Finite element analysis of a composite crash box subjected to low velocity impact

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Abstract. In this work, finite element analyses using LS-DYNA had been carried out to investigate the energy absorption capability of a composite crash box. The analysed design incorporates grooves to the cross sectional shape and E-Glass/Epoxy as design material. The effects of groove depth, ridge lines, plane width, material properties, wall thickness and fibre orientation had been quantitatively analysed and found to significantly enhance the energy absorption capability of the crash box.

1. Introduction
Crash tubes serve primarily as energy absorbers and are used in many applications to absorb energy particularly in the event of impact. In automotive application, these tubes are mainly used in absorbing impact energy during the frontal crash event. The tubes are required to be designed to absorb highest possible energy with minimum component weight. Lighter materials such as fiber composites and aluminum provide enhanced strength, durability and lower weight compared to the steel counterpart. Finite element analysis is one of the preferred virtual test method employed in the development of a new component design as analysis can be performed relatively faster and with less expense.

In the event of collision, car manufacturers require the passenger cabin not to deform excessively [1]. Therefore, it is necessary for the frontal part of the car to absorb as much energy as possible over a longer period of time to minimize occupant injury. Crash boxes are normally mounted at the front end of the car frame. In the event of frontal impact, these boxes are intended to collapse and absorb impact energy in order to reduce deformation of other vehicle components. Metallic crash tubes absorb impact energy via plastic deformation and the process can be further enhanced with the inclusion of foam material [2].

The fundamental process of an axial crash is briefly described in [3]. The process involves initiation of compressive strain accumulation at certain area of ridge lines followed by initial plastic buckling [3]. This collapses the area between the ridge lines and later initiates a series of plastic buckling events followed by multiple collapse of area between the subsequent ridge lines causing the load to fluctuate throughout the deformation process [3]. The energy absorption can be improved by ensuring high buckling load at the ridge lines and minimizing the buckling cycle time and load fluctuation [3]. Metallic crash tubes with annular grooves filled with polyurethane foam are reported to offer better energy absorption capacity by almost twofold compared to empty tubes [4]. In another study, experimental results of single and multi-cell aluminum thin wall tubes with different cross
sections under quasi static loading showed that the energy absorption of the multi-cell tube was greater [5].

An innovative cross sectional shape as part of a new crash box design was developed in a study by [3]. The box was designed with four grooves in the direction of impact with as many as 24 ridge lines enabling formation of finely detailed wrinkles and absorption of twice the impact energy as well as about 30% weight reduction compared to the conventional crash box. The ridge lines affected the buckling cycle time and the plane width was found to control the number of buckling generated during the crash in which a shorter plane width created more number of buckling [3].

Though metallic tubes offer high stiffness and strength, the setback is their weight. Fiber composite materials are known to have superior specific strength and specific stiffness compared to metallic counterparts. This directly means crash tubes designed using composite materials are lighter and can be efficient energy absorbers compared to the metallic tubes. The composite tubes can be made to collapse in a progressive manner in which energy absorption is dominated by fiber and matrix failure as well as delamination [6]. The mechanism of failure depends on the geometry of the tube, material properties, laminate orientation and impact speed. Layups made of (±85), (±75) and (±65) were found to fail in a progressive manner compared to (±55), (±45) and (±35) layups [6].

The objective of this work is to analyze the energy absorption characteristics of a composite crash box following a similar design approach proposed by [3] for metallic box. In the present work the analyses was carried out using finite element method, employing LS-DYNA as the analysis tool.

2. Method of investigation

This section provides a brief description on the fundamentals of crashworthiness parameters for an axially loaded thin walled member, outline on the method of investigation, validation of results for subsequent FEA investigation and results and discussions

2.1. Crashworthiness parameters of axially loaded thin walled member

The energy absorption characteristics of an axially loaded member can be determined from the load-displacement curve. It allows the determination of the peak impact load, the mean load, the crushing distance, energy absorbed, and specific energy absorption.

The peak load, $P_{\text{max}}$, must be kept small or reduced as it relates to the sudden deceleration in the event of impact, which is not desirable. The mean load, $P_{\text{mean}}$, and the crushing distance, $D_s$, are closely related to the energy absorbed by the tube. For a tube to absorb more energy it is required to either have the mean load to be higher or longer crushing distance. The area under the load-displacement curve represents the total energy absorbed, \( E_{\text{absorbed}} \), during the crash event whereas specific energy absorption is defined by total energy absorbed per unit mass, \( m \), or more commonly abbreviated as SEA.

\[
E_{\text{absorbed}} = \int P_{\text{mean}} D_s
\]

\[
SEA = \frac{E_{\text{absorbed}}}{m}
\]

2.2. Finite element modelling: result validation

As a first step to the FE analysis, a test case obtained from the literature [7] was validated. The case considered was a square E-glass/epoxy tube (25mm × 25mm), with 150mm length and 2.5mm wall thickness, hit by a 100kg impactor with an initial velocity 7.9m/s. The investigation was carried out using LS-DYNA, an explicit finite element solver. The composite material was modeled using MAT 54/55.

