Kenaf Fiber Reinforced Composites Tubes as Energy Absorbing Structures

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***Abstract*— Nowadays, natural fiber is increasingly used in automotive sectors especially for the non-load bearing application parts. Limited applications of natural fiber reinforced composite is due to the fact that the mechanical properties of natural fiber are full of uncertainties. In order to overcome this problem, natural fiber is formed into yarn fibers and then weaved to fabricate woven yarn kenaf fiber mats. In this work, woven kenaf mats are used to produce the cylindrical composite tubes when they are hardened with polymeric resin. Different fiber orientations and number of layers are used. The tubes are then compressed quasi-statically and the forces versus displacements are recorded automatically. The energy absorption performances and other crashworthiness parameters are calculated and discussed relating with fiber orientations and number of layers. It is found that higher energy absorption capabilities can be obtained if higher numbers of layers are used. However, it is depend on the fiber orientations. In term of failure mechanisms, the composite wall collapsed through the localized wall buckling and progressively collapsed as the force increased. Similar patterns of crushing mechanisms are observed especially in the second stage of deformation due to the larger wall fragmentations.**

I. Introduction

Due to higher environmental awareness and sustainability among researchers, natural fiber is increasingly used to replace the synthetic fiber especially for fabricating the automotive components due to their low density, high specific strength and relatively good in mechanical properties. Several studies can be found [1-4] focusing the development of eco-friendly bio-composites to replace non-biodegradable fiber reinforced composites.

Tremendous amount of works have been found on the investigations of crashworthiness performances of metals [1] and composite materials fabricated using synthetic fiber [2]. However, lack of number of works found in investigating the crushing capabilities of natural fibers [3]. Alkbir et al. [4] investigated the effect of geometry of hexagonal tubes using natural kenaf fiber reinforced composites. Five hexagonal angles are used to fabricate the tubes and they are then crushed quasi-statically. They are found that the angles played an important role in determining the crushing performances. Yan and Chouw [5] studied the crashworthiness characteristics of flax fiber reinforced composite tubes. Three important parameters are investigated such as inner diameters, number of plies and length-to-diameter ratio. From the experimental works, it is found that the flax fiber reinforced composite tubes is potentially used as an energy absorbing device in managing the collisional events.

Additionally, most of the natural fibers used are randomly oriented [6]. Recently, several research works conducted in [3-7] 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 of kenaf fiber composites can also be found in [11, 12].

Therefore, this work present the crushing responses of the composite tubes fabricated using woven kenaf mats. The composite wall is constructed using two and three layers of woven mats. For each type of layers, four fiber orientations are used. For two layers, the fiber orientations are [$0^0/0^0$], [$0^0/15^0$], [$0^0/30^0$] and [$0^0/45^0$]. On the other hand for three layers, the fiber orientations are [$0^0/0^0/0^0$], [$0^0/15^0/0^0$], [$0^0/30^0/0^0$] and [$0^0/45^0/0^0$]. The composite tubes are quasi-statically crushed in order to obtain their force versus displacement curves. Then the crashworthiness parameters are extracted and analyzed. The collapse mechanisms are also observed and discussed in order to understand the effect of fiber orientations on the crashworthiness performances.

II. Energy Absorptions Characteristics

Crashworthiness characteristic defined as the capability of a vehicle to protect occupants from structure response by dynamic crush load with probability of injury. Therefore, it is an important parameter for vehicle design and it has been a hot topic of engineering study and researches for engineers and scientists over the years. The circular high – strength steel tubes are modelled as an absorber device to absorb several energy absorptions when collapsible impact applied in eccentric loading condition.

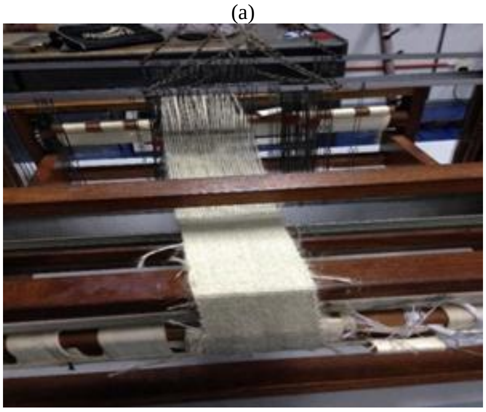
The load – carrying capability can be evaluated for the following two force levels [2]. Maximum force which is generally defined as peak force, P_{peak}. The peak force of a component is the highest load required to cause significant permanent deformation or distortion. The value of peak load was concerned by two factors, it's because of low – speed and low – energy impact. It also peaks load was occurring when the maximum load observed in the useful stroke of the energy absorbing device [2]. Absorbed crush energy which refers to the area under the force – deformation curve and it can be determined using Eq. (1):

$$E = \int_{o}^{d\max} Pd\partial \quad (1)$$

Specific absorbed energy, E_S is defined as the absorbed crush energy per unit of the crushed specimen mass as in Eq. (2):

$$E_S = \frac{E}{m} \quad (2)$$

(a)



(b)

(c)

Fig. 1. (a) As-received kenaf yarn; (b) Weaving process; (c) Finished woven mats.

