Axial Crushing Energy Absorption Capability of Steel/Kenaf Fibre Hybrid Cylindrical Tubes

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Abstract—According to the literature survey, tremendous number of works can be found in discussing the crushing behaviour of hybrid composite/metal tubes. Most of them dealt with the synthetic fibres but not many reports on the utilizations of natural fibres. Therefore, this paper presents the axial crushing behaviour of steel/kenaf hybrid cylindrical tubes under compressive force. 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 fibre 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 fibre around the steel tubes capable to slightly enhance the crushing performances. During progressive collapses, fibre splaying mode was observed with large composite wall fragmentations.

Keyword-Kenaf Natural Fibre, Hybrid Composite, Crashworthiness, Energy Absorption, Crushing

I. INTRODUCTION

In general, the purpose of introducing two materials in a single composite is to take an individual advantage and then minimized other disadvantage. There are tremendous amount of works conducted to study the mechanical behavior of hybrid composites can be found [1-7]. Most of the works focused to hybrid the fibers in polymer composites. The review of fiber hybridization of polymer composites has been recently conducted by Swolfs et al. [8]. The introductions of synthetic fiber by wrapping them around the metal tubes have attracted many researchers and tremendous amount of research works may be found in open literature [9-15]. Shin et al. [10] conducted an experimental investigation on axial crush and bending collapse of aluminum/GFRP hybrid square tubes. Different fiber orientations are wrapped around the square tubes and then quasi-statically compressed. On the other hand, they also developed a mathematical model to predict the collapse behavior. It is found that both results showed a good agreement.

Jung et al. [11] investigated the aluminum/GFRP hybrid square tube beam reinforced by a thin composite skin layer under 3-points bending moment. According to their results, aluminum tube with 0.5 mm thick and fiber orientation of [0^0/90^0] showed the largest improvement in both maximum moment and energy absorption performances. El-Hage et al. [12] numerically conducted the quasi-static axial crush on square aluminum-composite hybrid tubes. The fiber orientation angle in the overwrap is varied between [$\pm 30^0$] and [90^0] with respect to the tube's axis. It is found that the highest value of crashworthiness parameter is obtained when 90^0 fiber angles is used. Chasemnejad et al. [13] hybridized the box structures and studied the failure due to the delamination under mode I and II loading both experimentally and numerically. It is found that the hybrid structures showed better performances of energy absorptions compared with non-hybrid tubes. The numerical simulations also showed similar results as compared with the experimental works. Conceptual selection of car bumper beam with developed hybrid bio-composite material is studied by Davoodi et al. [14]. They considered the frontal curvature, thickness and overall dimensions as parametric factors. Six-weighted criteria which are deflection, strain energy, mass, cost and easy manufacturing and the rib dimensions as evaluation matrix. From the result, it is found that bio-composite material can be used for small car's bumper.

Mirzaei et al. [15] experimentally and analytically assessed the axial crushing hybrid tubes under quasi-static load. The experimental results reveal that stacking sequence has a considerable effect on crashworthiness characteristics, for example for layup [90^0/0^0/0^0/90^0], the absorbed energy is more than three times of aluminum tube with the same aluminum wall thickness. Also the aforementioned layup has better energy absorption compared to [90^0/90^0/90^0/90^0] which has been previously proposed as the best layup. Several research works on kenaf fiber reinforced composites can be found elsewhere [16-18]. Based on the author's knowledge, lack of works conducted to study the crushing response of hybrid natural fiber/metal tubes available.

Therefore, this paper presents the application of kenaf yarn fiber wrapped around the steel tubes and then quasi-statically compressed in order to obtain the force-displacement curve. One and two layers of composite materials are used and different fiber orientations are implemented. The energy absorption performances are then calculated and analyzed in term of number of layers and fiber orientations. Failure mechanisms of hybrid fiber/steel tubes are observed and discussed.

