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CRUSHING MECHANISMS OF CYLINDRICAL WINDING KENAF FIBER REINFORCED COMPOSITES

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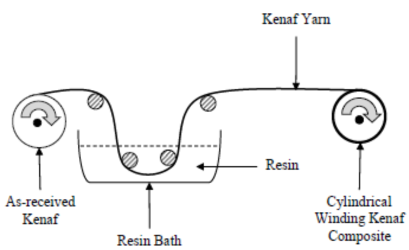
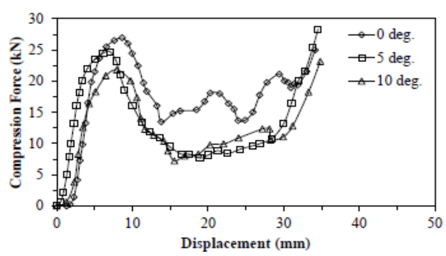
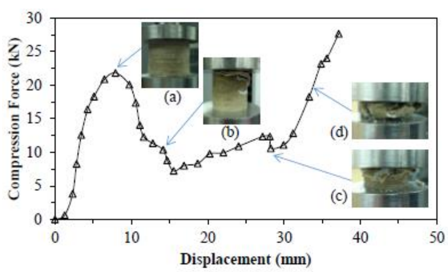
Graphical abstract







Abstract

This paper presents the crushing behavior of cylindrical kenaf fiber reinforced composites subjected to axial compressive loading. Lack of information available on the study of cylindrical composites fabricated using kenaf yarn fibers where it is wound around the cylindrical mold. There are two important parameters are used during the composite fabrications namely fiber orientations (0^{0}, 5^{0} and 10^{0}) and number of layers (1, 2 and 3 layers). These composite tubes are crushed axially and forces versus displacement curves are recorded. Then, the specific energy absorptions and force ratios are determined. As expected, increasing the number of layers increased the specific energy absorptions but it is not significantly affected the force ratio even different fiber orientations are used. During progressive collapses, most of the failures mechanisms observe are localized buckling with large wall fragmentations.

Keywords: Yarn kenaf fiber, Woven kenaf fiber, Crushing, Energy absorption

Abstrak

Kajian ini membincangkan kelakuan penghancuran komposit serat kenaf berbentuk silinder yang dikenakan beban mampatan paksi. Kurang maklumat yang boleh didapati dalam mengkaji komposit silinder yang diperbuat daripada lilitan serat kenaf yang berbentuk yan. Terdapat dua parameter yang penting iaitu orientasi serat (0^{0}, 5^{0} and 10^{0}) and bilangan lapisan (1, 2 and 3 lapisan). Komposit ini kemudiannya dihancurkan secara paksi dan lengkungan daya melawan anjakan direkodkan. Penyerapan tenaga tentu dan nisbah beban ditentukan. Seperti jangkaan, dengan meningkatkan bilang lapisan telah meningkatkan keupayaan penyerapan tenaga tentu walaubagaimanapun telah memberikan kesan yang sedikit tehadap nisbah beban walaupun orientasi serat yang berbeza digunakan. Semasa proses peruntuhan komposit berlaku, kebanyakan mekanisme kegagalan yang dicerap adalah lengkokan setempat dengan serpihan komposit yang besar.

Kata kunci: Komposit Silinder, Penghancuran, Penyerapan tenaga paksi

1.0 INTRODUCTION

In the beginning of automotive or aerospace industries, metallic materials are widely used as an energy absorbing material for a crashworthiness application. Generally, metals absorb crushed energy through only plastic deformation during progressive collapse. However in comparison, composite materials absorb crushing energy through varieties of macro- and micro-failure mechanisms [1-5].

Consequently, a lot of researches conducted to study the crashworthiness performances for synthetic fiber reinforced composites can be found [6-16]. Due to environmental and sustainable concerns, natural fibers are given an opportunity to replace the synthetic fiber due to several reasons [5]. According to literature survey, an increasing number of works can be found on the use of natural fibers for crashworthiness applications [7-16]. On the other hand, there is lots of information on kenaf fiber composites especially regarding to the mechanical behavior [8-10] but not on the crashworthiness aspects [11].

