Original Article

The crashworthiness performance of stacking sequence on filament wound hybrid composite energy absorption tube subjected to quasi-static compression load

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\textbf{ARTICLE INFO}

\begin{tabular}{ll}
Article history: & \\
Received 19 August 2019 & \\
Accepted 3 November 2019 & \\
Available online 10 December 2019 & \\
\end{tabular}

\textbf{Keywords:}

Stacking sequence  
Winding orientation  
Kenaf/glass composites  
Epoxy  
Energy absorption

\textbf{ABSTRACT}

This study investigates the energy absorption response of hybrid kenaf/glass fibre-reinforced epoxy when subjected to an axial quasi-static compression load with the effect of three stacking sequence of hybrid kenaf/glass reinforced epoxy. To characterise and evaluate the physical and mechanical properties, the hybrid composite tube was compared with synthetic glass fibre-reinforced epoxy. The hybrid and synthetic composites tube sampling were prepared by using automated filament winding technique which it provides the process with a proper fabricating procedure, quality control and stable process due to the mixture/ratio of the fibre and resin volume controlled by the winding speed and fibre tension. Crashworthiness mechanism of hybrid and synthetic composite tubes specimen were discussed to understand failure modes behaviour and energy absorption characteristics in term of quasi-static compressive response. Four different failure modes were observed in crushing tests as fibre/resin fracturing, local buckling, brittle fracturing and delamination. In the view of fibre stacking sequence aspect, fibre volume fraction in the hybrid specimen (HTS45-A) is a highest compared to other specimen and at the same time alleviates the capabilities in progressive failure with the significant increase 28\% of initial peak load and 68\% of the energy absorbed compared to the glass fibre-reinforced epoxy tube. Meanwhile, the glass fibre-reinforced tube showed the greatest specific energy absorption characteristics with the lowest initial peak load value with stability in progressive crushing behaviour. Also, experimental results have showed that kenaf fibre could be utilised as a potential reinforcement material in hybridisation with synthetic glass fibre composites as energy absorption tube application.

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https://doi.org/10.1016/j.jmrt.2019.11.006
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1. Introduction

Fibre-reinforced polymers receive considerable attention in various structural applications. Conventional materials used in fibre-reinforced polymer composites, such as carbon fibres and glass fibres have great features in high tensile strength, chemical resistance, dimensional stability as well as excellent insulation properties. Meanwhile, natural fibres have other great of interest. They are abundantly available around the world, especially in tropical Asian countries. Utilising natural fibres such as kenaf, jute, hemp and wood pulp as a reinforcement in composite energy absorption tubes is an alternative answer to negative environmental effects due to disposal process of synthetic fibre which are not easily degraded. Therefore, the hybridisation of natural fibre with stronger and more corrosion-resistant synthetic fibre will generally enhance the stiffness, strength and moisture-resistant behaviour. Hence, a balance between the environmental impact and performance aspect can be achieved.

Due to the demand for higher mechanical performance, lower cost and sustainability of natural fibres, the pre-treatment of natural fibres has normally improved the interfacial bond or fibre–matrix adhesion by demonstrating significant mechanical and tensile properties [1–7]. Therefore, the need for sustainable hybrid natural/synthetic materials in various industrial applications have increased, numerous studies have attempted to enhance the performance of hybrid natural/synthetic fibre-reinforced composites with diverse model of optimisation, such as geometry tubes design [8,9], technique of manufacturing [10,11], fibre orientation [12,13], stacking sequence [14–17] and collapse mechanism [2,8,12,13]. Although, the approach of hybrid nature/synthetic composite tube performance is still less exploring for energy absorption tube application.

The concept of hybridisation provides flexibility to design engineers in tailoring material properties according to other specific requirements, which is one of the major advantages of the hybridisation concept in composite structures. Mahdi et al. [20] investigated the of natural fibres as hybrid component fillers, which the result of in mechanical properties significantly enhanced the tube with damage tolerance and energy absorption value has been improved. The study of Albahash and Ansari [5] on natural jute fibre with Kevlar composites in the application of energy absorption tube has shown that the hybrid natural/synthetic fibre-reinforced polymer have a better result in crashworthiness efficiency compared with single natural jute fibre. Meanwhile, Özpek et al. [16] have explored the hybrid basalt/glass pipes under quasi-static compression and achieved the stability in failure modes and crashworthiness characteristics while energy absorption capability increases. Ricciardi et al. [17] studied the effects of hybridisation and stacking sequences on the impact damage mechanisms of epoxy hybrid basalt/flax composites, fabricated through vacuum resin infusion process. Results highlighted the hybrid with different symmetrical stacking sequences have relevance in the composite design to meet specific requirements of mechanical and impact behaviour.

