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Crushing Performances of Kenaf Fibre Reinforce Composite Tubes

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ABSTRACT

The quest for sustainable and eco-friendly materials has led to a burgeoning interest in natural fibers as reinforcements in composite materials. Kenaf fiber, derived from the Hibiscus cannabinus plant, presents a promising avenue for enhancing the mechanical and energy absorption properties of composite tubes. This study focuses on the fabrication of composite tubes using a combination of kenaf fiber and epoxy resin. The composite tubes were then subjected to compressive testing to evaluate their energy absorption performances. The fabrication process involved the impregnation of kenaf fibre with epoxy resin, followed by winding and curing to form composite tubes. Different configurations of kenaf fiber content were utilized to investigate their impact on the structural integrity and energy absorption capabilities of the tubes. Compressive testing was conducted to assess the energy absorption behaviour under axial loading conditions. The results revealed that the incorporation of kenaf fiber significantly influenced the energy absorption capabilities of the composite tubes. Higher kenaf fiber content demonstrated improved energy absorption performance, showcasing the potential of kenaf fiber as an efficient energy-absorbing reinforcement. The findings of this study offer valuable insights into the use of sustainable and renewable resources, such as kenaf fiber, in enhancing the mechanical and energy absorption properties of composite structures, thereby contributing to the development of eco-friendly and high-performance materials.

1. Introduction

In the pursuit of sustainable and environmentally conscious solutions, the exploration and utilization of renewable resources for material development have gained paramount importance. Amongst the diverse range of materials, natural fibers have emerged as a promising class of sustainable reinforcements, offering eco-friendly alternatives to conventional synthetic materials. Kenaf fiber, sourced from the Hibiscus cannabinus plant, is one such natural fiber exhibiting potential applications in composite materials. This study focuses on investigating the efficacy of kenaf fiber as

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a reinforcing component in composite tubes, particularly concerning its energy absorption capabilities under crushing conditions.

Crushing, a fundamental mechanical process, is pivotal in various applications such as automotive safety, packaging, construction, and aerospace, where energy absorption is a critical performance metric. Enhanced energy absorption during crushing ensures improved structural integrity and occupant safety. Composite tubes, amalgamating kenaf fiber with other materials, possess the potential to optimize energy absorption characteristics, making them a compelling choice for impact-resilient applications. The developing demand for green products within the composites industries reducing the utilization of synthetic materials in plenty engineering applications. The diversity of the energy absorption system implies certain applications, especially in the technological discipline. Recently, an energy absorption system focused on varying the characteristics and properties of the material has attracted a lot of attention. Many automotive industries are exploitation cellulose fibres to replace conventional fibre like glass and carbon for reinforcement into compound matrix [10]. Natural fibre composites can be widely applied as sustainable energy absorbing structures at low cost. The fibre works to improve the mechanical properties of the composite material to ensure that the outcome reacts as the result expected.

Supian *et al.,* [1] studied the winding orientations on energy absorption and failure modes of filament wound kenaf/glass fiber reinforced composite tubes. According to their results, the crashworthiness performances (P_{max}, EA and SEA) of kenaf/glass hybrid composite tubes increases with increasing of winding orientations parameters (±30°<±45°<±70°). Meanwhile, the crashworthiness performance value of glass composite tube specimens was varied and not proportionate with the winding orientation parameter. Furthermore, the kenaf/glass hybrid composite tube specimens have demonstrated better of crashworthiness performance compared to the synthetic glass composite tube. On the other hand, Alkated *et al.,* [2] investigated on the effect of vertex angles on the energy absorption of kenaf fiber elliptical composite cones under axial compressions. They concluded that the elliptical composite cones with different vertex angle were successfully fabricated where catastrophic failure mode occurs when P_i is greater than P_{cr}. When the angle of cones is changed, they affected the crushing performances. A review on the drop weight impact characteristics of bast reinforced composites is conducted by Pingulkar *et al.,* [3]. According to the results of increasing the fiber content in the laminated composites increases energy absorption and resistance to impact and hybridization with a high modulus fiber as outer layers significantly improves the performance of composites under low-velocity impact loading. Several other interesting research works are conducted, and they can be found elsewhere [4-10].

Ismail *et al.,* [11-14] used kenaf fiber in the woven form to fabricate composite tubes and plates. Impact strength, fatigue and tensile performances are investigated where the relationship between fiber orientations and number of layers with mechanical performances are the subject of interest. Sound absorption of composite plates fabricated using kenaf fiber is also considered as in [15]. A comparative study is conducted by [16] stated that that the stacking sequences had no significant effect on tensile strength, but fracture strain increased by 58% produced by LMD fibres. However, the use of HMB fibres in the outmost layers significantly improved flexural strength up to 49% higher than that of LMD fibres. In contrast, the impact strength of the green hybrid composites using LMD fibres in the outmost layers was 21% higher than that of its counterpart. Like other plant fiber composites, both composites had an increased water absorption capacity of up to 39% due to increased fibre content. These stacking sequence properties are essential to fabricate a specific application to ensure properties suitable for the job's features. High modulus and brittle composites require a high load to deform permanently, as well as low modulus and ductile composites. The review by [17] summarized various methods of manufacturing kenaf/Polylactic acid (PLA) composites have been discussed meticulously, as delineated in recently published scientific literatures. They delve into the chemical modification of kenaf fiber, examining its consequential impact on tensile strength and thermal stability of the kenaf/PLA composites. The review illuminated the role of innovative 3D printing techniques and fiber orientation in augmenting the mechanical robustness of the kenaf/PLA composites. Sathyaseelan *et al.,* [18] used areca (A)/kenaf (K) fiber reinforced hybrid epoxy composite plates to investigate the ballistic impact performances and found that the pure Kenaf fiber composite plate KKKKK absorbed less impact energy than the pure AAAAA. This justifies that the natural fiber areca can alter its properties by reacting with the binding material. Composites KAKAK and AKAKA made with skin of areca and alternate layers of kenaf fibers absorbed more amount of energy than the pure KKKKK Laminate. This suggests that the kenaf fibers acting as cladding had suppressed the change in properties of the areca fibers and other relevant references can be found elsewhere [19-22].

