Effect of triggering angles on the crushing mechanisms of hybrid woven kenaf/aluminum hollow cylinders

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Abstract. This paper presents the effect of triggering angles constructed on the top of hybrid woven kenaf/aluminium hollow cylinders on the energy absorption performances. The crushing performances of aluminium tubes can be found widely in open literature. However, lack number of work on the hybridizing the aluminium tubes with woven kenaf fibre is found. Woven kenaf mats are produced and bathed with polymeric resin before they are wrapped around the aluminium tubes twice. Different fibre orientations, ±θ are used where θ = 0, 15, 30 and 45. Once the hybrid composite hardened, one of their end are chamfered using different angles of 0°, 30°, 45° and 60°. The tubes are quasi-statically compressed in order to obtain their force-displacement responses and crashworthiness parameters are extracted and discussed with the relation of fibre orientations and chamfering angles. It is found that the chamfering angles are only affected the force-displacement curves during the first stage of elastic deformation whereas there is no obvious effect in the second stage. However, varying the fibre orientations are slightly increased the force-displacement curves especially when the fibre is orientated with 30°. Based on the fracture mechanism observations, most of composite experienced large fragmentation indicating that the composites absorbed the crushing energy ineffectively.

1. Introduction

Natural fibers are now a bright potential in reinforcing polymer composites due to their ecofriendly aspect and sustainability. These kind of fibers are considered to have tremendous number of applications since they have good mechanical and physical properties over synthetic fiber such as relative low weight, low cost, good mechanical performances and etc. [1]. Applications of natural fiber for automotive parts can be found in [2, 3]. One of the interest point to be considered is the utilization of natural fiber for the energy absorbing structures made of natural fibers.

Meredith et al. [4] developed conical shaped geometry fabricated using natural fiber before it is subjected impact loading. It is found that the cones exhibited high values of SEA: unwoven hemp 54.3 J/g, woven flax 48.5 J/g and woven jute 32.6 J/g. The SEA was influenced primarily by fiber volume fraction, Vf where a high Vf leads to high SEA. Significant variability in SEA resulted from the variation in fiber strength and Vf as a result of the vacuum assisted resin transfer molding manufacturing process. Laban and Mahdi [5] studied the performances of energy absorption of cotton fiber/epoxy composite square and rectangular tubes where the effect of cross-sectional aspect ratios
are emphasized. The experiment also showed that the cross-sectional aspect ratio significantly affects the load carrying and energy absorption capability. The buckling failure mode has been identified as the primary failure mode for the rectangular tubes under the different loading conditions. Tubes with cross-sectional aspect ratio of 2.0 have the best load carrying capacity.

Ismail [6] presented the tensile strength of woven yarn kenaf reinforced polyester composites. Two important parameters are studied such as fiber orientations and number of layers. According to the results, it is shown that fiber orientations greatly affected the ultimate tensile strength but it is not for modulus of elasticity for both types of layers. It is estimated that the reductions of both ultimate tensile strength and Young’s modulus are in the range of 27.7-30.9% and 2.4-3.7% respectively, if the inclined fibers are used with respect to the principal axis.

Lateral crushing performances of woven kenaf composites can also be found in [7]. As-received kenaf yarn is firstly submerged into a resin bath before it was wrapped around the cylindrical mould. Two important parameters were considered during the composite preparation stage which were fiber orientations (0°, 5° and 10°) and number of layers (1, 2 and 3 layers). Then, the hardened composite tubes were positioned horizontally prior to quasi-static compression. Lateral crushing resistances of the composite tubes are compared in term of specific energy absorptions, force ratios and deformation modes. Lastly, these crashworthiness parameters are discussed relating with fiber orientations and number of layers. Axial energy absorption capabilities of woven kenaf fiber reinforced composites are available in [8-11]. Works on fiber hybridizations with the metallic cylinders can be found in [12, 13]. For an example Ismail [12] hybridized aluminum tubes with kenaf yarn composites and compressed quasi-statically and obliquely. It is found that specific energy absorption performances increased when the numbers of layers are increased, fiber orientations are not played an important role in increasing the capabilities of specific energy absorptions, force ratios decreased when the numbers of layers are increased but it is significantly not affected the energy absorption performances and fiber orientations seemed not to affect the force ratios. However when fiber orientations increased, force ratios are slightly decreased.

