A study on the crushing behavior of basalt fiber reinforced composite structures

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Abstract. The crushing behavior and energy absorption capacity of basalt fiber reinforced hollow square structure composites are studied under axial compression. Using the hand layup technique, basalt fiber reinforced composites were fabricated using general purpose (GP) polyester resin with the help of wooden square shaped mould of varying height (100 mm, 150 mm and 200 mm). For comparison, similar specimens of glass fiber reinforced polymer composites were also fabricated and tested. Axial compression load is applied over the top end of the specimen with cross head speed as 2 mm/min using Universal Testing Machine (UTM). From the experimental results, the load–deformation characteristics of both glass fiber and basalt fiber composites were investigated. Crashworthiness and mode of collapse for the composites were determined from load–deformation curve, and they were then compared to each other in terms of their crushing behaviors.

1. Introduction

In structural automotive parts, fiber reinforced polymer composites can be a predominant material because of their significant weight reduction. The study of the crush behavior of the composites will be very useful for future lightweight composite vehicles.

Sundarraja et al. [1] studied the carbon fiber reinforced polymer (CFRP) fabrics in axial strengthening of hollow square sections (HSS). It was found that thickness of the composites play major role. An increase in CFRP strips' thickness will result in the delay of the buckling and also leads to inward buckling. Mamalis et al. [2] investigated the crashworthy of square composite material tubes subjected to static axial compression. The mode of collapse of the composites was analyzed with both experimental and numerical methods. Shanmugavalli and Sundarraja [3] studied the behavior of the circular hollow steel under compression. It was found that CFRP composites greatly improved the load carrying capacity of the circular steel tube and also maximum deformation was controlled by CFRP layers. Kathiresan et al. [4] investigated the axial compression of thin-walled E-glass fiber/epoxy resin reinforced (GFRP) composite conical frusta. To study the crashworthiness of conical shells, E-glass fibre reinforced polymer (GFRP) conical specimens were fabricated with a semi-apical angle ranging from 15° to 27°. The mode of collapse was investigated through experiments as well as the FEA ABAQUS package.
Anne et al. [5] studied the tension and compression, and the energy of deformation of braided glass-fiber/epoxy circular tubes with polymer foam cores. It revealed that the foam filled circular tubes exhibit good energy absorbing characteristics. Ataollahi et al. [6] focused on natural silk/epoxy composite square tubes energy absorption and failure response of the composites. It was observed that the energy absorbed by the longest and thickest square tube took a long time to reach the compaction zone. Melo et al. [7] investigated the energy absorption capacity of glass/polyester composite tubes. Two types of layup were used ([0/90] and [± 45]) and it was observed that significant influence of the cross sectional geometry on energy absorbing capacity and [0/90] showed the highest specific energy absorption. Christopher et al. [8] studied the energy absorption and mechanical behavior of GRP composites using the compressive tests. Gauss-Legendre rule was used to evaluate the area under the stress-strain curve as a measure of amount of energy absorbed per unit volume of material. From this study, the mechanical parameters needed for the automobile components design were determined. Muralikannan et al. [9] studied the energy absorption of circular tubes composites under axial compression in quasi static and impact loading. The glass fiber was used with hand layup techniques. It was observed that mean load and specific energy absorption increases with the increase in tube thickness. Paolo et al. [10] studied the crush energy absorption of composite channel section specimens. Hand layup techniques were used to fabricate the composites with different geometries. It was found that the small corner element was the most efficient in absorbing energy per unit mass compared to those with longer flanges, particularly the square tube.

Wei et al. [11] numerically investigated the crushing behavior of composite structures using ABAQUS/Explicit. The numerical results agreed well with the experimental results in terms of the intra-laminar and inter-laminar damage for a range of stacking sequences. Sivakumar Palanivelu et al. [12] experimentally investigated the progressive deformation behavior of uni-directional pultruded composite tubes subjected to an axial impact load with three impact velocities (i.e. 9.3, 12.4 and 14 m/s). Louis et al. [13] studied the crushing behavior of a carbon–epoxy composite experimentally. It was found that energy absorption is independent of strain rate as the total energy absorption appeared largely associated with fiber-dominated fracture.

Based on the literatures, this current study was proposed with basalt fiber as reinforcement. The hand layup techniques were used to fabricate the square tube section composites that would be subjected to axial compression load.

2. Experimental details
In this section, the discussions are centered on the material selection and fabrication processes.

2.1. Materials used
The basalt fiber was purchased from ASA Tec. Austria while the GP polyester resin was purchased from GVR Traders, Madurai, India.

