Energy absorption and deformation pattern analysis of carbon fibre reinforced composite crash box under frontal load model

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Abstract. Crash boxes as a passive safety system in vehicles had been developed to produce high energy absorption performance. This study investigates the influence of cross-section geometry and fibre orientation angle on the composite crash box design to determine deformation pattern and energy absorption performance. The cross sections studied are circles and squares with variations in fibre orientation angles 0°, 15°, 30°, 45°, 60° and 75°. Carbon Fibre Epoxy CFS003 / LTM25 Prepegs with the type of plain woven fibre used to model crashbox structures. The computer simulation test model was carried out using a frontal load model with velocity of 7.76 m s⁻¹. The results showed a circle cross-section at each variation of the orientation angle has a higher energy absorption than a square cross-section. Deformation patterns in each model show different characteristics including fragmentation mode, lamina bending, brittle fracturing, and local buckling as well as a combination of several patterns. The highest energy absorption obtained in the C60 model was 3.664 kJ with Specific Energy Absorption (SEA) of 36.799 kJ kg⁻¹ and a CFE value of 0.59. While the lowest energy absorption occurs in the S45 model with 1.287 kJ which has a SEA value of 12.667 kJ kg⁻¹ with a CFE of 0.49. The CFE value indicates that the model with a circular cross section has better crushing stability than a squarecross section.

Keywords: composite crash box, cross-section, fibre orientation, deformation pattern, energy absorption

1. Introduction
Crash box is a passive safety devices to prevent the effects of collisions by absorbing energy from the collision. The purpose is to lower crash energy received by other engine components and reduce the possibility of fatal injuries. The level of energy absorption from a crash box commonly called a crashworthiness. Composite materials are in demand because it has great number of weight to strength ratio than common metal. Comparison of the crash box application composed by aluminium and carbon fibre composite in the level of energy absorption has been further studied. The optimum design of aluminium and carbon fibre crash boxes is developed by using Multi Design Objective (MDO) method [1]. Both of them were compared to its optimum conditions. The result is in carbon fibre has higher 17.4% energy absorption and 27.4% higher specific energy absorption than aluminium crash boxes. The energy absorption was examined on Aluminium Tube, CFRP (Carbon Fibre Reinforced Polymers) Tube and Hybrid Tube (Aluminium and
CFRP) [2]. The result showed that from seven models tested, CFRP Tube has a higher specific energy absorption than other models. These results concluded that the application of carbon fibre as a crash box material has advantages over aluminium material. The combination of complex failures experienced by composite materials results in a high amount of energy that can be absorbed [3]. This is one of the advantages of composite materials as crash box structure. Therefore, strength testing of various kinds of composite materials is carried out to ensure the response of the material fulfills the requirement. In the next study, the mechanical properties on Woven and Unidirectional Fibre Glass and Carbon were compared [4]. The orientation angles of specimen are set as 0° and 90° against the direction of loading. It concludes that there is a significant difference between the strength in the longitudinal and transversal direction of the fibre. In addition, uniaxial testing of a fibre orientation angles combination showed that the angle [0/90] has a maximum stress value greater than [45/-45] [5]. The objective of this study is to investigate the effect of cross-section geometry and fibre orientation angle on deformation pattern characteristic and energy absorption performance.

2. Method and material
This study is conducted using computer simulations with ANSYS Workbench 18.1 software for pre-processing and solving processes. In ensuring the validity of testing, this study was verified with previous experimental research. The parameter design of this study are the crash box cross section geometry and the fibre orientation angle. All model specifications are shown in Table 1.

| No | Model | Cross Section | Orientation Angle |
|----|-------|---------------|-------------------|
| 1  | C0    | Circle        | [0]_8             |
| 2  | C15   | Circle        | [15]_8            |
| 3  | C30   | Circle        | [30]_8            |
| 4  | C45   | Circle        | [45]_8            |
| 5  | C60   | Circle        | [60]_8            |
| 6  | C75   | Circle        | [75]_8            |
| 7  | S0    | Square        | [0]_8             |
| 8  | S15   | Square        | [15]_8            |
| 9  | S30   | Square        | [30]_8            |
| 10 | S45   | Square        | [45]_8            |
| 11 | S60   | Square        | [60]_8            |
| 12 | S75   | Square        | [75]_8            |