According to the literature above, lack number of works found on the investigation of crushing performances of kenaf fiber reinforced composite through filament winding technique. Therefore, the purpose of this study is to conduct crushing experimentations on the composite tubes fabricated using different fiber orientations and number of layers. Crushing performances such as peak force, average load, energy absorption and specific energy absorption are determined to examine the relationship with fiber orientations and number of layers.

2. Methodology

The filament winding method used to fabricate the cylindrical composites. Kenaf fiber is firstly submerged into resin bath. Proper consideration is ensured so that the resin is fully penetrated the fiber yarn, then they are wound around the mould at certain angle of rotations. Figure 1(a) shows the as received kenaf yarn and Figures 1(b) and 1(c) respectively reveal the cylindrical mould and the kenaf wound around it. Once the fiber hardened, the mould is removed as in Figure 1(d). On the other hand, Figure 1(e) shows the schematic diagram of cylindrical tubes used in this work where the total height is 75mm, internal diameter is 50mm and the external diameter is determined by the number of layers. There are 2, 3 and 4 layers of kenaf is used to fabricate the composite tubes and the fiber orientations selected are 0, 15, 30 and 45^0.

To investigate the crushing performances, all tubes are quasi-statically crushed at a crosshead speed of 1.5mm/minute. In general, force-displacement curves are recorded for each sample as in Figure 2. There are three important crushing parameters are investigated such as peak force, P_{max}, Average force, P_{avg} and energy absorption capability or the area under the curve, E. On the crushed sample is reached a densification stage, compression test is terminated. In this stage, all the composite crushed densely then the force increased gradually.

(a) (b) (c)

(d) (e)

Fig. 1. (a) As received kenaf fiber, (b) Cylindrical mold, (d) Kenaf fiber wrapped around the mold (d) The hardened cylindrical composite tubes and (e) The schematic diagram of cylindrical tube

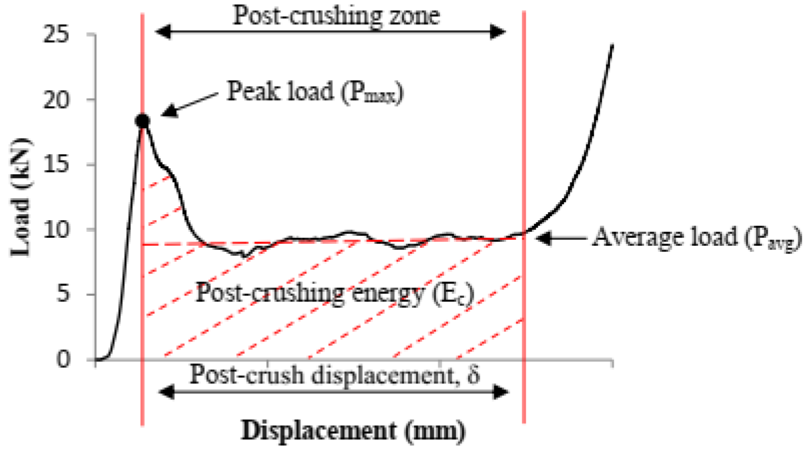


Fig. 2. Force versus displacement of typically crushed composite tubes

3. Results

3.1 Overall Crushing Performances

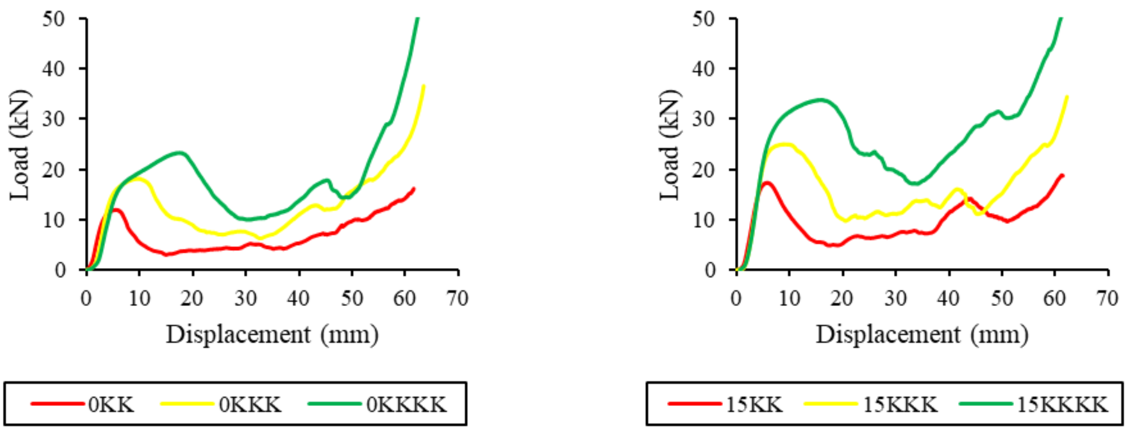
Experimentations have been conducted and overall results of data is analysed and deliberated. The energy absorption capability performance calculated by evaluating the results of a compression test. The characteristic of the selected material reviewed in comparing the specimens of different parameters such as fibre orientation and number of plies. The evaluation of the graphical result is the decisive phase in determining the performance rate of absorption for all samples involved. Sample performance calculated by the collective data and values for the analysis. The performance of peak load (P_{max}), average load (P_{avg}), energy absorption (EA), specific energy absorption (SEA) and crushing force efficiency (CFE) comparison of kenaf composite as listed in Table 1. Based on Table 1, the energy performance depends entirely by the number of plies. The number of layers fully affects the energy absorption and SEA for kenaf fibre composite which increases the performance with the addition of ply. Sample with the same number of plies with different orientation performs the different energy absorption capability.