Even though the application of natural fibre as reinforcement in hybrid composite tubes is not a contemporary topic, however there were limited studies mutually indicate a potential for natural fibres as excellent alternates materials through hybridisation with synthetic fibres. Moreover, most of the previous studies have focused on the crashworthiness performance of specific fibre-reinforced composite tubes with the influence of interply fibre hybridisation. The effect of stacking sequence performance will investigate various mechanical properties and failure mode responses of quasi-static compression loads. Several hybrid composite tube configurations with different kenaf and glass intraply stacking sequences are then compared to the synthetic glass fibre composite tube to differentiate the crashworthiness performance and failure mode behaviour. Therefore, this present study of fibre hybridisation of kenaf/glass fibre composite tube with the influence of intraply fibre hybridisation of composite tube. Otherwise, the influence of intraply hybrid composite tube using the filament winding technique has possesses advantages for distinct fibres to placement/positioning on rotating mandrel and to provide a balanced mixture of resin, hybrid fibre volume content and low void. Moreover, the hybrid kenaf/glass composite tube in this study has defined into six layers of kenaf and glass roving fibres with winding angle of ±45° for intraply hybrid and synthetic composite tube specimens.

2. Materials and methods

2.1. Raw material

The subsequent materials were used for laminate preparation in the filament winding technique. The kenaf fibre yarn (Kenaf 2000) was provided by Innovative Pultrusion Sdn. Bhd. without any surface treatment. The glass fibre (E-Glass) was provided by Owens Corning Advantex®, while the epoxy was from Sirim-Tech Venture Sdn. Bhd. The D.E.R.™ 324 Epoxy Resin properties exhibited good resistance against acids and against slow and rapid deformations (impact). The features of the epoxy resin include curing at room temperature; displaying good mechanical property. To feasibly remove the wound tube from the mandrel, the wax or release agent was applied onto the surface of the mandrel before beginning the winding process. The function of the release agent will help minimise or prevent the amount of air bubbles present and stop the void content inside the composite. The combination of hybrid fibres consists of two fibres (kenaf and glass fibre) placed and aligned together in the form of wet fibre band composites. The cross-sectional diameter of the employed glass fibre was 13-μm; and for kenaf fibre, it was 1 ± 0.5 mm.

2.2. Hybrid composite with stacking sequence fabrication

In this study, the preparation of hybrid tubes was customised with fibres continuously towed from kenaf fibre yarn, glass fibre and epoxy resin. The kenaf and glass fibres were merged into a resin bath. The resin-comb function separated the placement of fibres until the impregnation process, whereby the placement of both wet fibres on the aluminium mandrel formed the fibre band layer composite shells. The hybrid tubes consist of a six-ply stacking sequence (N) with three different
parameter groups of hybrid fibre composition. All specimens with the winding orientation were fixed at $\theta = 45^\circ$. The glass fibre-reinforced epoxy tube was fabricated with a normal filament winding composition of nine-ply stacking sequence of glass fibre composition to achieve the same thickness as the hybrid tube.

Three different stacking sequences of hybrid kenaf/glass-reinforced epoxy tubes were prepared. The size of three hybrid tubes and glass fibre-reinforced epoxy specimens (sizes: inner diameter 50 mm × length 100 mm) were cut from the original length of 1 m to test the configuration. Fig. 1 presents the carriage function that wrapped the hybrid fibres along the aluminium mandrel. Fig. 2 displays the hybrid kenaf and glass fibre setups according to three stacking sequences of fibre placement. In Fig. 3, parameter 1 of Fig. 3(a) shows that the hybrid kenaf/glass fibre band is equal and arranged in an alternating sequence of kenaf and glass fibres. Parameter 2 of Fig. 3(b) shows that the hybrid specimen was also set in an alternating sequence but the composition of kenaf fibre was less than the glass fibre. For specimen 3 in Fig. 3(c), the setup for the specimen with the hybrid fibre composition of glass fibre was shown to be more prominent from the kenaf fibre composition.