The result of the simulation, impact load vs. displacement, is shown in Figure 1. The peak impact load and energy absorbed obtained from the current simulation are 34.13kN and 1596.45kJ
respectively. The results are very close to the ones reported in [7] which were 33.42kN for the peak impact load and 1560.10kJ for the total energy absorbed.

![Load-displacement curve](image1.png)

**Figure 1.** Load-displacement curve

2.3. **Finite element modelling, results and discussion**

In this section, the effects of different design parameters on the energy absorption of composite crash boxes will be presented. The cross section of the crash box is shown in Figure 2 with total cross sectional area of 3750mm² and height of 150mm.

![Cross sectional shape of crash box design](image2.png)

**Figure 2.** Cross sectional shape of crash box design, adopted from [3]

![FEA model of the crash box](image3.png)

**Figure 3.** FEA model of the crash box

da. 20 ridge lines  
b. 24 ridge lines
The attributes of the sample design and geometry are shown on Figure 3 and 4. The geometrical effects of grooves depth, $H_g$, plane width, $W_p$, and different material properties were studied. The dimensions of each model are summarized in Table 1.

| Simulation Number | Material          | Thickness (mm) | Dimension (mm) | Fiber orientation |
|-------------------|------------------|----------------|----------------|------------------|
| 1                 | E-Glass/Epoxy    | 2.5            | 15 10          | [45/-45]         |
| 2                 | E-Glass/Epoxy    | 2.5            | 15 12.5        | [45/-45]         |
| 3                 | E-Glass/Epoxy    | 2.5            | 15 15          | [45/-45]         |
| 4                 | E-Glass/Epoxy    | 2.5            | 11.5 15        | [45/-45]         |
| 5                 | E-Glass/Epoxy    | 2.5            | 12.5 15        | [45/-45]         |
| 6                 | E-Glass/Epoxy    | 2.5            | 13.5 15        | [45/-45]         |
| 7                 | Steel            | 2.5            | 11.5 15        | -                |
| 8                 | Aluminum         | 2.5            | 11.5 15        | -                |
| 9                 | E-Glass/Epoxy    | 2.5            | 11.5 15        | [0/90/0]s        |
| 10                | E-Glass/Epoxy    | 2.0            | 11.5 15        | [45/-45]         |
| 11                | E-Glass/Epoxy    | 2.5            | 11.5 15        | [45/-45]         |
| 12                | E-Glass/Epoxy    | 3.0            | 11.5 15        | [45/-45]         |
| 13                | E-Glass/Epoxy    | 2.5            | 11.5 15        | [45/-45]         |
| 14                | E-Glass/Epoxy    | 2.5            | 11.5 15        | [0/45/90/-45]    |
| 15                | E-Glass/Epoxy    | 2.5            | 11.5 15        | [0/30/90/-30]    |
| 16                | E-Glass/Epoxy    | 2.5            | 11.5 15        | [0/90]           |

2.3.1. **Effect of groove depth.** Table 2 shows the effect of groove depth, where the highest peak load and mean load are observed for groove depth of 15mm. As the groove depth is reduced, the values of the peak and mean loads are reduced as well. Although higher groove depth will lead to higher energy absorption, it will also increase the peak load which is not desirable.

| Simulation Number | Peak Load (kN) | Mean Load (kN) | Deformation (mm) | Absorbed Energy (kJ) | Specimen Mass (kg) | (SEA) (kJ/kg) |
|-------------------|----------------|----------------|------------------|----------------------|--------------------|--------------|
| 1                 | 88.95          | 32.72          | 115.00           | 3.763                | 0.216              | 17.4         |
| 2                 | 92.85          | 35.20          | 115.00           | 4.048                | 0.229              | 17.6         |
| 3                 | 100.60         | 37.44          | 115.00           | 4.306                | 0.243              | 17.7         |

2.3.2. **Effect of ridge lines.** Table 3 shows the effect of ridge lines on the peak and mean loads as well as on energy absorbed. The highest peak load is observed for the case 20 ridge lines whereas increasing the ridge lines to 24 resulted in reduction of peak load but higher mean load. The $SEA$ is also higher in the case of 24 ridge lines. Although higher groove depth can increase the energy absorption, increasing the number of ridge lines is seen as a better option since it does not increase the peak load.