Table 1
Crushing performances of kenaf reinforced composite tubes made of filament winding technique

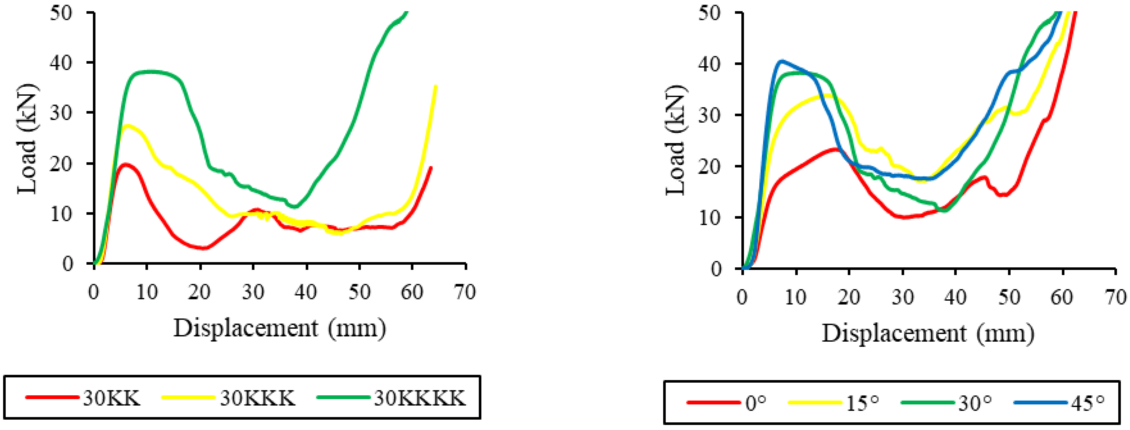
Specimen	Layers (N)	Angle (°)	m (g)	P_{max} (kN)	P_{avg} (kN)	EA (kJ)	SEA (kJ/kg)	CFE (%)
0KK	2	0	40.6	11.94	4.82	191.58	10.18	0.40
0KKK	3	0	62.1	18.15	9.78	456.63	13.85	0.54
0KKKK	4	0	77.0	23.29	14.53	714.57	16.03	0.62
15KK	2	15	46.2	17.33	8.78	451.39	16.05	0.51
15KKK	3	15	64.2	25.01	14.47	651.37	18.13	0.58
15KKKK	4	15	81.6	33.84	24.65	1230.17	24.49	0.73
30KK	2	30	46.3	19.71	7.97	457.52	14.35	0.40
30KKK	3	30	62.7	27.45	12.18	698.17	16.34	0.44
30KKKK	4	30	85.0	38.26	22.82	868.03	22.32	0.59
45KK	2	45	53.8	21.13	7.71	450.18	12.48	0.37
45KKK	3	45	75.6	31.63	15.49	731.19	16.13	0.49
45KKKK	4	45	100.4	40.49	25.59	853.75	20.35	0.63

3.2 Effect of Number of Layers on the Force-Displacement Curves

The difference in the number of plies is directly proportional with the energy absorption of the samples. The specimens with the higher number of layers hitting the highest load values at all stages indicates the better performance in energy capability. For all sample, sample with increase in layers for all fibre orientation increasing the energy absorption capability involving overall performance from beginning to the end of the progressive graph. Figure 3 shows comparison of load-displacement curved of kenaf fibre composites with progressive failure pattern in different number of layers for fibre orientation of (a) 0°, (b) 15°, (c) 30°, and (d) 45°. In term of energy capability reviewing the graph, fibre orientation has no connection with the performance of all the specimen. The additional layers produce better strength on mechanical properties, thus will absorb better in energy absorption capability. For kenaf fibre composite, it can be concluded that all the peak load, average load and energy absorption will increase in addition of fibre layers in all fibre orientation that involve.



(a) (b)

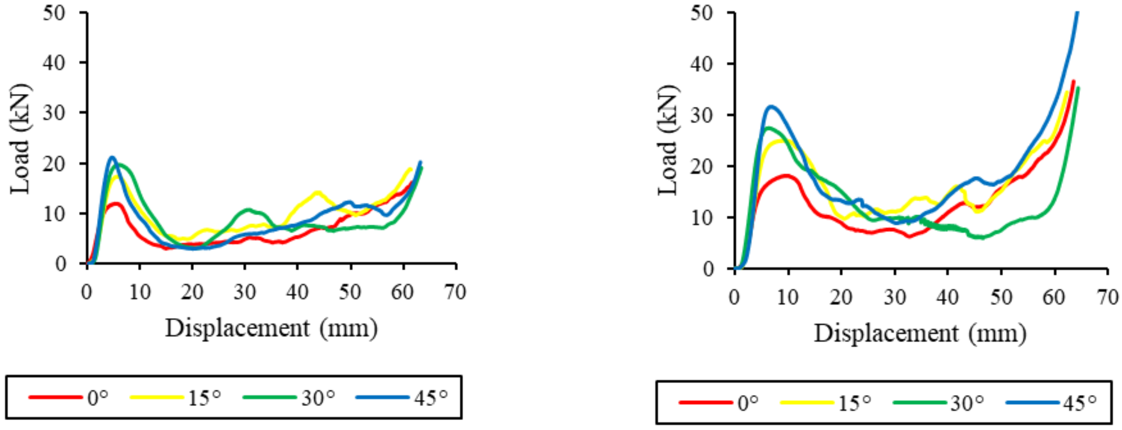


(c) (d)