The fabricated hybrid kenaf/glass fibre composite tube as well as the glass fibre composite tube are then cured under room condition and exposed to direct heat ($32^\circ$C) for 24 h using an industrial spotlight. The specimen tubes were rotated in slow-motion for an optimum curing process, avoiding any residual air bubbles. Next, the tubes were cured at room temperature for 24 h. For the quick and easy removal of composites, a wax paste was applied on the aluminium mandrel’s surface as a release agent from the mould before the fabrication process [21].

### 2.3. Fibre/matrix volume fractions

Samples of hybrid kenaf/glass reinforced epoxy composite laminates were taken for measurements of volume using the standard of fibre burnout method ASTM 2734. The Electric Muffle Furnace will burn off the matrix component and remaining of ash can be weighing from known values and weight, from which the densities were calculated (Fig. 4). Then, the densities of the resin, the reinforcement, and the composites are measured by separately. Theoretical composite density calculated based on the Rule of Mixtures for the density and the fibre/matrix volume fraction obtained has been shown in Table 1. The equation can be expressed as

$$\rho_H = \eta_K \rho_K + \eta_G \rho_G + (1 - \eta_K - \eta_G) \rho_M$$

where $\rho$ is density, $\eta$ is fibre volume fraction, and subscripts $K$, $G$, $M$ and $H$ stand for Kenaf, Glass, Matrix and Hybrid composite, respectively. The fibre volume fractions of HTS-45A, HTS-45B, NTS-45B composites tubes were 30.44%, 58.78%, 61.37% and 58.63%, respectively, while the density of hybrid (KF + GF), non-hybrid (GF) and matrix was 1.43 kg/m$^3$, 2.56 kg/m$^3$ and 1.60 kg/m$^3$ correspondingly. Though hybrid fibre volume fractions vary slightly across HTS-45A TO HTS-
Fig. 2 – Hybrid kenaf/glass fibre placement setup (intraply) in resin bath.

Fig. 3 – Stacking sequence of hybrid fibre bands’ arrangement setup with a comb in a resin bath.
Intraply layout decreases to examine the effect of kenaf fibre as reinforcement in different stacking sequence of hybrid natural/synthetic tube.

2.4. **Quasi-static axial crushing test**

The mechanical assessment was conducted with a standard compressive test using a Universal Testing Machine (UTM)
Instron 5567 (load 100 kN). The references of standard code according to ASTM D7336M-12 were followed. The tested specimens were performed using of the uniaxial quasi-static compression, with the crosshead speed of 5 mm/min. The total absorbed energy takes place approximately at 80% of the axial compression load displacement. To evaluate the crushing damage of structures in the stacking sequence, three replicated tests were conducted to ensure experimental reliability in final result and of the crushworthiness behaviour. According to the load–displacement curves in Fig. 7, the axial quasi-static compression load has created crushworthiness characteristics such as:

Peak load or \( P_{\text{initial}} \) is usually indicated highest point in post-crushing zone. Meanwhile for the mean load known as \( P_{\text{mean}} \), which is defined as the total absorbed energy per crushed tube displacement (\( \Delta L \)), with force value (\( P \)) at each compression distance. Therefore, \( P_{\text{mean}} \) was calculated with Eq. (2):

\[
P_{\text{mean}} = \frac{\int_0^{\Delta L} P(L) \, dL}{\Delta L}
\]

Meanwhile, energy absorbed (EA) in Eq. (2) is the force value at each compression distance (\( \Delta L \)), which it evaluates the area under load–displacement, where the \( P \) is the force value.

\[
EA = \int_0^{\Delta L} P(L) \, dL
\]

The crushworthiness properties in composite tube structure can be described as specific energy absorption (SEA) in Eq. (3) to calculate the energy absorbed per unit of crushed specimen, where the \( M \) is the crushed specimen mass.

\[
\text{SEA} = \frac{\int_0^{\Delta L} P(L) \, dL}{M}
\]

Crush load efficiency (CLE) is a stability crushworthiness characteristic in crushing process event, which is the percentage ratio of \( P_{\text{mean}} \) to \( P_{\text{max}} \), calculated with Eq. (4).

\[
\text{CLE} = \frac{P_{\text{mean}}}{P_{\text{max}}} \times 100
\]

3. Results and discussion

3.1. Quasi-static crushing failure modes

The failure of hybrid kenaf/glass composite tubes varied from that of conventional composite tubes since the material properties of the mixed fibres had different stacking sequences in the layer of filament winding tube. Mamalis et al. [22] reported that the crushworthiness of the composite energy absorption tube of synthetic fibre-reinforced polymers have three failure modes: mid-length buckling, local buckling and progressive end crushing. The study of Hull [23] had indicated that the progressive folding with a hinge and Euler’s overall column buckling are the classifications of failure modes observed. Therefore, this present study investigates the different mechanisms of each stacking sequence parameters.

