Behaviour of hybrid jute-glass/epoxy composite tubes subjected to lateral loading

A A Khalid
Department of Mechanical Engineering, Faculty of Engineering, Institut Teknologi
Brunei, Gadong, BE 1410, Brunei Darussalam
E-mail: asad.khalid@itb.edu.bn

Abstract. Experimental work on hybrid and non-hybrid composite tubes subjected to lateral loading has been carried out using jute, glass and hybrid jute-glass/epoxy materials. Tubes of 200 mm length with 110 mm inner diameter were fabricated by hand lay-up method to investigate the effect of material used and the number of layers on lateral-load-displacement relations and on the failure mode. Crush force efficiency and the specific energy absorption of the composite tubes were calculated. Results show that the six layers glass/epoxy tubes supported load higher 10.6% than that of hybrid jute-glass/epoxy made of two layers of jute/epoxy four layers of glass/epoxy. It has been found that the specific energy absorption of the glass/epoxy tubes is found higher respectively 11.6% and 46% than hybrid jute-glass/epoxy and jute/epoxy tubes. The increase in the number of layers from two to six increases the maximum lateral load from 0.53KN to 1.22 KN for jute/epoxy and from 1.35 KN to 3.87 KN for the glass/epoxy tubes. The stacking sequence of the hybrid tubes influenced on the maximum lateral load and the absorbed energy. The maximum load obtained for the six layers jute-glass/epoxy tubes of different staking sequence varies between 1.88 KN to 3.46 KN. Failure mechanisms of the laterally loaded composite tubes were also observed and discussed.

1. Introduction
Composite materials have a wide range of applications because of their high stiffness and strength with respect to weight. In addition, composite materials have high corrosion resistance, thermal expansion, thermally resistive and considered as non-conductive materials. Collapse behaviour of thin-walled tubular structures made of metals and composites has received considerable attention for their application to the design for crash-worthiness of energy absorbing devices [1]. The crush behaviour of composite structures offers distinct advantages for automotive applications and has been the subject of numerous investigations [2]. Several studies were carried out to investigate the energy absorption capability and failure mechanism of composite structures like tubes [3-14] and cones [15-22] at different testing conditions.

Composite tubes under axial loading are widely used by researchers as energy absorption structures due to the high energy absorption capability of these tubes. However the axially loaded tubes can exhibit unstable deformation with large fluctuations compared to the tubes under lateral loading. The energy absorption capability of laterally loaded tubes is better than the tubes under lateral indentation [3]. Eyvazian et al. [5] performed an experimental study on corrugated aluminium tubes under lateral loading. The authors concluded that the crushing load and the energy absorption are improved with the corrugations. The highest energy attained is by using tubes with inner and outer corrugations [5]. Baroutaji et al. [6] studied the behaviour of oblong tube subjected to quasi static lateral loading. The
authors used three indenter types; flat plate, cylindrical and a point load with two constraints; inclined and vertical. They concluded that the unconstrained oblong tube laterally loaded by flat plate indenter show nearly perfect response with maximum efficiency. In fact, unstable deformation is produced with low energy absorption when the cylindrical and point indenters are used [6].

It is found that the energy absorption of composite and non-composite tubes under lateral will be enhanced when polyurethane foam is used to fill these tubes. In addition, more stable deformation can be achieved with using the foam filled tubes compared to empty tubes under lateral loading [7-9]. Zuraida et al. [10] investigated the behaviour of hybrid filament wound composite tubes under quasi static lateral indentation. The authors found that the stacking sequence of hybrid composite tubes under lateral indentation can be used to improve the structure strength and performance of these tubes. It is also proved that the circumferential and axial strains for the inner and outer sides of hybrid tube surface are dependent on the type of fibre used and on the stacking sequence [10].

The main focus of this study is to determine the load-displacement response and the energy absorption of jute, glass and hybrid jute-glass/ epoxy composite tubes under lateral loading. Furthermore, the study aims to investigate the effect of hybridization and stacking sequence of composite layers on the performance of the composite tubes. The failure mechanisms of the laterally crushed tubes is also observed and discussed.

