Axial quasi-static crushing behaviour of cylindrical woven kenaf fiber reinforced composites

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Abstract. This paper presents the crushing responses of cylindrical woven kenaf fibre reinforced composites under quasi-static compression. Kenaf fiber in the form of yarn is weaved into woven mat. It is then submerged into polyester bath before it is wrapped into a cylindrical shape. There are two important parameters investigated such as number of layers and fiber orientations. According to the experimental results, as expected increasing the number of layers increased the energy absorption performances. However, increasing the fibre orientations from 0° to 45° capable to decrease the energy absorption capability. It is also observed that during progressive collapses, localized buckling is the dominant failure mechanism where there is no large composite fragmentation occurred.

1. Introduction

The utilizations of natural fibers in fabricating the composite structures increased especially for non-load bearing applications. Due to environmental awareness and the potential of natural fibers, some researchers [1-10] investigated the capability of these fibers to withstand under quasi-static and dynamic forces. One of the important research areas for composite applications is crashworthiness where the composite is used to manage the crushing behavior in order to minimize the injuries or fatalities.

Crushing performances of engineering materials for an example metal [1] and synthetic fiber reinforced composites [2] can be found tremendously in open literature. However, due to environmental awareness among researchers, synthetic fibers are increasingly replaced with natural fibers. One of the aspect of research works conducted using natural fiber is crashworthiness [3]. According to literature survey, lot of works conducted to study the crushing behavior of natural fiber and most of them used randomly oriented fibers in fabricating the composites. It is hard to find the works deal with the woven natural fiber reinforced composites. For an example Alkbir et al. [4] conducted an investigation on the effect of geometries of hexagonal tubes fabricated using natural kenaf fibers. In their studies, angles played an important role in determining the crushing performances.

On the other hand, Yang and Chouw [5] performed an investigation on the crashworthiness characteristics of flax composite tubes. In fabricating their composite tubes, three crucial important factors are used for example inner diameter, number of thickness and length-to-diameter ratios. They stated that flax fiber has a great potential to be used as an energy absorbing fiber.
Additionally, most of the natural fibers used are randomly oriented [6]. Recently, several research works conducted in [3-9] concentrating on the applications of oriented fibers in producing the composite tubes. Ismail and Sahrom [10] investigated the lateral crushing energy absorption of cylindrical kenaf fiber reinforced composites. Three fiber orientations and number of layers are used in making the composite tubes and they are quasi-statically crushed. It is found that crushing response is strongly related with the number of layers and unfortunately fiber orientation is not played an important role in affecting the energy absorption. Some works on axial energy absorption since the tubes are crushed laterally of kenaf fiber composites can also be found in [11-20].

In this work, kenaf fiber in the form of yarn is weaved into a plain woven mat. The woven mat is firstly immersed into a polyester resin bath before it is wrapped around the cylindrical mold. There are three type of thicknesses are considered such as two, three and four layers. Each layer is aligned to the specific directions for example 0°, 15°, 30° and 45°. Once the composite tubes hardened, they are quasi-statically crushed to obtain the responses of force versus displacement. Then, the crashworthiness characteristics are extracted and discussed with the relation with of number of layers and orientations.

2. Experimental Program

In this work, kenaf fiber in the form of yarn is used and then weaved into a plain woven type structure where there are two sets of fiber such as warp and weft. There fibre are perpendicular to each other and thus creating an unbalanced plain woven mat. The number of warp and weft are determined with 6x4 where there are 6 yarns in warp and 4 yarns in weft directions per 10mm². An in-house weaving machine is used as shown in Figure 1(a) and the completed woven mat is revealed in Figure 1(b).

Figure 1 (a) Weaving process using in-house machine and (b) Completed woven kenaf mat.