Three different stacking sequences of intraply hybrid kenaf/glass fibre were used to investigate the different mechanisms of each stacking sequence parameters into energy absorption capability and crushworthiness behaviour to justify the ability of hybrid nature/synthetic composite tube compared to synthetic energy absorption tube. Thus, the data achieved are presented in Table 2. Fig. 5 has shown the progressive crushing of hybrid and synthetic composite tube exhibited four types of failure modes. The final condition of deformation tube in Fig. 6 has justified the collapse behaviour of hybrid kenaf/glass and glass fibre composite tube in quasi-static compression load manner.

3.1.1. Mode I – fibre/matrix cracking

Mode I featured fibre/matrix cracking at the middle section of the crushed tube. This failure mode is associated with the crushing mechanism that involves extensive matrix deformation and matrix fragmentation along the fibre line and breaks the tube into two sections of large wedged pieces. The final deformation pattern of the broken wall had spread outwards (Fig. 5(a)) while some of the fibres became tangled and slit from the outer wall layer during the crushing process (Fig. 5(b)). This indicates that this type of failure mode exhibited high-energy absorption.

Apart from that, an unexpected fibre breakage for both of composite tube wall does not display during any of post-crushing phase, it is characterised earlier by matrix crazing along the fibre line undulation, while it is followed by progressive microcracking phenomena and this occurrences of complete cracking at residual post-crushing stage from fibre fracture to wide-ranging fracturing between the fibres and the matrix of hybrid and non-hybrid composite tube observed in Fig. 5. Moreover, Fig. 6 indicated that fibre/matrix cracking phenomena contribute into fracturing of local buckling or delaminate mode was developed from both ends accompanied by transverse shearing and matrix fragmentation into main energy absorption mechanism. Meanwhile, progressive crushing of stacking sequence of specimens HTS-45C (hybrid tube) and NTS-45B (glass composite tube) in Fig. 5 was described by stable load–deformation behaviour, where the load reduced due to continuous buckling.

3.1.2. Mode II – local buckling

Mode II is a combination of progressive failure mode and local buckling mode. This process was initiated by matrix crazing and cracking caused during the buckling of transverse fibres. The specimen tube initially developed and experienced a progressive failure mode, which was followed by both matrix fragmentation and transverse shearing after the highest peak. Mode II was an ideal crushing phase for the energy dissipation mechanism. During the final stage of the crushing process, the tube was intact and did not break into wedged pieces or large debris. This stage exhibited a stable load-carrying capacity.

Fig. 7 shows the common manner of load–displacement curve for specimen of HTS-45C and NTS-45B. For specimen HTS-45C, the condition of crushing behaviour was subjected to strength and buckling constraints due to fibre fraction of glass.
Fig. 5 – Collapse mode behaviour: (a–c) Hybrid kenaf/glass-reinforced epoxy composite specimen tubes and (d) glass fibre-reinforced epoxy composite specimen tube.

Fig. 6 – Final crushing morphologies of specimens under axial quasi-static crushing load.
**Table 2 – Results of the composite tube under quasi-static compression load.**