The observed value is deformation patterns and the level of energy absorption of carbon fibre composite box crashes with a simulated frontal crash test. The height of crash box is set as 150 mm and thickness of crash box is 2 mm as shown in the Figure 1. Crash box material is CF5003 / LTM25 Carbon-Epoxy Prepegs [6,7] and it consists of 8 laminate with 0.25 mm thick each. The material model used is MAT_055 which is devoted to orthotropic materials and has the capability to be used on shell elements.
Meshing was carried out manually with a 2 mm element size for a crash box. Element generated is done using quadrilaterals method with 15516 elements and 15066 nodes. For meshing of impactor is done automatically by the software. This study uses the method of Instrumented Drop Test based on previous research [6]. Material model of a crash box is set as deformable body and the impactor is set as rigid body. The trigger mechanism is modelled with a thickness of 1 mm. The impactor velocity is applied with 7.76 m s\(^{-1}\). At the bottom of the crash box is defined as a support with fixed support. The acceleration of gravity used is 9.81 m s\(^{-2}\) with the direction parallel to the impactor direction. Simulation modelling is shown in Figure 2.

In this modelling, verification is done by using previous research, Boria et al. [8]. The verified model is a square cross section with a side length of 60 mm, height of 200 mm and a thickness of 2.0 mm with Carbon Fibre Woven GG200 Material and Orientation Angle of 0° (the direction of loading). The method used by Boria is the Drop Weight Test. Impactor has a mass of 294 kg and the impact velocity is set as 3.76 m s\(^{-1}\). From the simulation modelling, energy absorption has the error 1.92 % and CFE is 3.70%. The error value is relatively small compared to previous research, thus the simulation model is validated.

3. Result and discussion

3.1 Simulation result data

Table 2 shows the simulation results of 12 composite crash box models. Force and displacement graphs obtained from the simulation results are in the form of raw data and then a filter process is carried out to reduce sharp force changes due to element removal [9]. By using filter process, the magnitude of mean force and energy absorption (EA) does not change, but the graph becomes smoother and the value of the peak force changes. The test results show that the highest energy absorption is in the C60 model with 3.664 kJ and the lowest is in the S45 model with 1.287 kJ.
### Table 2. Simulation result data

| Model | Mass (kg) | Displacement (mm) | $P_{\text{peak}}$ (kN) | $P_{\text{mean}}$ (kN) | CFE (kJ) | EA (kJ kg$^{-1}$) | SEA (kJ kg$^{-1}$) | Deformation Mode |
|-------|-----------|-------------------|--------------------------|-------------------------|----------|------------------|-------------------|------------------|
| C0    | 0.09957   | 143.18            | 26.1                     | 13.9                    | 0.53     | 2.085            | 20.985            | Brittle Fracturing |
| C15   | 0.09957   | 143.18            | 31.1                     | 15.1                    | 0.48     | 2.272            | 22.989            | Lamina Bending |
| C30   | 0.09957   | 143.18            | 37.8                     | 22.1                    | 0.58     | 3.327            | 33.657            | Local Buckling |
| C45   | 0.09957   | 143.18            | 22.0                     | 10.5                    | 0.53     | 1.584            | 15.907            | Fragmentation |
| C60   | 0.09957   | 143.18            | 41.3                     | 24.4                    | 0.59     | 3.664            | 36.799            | Fragmentation and Local Buckling |
| C75   | 0.09957   | 143.18            | 34.2                     | 16.7                    | 0.49     | 2.517            | 25.462            | Brittle Fracturing |
| S0    | 0.10155   | 143.18            | 23.0                     | 10.2                    | 0.44     | 1.542            | 15.188            | Local Buckling |
| S15   | 0.10155   | 143.18            | 29.8                     | 12.9                    | 0.43     | 1.936            | 19.590            | Lamina Bending |
| S30   | 0.10155   | 143.18            | 32.8                     | 17.2                    | 0.52     | 2.586            | 25.463            | Local Buckling |
| S45   | 0.10155   | 143.18            | 17.4                     | 8.5                     | 0.49     | 1.287            | 12.677            | Local Buckling |
| S60   | 0.10155   | 143.18            | 35.7                     | 16.8                    | 0.47     | 2.395            | 23.586            | Fragmentation and Local Buckling |
| S75   | 0.10155   | 143.18            | 24.1                     | 12.2                    | 0.53     | 1.828            | 18.009            | Local Buckling |