2. Experimental work

2.1. Materials and fabrication

Composite tubes were fabricated by hand lay-up method using woven roving \([-45^\circ]\) jute/epoxy and glass/epoxy materials. A PVC tube of circular cross-section of 110 mm diameter was used as a mould to fabricate the composite tubes. Two circular plywood plates of 10 mm thickness were fitted inside the hollow tubes at each side. The plywood was used in order to extract the fabricated composite tubes from these mandrels after curing. Table 1 shows the dimensions of the fabricated composite tube and cone specimens. Samples of the fabricated specimens are shown in figure 1. The terms J and G are respectively jute and glass fibres. The numbers 2, 4 and 6 referred to the number of layers of the composite laminate structures.

| Specimen type | Inner diameter D (mm) | No of layers | Wall Thickness t (mm) | Length |
|---------------|-----------------------|--------------|-----------------------|-------|
| J2            | 110                   | 2            | 2.15                  | 200   |
| J4            | 110                   | 4            | 3.94                  | 200   |
| J6            | 110                   | 6            | 5.82                  | 200   |
| G2            | 110                   | 2            | 2.46                  | 200   |
| G4            | 110                   | 4            | 4.13                  | 200   |
| G6            | 110                   | 6            | 6.26                  | 200   |
| J2G2J2        | 110                   | 6            | 5.93                  | 200   |
| G3J3          | 110                   | 6            | 6.25                  | 200   |
| J3G3          | 110                   | 6            | 6.42                  | 200   |
| J6GJGJG       | 110                   | 6            | 5.96                  | 200   |
| G2J2G2        | 110                   | 6            | 6.41                  | 200   |
The mechanical properties of the jute and glass/epoxy materials were obtained from the literatures [23] and listed in table 2.

Table 2. Mechanical properties of jute and glass/epoxy lamina.

| Property | Description                     | Woven roving [±45] |
|----------|---------------------------------|--------------------|
| \( \rho \) | Density (kg/mm\(^3\))          | 1.6e-6             |
| \( E_{11} \) | Young’s modulus -longitudinal direction (MPa) | 17680               |
| \( E_{22} \) | Young’s modulus -transverse direction (MPa) | 17680               |
| \( G_{12} \) | In-plane shear modulus (MPa) | 3002               |
| \( G_{23} \) | Out of plane shear modulus (MPa) | 2860               |
| \( v_{21} \) | Minor Poisson’s ratio          | 0.29               |
| \( \chi_x \) | Longitudinal tensile strength (MPa) | 560                |
| \( \chi_c \) | Longitudinal compressive strength (MPa) | 380                |
| \( Y_x \) | Transverse tensile strength (MPa) | 29                 |
| \( Y_c \) | Transverse compressive strength (MPa) | 98                |
| \( S_e \) | In-plane shear strength (MPa)   | 45                 |

2.2. Testing procedure

Constant slow speed compression testing was performed using a computer-controlled servo-hydraulic Instron machine type 5584. The cross-head speed was adjusted at 2.5 mm/min. Composite tubes were laterally crushed between two parallel steel flat platens, one static and one moving. The fixed platen was fitted with a load cell from which the load signal was taken directly to the computer. For each test, the lateral load was plotted on the Y-axis and the crosshead displacement on the X-axis.

3. Results and discussion

3.1. Lateral loading characteristics

In this section results of the laterally loaded composite tubes are presented. Figures 2, 3 and 4 show the lateral load-displacement graphs of the composite tubes using jute (J), glass (G) and hybrid jute-glass (JG)/epoxy respectively. In figures 2,3,4 and 6 are referred to the number of layers. Study shown that the load increased linearly till the initial failure then the load fluctuates with a sharp drop till failure. The glass/epoxy tubes supported higher lateral load than the hybrid jute-glass/epoxy followed by the jute/epoxy tubes. In general, increase in number of layers from two to six show a significant increase in the maximum load obtained for the jute and glass/epoxy tubes as shown in figures 2 and 3.
It can be seen from figure 4 that the stacking sequence of hybrid composite tubes can be used to improve their strength and performance. For hybrid tubes with the external layers of glass/epoxy show higher strength and supported higher load than hybrid tubes with internal layers of glass/epoxy.

**Figure 2.** Load-displacement relation for jute/epoxy tubes.

**Figure 3.** Load-displacement relation for glass/epoxy tubes.
Figure 4. Load-displacement relation for jute-glass/epoxy tubes.

Figure 5 shows the effect of material used on maximum load obtained from the load-displacement graphs. This figure explains that the glass/epoxy tubes made of six layers supported the highest lateral load compared to the other tested tubes. The maximum lateral load obtained for the hybrid jute-glass/epoxy tubes made of six layers is significantly affected by the stacking sequence of the jute and glass fibers. In general, the hybrid jute-glass/epoxy tubes supported moderate lateral load compared to the load obtained from glass/epoxy tubes.