<table>
<thead>
<tr>
<th>Tube series</th>
<th>[±θ]m</th>
<th>dL (mm)</th>
<th>P_{max} (N)</th>
<th>P_{mean} (N)</th>
<th>EA (J)</th>
<th>SEA (J/g)</th>
<th>CFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kenaf – 3 fibre/glass – 3 fibre</td>
<td>80.00</td>
<td>59,200.3</td>
<td>38,712.37</td>
<td>3096.99</td>
<td>25.60</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>HTS-45A-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HTS-45A-2</td>
<td>[±45°]6</td>
<td>57,740.96</td>
<td>38,630.88</td>
<td>3090.47</td>
<td>26.19</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>HTS-45A-3</td>
<td></td>
<td>57,210.05</td>
<td>31,827.00</td>
<td>2546.16</td>
<td>20.87</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>HTS-45B-1</td>
<td></td>
<td>58,050.30</td>
<td>36,390.08</td>
<td>2911.21</td>
<td>24.22</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>HTS-45B-2</td>
<td>[±45°]6</td>
<td>37,452.29</td>
<td>30,442.13</td>
<td>2435.37</td>
<td>27.04</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>HTS-45B-3</td>
<td></td>
<td>35,734.12</td>
<td>22,715.88</td>
<td>1817.27</td>
<td>18.54</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>Kenaf – 2 fibre/glass – 4 fibre</td>
<td>80.00</td>
<td>37,064.62</td>
<td>29,919.50</td>
<td>2393.56</td>
<td>24.42</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>HTS-45A-1</td>
<td></td>
<td>36,750.34</td>
<td>27,692.50</td>
<td>2215.40</td>
<td>23.33</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Kenaf – 1 fibre/glass – 5 fibre</td>
<td>80.00</td>
<td>24,015.21</td>
<td>15,563.63</td>
<td>1245.09</td>
<td>17.79</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>HTS-45C-2</td>
<td>[±45°]6</td>
<td>25,982.55</td>
<td>19,371.25</td>
<td>1549.70</td>
<td>26.76</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>HTS-45C-3</td>
<td></td>
<td>24,901.22</td>
<td>12,353.25</td>
<td>988.26</td>
<td>15.61</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>Kenaf – 0 fibre/glass – 6 fibre</td>
<td>80.00</td>
<td>24,966.33</td>
<td>15,762.71</td>
<td>1261.02</td>
<td>20.05</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>HTS-45B-1</td>
<td></td>
<td>24,170.58</td>
<td>20,905.38</td>
<td>1672.43</td>
<td>24.43</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>HTS-45B-2</td>
<td>[±45°]6</td>
<td>25,368.38</td>
<td>24,566.38</td>
<td>1965.31</td>
<td>31.23</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>HTS-45B-3</td>
<td></td>
<td>24,746.64</td>
<td>19,564.00</td>
<td>1565.12</td>
<td>24.80</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>24,761.87</td>
<td>21,678.59</td>
<td>1734.29</td>
<td>26.82</td>
<td>0.88</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7 – Load–deformation characteristics of hybrid composite tube with multiple stacking sequences; hybrid fibre composition (kenaf and glass fibre) and non-hybrid composite tube (glass fibre-reinforced epoxy composite).

fibre which influence the strength and characteristic of progressive crushing behaviour. The fibre fraction of HTS-45C has also indicated that the intralaminar of kenaf and glass fibre model was not efficiently applied as hybrid composite tube in the term of optimisation the crashworthiness performance, due to influence of glass fibre composition is more dominant than kenaf fibre. Moreover, from Fig. 5 and 5, the hybrid (HTS-45C) and non-hybrid (NTS-45B) sample have showed that progressive local mechanism, where the hybrid sample which having a less kenaf fibre fraction has deformed with main local buckling mode where the first mode collapse was triggered by mode I and the buckling mode continues with wrinkling of mode III until end crushing process. Meanwhile, Fig. 5 shows that the non-hybrid tube has performed progressive crushing with first mode I and continue with buckling mechanism growing away from the crushed end.

3.1.3. Mode III – brittle fracturing

Mode III consisted of intraply brittle fracturing failure and crushing which occurred for all hybrid specimens. Most tube walls had deformed and splayed in a petal-like shape at the post-crushing stage. This failure mode illustrated the frictional endurance between the intralaminar hybrid fibre layering. A crushing tube of HTS-45A clearly formed the internal and external fronds along the fibre line (undulation) which provides a significant contribution to the energy dissipation mechanism despite the collapsed tube of the distinct lamina in bundles. Therefore, in this mode, the main energy absorption mechanism is fibre debonding and matrix fragmentation. The primary mode of failure noted in each intraply stacking sequence of hybrid kenaf/glass composite tubes investigated is brittle fracturing failure. As kenaf fibre has lower failure strength, therefore the boundary of failure has spread first
into kenaf fibre. Meanwhile, the brittle fracturing description of the hybrid with various type of kenaf/glass intraply stacking sequence plies causes cracks to develop at the undulation line of kenaf/glass interfaces, and the associated stacking sequence which represent of kenaf fibre, glass fibre and matrix percentage fraction inside the tube, resulting in sequential failure differential of the hybrid and non-hybrid composite tubes. As seen from Fig. 5 the specimens of HTS-45A, HTS-45B and HTS-45C showed the short intraply crack length along undulation fibre subsequently parallel-to-fibre cracking. Thus, brittle fracturing or transverse shearing (combination of longitudinal crack and transverse shearing) failure modes were observed in higher kenaf/glass fibre composition (HTS-45A and HTS-45B). Nevertheless, in Fig. 6, less fronds were gradually formed when glass fibre fraction increasing into hybrid kenaf/glass composite tube due to buckling and fibre breakage failures.