II. METHODOLOGY

An as-received kenaf yarn fibre with a diameter of 1 mm is used in this work as in Fig. 1(a). The fibre is wetted into the polyester resin bath before it is wound around the steel cylinders. Prior to winding process, the surface of the steel is coated with a thin layer of resin in order to maximize the bonding with the fibres. Fig. 1(b) shows the schematic diagram of the steel tubes with overall length is 100 mm and a diameter of 60 mm. Fig. 2 reveals an example of completed hybrid kenaf/steel tube used in this work. There are two types of layers are used namely single and double layers and different fibre orientations are also used as tabulated in Table 1.

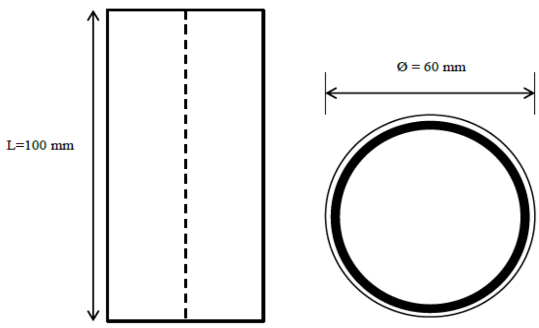
The actual length of the steel tube is more than 100 mm. Once the resin fully hardened, both ends of the tubes is trimmed out to eliminate the irregularities occurred at those ends. In order to investigate the crushing behaviour of kenaf/steel hybrid tubes, the samples are positioned vertically and then it is quasi-statically compressed at a constant cross-head displacement 1.5 mm/min. During the crushing process, the force-displacement curve is recorded automatically until the overall height of the samples reached around 75% before the testing is terminated. It is well known that the area under the curve is represented as the capability of the tubes to absorb the crushing energy and it is can be determined as:

$$E = \int_0^L P ds \tag{1}$$

where E is the capability of energy absorption and P is the crushing force and ds is the crushed length. Eq. (1) can also be represented as Eq. (2) as follows:

$$E = \int_0^L P ds = P_{mean}\left(S_{final} - S_{initial}\right) \tag{2}$$

where S_{final} and $S_{initial}$ are the final and initial crushed length.



(a)

(b)

(c)

Fig. 1 (a) Kenaf yarn bundle in the as-received condition, (b) The schematic diagram of the steel tube and (c) Completed hybrid kenaf/steel tube composites

TABLE 1. Different number of layers and fibre orientations used in this work

Type of samples	Fibre Orientations (θ^0)	Number of Layers
1	Empty tube	0
2	[0]	1
3	[30]	1
4	[45]	1
2	[0/0]	2
3	[30/-30]	2
4	[45/-45]	2

III. RESULTS AND DISCUSSION

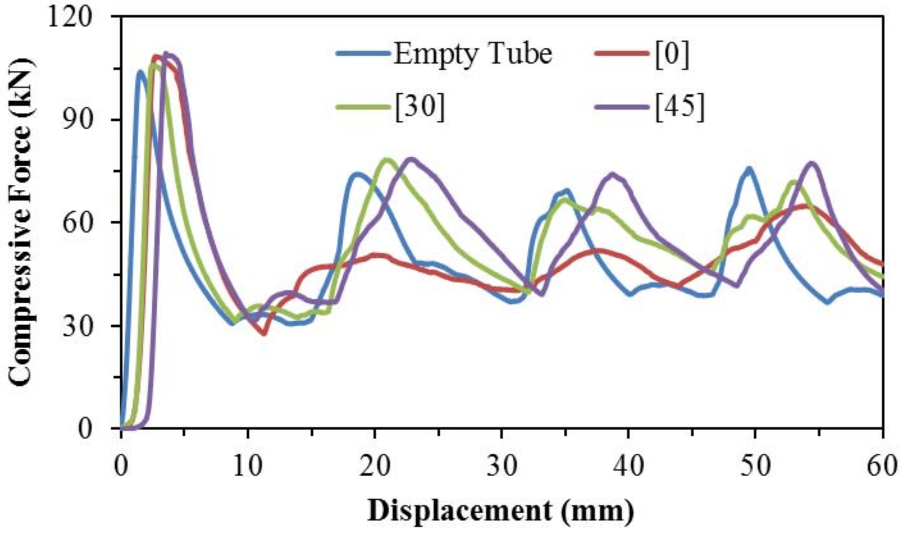
A. Effects of Steel/Kenaf Hybrid Cylindrical Tubes on the Force-Displacement Curves