On the other hand, Ismail [13] also hybridized the steel tubes with kenaf yarn before it is compressed quasi-statically. The kenaf yarn fibres were firstly wetted with a polymeric resin and it was then wound around the steel tubes. The tube diameter was kept constant 50 mm in diameter and fiber orientations were varied. The steel/kenaf hybrid tubes are aligned vertically and compressed quasi-statically. The force-displacement curves were recorded automatically and crashworthiness parameters were determined and related with the hybridization parameters. It was found that the present of kenaf yarn fiber around the steel tubes capable to slightly enhance the crushing performances. During progressive collapses, fiber splaying mode was observed with large composite wall fragmentations.

This paper presents the effect of different triggering angles on the crushing performances of hybrid woven kenaf/aluminum tubes under axial compression. There are four chamfering angles are selected such as 0°, 30°, 45° and 60°. Aluminum tubes are wrapped with two layers of woven kenaf mats where they are firstly wetted with polyester resin where each layer is oriented using different angles. Once the composite hardened (after 24 hours of curing time), they are quasi-statically compressed in order to obtain their force-displacement responses. Energy absorption performances are calculated according to the area under the curves and the crushing behavior are evaluated and analyzed.

2. Methodology

An industrial grade aluminum hollow tube is used with a thickness of 1mm and 50mm external diameter. The length of tube is 100mm where it is long enough to prevent global buckling. As-received kenaf yarn (as in Figure 1(a)) is weaved into a plain woven mat before it is wrapped around the outer surface of aluminum tube. The weaving process is conducted using an in-house facility as in Figure 1(b) and 1(c). While Figure 1(d) revealed the completed woven kenaf mat. Woven kenaf mat is firstly immersed into a resin bath where a proper care is given in ensuring resin penetrates into the fibers uniformly. The wet fiber mat is wrapped around the tube twice and each layer oriented
according to the specific orientation as tabulated in Table 1. Figure 1(e) shows the completed hybrid woven kenaf/aluminum hollow tube. This sample is positioned vertically between two flat rigid plates. The bottom plate is stationary while the upper plate is moved downward. The sample is compressed quasi-statically with a speed of 1.5 mm/min of cross-head displacement. The force versus displacement curves are recorded automatically where the area under the curves represent the capability of energy absorption, $E$ and it can be represented as:

$$E = \int_{0}^{t} P ds$$  \hspace{1cm} (1)

where $P$ is a force, $ds$ is a small element on the curve and $L$ is the crushed length. Instead of energy absorption performance, other important parameter such as force ratio, $\psi$ is also determined as in Equation (2).

$$\psi = \frac{P_{\text{mean}}}{P_{\text{peak}}}$$  \hspace{1cm} (2)

where $P_{\text{mean}}$ is the average force during the crushing process and $P_{\text{peak}}$ is the maximum or peak force just after the elastic deformation. Final crushed samples are also observed in order to study the effect of variations of fiber orientations on the crushing performances.

**Figure 1.** (a) As-received kenaf yarn, (b) Weaving machine, (c) Weaving process in progress and (d) Completed woven kenaf mat and (e) Hardened hybrid aluminum composite tube.
Table 1. Sample parameters and compression conditions.

| No. | Orientations | Layers | Chamfered angles |
|-----|--------------|--------|-----------------|
| 1   | [±0]         | 2      | 0°              |
| 2   | [±0]         | 2      | 30°             |
| 3   | [±0]         | 2      | 45°             |
| 4   | [±0]         | 2      | 60°             |
| 5   | [±15]        | 2      | 0°              |
| 6   | [±15]        | 2      | 30°             |
| 7   | [±15]        | 2      | 45°             |
| 8   | [±15]        | 2      | 60°             |
| 9   | [±30]        | 2      | 0°              |
| 10  | [±30]        | 2      | 30°             |
| 11  | [±30]        | 2      | 45°             |
| 12  | [±30]        | 2      | 60°             |
| 13  | [±45]        | 2      | 0°              |
| 14  | [±45]        | 2      | 30°             |
| 15  | [±45]        | 2      | 45°             |
| 16  | [±45]        | 2      | 60°             |