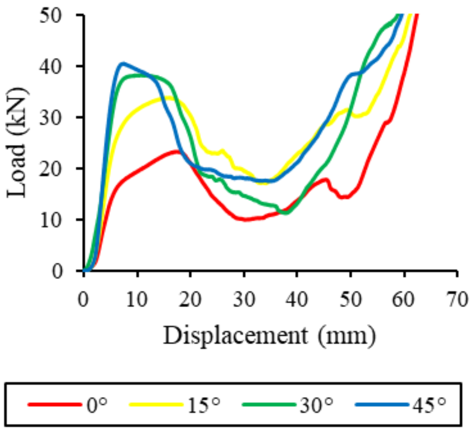
Fig. 3. Comparison of load-displacement curved of kenaf fibre composites in different number of layers for fibre orientation of (a) 0° (b) 15°(c) 30° (d) 45°

3.3 Effect of Fibre Orientation on the Force-Displacement Curves

The compression focus is directed to the corresponding angle in producing the energy absorption. The 0°, 15°, 30° and 45° represent by unique colour of the graph line which red, yellow, green, and blue respectively as illustrate in Figure 4. In term of energy absorption performance, the number of layers affect the energy absorption capability. The fibre orientation not significantly influence the performance in all the samples. Figure 4 shows comparison of load-displacement curved of kenaf fibre with 0°, 15°, 30° and 45° fibre orientation composites for (a) 2 layers, (b) 3 layers and (c) 4 layers. Pattern curves of load versus displacement graphs for all additional of thicknesses are the same behaviour. The difference is that the peak load that obtained depends entirely on the thickness of the layer. Increasing the number of layers leads to an increase in the peak load value without significantly influencing the fibre orientation.



(a) (b)

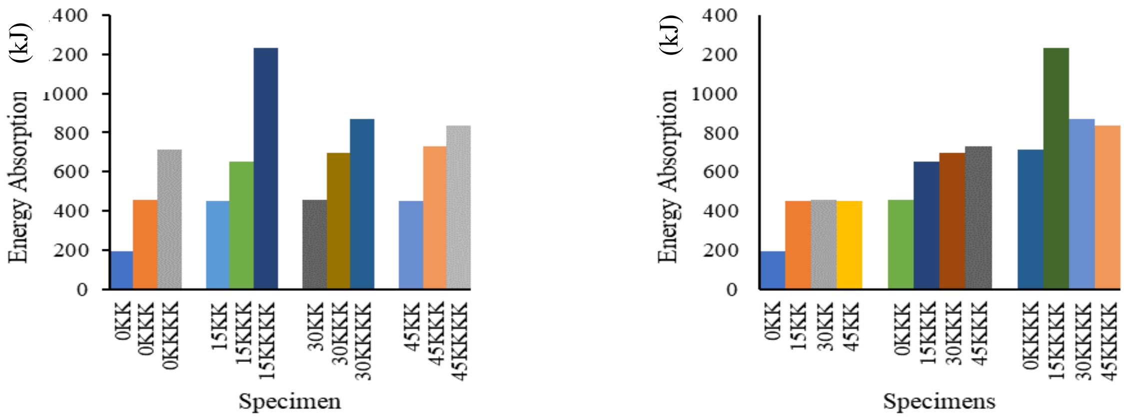


(c)

Fig. 4. Comparison of load-displacement curved of kenaf fibre with 0°, 15°, 30° and 45° fibre orientation composites for (a) 2 layers (b) 3 layers (c) 4 layers

3.4 Effect of Fibre Orientation on the Energy Absoption

The energy absorption performance of composites depending on the area under the load-displacement curves. This energy is usable for the calculation of load versus displacement graph. The calculation involves an average of energy absorption and a displacement curves. In general, the thickness and fibre orientation affecting the energy capability for specimens. The energy absorption in kenaf fibre composite fully depending on the number of layers with the same fibre orientation but display inconsistent behaviours when involving the changes in fibre orientation. Kenaf fibre with 4 layers with 15° fibre orientation perform the highest energy absorption with the value of 1230 kJ as well as the performance in the same number of layers that illustrated in Figure 5. Energy absorption of the specimens not significantly affect by the change of fibre orientation in term of number of layers and perform uneven energy capability when compare it with the same number of layers. Figure 5 shows the energy absorption of kenaf fibre in different number of layers with same angle direction and (b) energy absorption of kenaf fibre in same number of layers with different angle direction.



(a) (b)

Fig. 5. Energy absorption of kenaf fibre in (a) different number of layers with same angle direction and (b) energy absorption of kenaf fibre in same number of layers with different angle direction

3.5 Effect of Fibre Orientations on the Peak Force

There were a few energies performance considered to achieve the crashworthiness performance of structure such as peak load (P_{max}), average load (P_{avg}) and specific energy absorption (SEA). The indication of performance of crashworthiness structure is by looking for specific energy absorption because it involves the total performance of specimens that considering the energy absorption performance by the value of mass. The peak load can be directly linked from the load-displacement curve for each specimen. Significant differences were spotted between these two types of composites for peak loads, respectively. Peak load will represent the highest point of load by neglecting the compaction zone. The value of the compaction zone does not affect the energy absorption of the sample, since the increase in load during this period is associated with the total resistance of the compressed sample of 80% of the total length of the compound. At this stage, the mass of the tube has been fully compressed.

Considering specimens with the same tube inner diameter (d) and the same length-to-diameter h/d ratio (R), it is observed that the peak load on the test specimens perform higher value with an increase in several plies. In general, the number of plies significantly affects the peak load of the specimens. Figure 6 shows peak load for composite in (a) different number of layers with same angle direction and (b) energy absorption of composite in same number of layers with different angle direction for kenaf fibre. For both conditions, the peak load consistently performs in the same way which number of layers will affect the peak load value. Peak load for difference in fibre orientation recorded that the highest peak performance in 45° of fibre orientation for all specimens involved followed by 30°, 15° and 0°.