The response of steel/kenaf hybrid tubes under axial crushing forces is shown in Fig. 3. It is revealed a typical shaped of force-displacement curves for crashworthiness applications. There are three main stages where the first stage is a linear elastic deformation stage. The displacement is linearly increased when the force increased until it is reached the peak force. If the force is continued, the peak force is gradually dropped due to the plastic/fracture deformation and then it is called the second stage. In this stage, the applied force is fluctuated as the displacement is progressed. Generally, the numbers of force fluctuations are coincidently similar with the number of plastic folding. Once the wall deformation reached the other end of the tube, the densification stage has started and it is called third stage. The indication of this stage is the force is gradually increased with insignificant increment of displacement.

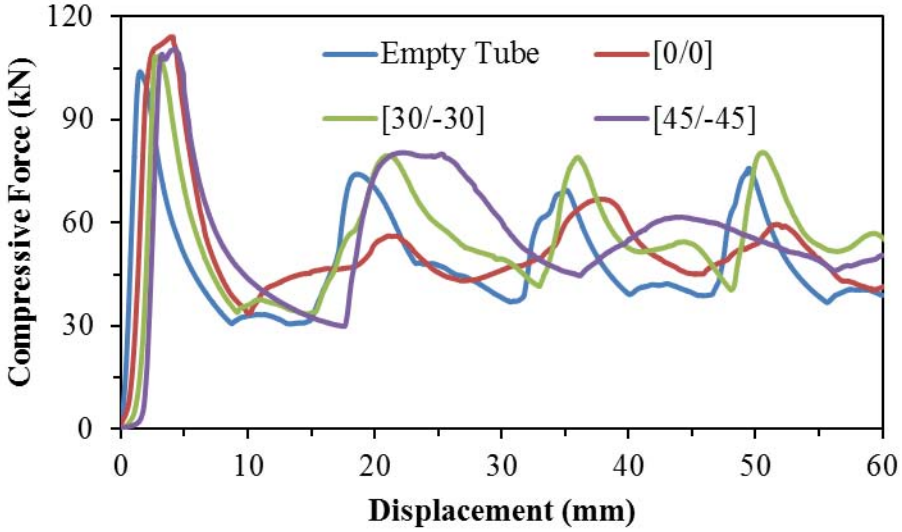
According to Fig. 3, the present of kenaf fibre around the steel tubes slightly increased the responses of force-displacement curves compared with the empty tubes. Fig. 3(a) shows the force-displacement curves for a single layer of kenaf fibre wound around the steel tubes. It is revealed that the use of inclined fiber slightly improved the maximum force. Similar behavior of force-displacement curves can be observed when two layer of kenaf fibre is used as in Fig. 3(b). The present of kenaf fibre is however insignificantly affected the force fluctuations where the number of maximum or minimum forces are identical for all types of composites. It is meant that the fibre strength is unable to resist the plastic deformation. In other word, the fibre failure strain is much lower than the steel.

B. Effects of hybridizations on the mean and peak forces

According to Fig. 4, the peak force is increased as the fibre orientation increased. Then, the peak forces are extracted and presented on the effect of hybridizations as in Fig. 4(a) while Fig. 4(b) presents the behaviour of mean force when different fibre orientation is used. It is found that both maximum and mean forces are higher when the fibre is wrapped around the cylinder compared with the empty tubes. It is also shown that the distributions of maximum and mean forces are significantly dependent on the fibre orientation where the forces increased when the fibre orientations are increased. Higher maximum force can also be obtained when the fibre is aligned 90^0 relative to the tube axis and it is decreased when the fibre is inclined. This is due to the fact that the horizontal fiber is capable to resist the radial deformation of the tubes. However, mean force is slightly increased when fiber inclination increased. This is probably related to the fibre strength where longer fibre can be obtained when the fibre is oriented more than 0^0. Therefore, higher mean force can be sustained during the progressive collapses.