The uses of natural fiber as an energy absorbing materials are conducted by Meredith *et al.* [6]. They used three types of conical woven natural fibers such as hemp, flax and jute reinforced composites. According to the experimental results, hemp fiber exhibited higher specific energy absorption performance and it is found that significant variability in energy absorption capabilities are obtained as results from the variations in fiber strength and the fiber volume fractions.

Mahdi *et al.* [7] used empty fruit bunch (EFB) as a reinforcing tool in conical composites where the cone vertex angles are used as a variable and then the effect of such angles on the performances of energy absorptions. Alkbir *et al.* [11] studies the energy absorption performances of hexagonal shaped tubes fabricated using non-woven kenaf fiber reinforced composites. Their work is to investigate the effect of hexagonal geometries on the crushing performances. According to the results, 600 hexagonal tubes exhibited better crashworthiness performances compared with other type of composites.

Yan and Chouw [12] used flax fiber in fabricating the composite tubes and quasi-statically crushed. Three parameters are investigated on the crushing performances such as inner diameters, number of plied and length-to-diameter ratios. According to their results, such parameters are played an important role in increasing the energy absorption capabilities.

However, it is hard to find the information related to the composites fabricated using wounded yarn of natural fiber to form composite cylinders or tubes [13-16]. In this work, as-received kenaf yarn is used to produce composite tubes. Kenaf yarn is firstly wetted with polymeric resin before it is wrapped around the cylindrical mold. Two important composite parameters are used such as fiber orientations and number of layers.

The composite cylinders are positioned vertically and it is compressed quasi-statically to obtain force-displacement diagrams. Two crashworthiness parameters are extracted from these diagrams such energy absorption capabilities and force ratios. Finally, the crushing performances are evaluated in term of fiber orientations and number of layers with an assisting of crushing modes.

2.0 EXPERIMENTAL

Kenaf fibre is used in this present study. It is in the form of as-received yarn as shown in Figure 1. An average diameter of the kenaf yarn is 1 mm. The fabrication process of the composite is shown in Figure 2 where the kenaf yarn bundle is firstly wetted with the polyester resin. Then, the process is continued where the fiber is properly warped around the cylindrical mould assuming that the fibre tension is constant. It is specially designed so that it can be easily removed once the composite is fully hardened as shown in Figure 3. A special attention is paid in order to ensure the wetting process is uniformly distributed on the whole kenaf surfaces.

Figure 1 A bundle of an as-received kenaf yarn fibre

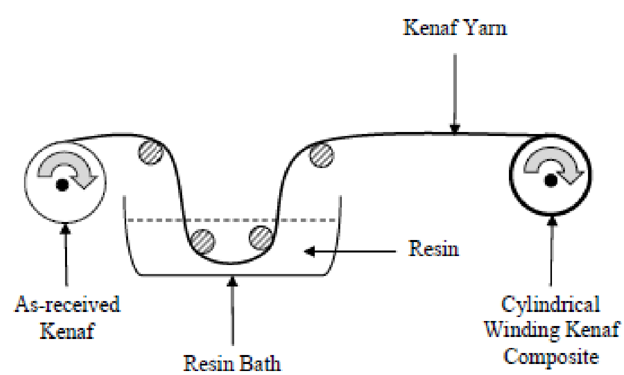


Figure 2 Schematic diagram of the winding process of the kenaf yarn fibre

Two important parameters are considered when fabricating the cylindrical composites (50 mm of inner diameter) such as fibre orientations (θ = 0, 5 and 10^0) and number of layers (L = 1, 2 and 3 layers). Once the composites are removed from the mould, both ends of the composites are trimmed to remove any excessive resin and fibres. In order to investigate the crushing behaviour, the composites are axially aligned and then they are quasi-statically compressed using a constant cross-head displacement 1.5 mm/min as revealed in Figure 4.