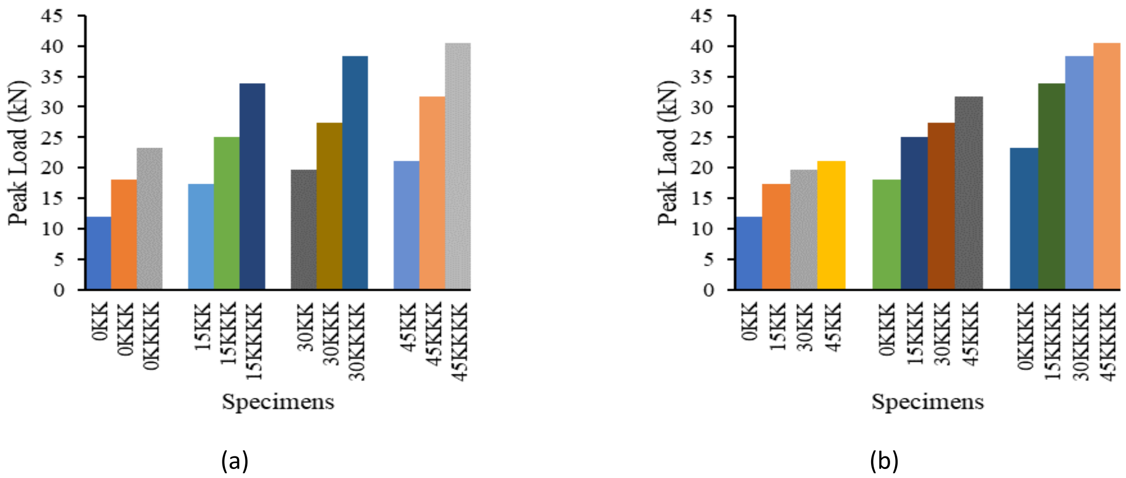
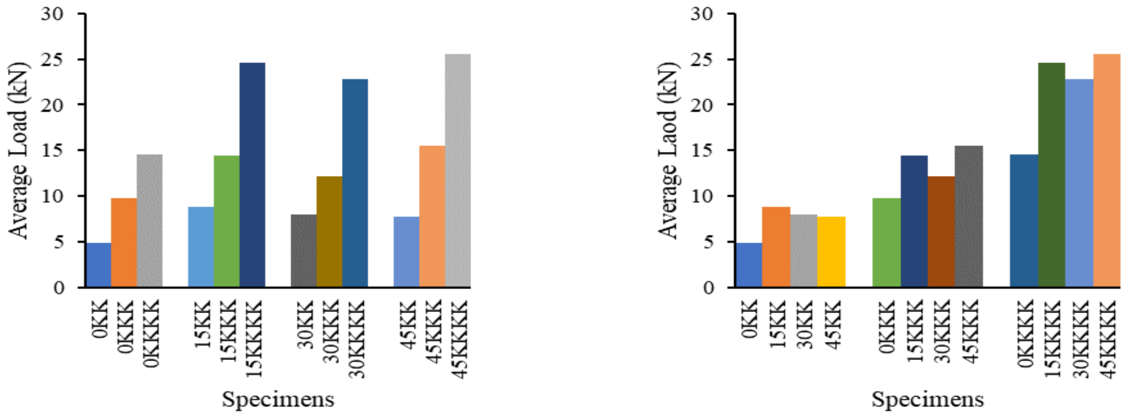


Fig. 6. Peak load for composite in (a) different number of layers with same angle direction (b) energy absorption of composite in same number of layers with different angle direction for kenaf fibre

3.6 Effect of Fibre Orientations on the Average Force

Specimen with the same number of layers in different fibre orientation recording inconsistent performance of energy absorption. The average load also affected by the number of layers which higher number of layers performing the highest absorbed energy compared to others. The performance of fibre orientation of 0° perform the lowest energy capability compared to others with all set with the same number of layers as shown in Figure 7. For other fibre orientation, absorption energy recorded uneven behaviour. Figure 7 shows the average load of kenaf composite in (a) different number of layers with same angle direction and (b) average load of hybrid composite in same number of layers with different angle direction.

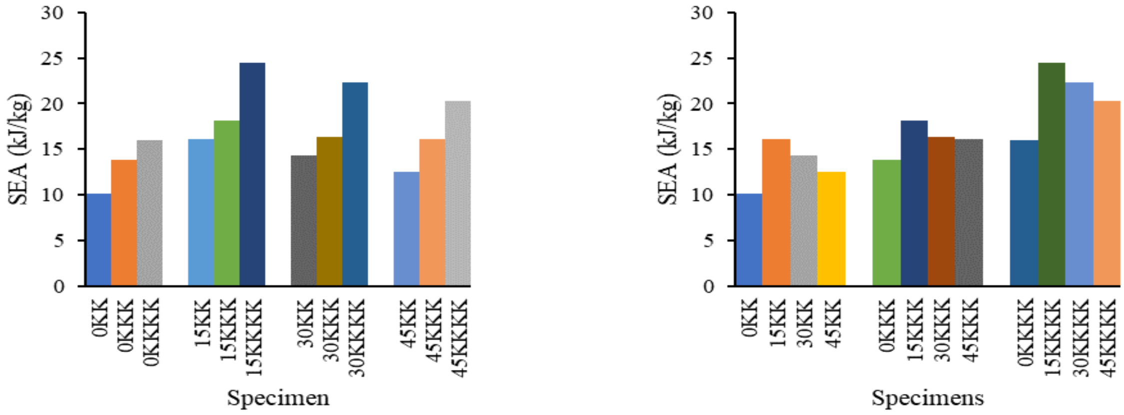


(a) (b)