Kenaf woven mats are then submerged into polyester resin and a special attention is paid to ensure resin uniformly distributed into the fibres. Then, wet kenaf mats are wrapped around the cylindrical mould before they are circumferentially compressed to squeeze out any excessive resin. After 24 hours of curing time, the mould is removed and any unwanted composites especially at both edges are trimmed smoothly to ensure the total length is 70mm. In this work, two, three and four layers are used and each layer has its own orientation as tabulated in Table 1.

Cylindrical-shaped woven kenaf reinforced composites are quasi-statically compressed using a constant cross-head displacement of 5mm/min. All composite tubes are crushed up to 60% of the original length in order to obtain the curves of force versus displacement. The area under the curves represented the energy absorption performances. On the other hand other crashworthiness parameters
are also determined such as peak force, mean force and force ratio. Peak force is defined as the maximum elastic force, mean force is the average fluctuating forces occurred during the collapsing processes and force ratio is the ratio between the peak with mean forces. The effect of fibre orientations and number of layers on the energy absorption performances and the force ratios are discussed.

Table 1 Types of sample used in this work.

| Samples | Orientation Θ° | Thickness (cm) | Inner Diameter (cm) | Length (cm) |
|---------|----------------|----------------|---------------------|-------------|
| C1      | [0°/0°]        | 0.5            | 5.0                 | 7.0         |
| C2      | [0°/15°]       | 0.5            | 5.0                 | 7.0         |
| C3      | [0°/30°]       | 0.5            | 5.0                 | 7.0         |
| C4      | [0°/45°]       | 0.5            | 5.0                 | 7.0         |
| C5      | [0°/0°/0°]     | 0.7            | 5.0                 | 7.0         |
| C6      | [0°/15°/0°]    | 0.7            | 5.0                 | 7.0         |
| C7      | [0°/30°/0°]    | 0.7            | 5.0                 | 7.0         |
| C8      | [0°/45°/0°]    | 0.7            | 5.0                 | 7.0         |
| C9      | [+15°/0°/-15°] | 0.7            | 5.0                 | 7.0         |
| C10     | [+30°/0°/-30°] | 0.7            | 5.0                 | 7.0         |
| C11     | [+45°/0°/-45°] | 0.7            | 5.0                 | 7.0         |
| C12     | [0°/0°/0°/0°]  | 1.0            | 5.0                 | 7.0         |
| C13     | [0°/+15°/-15°/0°] | 1.0        | 5.0                 | 7.0         |
| C14     | [0°/+30°/-30°/0°] | 1.0        | 5.0                 | 7.0         |
| C15     | [0°/+45°/-45°/0°] | 1.0        | 5.0                 | 7.0         |

3. Results and Discussion

Figure 2 shows the force-displacement curves of different layers cylindrical tubes under axial compression. It is found that as expected, the crushing responses are significantly related with the thicknesses of the cylindrical wall where the peak forces increased as the thickness increased. In general, the crushing responses can be divided into three stages, the first stage is the elastic deformation. In this stage, the displacement is proportional to the force. Once the tubes experienced the peak force, the first collapse occurred. Localized buckling is the responsible mechanism in collapsing the tubes normally initiated at the either at the upper or lower edges of the tubes. It is also observed that for four-layered tubes, large force drop occurred indicating that probably the tubes collapsed catastrophically as shown in Figure 2(c) compared with two-layered composite shown in Figure 2(a). Then, the crushing mechanism entered the second stage where the tube wall experienced progressive collapses. It is continued until all the composites are crushed and the force is gradually increased since there is no composites to be collapsed. It is then entered the last stage which is the densification stage. According to the final observation, composite wall still intact together and no large or small composite fragmentations can be observed. This is contradictory mechanisms as reported in [4, 5] where during crushing processes large composite fragmentations contributing to lower the crushing performances.

Figure 3 reveals the effect of number of layers on the crushing responses. Each composite tubes are fabricated using identical orientations but different in number of layers. It is also indicated that similar behaviour of crushing patterns can be observed where thicker the composites higher the responses of force-displacement curves. Even though higher peak forces are produced, the composites experienced catastrophic failure since the peak force dropped gradually. This behaviour contributed to lower the specific energy absorption.