Force-displacement curve for each sample is recorded automatically and the area under the curve represents the energy absorption performances. During the progressive collapses, the crushing mechanisms are observed for different crushed distances. Several important crashworthiness parameters such as peak and mean forces and specific energy absorptions are studied on the effect of fibre orientations and number of fibre layers.

(a) (b) (c) (d)

Figure 3 (a) Plastic mould, (b) Mould assembly, (c) Kenaf yarn wrapped around the mould and (d) Final composite tubes

Figure 4 Composite is laterally positioned before quasi-static compression loading

Two important crashworthiness parameters are considered such as force ratio, *FR* or it is sometime called crush force efficiency which is the ratio between mean force, P_{mean} and peak force, P_{peak} is as follows:

$$\mathrm{FR} = \frac{P_{mean}}{P_{peak}} \tag{1}$$

Another parameter is specific energy absorption, E_s. It is defined as the energy absorbed per unit mass of the uncrushed material. The energy absorption capability, *E* can be determined using the area under the curve and it can be presented as:

$$E = \int_0^L P ds \tag{2}$$

where *P* is the crushing force and *ds* is the crushed length. Eq. (2) can also be represented as Eq. (3) as follows:

$$E = \int_0^L P ds = P_{mean}\left(S_{final} - S_{initial}\right) \tag{3}$$

where S_{final} and $S_{initial}$ are the final and initial crushed length. In order to eliminate the effect of material's size, the specific energy absorption, E_s is normally used as follows:

$$E_s = \int_0^L \frac{P}{m} ds = \frac{P_{mean}}{m}\left(S_{final} - S_{initial}\right) \tag{3}$$

where, *m* is mass in kg and P_{mean} is the average force.

3.0 RESULTS AND DISCUSSION

Figure 5 shows the force versus displacement curves of the composites under quasi-static compressive loading when fibre orientations are varied. The curves show a typical crushing response where it is composed of three stages. The first stage is linear elastic deformation. In this stage, the force increases as a linear function of displacement until it is reached a peak force.

After that, the second stage is appeared where the peak force experiences sudden force drop. Severity of sudden force drop is greatly dependent on the material conditions. If the peak force is slightly dropped, it is indicated that the composite is appropriate for crashworthiness applications. If the force drop is large, it is indicated that the tube is experienced catastrophic failure or buckling occurred. The last process is a densification stage. This stage is not contributed to the energy absorption performances. It is indicated that all crushed materials are fully contacted or crushed.

As can be seen in Figure 5, it is revealed that an increasing the number of layers result higher crushing responses. On the other hand, if the fibre orientations are increased from 0^0 to 10^0, slightly produce lower force versus displacement curves. This is due to the fact that when the tubes are compressed axially, 0^0 fibre capable to resist the circumferential stress around the tubes. Figure 6 shows the crushing responses when different numbers of layers are compared for a single fiber orientation. As expected when the numbers of layers are increased, the crushing responses are also increased. However in general, increasing the fiber orientations decrease the overall responses of force versus displacement.