### 3.2 Deformation pattern

Composite crash boxes have more types of deformation than metal, including: lamina bending, transverse shearing or fragmentation, brittle fracturing and local buckling [10]. Composite materials, especially carbon fibre produce the brittle and stiff structure. In the C15 model, crack are formed at the beginning of the crushing (Figure 3a). It propagates along the axial direction of the crash box. Figure 3b shows that during crushing continues, patterns are formed like flower petals. Several part of crash box wall is bent out, it’s called external frond (Figure 3c). The patterns of flower petals and external frond shows lamina bending mode. This deformation pattern is also found in the S15 model. In the C45 model, shown in Figure 4, the deformation pattern shows that crash box breaks along during crushing and produce small fragments on the crash box wall. These fragments are formed continuously until the crushing process is complete. This characteristic shows the deformation pattern formed by the transverse shearing mode or fragmentation mode. In the C75 and C0 models there are external frond which tend to be shorter than the previous C15 model, shown in Figure 5. During the crushing process, there are parts of the crash box that break into small fragments.

The formation of external frond is a characteristic of the lamina bending deformation pattern and fragmentation is a characteristic of the transverse shearing. In conclusion C75 model has a brittle fracturing deformation pattern which is a combination of lamina bending and transverse shearing patterns based on the characteristics found. Different deformation patterns were found in models C30, S30, S45 and S75. At the beginning of the crushing showed that there was a longitudinal crack that tends to form an external frond. During the crushing, the wall is folded as shown in Figure 6 that prevents longitudinal cracks to propagate. Crash box forms folds continuously until the crushing process is complete. The deformation patterns that occur on this model is categorized as local buckling that characterized by the formation of these folds. Combination of fragmentation and local buckling deformation patterns was found C60 and S60 model. The characteristic is marked by the formation of folds and producing fragments during the crushing process, as shown in Figures 7.
Figure 3. Deformation Pattern on C15 model: a) Cracks Propagation on C15 model in the beginning crushing (b) Flower Petal Pattern, (c) External frond

Figure 4. Deformation Pattern on C45 model (a) Crushing Process, (b) Fragmentation

Figure 5. Deformation Pattern on C15 model (a) External frond, (b) Fragmentation

Figure 6. Folding on model S30

Figure 7. Deformation Pattern on C60 (a) Folding, (b) Fragmentation

Type of fibre used in this study is plain woven, where in one laminate there are two directions of knitted fibres perpendicular to each other. Referring from Hull et al. [11], the direction of fibre 0° has the role of resisting a given load and 90° (perpendicular to the axial crash box) that act as a hoop constraint. These combination of fibre prevent the formation of fold as the result of longitudinal cracks propagation during the crushing. Longitudinal cracks can occur due to the failure of the fibre that acts as a hoop constraint during loading. External frond that formed in the crash box wall is reduces the level of energy absorption. This is due to the formation of external frond showing the minimum fracture mode that occurs in the crash box. This is also indicates low
stress level that occurs because material does not reach its fracture strength. Hoop constraints have varied roles in various orientation angles in composite crash boxes which showed in the deformation character of each model.

3.3 Energy absorption

Energy absorption is calculated by measuring the area under the force-displacement curve. Figure 8 shows the results of all model that show the value of energy absorption. The diagram shows that the maximum energy absorption is obtained by the C60 model with 3664 J and the smallest is the S45 model with 1287 J. The graph above shows an increase in the value of energy absorption from an angle of 0˚ to 30˚, then fall at an angle of 45˚, up again at an angle of 60˚ and decrease at an angle of 75˚. This trend is shown in both cross-section geometries. This tendency is the same as found in study conducted by Hu et al. [12] that obtained maximum energy absorption value at an orientation angle of 60˚. Research conducted by Mahdi et al. [13] has different results where maximum energy absorption is obtained at an orientation angle of 75˚. It is important to note that in that study the test was conducted in a quasi-static method. In addition, the results of this study are also match with Thornton et al. [14] who said that the orientation angle (0/90)ₙ always have higher energy absorption than (±45)ₙ. Polar properties at orientation angles 0˚ and 45˚ are shown in Figure 9. The low energy absorption value at 45˚ orientation angle is caused by the composite strength at corresponding angle. In this study the Impactor loads the crash box in the axial direction of the crash box. Angle of 45˚ has the lowest strength among other orientation angles. As the result, crash box failed at a lower stress at that angle. This lowers the reaction force that occurs in the crash box, with the result reducing the area of the force-displacement graph.

