^3$
Longitudinal Compressive Strength ( $X_C$ )	570 MPa	484 MPa
Transverse Compressive Strength ( $Y_C$ )	320 MPa	143 MPa
Longitudinal Tensile Strength ( $X_T$ )	634 MPa	936 MPa
Transverse Tensile Strength ( $Y_T$ )	560 MPa	25.7 MPa
Shear Strength (SC)	94 MPa	16.1 MPa

**Table 2.** Mechanical properties for AL6061-T6 and ST37

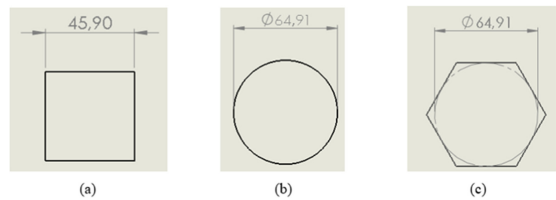
Properties	AL6061-T6	ST37
Young's Modulus (E)	68.9 GPa	188 GPa
Yield Strength ( $\sigma_y$ )	0.276 GPa	0.187 GPa
Poisson's Ratio	0.33	0.3
Density ( $\rho$ )	$2.7 \times 10^{-6} \text{ kg/mm}^3$	$7.3 \times 10^{-6} \text{ kg/mm}^3$
Cowper-Symonds constant (D)	$40 \text{ ms}^{-1}$	$40.4 \text{ ms}^{-1}$
Cowper-Symonds constant (p)	5	5

as comparison to Carbon Fibre Reinforced Plastic (CFRP) and Glass Fibre Reinforced Plastic (GFRP) in crashworthiness capability. The mechanical properties for CFRP [6] and GFRP [7] are shown in Table 1, whereas for ST37 [8] and AL6061-T6 [9] are shown in Table 2.

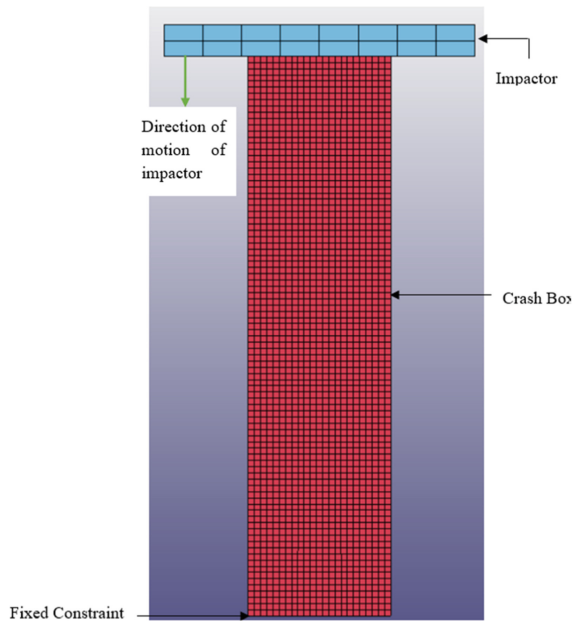
### 3 Finite Element Model

The cross-section of the crash box structure considered in this study were rectangular, circular, and hexagonal. The dimension for the cross-sections is shown in Fig. 1. The dimension shown is in millimetre.

The finite element analysis was performed using commercial explicit non-linear dynamic finite element-software of ANSYS LS-DYNA. Finite element model for quasi-static axial crush test is shown in Fig. 2. The length of the crash box structure was 180 mm, and the thickness was 1.05 mm. The element size for the geometry was set to 2.5 mm  $\times$  2.5 mm. The layer of fibre ply composed by 4 plies is represented by four integration point in shell element. The material card of



**Fig. 1.** Dimension of cross section of crash box for (a) rectangular (b) circular and (c) hexagonal (unit in millimetre)



**Fig. 2.** Finite element model for quasi-static axial crush test

MAT054\_ENHANCED\_COMPOSITE\_DAMAGE which is based on the Chang-Chang failure criterion was chosen to predict the response of composite material (CFRP and GFRP).

The bottom or base of the column was fixed in all direction. The impactor was modelled using rigid element. It was constrained in all direction except in y-axis to assure the impactor move on vertical direction. The weight of the impactor was set to 290 kg and travel with constant speed of 7.09 m/s.

The CONTACT\_AUTOMATIC\_NODES\_TO\_SURFACE was used to determine the contact interaction of impactor and crash box. To prevent self-penetration between each contacting elements, the contact card of CONTACT\_AUTOMATIC\_SINGLE\_SURFACE was used.

4 Validation for Finite Element Simulation

The validations are based on the previous study performed by Zhang et al. [7]. Composite material of GFRP with circular cross section was used in the study. The dimension of cross section is similar with Fig. 1(b). The comparison of crashworthiness variable between experiment [7] with the simulation in this study is shown in Table 3. The comparison of deformation pattern obtained from simulation between Zhang’s study [7] and this study was shown in Fig. 3.

The SEA for simulation in this study yield 6.4% difference with that for the experiment conducted by Zhang et.al. [7]. However, the deformation pattern obtained from FE simulation in this study matched with that from Zhang’s study.