Figure 4 indicates the effect of number of layers with different fibre orientations on the force-displacement curves under axial compressions. It is revealed that increasing the number of layers increased the responses of force-displacement. No strong effect is also observed on the force-
displacement curves if fibre orientations increased from 15° to 45°. However, the composites containing 15° fibre orientations sustained higher responses especially the peak forces. This is due to the fact that during crushing process, circumferential stress is the most dominant force. Then, 15° fibre orientation capable to resist the circumferential deformation and therefore strengthening the composite walls.

According to Table 2, it is obvious that increasing the angles from 0° to 45° have decreased the specific energy absorption performances regardless of their thicknesses. This is due to the fact that 0° fibre alignments capable to strengthen the composite wall circumferentially. During compression, fibres not only experienced axial but radial deformations then [0°/0°], [0°/0°/0°] and [0°/0°/0°/0°] capable to provide a maximum strengthening mechanism in axial and radial directions.

Figure 2 Continued….
Figure 2 Crushing responses of (a) two-, (b) three- and (c) four-layered cylindrical composite tubes under axial quasi-static compression.

| Specimens         | Peak force (kN) | Mean force (kN) | Energy absorption (kJ) | Specific energy absorption (kJ/kg) |
|-------------------|-----------------|-----------------|------------------------|-----------------------------------|
| 2-layers          |                 |                 |                        |                                   |
| [0°/0°]           | 62.4            | 20.7            | 1.025                  | 15.530                            |
| [0°/15°]          | 55.0            | 18.0            | 0.754                  | 11.781                            |
| [0°/30°]          | 42.1            | 11.2            | 0.687                  | 10.905                            |
| [0°/45°]          | 46.7            | 14.3            | 0.561                  | 9.350                             |
| 3-layers          |                 |                 |                        |                                   |
| [0°/0°/0°]        | 101.0           | 32.1            | 2.189                  | 22.567                            |
| [0°/15°/15°]      | 91.8            | 28.4            | 1.371                  | 14.581                            |
| [0°/30°/30°]      | 69.2            | 21.6            | 1.173                  | 12.748                            |
| [15°/0°/15°]      | 73.4            | 25.2            | 0.957                  | 10.638                            |
| [30°/0°/30°]      | 71.2            | 25.9            | 1.070                  | 12.442                            |
| [45°/0°/45°]      | 65.4            | 18.5            | 0.903                  | 11.153                            |
| 4-layers          |                 |                 |                        |                                   |
| [0°/0°/0°/0°]     | 123.7           | 24.2            | 6.414                  | 53.450                            |
| [0°/15°/15°/0°]   | 121.0           | 22.5            | 5.248                  | 47.280                            |
| [0°/30°/30°/0°]   | 93.1            | 19.5            | 3.583                  | 33.489                            |
| [0°/45°/45°/0°]   | 105.6           | 20.4            | 2.163                  | 21.2111                           |
Figure 3 Effect of number of layers on the force-displacement curves for composites contained (a) 15°, (b) 30° and (c) 45°.
Figure 4 Effect of fibre orientations on the force-displacement curves, (a) two-layered, (b) three-layered, (c) three-layered (different arrangements) and (d) four-layered cylindrical composite tubes.

4. Conclusion
An experimental program is conducted on cylindrical composite tubes fabricated using woven kenaf fibers. There are three different thicknesses are used depending on the number of layers. Each layer has its own orientation. The composite tubes are quasi-statically compressed and crushing response is automatically recorded. Then, several conclusions can be drawn such as:

1. Crushing responses of these composites are significantly depend on the number of layers and fiber orientations.
2. As expected increasing number of layers increasing the specific energy absorptions.
3. Increasing the fiber orientations from 0° to 45° capable to decrease the specific energy absorptions.
4. Most of the composites collapsed through localized buckling especially at the upper edge/moving plate boundary. Then, the buckled wall progressive collapsed without showing large composite fragmentations.

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