Fig. 7. Average load of kenaf fibre composite in (a) different number of layers with same angle direction (b) average load of hybrid composite in same number of layers with different angle direction

3.7 Specific Energy Absorption (SEA) of Composite Tubes

The specific energy absorption (SEA) is defined as the amount of energy absorbed by a substance per unit mass of crushed material. Generally, the larger SEA represents the better effectiveness of the energy absorber. SEA is excessively implemented in measure the comparative strength of various sorts of energy absorption construction. It is due to the specimen accumulating high resistant capability to absorb the impact of the compression test. On top of that, Specific Absorbed Energy (SAE) value will then be evaluated to demonstrate the comparison of material performance within all those material sequences. This is a very important energy performance that involves in crashworthiness structure because it represents the total energy absorption with the actual mass that is involved in crushing the specimens. Figure 8 illustrate the specific energy absorption (SEA) composite in different number of layers with same angle direction and (b) specific energy absorption of hybrid composite in same number of layers with different angle direction. The difference of SEA performance reflecting by weight of the composite, when the weight is higher, the value of the resulting burden is also higher. Figure 8 shows the specific energy absorption (SEA) composite in different number of layers with same angle direction and (b) specific energy absorption of hybrid composite in same number of layers with different angle direction. The fibre orientation of 0° perform the lowest SEA performance compared to another composite, followed by 45°, 30° and 15°. This pattern consistently occurs in the composite with same number of layers with different angle direction as show in Figure 8. It concludes that for kenaf fibre, the highest SEA performance involved the composite with 15° fibre orientation. The best SEA performance of hybrid composite is hybrid composite with 15° of fibre orientation. Figure 9 shows the SEA performance of the circular tubes with 8 layers of fibre. The study from Mahdi *et al.,* (2014) shows that the fibre orientation of 15° display the highest SEA, followed by 30° and 45° with the value of 7.927 kJ/kg, 6.585 kJ/kg and 5.789 kJ/kg respectively. For the conclusion, it demonstrates identical behaviour based on the changes of fibre orientation between both studies.



(a) (b)

Fig. 8. Specific energy absorption (SEA) composite in different number of layers with same angle direction (b) specific energy absorption of hybrid composite in same number of layers with different angle direction

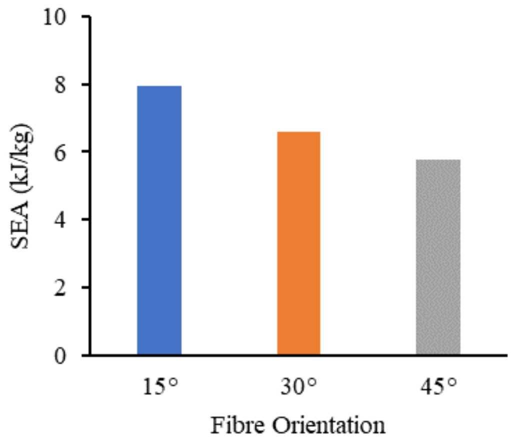


Fig. 9. SEA performance of the circular tubes with 8 layers of fibre

3.8 Crushing Force Efficiency (CFE) of Composite Tubes

CFE plays a significant role when involving incidents such as collisions that will increase the ability of the structure to withstand the impact. It is desirable that the CFE is close to unity for good energy absorption. In this case, the sample is crushed towards a load close to peak load, changes in deceleration can be minimized. The deviation of CFE from unity indicates a rapid change in deceleration and this should be avoided when designing a vehicle. For kenaf fibre, the CFE increasing proportionally with the addition of layers. Figure 10 shows the percentage of CFE for kenaf fibre composite in different number of layers with same angle direction and (b) energy absorption of composite in same number of layers with different angle direction. CFE fully depending on the number of layers but not affected with the change of fibre orientation with the same thickness as shows in Figure 10 (a) and (b).

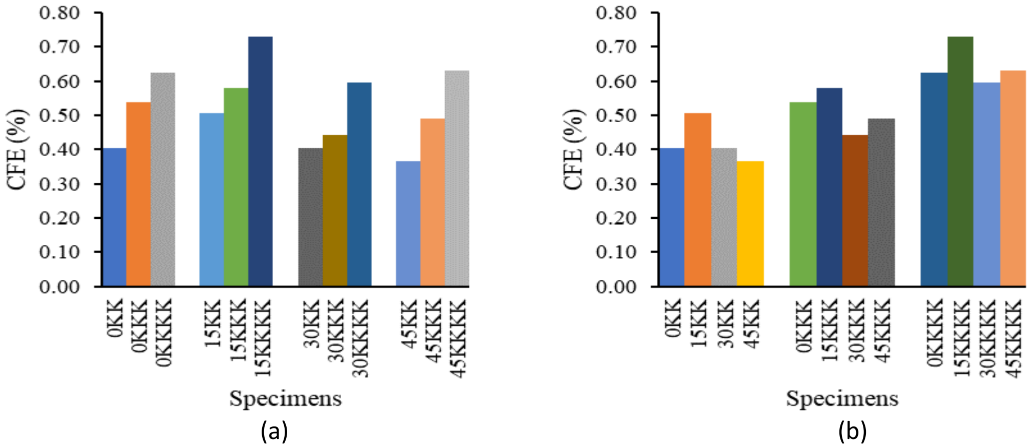


Fig. 10. CFE kenaf fibre composite in different number of layers with same angle direction and (b) energy absorption of composite in same number of layers with different angle direction

3.9 Collapse Mechanisms of Kenaf Fiber Reinforced Composite Tubes

The tubes 0KK were crushed progressively from one end by splaying mode. As the axial load increased, fragmentation of the specimens was observed. The failure starts at the maximum load also known as peak load with 11.94 kN load at 5.31 mm displacement. Subsequently, the load drops down and starts fluctuating as shown in Figure 11. After a small displacement, a steady fluctuating load was established as figure between point (b) to (c). With the platen moving downward, the longitudinal cracks advance by splitting the tube wall into many segments as shows in point (d). More declines down to load were observed at the final stages of crushing due to reduction of load resistance obtained from the remaining part of the specimen as shows in point (c) to (d). The load raises up at the end of compaction as illustrate in point (e).