![Figure 8. Energy Absorption on each model](Image)
At $0^\circ$ orientation angle, the impactor loads the crash box at its highest strength. However, the test results showed the lowest energy absorption above the $45^\circ$ angle. It could be affected by the value of CFE which shows the stability of the crushing process. In the square cross-section, the highest energy absorption is in the S30 model with 2586 J, followed by S60 with 2395 J. This is different from that found in the circle section which has the highest energy absorption in the C60 model. This difference could be caused by the low value of CFE on the S60 model of 0.47 compared to the CFE model of S30 of 0.52. Thus, it was concluded that the crushing of the S30 model is more stable than S60 resulted in has a better energy absorption value. Figure 8 shows that the circle has a higher value than the square cross section. This is in similar with the study conducted by Mamalis et al. [15] which said that a crash absorber with a square cross section has an energy absorption 0.8 times than circular. Energy absorption is influenced by the critical load value needed by the crash box to be deformed. The greater the cross-sectional inertia, affected the critical load to increase. This shows that the increase of the critical load, force-displacement curve area is extended. Thus, the greater the energy absorbed. It should be concern that large critical load lead the peak load value to be higher. It can increase the value of CFE and lead crushing process becomes less stable. Jacob et al. [16] states that composite crash boxes that fail progressively, or stably, have an area under the displacement force curve that is greater than catastrophic failure where the crushing process is unstable. The circle has a higher inertia value of 358802 cm$^4$ compared to a square of only 318101 cm$^4$. In accordance with the explanation presented in the previous paragraph, the circle has a higher energy absorption than the square. This is due to the high area moment of inertia which that increase the critical load.

3.4 Crushing force efficiency
Figure 10 shows the distribution of CFE at different orientation angles on a circle and square cross section. The graph shows that the CFE on the circle section has a higher value than the square section. This shows that the crushing process that occurs in the cross section of the circle occurs more stable and tends to go through progressive failure. Deviations are found at an angle of 75° which shows a higher S75 CFE value than C75. This shows that crushing that occurs in the S75 model occurs stably and tends to fail progressively. The relationship between the CFE value and its energy absorption in the circle cross section can be seen in Figure 11 and in the square section in Figure 12. The graph shows that there is a direct correlation between the level of energy absorption and the value of CFE. It can be seen that energy absorption and CFE show the same trend. For instance the C60 model which has the highest energy absorption rate of 3664 J, has the highest CFE value of 0.58.
A slightly different tendency is found in crash boxes with square sections. The highest CFE was found in the S75 model with 0.53 whereas the absorption of energy was only 1828 J. The highest energy absorption in the square section was found in the S30 model with 2586 J which had a CFE value of 0.52, slightly below S75. This deviation could be observed in the S75 deformation pattern that occurs where the crash box is deformed by forming folds and the crushing process is more stable. Tobby and Bahadini [17] investigated that crash boxes with square sections tend to have CFE and energy absorption levels lower than the circle, it is caused by the presence of sharp angles so that it acts as a stress concentrator. As a result of this stress concentration, the material at the edge of the geometry had higher stress than other regions. It is causes cracks that spread along the corner of the square. Thornton [14] stated that the most important parameter in the design of
composite crash boxes is to ensure that the crushing process occurs stably and through progressive failure that results in a high level of energy absorption. In this case the crash box with a circular cross section has the advantage. It is because circle does not have an angle that triggers stress concentrations. As the result the crushing process is more stable and absorbs greater value of impact energy.

3.5 Specific energy absorption
Specific energy absorption (SEA) is the energy absorbed by a structure per unit mass. The specific energy absorption value is obtained from the amount of energy absorption divided by the mass of the crash box. Figure 13 shows SEA on each model with composite crash boxes have SEA values in the range of 12.667 - 36.799 kJ kg⁻¹. The highest SEA value obtained in the C60 model was 36.799 while the lowest was in the S45 model with 12,677. The previous study showed that mild steel crash boxes with circular cross-sections have SEA values on 20.58-21.84 kJ kg⁻¹ [6]. Square cross section has SEA value in the range of 15.08-15.79 kJ kg⁻¹. The SEA values in this study shows that the majority of specimens have better SEA values. Only the orientation angle 0° and 90° have values below the previous study. This shows that the fibre orientation angle is an important parameter in the design of a composite crash box besides the CFE value in the crushing.

4. Conclusion
As observed, several deformation modes occurred on crash box models. Half of the model experienced similar deformation mode with the corresponding angle. On C60 and S60 model, there is combination of fragmentation and local buckling deformation mode. Model C60 has the highest energy absorption among all the models. However, on square cross section, model S30 has the highest energy absorption value. Energy absorption shows similar trend with CFE, where model with high energy absorption performance also has high value of CFE. The crushing of circle cross-section is occurred more stable than square cross-section. SEA of the composite crash box varies with large range value compared to metal material.
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