3. Results and discussion

Figure 2 shows the force-displacement responses of hybrid composites when upper edges are chamfered with different angles. In general, chamfering the tubes capable to increase the peak forces. However, it is strongly depend on the fiber orientations. For the fiber orientation of 0° and 15°, it is seemed that chamfering the upper edge with specific angles do not played an important role in increasing the peak force when compared with other orientations such as 30° and 45°. This is probably due to the fact that 0° and 15° fiber orientations capable to resist the deformation only in the lateral direction. For higher orientations (30° and 45°), the fiber not only constraint the deformation laterally but obliquely and therefore increasing the peak forces. In the second or plateau stages, the effect of triggering angles on the force-displacement responses are insignificant where there is no obvious distinct. However, the responses of hybrid composite tubes are relatively higher that empty tubes due to the present of layer of composites. This is indicated that chamfering angles played an important role only in the first stage. Many research reports have found similar mechanisms regardless of material type [7-13].
Figure 2. Effect of chamfering angles on the force-displacement curves for different fibre orientations, (a) 0°, (b) 15°, (c) 30° and (d) 45°.

Figure 3. Effect of fibre orientations on the force-displacement curves for different chamfering angles, (a) 0°, (b) 30°, (c) 45° and (d) 60°.
Figure 4. (a) Effect of triggering angles on the force ratios and (b) Effect of fibre orientations on the force ratios.

(a) (b)

Figure 5. Hybrid tube deformation at different compression stages (a) initial condition, (b) 25 mm deformation, (c) 45 mm deformation, (d) 55mm deformation and (e) an aerial view of 55mm final deformation.

Figure 3 shows the effect of fiber orientations on the force-displacement curves when chamfering angles are varied. In general, it is seemed that increasing the chamfering angles slightly reduced the peak forces. Figures 3(a) and 3(b) reveal the force-displacement responses for the hybrid tubes chamfered with 0° and 30°, respectively. It is observed that hybridizing the aluminum tubes with woven kenaf mat capable to increase the peak forces compared with empty tubes, it is also observed that 30° fiber orientation produced the highest peak forces. This is probably if the fiber oriented at 30°, it is capable to resist the deformation in both directions laterally and axially. Therefore strengthening the hybrid tubes. When the chamfering angles are further increased, there is no significant effect on the peak forces are observed indicating that the present of composite layer wrapped around the outer
surface of the tubes do not contributed to the enhancement of the peak forces as compared with the peak forces of empty tubes.

Figure 4 reveals the effect of chamfering angles and fiber orientations on the force ratios, respectively. In general, there are no strong relationship between chamfering angles and fiber orientations on the force ratios. However, Figure 4(a) shows that the chamfering seemed to slightly decrease the force ratios for all type of fiber orientations. This is due to the fact that when the upper edge is chamfered, it is acted as a triggering mechanism where the tube is easily crushed in the very initial stage as compared with untampered edge. Therefore, the force ratio is relatively lowered can be produced. While Figure 4(b) obviously observed that 45° fiber orientation offered the lowest force ratios probably due to no fiber oriented at 0° worked to restraint the tube deformation laterally.

Figure 5 shows the sequences of the tube deformations under quasi-static axial compression. Figure 5(a) shows the initial condition of the tube while Figures 5(b) and 5(c) show the crushing mechanisms when the tubes are crushed approximately at 10 and 20 mm, respectively. On the other hand, Figures 5(d) and 5(e) show the final crushed geometry when the tube is crushed in half of its middle height. It is revealed that large composite fragmentations are observed indicating that they are absorbed the crushing energy insufficiently.

4. Conclusion
Based on the experimental results, there are no strong relationship between the effect of chamfering and orientation angles on the force ratios. All chamfering angles offered better force ratios except for the case of 30°. Lower force ratio indicating that the hybrid tubes seemed to collapse catastrophically or they experienced a sudden drop. On the other hand, the effect of fiber orientations on the force ratios are almost insignificant. However, 15° fiber orientation showed slightly higher than others. In term of fracture mechanism for all cases, large composite fragmentations are observed revealing that the composite ineffectively absorbed the crushing energy.

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