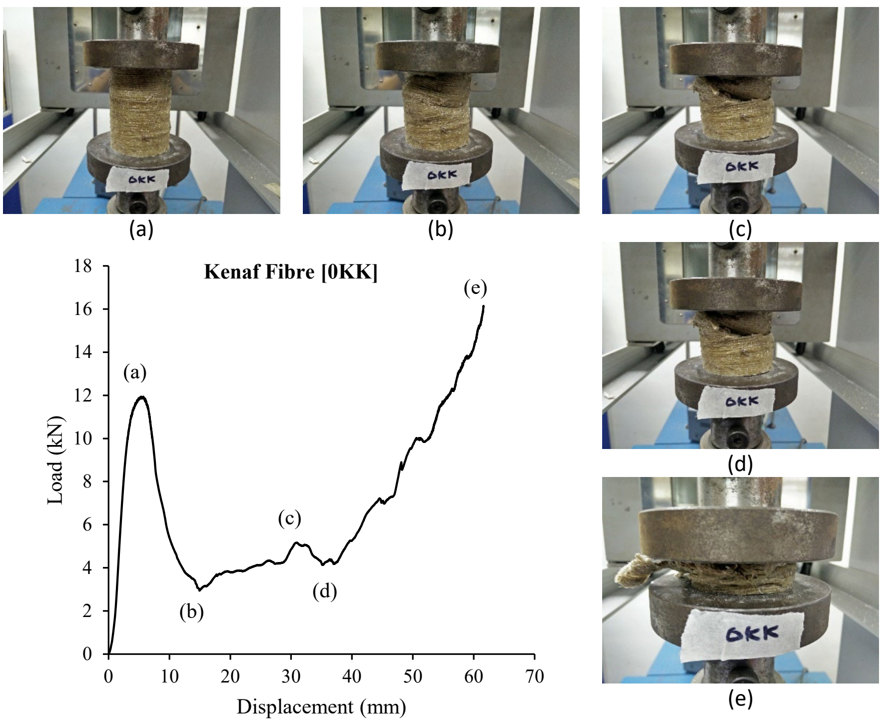


Fig. 11. Load-displacement and deformation of 2 layers of kenaf fibre (KK) cylindrical with the tube angle of 0° specimen

In general, the composite failure consists of these three main failure modes involving fibre failure, matrix crack and fibre-matrix failure. As the body of specimens contact the platen, the compression load increase and the specimens start failing in progressive manner. At point (a) formation of cracks start on the top of specimens initiate the peak load of the specimens as shown in Figure 12. The moving platen moving downward, the specimens start to break as its call fibre breakage as shows in point (b). As the applied load continues, shear failure occurs in area nearly bottom of specimen as illustrate in point (c). The crushing and splitting continue until point (d). The starting point in the crushing when the specimens show the highest resistant indicate the highest energy capability before the fibre failure observe in point (a). After this peak load phase, its starts decreasing the energy capability of the full body as shows in graph by the point (a) to (b) as in Figure 13 At the point (c), formation of local buckling that followed by the forming of the global buckling the perform the interfacial failure with the fibre crushing behaviour represent in Point (d).

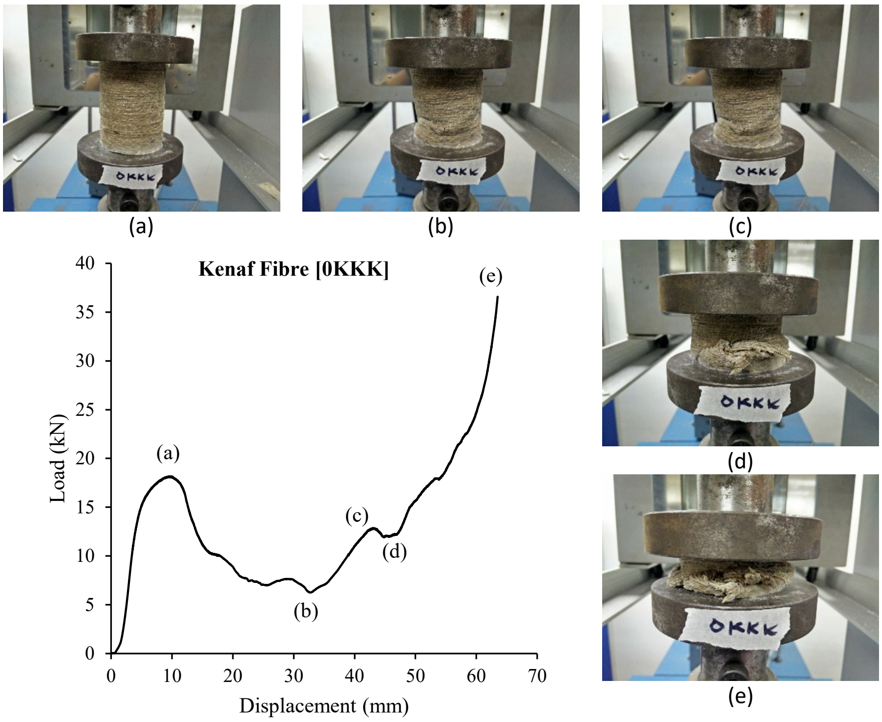


Fig. 12. Load - displacement and deformation of 3 layers of kenaf fibre (KKK) cylindrical with the tube angle of 0° specimen