Average crushing force, P_m obtained by the following equation, when the load and post – crush deformation was defined as δ and P_m respectively as in Eq. (3):

$$P_m = \frac{1}{\partial}\int_0^{\partial} Pd\partial \quad (3)$$

Crush force efficiency, η is the ratio of the average crushing force, P_m to the peak force, P_{peak}. The information from the force-deformation curve got the average and peak force is important parameters to be determined the deceleration that will be experienced by the crashworthiness impact. It also as the ratio to determine the crush force efficiency and in general their value approaches unity, the better is the performance of the energy absorbing structure.

III. EXPERIMENTAL PROGRAM

The as-received kenaf fiber in the form of yarn of 1mm in diameter is weaved to produce a plain woven fiber mat using in-house weaving machine. Figure 1(a) shows the roles of kenaf yarns used in this study while Figure 1(b) reveals the process of making the woven mats. Figure 1(c) shows the complete woven mats. The woven mats are submerged into a resin bath and at the same time roller is used to squeeze the resin uniformly into the mats. Then the wet woven mats are wound around the cylindrical mould (Fig. 2(a)) before they are circumferentially compressed to expel the excessive resin. After 24 hours, the composites are fully hardened and removed from the mould. Both ends of the composite tubes are trimmed in order to remove the unnecessary fibers and hardened resin as shown in Fig. 2(b).

(a)

(b)

Fig. 2. (a) Wet and wrapped woven kenaf around the mold; (b) The hardened cylindrical woven kenaf composites.

In this work, the total height of the tube is 70mm and the thickness is depend on the number of layers. Two main types of composite tubes are produced namely 2 and 3 layers producing 5 and 7 mm in thicknesses, respectively. The details of these composites are tabulated in Tables 1 and 2. The tubes are positioned vertically and compressed quasi-statically under the constant cross-head displacement of 5.0mm/min. The tubes are crushed approximately 80% of its height.

The force versus displacement curve for each composite conditions is recorded automatically where the area under the curve represents the energy absorption performances. Other important crashworthiness parameters are investigated such as peak and mean forces, P_i and P_m, respectively. The peak force is defined as the maximum force of an elastic deformation before the composite shows the initial sign of failure. Mean force is obtained by averaging the maximum and minimum forces around the fluctuated region.

TABLE 1
TWO LAYERS OF COMPOSITE TUBES.

Samples	Fibre Orientations, 0^o	Internal Diameter, mm
A1	$[0^0/0^0]$	70
A2	$[0^0/15^0]$	70
A3	$[0^0/30^0]$	70
A4	$[0^0/45^0]$	70

TABLE 2
THREE LAYERS OF COMPOSITE TUBES.

Samples	Fibre Orientations, 0^o	Internal Diameter, mm
B1	$[0^0/0^0/0^0]$	70
B2	$[0^0/15^0/0^0]$	70
B3	$[0^0/30^0/0^0]$	70
B4	$[0^0/45^0/0^0]$	70