2.2. Fabrication of hollow square tube
The hollow square tube composites were fabricated using the hand layup techniques. For the fabrication of the composites, a specific mould was prepared with the required dimension of the composites. The mould was prepared with the dimension of 100 mm² and different heights of 100 mm, 150 mm and 200 mm as presented in Figure 1. For the fabrication, equal weight % of woven basalt fiber and polyester resin were taken (50/50 by weight), and for the curing process, the methyl ethal ketone per oxide was used and the cobalt naphthalene was taken as accelerator. Resin mixture was mixed thoroughly using mechanical stirrer and homogenous mixer resin was used. Similar procedure was followed for all the composites fabricated. The fabricated specimens are presented in Figure 2 and their details are tabulated in Table 1.
Table 1. Details of hollow square tube composites

| Specimen | Heights (mm) | Width (mm) | Thickness (mm) | Maximum Load (kN) | Maximum Elongation (mm) | Load at peak (kN) | Compression strength (N/mm²) |
|----------|--------------|------------|----------------|-------------------|------------------------|------------------|-----------------------------|
| Basalt -10 | 100          | 100        | 3              | 450               | 45                     | 23.76            | 20.042                      |
| Basalt -15 | 150          | 100        | 3              | 600               | 80                     | 28.710           | 23.806                      |
| Basalt -20 | 200          | 100        | 3              | 300               | 100                    | 16.44            | 14.123                      |
| Glass -10  | 100          | 100        | 3              | 300               | 35                     | 5.502            | 5.867                       |
| Glass -15  | 150          | 100        | 3              | 300               | 45                     | 7.806            | 7.544                       |
| Glass -20  | 200          | 100        | 3              | 300               | 70                     | 2.970            | 2.552                       |

2.3. Axial compression test

The axial compression test was conducted on samples with cross head speed of 2 mm/min using Universal Testing Machine (UTM) (Model – TUE CN -600) of 40 ton capacity. The UTM setup was integrated with a computer. The specimen was placed between top and bottom platen as presented in Figure 3. The mode of collapse of square tubes was observed and load–deformation curve was obtained from the software. Three specimens were tested for each of the composites. The load deformation curve was obtained from the area under the load–deformation characteristic curves.

3. Results and discussion

The axial compression loading on the specimens was carried out experimentally and the compression test values are presented in the above Table 1. The load–deformation characteristic curve obtained from axial compression test is presented in Figure 4. From the plot, it can be observed that the initial rise of load was the pre-buckling condition of the specimen, which showed a high load resistance and the deformation was minimum. However, once the composites reached the high peak load, they experienced non–linear mode of collapse [14]. This type of collapse is called as buckling. At this stage, due to axial compression load, the composites started to collapse from top towards the bottom of the specimen. After the buckling, rapid
deformations began at buckled region that were non–linear mode collapse. During this rapid deformation, significant load fluctuations was observed in all specimens [4].

![Figure 3. Axial compression testing of composite](image)

From the load deformation characteristic curve, it was observed that increasing the height made larger elongation of the specimens for both basalt and glass fiber composites. For load carrying capacity, the 150 mm height composites exhibited better property than the other combinations. Compression strength of the composites also showed the same trend as that of load carrying capacity [12]. Specimen having low height attained lower energy absorption than the higher height specimens.

3.1. Modes of collapse
The modes of collapse for all basalt square tube specimens and glass fiber square tubes were analyzed and compared. They are shown in Figure 5, Figure 6, Figure 7 and Figure 8. Formation of local buckle was observed when increasing the height of square tube specimens [4]. During the local buckle, inter-laminar crack was observed at the buckled area. Similarly, by decreasing the specimen height, the outward mode of collapse was observed to be an extensive bending of lamina bundles [1].

![Figure 5. Collapse of basalt fiber composites – 100 mm width and 200 mm height specimen](image)  

![Figure 6. Collapse of basalt fiber composite - 100 mm width and 150 mm height specimen](image)
Different modes of failures were identified on the square tube during the axial compression. The main failure of the composites was the formation of local buckling (see Figure 8) after the pre-buckling stage. The laminate bending was noticed at particular distance of the specimen from the top. During this period, symmetrical mode of collapse was evident. When it reached the buckling stage, load resistance of the specimen dropped due to further axial compression [10]. After the buckling stage, the specimens collapsed drastically in the post-buckling. At this point, it developed non-symmetrical mode of collapse and the composite tube accomplished different mode shape.

4. Conclusion

In this study, crushing behaviors of basalt fiber composite specimens and glass fiber specimens from the axial compression test were analyzed experimentally. Based on the experimental values, the steps of failure and load–deformation graphs were derived. From the load deformation curve, performance of the specimen was calculated. From the observation of the mode of collapse of the composites, it was noticed that all tested square specimens initially formed local buckling. By overall observation, it the basalt fiber specimen showed higher initial collapse load, higher average load and higher ultimate peak load than the glass fiber specimens. They also absorbed more energy before they collapsed. The basalt fiber based composites had three to five times greater energy absorption capability than glass fiber based specimens.

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