3.1.4. Mode IV – delaminate
Mode IV featured plies or fibres peeling off from the matrix prior to collapse. Thus, the hybrid specimen in this study presented a combination of transverse shearing crushing modes in Mode I and Mode II. This led to localised and global failures of hybrid composite tubes. Other failure mode conditions were linked, which concludes the crushworthiness in the delamination failure mode condition. All specimens have shown identical results at the post-crushing zone. At this mode, all specimens further displayed other progressive failure mode behaviours such as fibre fracture, fibre debonding and matrix cracking.

A clear delaminated region around the final crushing phase is seen in Fig. 6. It is seen that, the delaminated region seen at cross-section surface is clear than that observed at tube wall surface. The compression load occurs at the cross-section surface throughout crushing process have resulted in cross-section surface matrix cracks at the outer tube wall and cracking/delamination at the inner tube wall. As the crushing process take place, the energy level increases and more collapse behaviour such as multiple delamination, fibre whisker, fibre breakage, matrix crack and frond at inner and outer tube wall. The progressive crushing behaviour of hybrid and non-hybrid tube samples is provided in Fig. 5, where failure mechanisms on crushing of stacking sequence for hybrid HTS-45A led to more fracturing which generate the frond debris meanwhile the non-hybrid tube (NTS-45B) and hybrid tube HTS-45C are shown more obvious delaminate failure mode with irregular layer delamine deformation.

3.2. Stacking sequence – effect of failure mode mechanism
The main mechanical characteristics of composite structural materials used in many high-performance applications require increased specific strength and stiffness properties. Therefore, composite structure properties regarding crushworthiness are still the main functions or important criteria when forming the design within the energy absorption tube. The crushworthiness is also known as the capability of the structure to be progressively crushed, thus minimising or dissipating the external force/impact of energy. According to the study of Obradovic et al. [24], each composite structure configuration of the crushworthiness characteristics behavioural effects is different. It may depend on geometrical and material properties which perform in various modes of failure, making the failure mode criterion very complicated [25–29].

Load deformation characteristic as shown in Fig. 7 is present the crushing process which commonly distributed into three crushworthiness zone as initially known as pre-crushing zone, post-crushing zone and final compaction zone. The initial peak load was determined as a local stress concentration where at this point the microfracture of inter or intralaminar cracks are nucleated and propagate into crushing in progressive or catastrophic manner at post-crushing stage. At this stage, the crushworthiness parameters will measure the failure mechanism and crushworthiness characteristics of all specimens. Finally, after post-crushing stage commences. At this stage, the structure of composite tube was compacting when all the crushing debris and the folded tube wall accumulate at bottom of the tube and force load is increasing. Therefore, there were differences in load displacement distance of the specimens before crushing tubes are compacting and increase in load caused the debris densification.

3.2.1. Peak load (P max) and mean load (P mean)
Both the peak and mean loads can be accurately predicted. Therefore, the benefits of ductile behaviour in the study of composite tubes can be customised with damage tolerance parameters such as flaws and voids, porosity in fibre/matrix composition and tube geometry. Initially, the shell of composite tubes will behave elastically, and the load rises at a constant rate to a peak value (P max) and then drops abruptly. The scale of the peak load and average load was significantly affected by the shell geometry and material characteristics. Moreover, the collapse mechanism (such as initial high peak load) can be controlled into a desired collapse mechanism by the proportion of fibre/matrix composition and the arrangement of fibre orientation and layer sequence (stacking sequence) in the tubes. The study of Harwood et al. [30] on graphite FRP tubes had considered the peak load with different micro-fracturing mechanisms. The angle substance by the contact region has become a load function in several studies related to composite tubes with winding orientation. In another study, the peak load mechanism was controlled by a triggering mechanism. It was characterised by various triggers with the purpose of reducing the initial peak load and maximising the energy absorption capacity [31]. Meanwhile the initial micro-fracturing of hybrid kenaf/glass composite tube occurred with small cracks of hybrid intraply which undulation on hybrid tube wall contribute into earlier by matrix crazing with local compression load as microfracture are determinative of initial peak load point [32].