Table 3. Validation to experimental result

Variable	Experiment [7]	Simulation	Error
Maximum Deformation (mm)	60	60	-
Specific Energy Absorption (SEA) (kJ/kg)	15.15	16.12	6.4%

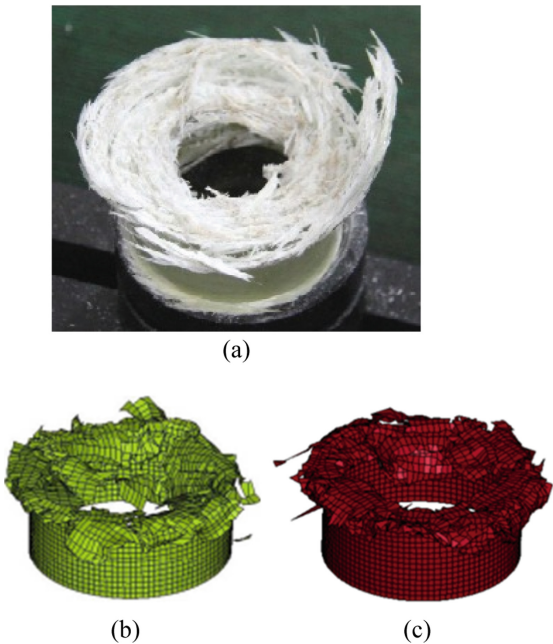


Fig. 3. Comparison of deformation obtained from (a) experiment [7] (b) Zhang’s simulation [7] and (c) FE simulation

## 5 Crashworthiness Analysis of Crash Box Structures

The crashworthiness is examined through parameters in the form of the specific energy absorption that can be accepted by the crash box structure. In this study, the effect of material and cross-sectional shape on specific energy absorption (SEA) and deformation pattern are investigated.

### 5.1 Effect of Material

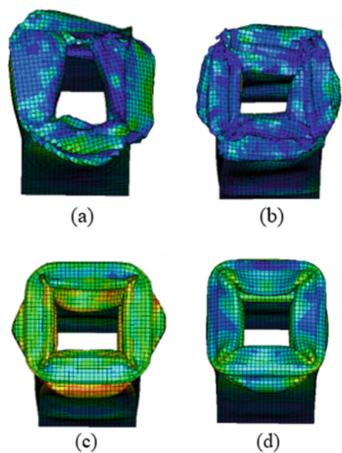
Figure 4 shows the deformations of CFRP, GFRP, aluminum 6061-T6 and ST37 mild steel for rectangular cross section under the axial crush simulations. Aluminum 6061-T6 and ST37 mild steel are shown to have linear deformation, while CFRP and GFRP have a form of the progressive folding deformation which is preferable in crashworthiness.

The result of crashworthiness analysis for different material with rectangular cross-section is shown in Table 4. The largest axial force value is found in CFRP, whereas the largest energy absorption is found in ST37 mild steel. Although the Energy Absorption (EA) for iron-based material is larger than that for composite material, the lightweight of the composite increase the Specific Energy Absorption (SEA). The energy absorption of CFRP is half of that for mild steel, however the weight of the CFRP is 25% of that for mild steel with the same dimension. It is found that the CFRP has the largest SEA among all material due to its strength and lightweight.

### 5.2 Effect of Cross-Section

The result of crashworthiness analysis for different cross-section using CFRP material is shown in Table 5. Hexagonal shape has the largest specific energy absorption due to less weight with the largest cross section area among circular and rectangular.

The deformation CFRP with different cross-section shape is shown in Fig. 5. The hexagonal shape shows the stiffest crush box structure.



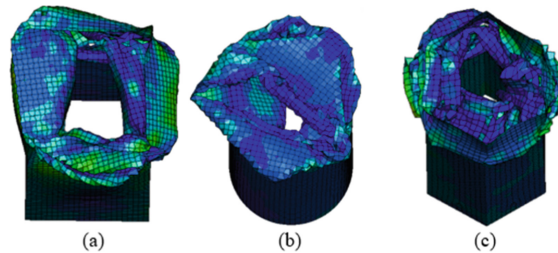
**Fig. 4.** Deformation for rectangular cross section for material of (a) CFRP (b) GFRP (c) AL6061-T6 (d) ST37 Mild Steel

**Table 4.** Result of crashworthiness analysis for different material with rectangular cross-section

Material	Max. Deformation (mm)	Max. Load (kN)	EA (J)	Mass (kg)	SEA (kJ/kg)
CFRP	68.442	75.06	754.6	0.0624	12.08
GFRP	69.195	50.25	499.9	0.0694	7.02
ST37	66.136	72.17	1592.5	0.2543	6.26
AL6061-T6	68.194	54.39	918.4	0.0937	9.80

**Table 5.** Result of crashworthiness analysis for different cross-section using CFRP

Material	Max. Deformation (mm)	Max. Load (kN)	Cross-section area (mm <sup>2</sup> )	Mass (kg)	SEA (kJ/kg)
Rectangular	68.442	75.06	197.19	0.0624	12.08
Circular	69.005	58.98	217.58	0.0490	12.84
Hexa-gonal	68.512	55.07	239.92	0.0468	16.76

**Fig. 5.** Deformation of CFRP for cross-section of (a) rectangular (b) circular and (c) hexagonal

## 6 Conclusions

The crashworthiness of Carbon Fibre Reinforced Plastic (CFRP) crash box structure was investigated by finite element method. The quasi-static analysis was carried out by using the finite element software of LS-DYNA, then the energy absorption of the crash box structure was examined. The crashworthiness of Glass Fibre Reinforce Plastic (GFRP), ST37 mild steel and Aluminum 6061-T6 were also analysed. The influence of material and cross-sectional shape on specific energy absorption (SEA) and deformation pattern were investigated. The results are summarized as follows:

- The largest axial force value was found in CFRP, whereas the largest energy absorption was found in ST37 mild steel.
- CFRP had the largest SEA due to its strength and the lightweight.

- The cross-section of hexagonal shape had the largest specific energy absorption due to its stiffness, less weight and had the largest cross section area among circular and rectangular.

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