(a)



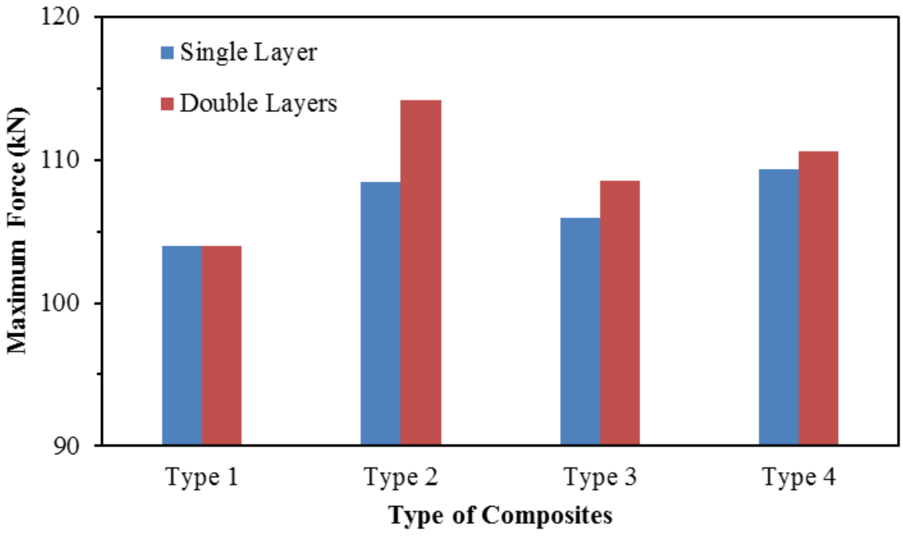
(b)

Fig. 3. Effect of hybridizations of steel/kenaf fibre tubes of (a) single and (b) double layers of kenaf fibre for different fibre orientations.

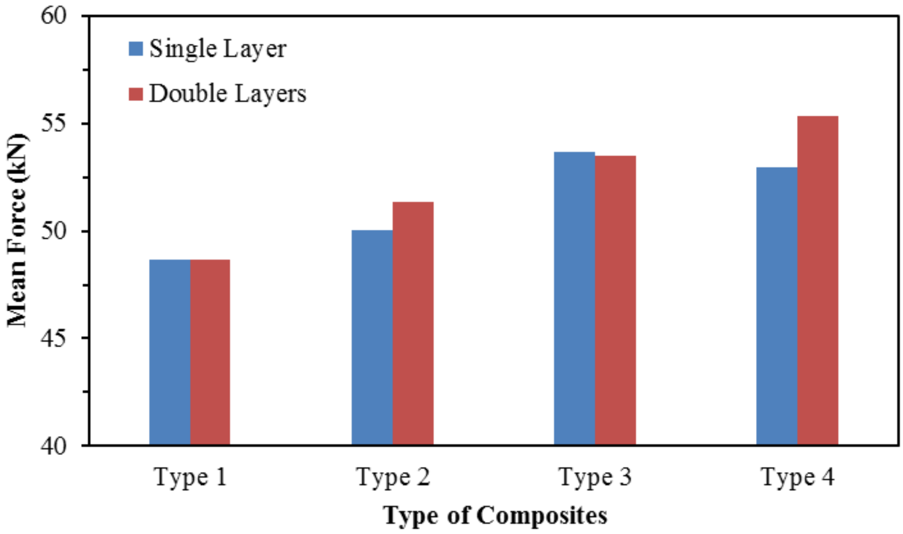
C. Effects of hybridizations on the Energy Absorption Performances

The performances of energy absorption for different fibre orientations and number of layers are presented in Fig. 5. In general, the energy absorption increased as compared with the empty tube. On the other hand, it is also increased when fibre orientation is increased. According to Fig. 4(b), changing the fibre orientation also affected the mean force. Then, referring to Eq. (2), the mean force is proportionally related with the energy absorption where if the mean force increased, it is also increased the energy absorptions.

Fig. 5 also indicated that one and two layers of composites wound around the tubes have no significant effect on the energy absorption capability. This is probably the strength of fibers are not sufficient enough to sustain the tube deformations. On the other word, the failure strain of fiber is relatively smaller than the steel tubes consequently the fibers experienced a premature failure.