Crushing process and load-deformation curve as shown in Figs. 5 and 7, have been divided into three main stages as known as pre-crushing, post-crushing and material densification/compaction. Further, the propagation of progressive crushing in post-crushing phase occurred with various of measure crushworthiness parameters where it concludes the understanding of failure mode mechanism and behaviour. And the last process of progressive crushing of both composite tubes was pointed into drastic of load increases and
the gain compression value stopped until material densification showed in Fig. 7. The value in $P_{\text{max}}$ was dominated by Hybrid specimen (HTS-45A), where the tube has achieved 58,050.50 kN (Fig. 8), due to stacking sequence and fibre fraction of kenaf and glass fibres are equal compare to other hybrid fibre fraction stacking sequence. Table 1 shows that the value of HTS-45A was 57.34% more than non-hybrid NTS-45B specimen. Meanwhile, the average value of each load of stacking sequence composite tubes in post-crushing stage represents as mean load. Hybrid specimen HTS-45A with stacking sequence of (kenaf-3/glass-3) intraply indicated highest mean crushing load as 36,390.08 kN (Fig. 9) due to progressive crushing of mode I, II, III and IV. Moreover, the hybrid specimen HTS-45C has indicated the lowest $P_{\text{mean}}$ with 15,762.71 kN and non-hybrid specimen NTS-45B indicated $P_{\text{mean}}$ value (21,678.59 kN) in the range of hybrid range value. Therefore, hybrid and non-hybrid has proved that two fibres can be integrated functionally in applications, and kenaf could potentially perform as reinforcement in hybrid energy absorption tube.

3.2.2. Energy absorption (EA) and specific energy absorption (SEA)

The present study was designed to axially collapse with the parameter stacking sequence at a constant load of 100 kN. The absorbed energy ranged between 1.3 and 3.3 kJ, which was attributed to the combination of diverse shear failures of the matrix causing the tubes to break into large pieces. Delamination behaviour occurred at the final crushing stage [25]. The SEA is described as the sum of absorbed energy per unit mass. This value is used to compare the energy absorption capability of numerous variables for a specific material.

Load–displacement curve with different stacking sequence and progressive crushing process was presented in Figs. 5–7, where all samples had performed various model of failure modes. As shown in Fig. 10, hybrid sample of HTS-45A had a highest EA and hybrid sample HTS-45C recorded the lowest in EA. The cause of the HTS-45C was the lowest in EA due to the fibre fraction of the sample was also a lowest amongst all specimens including non-hybrid specimen sample. From Table 2, the data shown the HTS-45C and NTS-45B had a slightly same of the peak load value due to the fibre fraction of kenaf fibre can be negligence and the strength of glass fibre was prominently during this phase. Moreover, from the comparison of EA in Fig. 10 and fibre placement of hybrid fibre band in Fig. 3 has concur the result of stacking sequence of HTS-45C sample was the lowest due to unbalance of hybrid fibre fraction (K-1/G-5) less stable while crushing process and this stacking sequence was enabled HTS-45C to absorbed more compression load during crushing process. However, the hybridisation of stacking sequence of HTS-45B (K-2/G-4) was marginally same with non-hybrid sample NTS-45B of pure synthetic composite tube. The value of distinct stacking sequence of hybrid and non-hybrid specimens revealed that the hybrid HTS-45A has prominent EA values from amongst the specimens. This provides the pre-assumption that equal hybrid fibre from natural kenaf fibre in this stacking sequence parameter has yielded additional reinforcement to absorbed energy values.