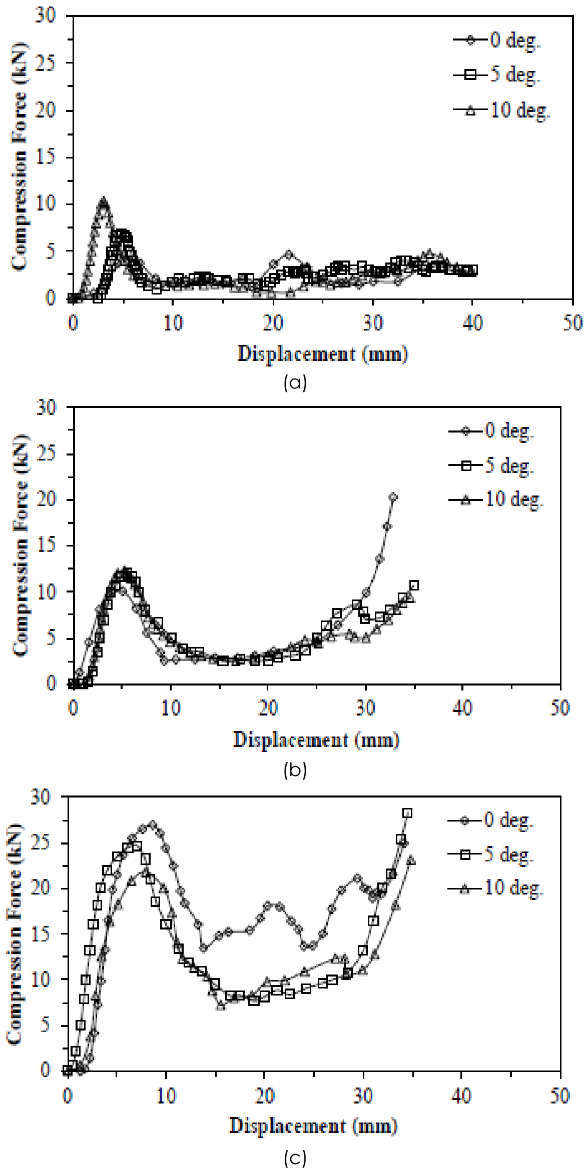


Figure 5 Crushing responses of kenaf fibre reinforced composites, (a) 1 layer, (b) 2 layers and (3) 3 layers

Figures 7 and 8 depict the comparisons between the effects of composite parameters with the crashworthiness performances. Figure 7(a) shows that increasing the fiber orientations seem not to increase the specific energy absorption significantly however decreasing the force ratios. For a single layered composite, increasing the fiber orientation is not increased the performances of energy absorption.

It is indicated that fiber orientations are not the key factor in increasing energy absorption especially for single layer composite tubes. This is probably due to the fact that the single layer does not have enough strength to retain the compressive force even different numbers of layers are used. However, if the number of layers is greater than or equal to two is used, varying the fiber orientations significantly increased the energy absorption capabilities.

This is also can be related with the thickness of the tubes where two layered composites (approximately 2mm in thickness) capable to sustain the compressive force.

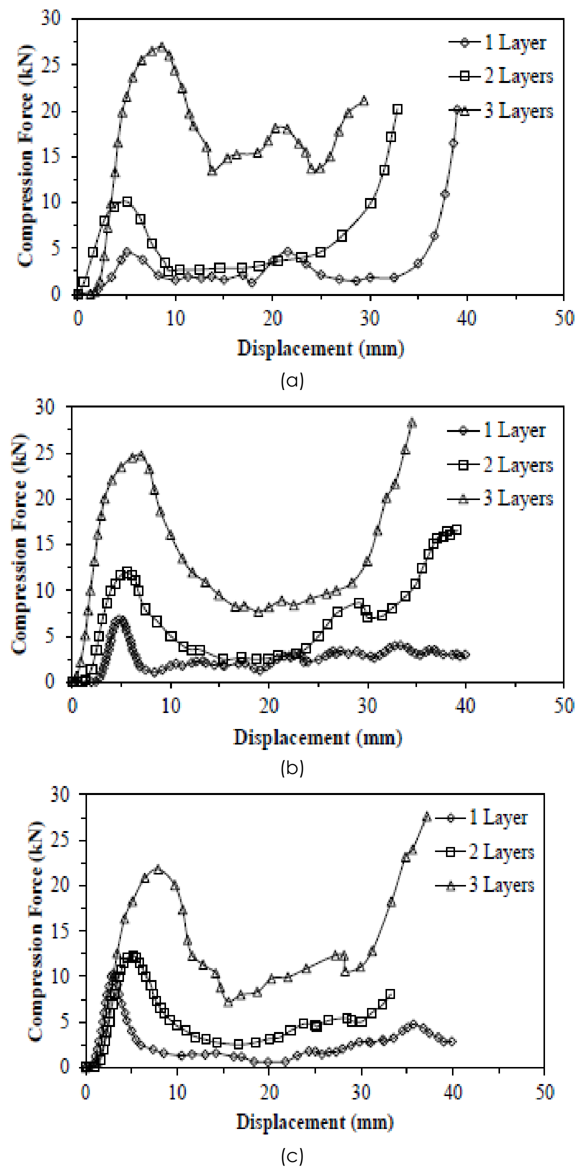
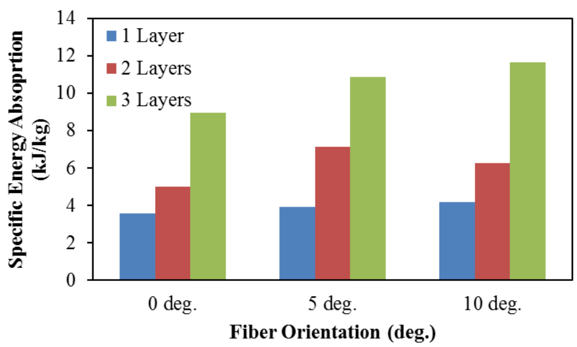