| Simulation Number | Peak Load (kN) | Mean Load (kN) | Deformation (mm) | Absorbed Energy (kJ) | Specimen Mass (kg) | (SEA) (kJ/kg) |
|-------------------|----------------|----------------|------------------|----------------------|--------------------|--------------|
| 3                 | 100.60         | 37.44          | 115.00           | 4.306                | 0.243              | 17.7         |
| 4                 | 87.35          | 42.72          | 115.00           | 4.913                | 0.133              | 36.9         |
2.3.3. Effect of plane width. Table 4 shows the effect of plane width on the peak and mean loads as well as on energy absorbed. From the results it can be seen that shorter plane width leads to higher mean load and better \( \text{SEA} \). However, it also increases the peak load.

| Simulation Number | Peak Load (kN) | Mean Load (kN) | Deformation (mm) | Absorbed Energy (kJ) | Specimen Mass (kg) | (SEA) (kJ/kg) |
|-------------------|----------------|----------------|------------------|----------------------|-------------------|---------------|
| 4                 | 87.35          | 42.72          | 115.00           | 4.913                | 0.133             | 36.9          |
| 5                 | 86.15          | 29.03          | 115.00           | 3.338                | 0.137             | 24.4          |
| 6                 | 86.88          | 27.38          | 115.00           | 3.149                | 0.140             | 22.5          |

2.3.4. Effect of material properties. Table 5 shows the effect of material properties on the crashworthiness parameters. As can be seen from the table, steel tube results in highest peak and mean loads. A comparison between aluminium and \([0/90/0]\) composite shows, composite results in higher peak and lower mean loads compared to aluminium but the benefits can be observed in terms of \( \text{SEA} \).

| Simulation Number | Peak Load (kN) | Mean Load (kN) | Deformation (mm) | Absorbed Energy (kJ) | Specimen Mass (kg) | (SEA) (kJ/kg) |
|-------------------|----------------|----------------|------------------|----------------------|-------------------|---------------|
| 7                 | 445.30         | 156.11         | 52.61            | 8.213                | 0.581             | 14.1          |
| 8                 | 183.14         | 92.94          | 102.59           | 9.535                | 0.200             | 47.7          |
| 9                 | 230.74         | 76.15          | 101.72           | 7.750                | 0.133             | 58.1          |

2.3.5. Effect of wall thickness. Table 6 shows the effects of wall thickness on the crashworthiness parameters. The results show that the peak and mean load increased significantly with the increase in wall thickness. Since increasing the wall thickness results in higher mean load, this means, greater energy will be absorbed by the crash box thus improving protection. Improvement in terms \( \text{SEA} \) is also observed with the use of higher wall thickness.

| Simulation Number | Peak Load (kN) | Mean Load (kN) | Deformation (mm) | Absorbed Energy (kJ) | Specimen Mass (kg) | (SEA) (kJ/kg) |
|-------------------|----------------|----------------|------------------|----------------------|-------------------|---------------|
| 10                | 66.80          | 27.35          | 122.72           | 3.360                | 0.107             | 31.3          |
| 11                | 87.35          | 42.72          | 115.00           | 4.913                | 0.133             | 36.9          |
| 12                | 110.02         | 47.90          | 116.36           | 5.580                | 0.159             | 35.0          |

2.3.6. Effect of fibre orientation. Table 7 shows the effects of fibre orientation on the crashworthiness parameters. As can be seen from the table, quasistatic layup provides improvements in terms of mean load and \( \text{SEA} \) compared to other layups as it strengthens the performance of the tube in axial direction. The [0/90] orientation is also seen here to improve the energy absorption compared to the [45/45] layup.

| Simulation Number | Peak Load (kN) | Mean Load (kN) | Deformation (mm) | Absorbed Energy (kJ) | Specimen Mass (kg) | (SEA) (kJ/kg) |
|-------------------|----------------|----------------|------------------|----------------------|-------------------|---------------|
| 13                | 87.35          | 42.72          | 115.00           | 4.910                | 0.133             | 36.9          |
| 14                | 135.16         | 67.85          | 98.17            | 6.660                | 0.133             | 50.0          |
| 15                | 142.71         | 58.05          | 105.88           | 6.140                | 0.133             | 46.1          |
| 16                | 119.64         | 43.18          | 114.57           | 4.950                | 0.133             | 37.1          |

3. Conclusions
A finite element analyses was carried out to investigate the effects of groove depth, ridge lines, plane width, material properties, wall thickness and fibre orientation on the energy absorption characteristics.
of a composite crash box. The analyses concluded the use of 15 mm groove depth, 24 ridges lines and
11.5 mm plane width significantly improves the specific energy absorption capability as compared to
the conventional crash boxes. It is also observed that the use of higher wall thickness and proper fibre
layup greatly affects the energy absorption of the crash box. The study concludes that proper selection
of design parameters can be used to improve the energy absorption capability of crash boxes made of
composite materials and they can be made comparable in performance to that of convention metal
tubes.

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