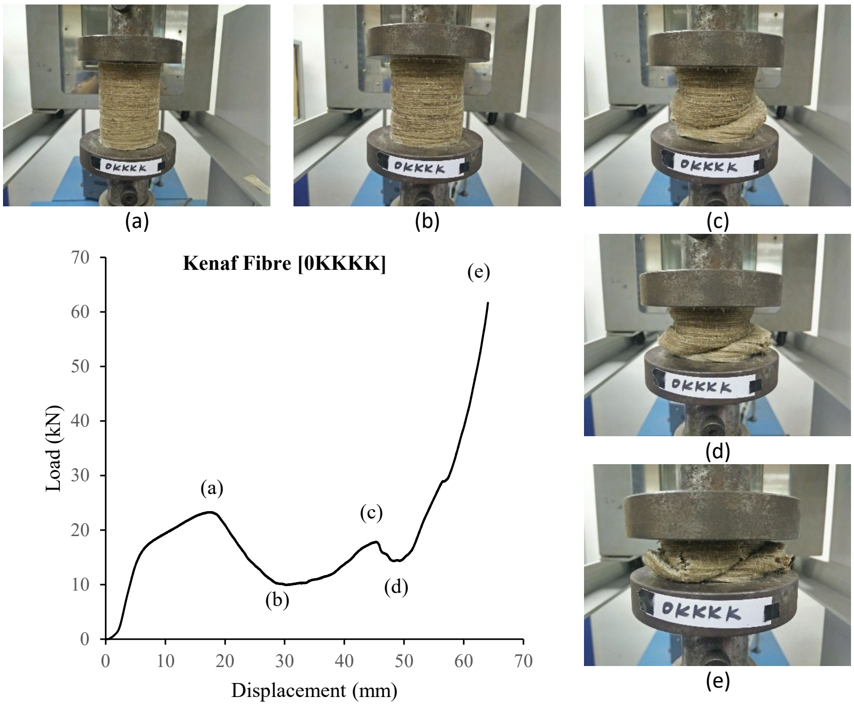


Fig. 13. Load-displacement and deformation of 4 layers of kenaf fibre (KKKK) cylindrical with the tube angle of 0° specimen

Right after point (a) which called peak load, there is large drop to point (b) and the load curve fluctuates significantly along the displacement path. From point (c) to (d), the specimens experience of splaying crushing mode as shown in Figure 14. These segments were forced by the axial load to bend outwards in the shape of fronds. At the end of the compression, the value from point (d) to (e) ignored which not significant with the energy absorption analysis. The graph performs identical progressive curve pattern.

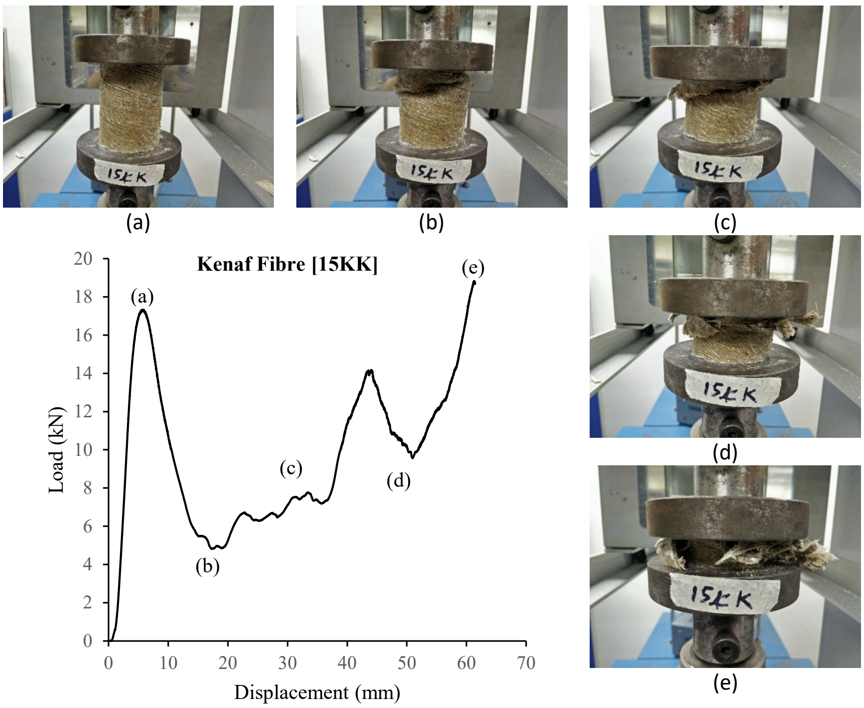


Fig. 14. Load-displacement and deformation of 2 layers of kenaf fibre (KK) cylindrical with the tube angle of 15° specimen

4. Conclusions

From the experimental results, the energy absorption performances of axially compressed cylindrical composites are calculated and the corelation between fibre orientation and number of layers on the energy absorption capability are analysed and summarised below:

i. Peak load, P_{max}, average load, P_{avg} and specific energy absorption, SEA proportionally affected by the fibre orientation and number of layers.
ii. P_{max} increases in the change of fibre orientation from 0°, 15°, 30° to 45°.
iii. The additional of number of layers increasing the value of the P_{max}, P_{avg} and SEA.
iv. SEA performances increased in additional numbers of layers on kenaf fibre composite.
v. The change in fibre orientations from 0°, 15°, 30° to 45° increasing the capabilities of specific SEA.
vi. For kenaf fibre composite, the hierarchy of energy capability consistent with specimens with 0° exhibit the lowest SEA, followed by 45°, 30° and 15°. This pattern repeats consistently with the change number of layers.

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