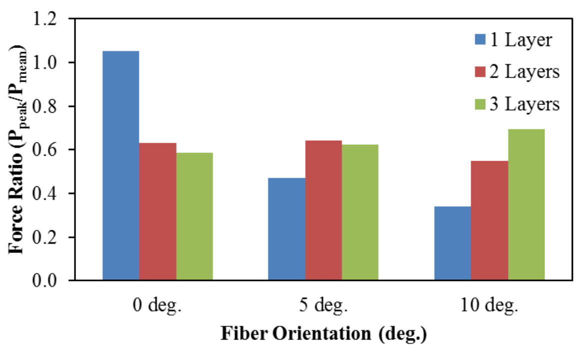
Figure 6 Crushing responses of kenaf fibre reinforced composites, (a) 0^0, (b) 5^0 and (3) 10^0

For 0^0 fiber orientated composites, the fibers are only supported the circumferential forces therefore higher tendency of the composites to failure by fiber splaying mechanism. If the composites failed through this type of mechanism, their energy absorptions are lowered. Relatively, lower specific energy absorption can be obtained for 0^0 fiber orientated composites even thicker tubes are used in comparison with other type of composites.

Figure 7(b) reveals the effect of fiber orientations on the force ratio. It is an indication of the severity of force drop after experiencing the peak force. It is also showed that 0^0 fiber oriented composites produced high force ratio. When higher force ratio is obtained, it is indicated that the tubes have failed catastrophically. Thus, lower energy absorption performances are obtained. On the other hand, when different fiber orientations are used such as 5 and 10^0, force ratio is then decreased and therefore increasing the energy absorption capabilities.



(a)

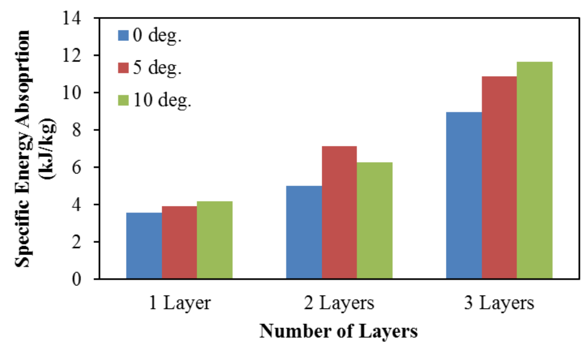


(b)