(a)



(b)

Fig. 4. Effect of hybridizations of steel/kenaf fibre tubes on (a) Mean and (b) Maximum forces of kenaf fibre for different fibre layers.

D. Effects of hybridizations on the Crushing Mechanisms

Fig. 6 shows the force-displacement curve of steel/kenaf tube under axial crushing force. Four different positions of progressive collapses are captured and analysed. Point (a) reveals the condition under the elastic deformation where the displacement is linearly related with the force. Once the applied force is greater than the peak force, the first lobe of the wall deformation is initiated where the resistance of hybrid tube is suddenly dropped as shown in point (b). It is indicated that the first formation of the lobe or localized plastic wall buckling. According to the failure mechanism observed, most of the fibres are splayed out with small wall fragmentations. Points (c) and (d) show the failure mechanism when the crushing force is continued. This region is also called the plateau stress region where the force is fluctuated as the uncrushed length decreased. Similar failure mechanisms are observed trough out the progressive collapse. After point (d), the densification stage started where the force is gradually increased with insignificant displacement. This stage is also not contributed to the performance of energy absorptions.

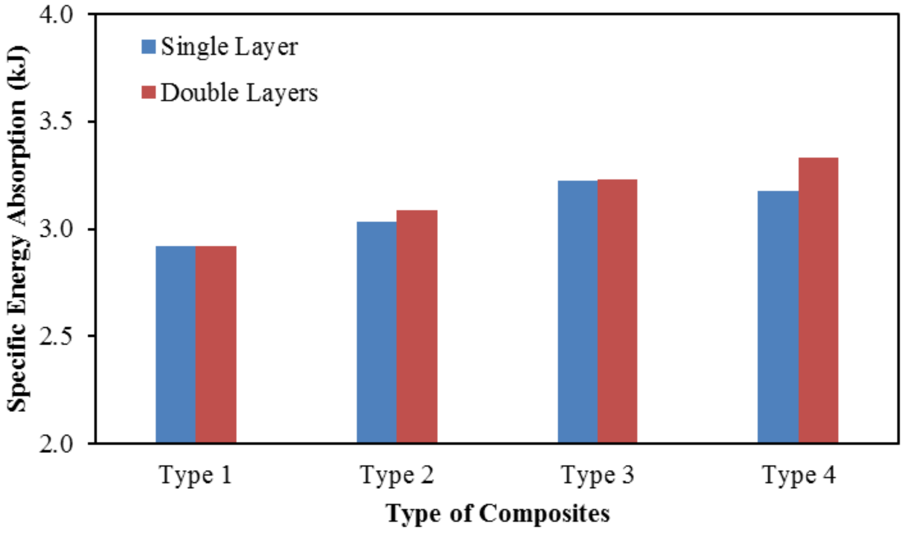


Fig. 5. Effect of hybridizations of steel/kenaf fibre tubes on energy absorption performances for two types of layers.

IV. Conclusion

The crushing behaviors of steel/kenaf hybrid tubes were experimentally investigated. As-received kenaf yarn was wetted with polymeric resin before it was wound around the cylindrical tubes. Different fibre orientations were used as follows [0^0], [30^0] and [45^0] for a single layer and [$0^0/0^0$], [$30^0/-30^0$] and [$45^0/-45^0$] for double layers. The hybrid tubes are positioned vertically before they were quasi-statically compressed and the force-displacement curves were then automatically recorded. Energy absorption performances and other type of crashworthiness parameters were determined and their behaviors were then related with the material conditions. From experimental results, several conclusions can be drawn as follows:

i. The crashworthiness performances of steel/kenaf hybrid tubes were higher than empty tubes.

ii. The present of kenaf yarn fiber around the steel tubes were slightly increased both mean and peak forces. However, 0^0 fiber orientation capable to produce higher peak force compared with other types of orientations.

iii. Increasing the fiber orientations yield to increase the mean forces. Consequently, higher mean force results higher energy absorption capability.

iv. The empty tubes crushed through the plastic deformation alone. However, steel/kenaf tubes collapsed through the combinations with macro- and micro-fracture mechanisms such matrix cracking and fiber splaying mode and therefore increasing the capability to absorb crushing energy.