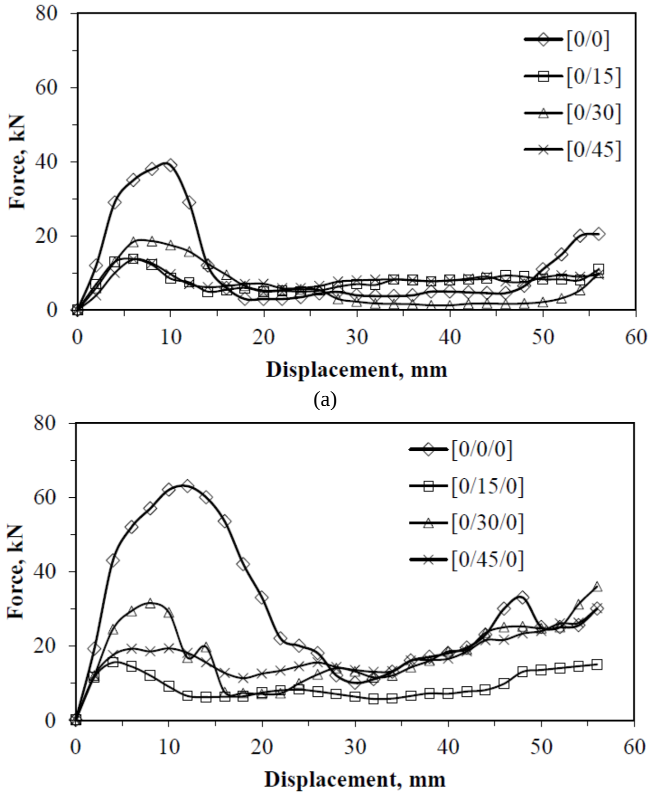
IV. RESULT AND DISCUSSIONS

The force versus displacement curves are displayed in Figure 3 for two and three layered composites, respectively. The behavior of the force-displacement curves are typical where there are three main stages occurred. The first stage is the linear elastic deformation where the force is almost linearly proportioned with the deformation. Then the flattened or plateau stage where the forces fluctuating as the collapse progresses. For the metal tubes, significant force fluctuations can be observed clearly [12]. This is due to the fact that most of the metal collapsed plastically. However, for the composite materials, the collapse mechanisms are controlled by various type of toughening mechanisms [2-5]. The last stage is the densification where there is no more composites to be crushed. All the composites are accumulated densely. If higher force is applied, slightly insignificant deformation can be observed.

Obviously, thicker the thicknesses higher the forces to crush the composite tubes are required. However, this is only true for the cases of $[0^0/0^0]$, $[0^0/30^0]$, $[0^0/0^0/0^0]$ and $[0^0/30^0/0^0]$ fiber orientations. For the composites fabricated using the fiber orientations of $[0^0/15^0]$, $[0^0/45^0]$, $[0^0/15^0/0^0]$ and $[0^0/45^0/0^0]$, the curves of force versus displacement are insignificantly changed. This is indicated that varying the fiber orientations is not the key factor in increasing the crushing resistance of the composites.

Two crashworthiness parameters are determined such as the peak force and specific energy absorption (SAE). The peak forces are determined directly from the force-displacement curves and energy absorption capabilities are calculated considering the areas under the curves. Table 3 summarizes the crashworthiness performances. It is revealed that 0^0 fiber orientations resulted the highest specific energy absorption (SEA) compared with other types of fiber orientations. When the angle is increased, the specific energy absorption slightly reduced. However when the fiber angles are oriented up to 45^0, the SEA increased.

This behavior occurred similarly for both number of layers considered in this work. In comparison for both cases, three layers composite tubes produced higher SEA compared relatively with double layered composites. For three layer composites fabricated using $[0^0/0^0/0^0]$, the value of SEA is almost double compared with the $[0^0/0^0]$ composites. Obviously, when fiber is oriented at 15^0, the SEA for both cases of composites is unchanged. This is indicated that 15^0 oriented fibers played an insignificant role in determining the SEA.



(a)

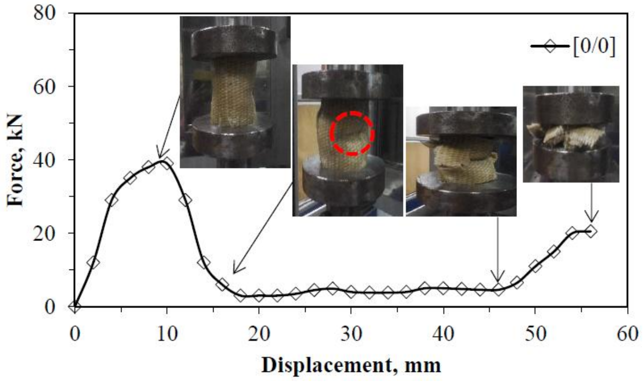
(b)

Fig. 3. Force versus displacement curves for (a) two and (b) three layers woven kenaf fiber reinforced composites.

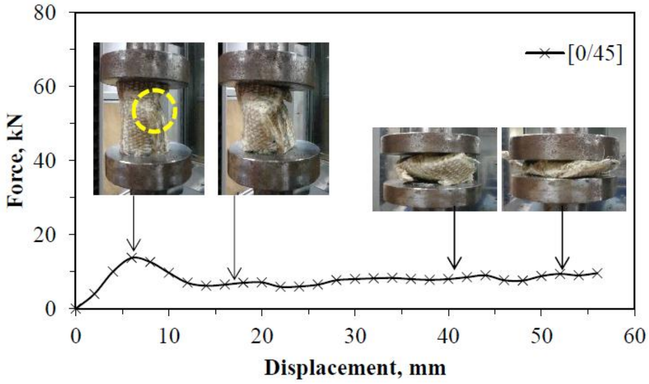
TABLE 3
TWO IMPORTANT CRASHWORTHINESS PARAMETERS PEAK FORCES AND SPECIFIC ENERGY ABSORPTION.