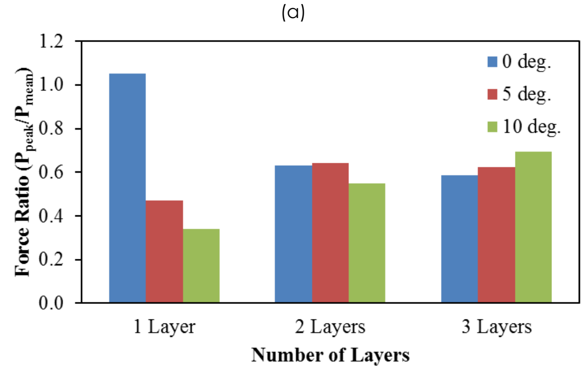
Figure 7 Effect of fiber orientations on the (a) specific energy absorptions and (b) force ratios

While, Figure 8 depicts that increasing number of layers significantly increase both specific energy absorptions and force ratios. Figure 8(a) reveals the influence of number of layers on the performances of energy absorption. As expected, thicker the tube thicknesses, higher the energy absorptions. For single layered composite tubes, the roles of fiber orientations are not significant where increasing the fiber orientations are slightly increased the energy absorptions. However, the orientations have played an important role when two or more number of layers is used. This is due to the fact that the 0^0 fiber orientations or the longitudinal fibers are only supported the circumferential stress but not the vertical deflection. On the other hand if the fibers are inclined, it is capable to retain the vertical displacement and therefore producing stronger composite tubes.

Figure 8(b) indicates the effect of number of layers on the force ratios. If lower force ratio is obtained, mean force is much greater than the peak force indicating the tube failed catastrophically. Based on the Figure 5, the pattern of force drop for all types of tubes are almost similar where Figure 8(b) supported the findings. However, the force ratios for single layered composites are slightly lower than other types of composites.



(a)



(b)

Figure 8 Effect of number of layers on the (a) specific energy absorptions and (b) force ratios

Figure 9 indicates the progressive collapses of the composite tubes under quasi-static compressive loading for 3 layers and 10^0 fiber orientation composites. There are four important stages are captured for analysis. Point (a) reveals the elastic deformation of the composite which. The maximum force at the end of the elastic curves is called the peak force.

Once the force is greater than the peak force, the composite wall starts to disintegrate where the failure process initiates between two fibers before the wall experiences a localized buckling as in a point (b). According to point (b), there is no significant wall fragmentation occurred. This behavior contributes to the large peak force drop. The localized buckling progressively occurred along the wall height and the crushed composites accumulated inside the tube. Similar patterns of failure mechanisms are observed from points (b) to (c). The densification stage starts when the entire composite wall has crushed and they are all in contact to each other. Force gradually increases with insignificant displacement and they are lack of contributions in increasing the energy absorption performances.

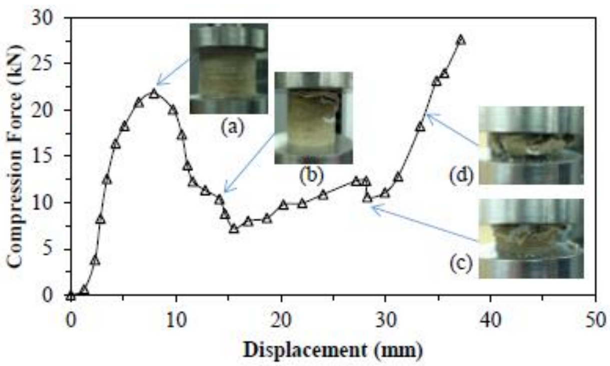


Figure 9 Failure mechanisms at different crushing levels

4.0 CONCLUSION

According to the experimental results, the following conclusions can be drawn:

i. When the number of layers are increased, as expected the responses of force-displacement curves are higher than single layered composite tubes.
ii. Higher energy absorption performances can be obtained using thicker composite tubes. On the other hand, increasing the fibre orientations from 0 to 10^0 are also increased the energy absorption significantly.
iii. Thicker the tube thicknesses, higher force ratios can be obtained. Consequently, better energy absorption capabilities are produced.
iv. A localized wall buckling dominated the failure mechanisms. Large wall fragmentations are observed during the progressive collapses therefore responsible for large sudden force drop.

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