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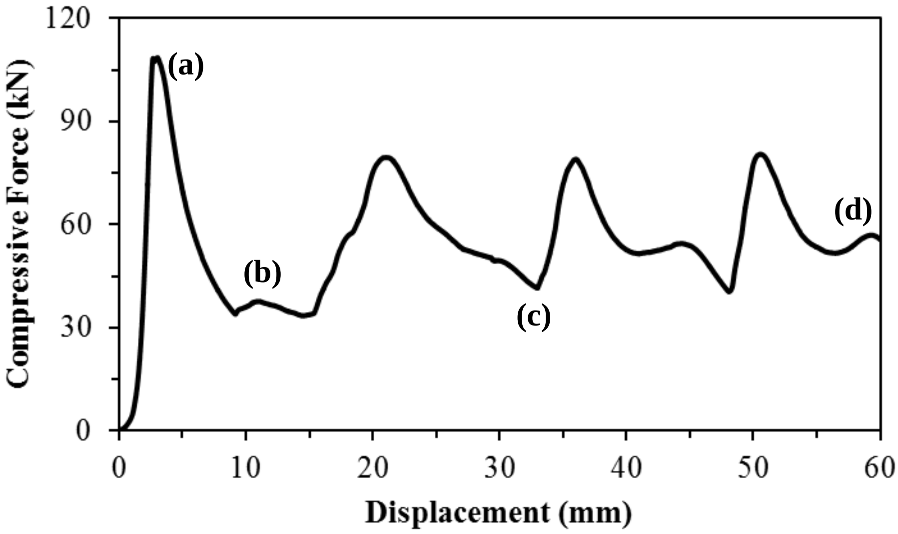

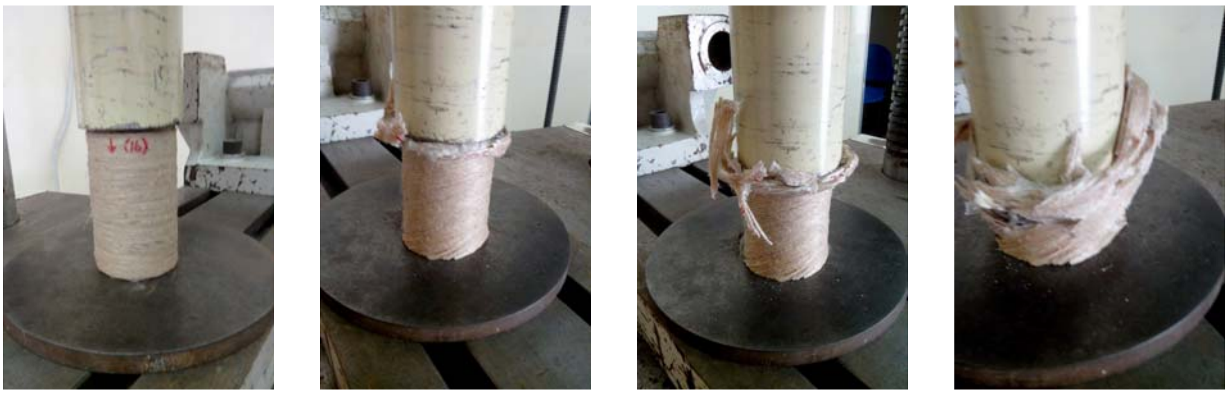

(a) (b) (c) (d)

Fig. 6. Progressive collapse of steel/kenaf hybrid tube with [30/-30].

AUTHOR PROFILE

Al Emran Ismail was born in 1977 and obtained his first and second degrees from Universiti Putra Malaysia (UPM) in 2000 and Universiti Teknologi MARA (UiTM) in 2003, respectively. After 5 years working in Universiti Tun Hussein Onn Malaysia (UTHM), he continued his studies in Universiti Kebangsaan Malaysia (UKM) for PhD degree and graduated in 2012. His expertise in the area of fracture mechanics. He is also interested in natural fibre reinforced composites for crashworthiness applications.