Samples	Peak Force, kN	Specific Energy Absorption, kJ/kg
[0˚/0˚]	39.0	9.8258
[0˚/15˚]	13.8	6.7625
[0˚/30˚]	18.6	5.5651
[0˚/45˚]	13.7	7.4333
[0˚/0˚/0˚]	63.0	17.2721
[0˚/15˚/0˚]	15.5	5.3787
[0˚/30˚/0˚]	31.5	10.9783
[0˚/45˚/0˚]	19.3	10.6389

The behavior of force-displacement curves can also be discussed by observing their crushing mechanisms. For two and three layered composites, fiber orientations of $[0^0/0^0]$, $[0^0/45^0]$, $[0^0/0^0/0^0]$ and $[0^0/45^0/0^0]$ are considered respectively as shown in Figures 4 and 5. It is obvious that higher crashworthiness parameters are obtained when the tubes are fabricated using 0^0 fiber orientations. It is also observed that the composites contain 45^0 oriented fibers produced lower crushing responses. This is due to the fact that collapse mechanisms played an important role in determining the force-displacement curves. Considering to Figures 4(b) and 5(b) at the peak points on in the yellow circle, both type of tubes experienced the global buckling.

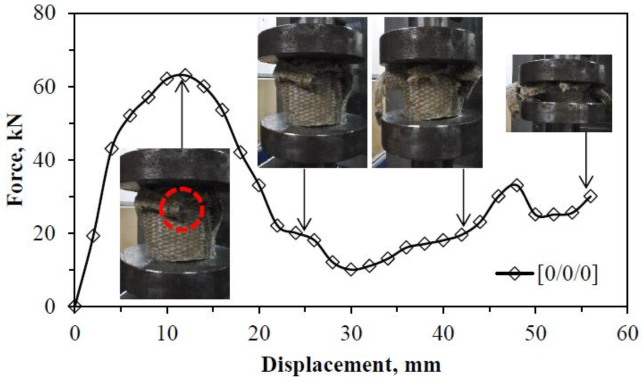


(a)

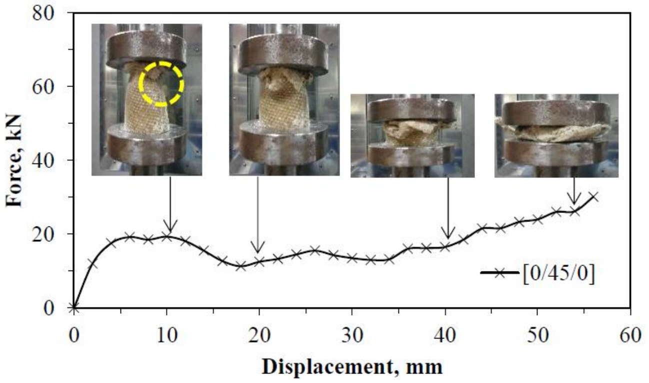


(b)

Fig. 4. Effect of fiber orientations on the crushing mechanisms of (a) [$0^0/0^0$] and (b) [$0^0/45^0$].



(a)



(b)

Fig. 5. Effect of fiber orientations on the crushing mechanisms of (a) [$0^0/0^0/0^0$] and (b) [$0^0/45^0/0^0$].

It is well known that when global buckling occurred, the composite tubes experienced catastrophic failure where after experiencing the peak force, it is gradually dropped. This behavior then lowered the area under the curve and consequently reduced the capability of the composites to absorb the crush energy effectively.

On the other hand, Figures 4(a) and 5(a) show the collapse mechanisms of the composites fabricated using 00 fiber orientation which is produced the highest force-displacement curves. At the initial stage, the tube wall collapse through the localized buckling (the red circle). Once the force is continually applied, no global buckling is observed. It is also found that the localized buckling acted as a new triggering site before the intact wall starts to experience the progressive collapses. This type collapse mechanism is responsible to enhance the force-displacement curve and then increase the crushing energy absorption performances.

V.CONCLUSION

In this work, kenaf fiber in the form of yarn is plain-weaved to produce a woven kenaf mat. Two types of composite tubes are produced such as two and three layered composites. For each two and three layered composite tubes, the following fiber orientations are selected namely [$0^0/0^0$], [$0^0/15^0$], [$0^0/30^0$], [$0^0/45^0$] and [$0^0/0^0/0^0$], [$0^0/15^0/0^0$], [$0^0/30^0/0^0$], [$0^0/45^0/0^0$], respectively. The composite tubes are then quasi-statically crushed to obtain the force-displacement curves. Then, an important crashworthiness parameter is extracted from such curves such energy absorption performances. The following conclusions can be considered:

1. For the composites produced using [$0^0/0^0$] and [$0^0/0^0/0^0$] fiber orientations, better force-displacement curves are observed compared with other type of composites. However as expected, the [$0^0/0^0$] is lower that the [$0^0/0^0/0^0$] composites due to different in tube thicknesses.
2. When the composites contained 15^0 fiber orientations in their configurations, there is no significant specific energy absorption found for both two and three layer composites.
3. During progressive collapses, global buckling is observed especially for the composites contained 45^0 fiber orientations. Similar crushing pattern is observed for three layered composites.

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