Fig. 11 presents the relative graph of SEA values for the samples with distinct hybrid stacking sequence effects as well as synthetic composite sample tube. However, instead of the mass consideration of the composite tube specimen, the spe-
specific energy absorption should be distinguished to provide the reliable information to be understandable about energy absorption. From Fig. 11, the specific energy absorption values of hybrid and non-hybrid composite tubes HTS-45A, HTS-45B, HTS-45C and NTS-45B were 24.22 J/g, 23.33 J/g, 20.05 J/g and 26.82 J/g respectively. The SEA values of non-hybrid composite tubes are slightly higher than all hybrid stacking sequence samples and has proved that the hybrid composite tubes with vary of stacking sequence parameter are not only have capability in energy dissipation and reliability in energy absorption mechanism but also in specific energy absorption.

3.2.3. Crush Force Efficiency (CFE)

In the study of composites, one indicator presented would be the Crush Force Efficiency (CFE) which determines whether a failure is progressive or catastrophic. For good EA characteristic, the experiment should have the CFE value close to unity. CFE is the main attribute to measure the crushworthiness performance of EA and the stability of the crushing process [33]. The study parameter by Tarlochan et al. [29] had defined the ratio of average and peak forces related to the deceleration experienced by vehicle occupants due to the crushing event as being close to unity. The absorber is crushing at a value close to the peak load, hence minimising the fluctuations in deceleration (as preferred from any absorber design). If this ratio is away from unity, there are rapid changes in deceleration. This would not meet the favourable requirements of best energy absorption design in the application. In every crushworthiness structural study, the CLE value that is close to the unity value will display better performance in the energy-absorbing structure, making it more qualified in the application of energy absorption tubes. The crush load efficiency shown in Fig. 12, indicates that NTS’s sample was obviously close to unity value, which mean the NTS crushing behaviour has performed in stable condition. Meanwhile the CFE value of HTS’ specimens was lower than the NTS with unstable crushing behaviour, otherwise hybrid specimens are capable of absorbing the crushing load progressively due to the HTS’s specimen could progressively crush without catastrophic behaviour.

4. Conclusions

The study of hybrid kenaf/glass-reinforced epoxy composite tubes (HTS-45A, HTS-45B and HTS-45C) was accomplished to investigate the effect of stacking sequence on the crushworthiness performance with three different hybrid fibre band arrangements for fibre stacking and the result has compared to synthetic specimen tube (NTS-45B) to evaluate the performance of crushworthiness of the energy absorption tube. The descriptions from the crushing region demonstrated four distinct crushing modes of all composite tube specimens.

From the above outcomes, the stacking sequence was shown to have a significant effect on the energy absorption performance of the hybrid natural/synthetic fibre composite tube, as described in the following results:

a) In all cases, the stacking sequence of specimen HTS-45A was found to absorb more energy compared to other specimens. The hybrid specimen tube achieved a lower value for SEA, approximately 9–25% lower compared to the non-hybrid composite tube specimen.

b) The CFE ratio of the stacking sequence specimen for HTS’s is lower than NTS’s specimen. The CFE value of NTS was approximately close to unity, where it showed the crushing behaviour was in stable condition, meanwhile for HTS’s crushing behaviour it was displayed with various failure modes condition. Therefore, from CFE value, it has verified that the specimen of hybrid and synthetic composite tubes can be performed into progressive crushing and can achieve the required performance in energy absorption tubes.

c) The effect of the stacking sequence of hybrid natural/synthetic with equal fibre composition (kenaf – 3 fibre/glass – 3 fibre) with the fibre/matrix volume fraction (fibre = 67.04, matrix = 32.96), has yielded the highest result for the ideal parameter in the hybrid composite tube for stable quasi-static compression load, in comparison to the synthetic glass fibre-reinforced epoxy composite tube.

d) Various fibre/matrix volume fractions in Table 2 have contributed the effect of crushworthiness characteristic. The sample from HTS-45A (kenaf – 3/glass – 3) tube has showed
that the best ratio fibre/matrix of hybrid composite tube with contribution of total fibre is greater than matrix, and it has responded in good crashworthiness mechanism characteristic, more stiffer and absorbed more energy compared to other tube specimens.

**Conflicts of interest**

The authors declare no conflicts of interest.

**Acknowledgements**

The authors would like to show appreciation to Universiti Putra Malaysia for financial support via the Graduate Research Fellowship (GRF) scholarship through the School of Graduate Study (UPM/SPS/GS47054) for providing a scholarship to the principal author to carry out this research project and HiCOE grant (6369107) from Ministry of Higher Education Malaysia.

**REFERENCES**