Figure 5. Maximum load of the laterally crushed composite tubes.
3.2. Lateral loading characteristics

The crush force efficiency (CFE) is an important factor to measure the crush performance and to evaluate the crushworthiness of energy absorber components. The CFE for the composite tubes under lateral loading is determined using equation 1. Results show that the crush force efficiency for hybrid jute-glass/epoxy tubes and glass epoxy are found higher than jute/epoxy.

\[
\text{CFE} = \frac{F_{\text{mean}}}{F_{\text{max}}} \tag{1}
\]

where, \(F_{\text{mean}}\) and \(F_{\text{max}}\) are the mean and maximum crush failure loads respectively.

3.3. Specific Energy Absorption

The specific energy absorption (SEA) for the composite tubes under lateral loading can be calculated as follows:

\[
\text{SEA} = \frac{E_t}{m} \tag{2}
\]

where, \(E_t\) is the total absorbed energy represented by the area under the load-displacement graph and \(m\) is the mass of the tube. Table 3 shows the results of \(\text{SEA}\), mean and maximum crush loads of the composite tubes subjected to lateral loading. By referring to table, \(\text{SEA}\) is improved by using the hybrid composite tubes.

| Specimen type | Mass (g) | Mean load \(P_{\text{mean}}\) (KN) | Maximum load \(P_{\text{max}}\) (KN) | Crush force efficiency (CFE) | Specific energy absorption SEA (J/Kg) |
|---------------|---------|----------------------------------|---------------------------------|-----------------------------|---------------------------------|
| J2            | 110     | 0.38                             | 0.53                            | 0.72                        | 143                             |
| J4            | 230     | 0.63                             | 0.85                            | 0.74                        | 210                             |
| J6            | 337     | 0.92                             | 1.22                            | 0.75                        | 360                             |
| G2            | 125     | 1.16                             | 1.35                            | 0.86                        | 250                             |
| G4            | 256     | 2.08                             | 2.65                            | 0.78                        | 380                             |
| G6            | 366     | 3.44                             | 3.87                            | 0.89                        | 795                             |
| J2G2J2        | 362     | 1.54                             | 1.88                            | 0.82                        | 460                             |
| G3J3          | 376     | 2.61                             | 2.82                            | 0.93                        | 580                             |
| J3G3          | 384     | 2.70                             | 2.89                            | 0.93                        | 596                             |
| JGJGJG        | 368     | 3.08                             | 3.28                            | 0.94                        | 670                             |
| G2J2G2        | 375     | 3.31                             | 3.46                            | 0.96                        | 705                             |

3.4. Failure mode

One of the important factors to evaluate the crushworthiness of the composite structures is the failure mechanisms. Composite tubes were fixed between two flat steel plates as shown in figure 6 where the load applied laterally on the tubes. Photographs of compression process leads to failure were taken to observe the progressive crushing mechanism on the composite tubes. In general, the tested tubes fractured at the centre position where cracks propagated at the top and bottom sides along the longitudinal direction of the tube. It can be seen that four longitudinal fracture lines are developed during the crushing process. Two fracture lines are formed close to the lines of contact between the tube and the flat platens. With further increase in the crushing distance and upon the complete of the compression process, another two fracture lines are formed diametrically opposite to each other.
4. Conclusion
In this paper, experimental tests were carried out to investigate the effect of lateral loading on the load-displacement relationship, specific energy absorption and failure mode of hybrid and non-hybrid composite tubes. Hand lay-up method is used to fabricate carefully the composite tubes of 2, 4 and 6 layers carefully. Results of the load-displacement graphs show that the maximum lateral load obtained for six layered glass/epoxy is found higher 10.6% than hybrid jute-glass/epoxy. The specific energy absorption of the glass/epoxy tubes is found higher respectively 11.6% and 46% than hybrid jute-glass and jute/epoxy tubes. The increase in the number of layers from two to six increased the maximum lateral load from 0.53KN to 1.22 KN jute/epoxy tubes. The increase was from 1.35 KN to 3.87 KN for the glass/epoxy tubes. The stacking sequence of jute and glass fibers has an effect on the performance of the composite tubes under lateral loading. The maximum lateral load varied from 1.88 KN to 3.46 KN with using different stacking sequence of the jute and glass fibers. In general, similar failure mechanism has been obtained from the fractured composite tubes where cracks propagate at the center position of the tube at the top and bottom sides of the tube. The post peak failures showed a significant deformation at the crack line position and then lead to the final fracture.

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Figure 6. Failure mode for composite tubes under lateral loading.
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