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Tensile and impact properties of cost-effective hybrid fiber metal laminate sandwich structures

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Abstract

Hybrid composite materials, which combine two or more types of fiber in a single matrix, have currently drawn the interest of researchers. This research investigates the tensile and impact properties of hybrid kenaf/glass reinforced metal laminates (FMLs) with different fiber orientations and stacking configurations. FMLs were formed by sandwiching the annealed aluminum 5052 sheets to the composite laminates using hot press molding compression technique. The tensile test was performed at a quasi-static rate of 2 mm/min with reference to ASTM E8 whereas Charpy impact test was conducted using impact pendulum tester according to ASTM E23. Results showed that improvement in tensile and impact strength was observed in hybrid FMLs compared to kenaf fiber reinforced FMLs. Fiber orientation of ±45° reduced the tensile strength but increased the impact strength of FMLs in comparison with fiber orientation of 0°/90°. Overall, hybrid FMLs incorporated with a fiber stacking sequence of glass/kenaf/glass showed superior characteristic in tensile and impact performance.

KEYWORDS

fiber metal laminates, hybrid composites, impact properties, kenaf fibers, tensile properties, thermoplastic

1 | INTRODUCTION

Currently, aluminum and steel alloys are the primary materials employed in automobile and aircraft industries. Nevertheless, metallic alloys demonstrated poor fatigue crack resistance characteristic, which could result in catastrophic failure of the entire structures. Thus, to improve the fatigue crack resistance of the materials, the combination of metallic alloys and fiber reinforced polymer (FRP), namely fiber metal laminates (FMLs) have been introduced. Owing to the presence of fibers in the laminates, FMLs possess excellent damage tolerance characteristic compared to metallic alloys.[1] The composite laminate provides second load path where part of the load is transferred from the metallic layers to the fibers, consequently leading to improved fatigue crack resistance. In addition to superior fatigue crack resistance, FMLs are also lighter than conventional aluminum and steel, which is the desired characteristic, especially in transportation sectors to improve the fuel efficiency. Literature studies have shown FMLs possess excellent lightweight characteristic compared to monolithic aluminum.[2,3] Glass laminate aluminum reinforced epoxy (GLARE) structures are among the most commercially used FMLs due to their high mechanical strength. However, the major shortcomings of GLARE are the long processing time for curing and the nonrecyclability characteristic of thermoset matrix. The major shortcomings of GLARE have triggered the use of thermoplastic instead of the thermoset matrix in FMLs. Thermoplastic matrix is moldable after the initial process that enhance the recyclability of the materials.[4] The ease of processing and excellent recyclability of thermoplastic are beneficial to the FMLs processing and the environment.

To maximize the use of environment friendly materials, natural fibers are introduced in thermoplastic-based composite materials to reduce the dependence on synthetic fibers. However, the contemporary trend of replacing human-made fibers in FRP composites with natural fibers can also be extended to FMLs. It is well known that natural fibers offer several outstanding characteristics over synthetic fibers. The commonly cited advantages include low density, low cost, high specific mechanical properties, and biodegradability.[5–8] These advantages made natural fibers attractive to the researchers. The recent trend has shown the tremendous growth of using natural fibers in automotive industries due to the advantage of improved fuel efficiency which could result in vehicle weight reduction.[9,10] Kenaf fibers are one of the most widely used natural fibers due to their ease of cultivation, rapid growth, and low cost. Furthermore, another attractive feature in kenaf is that 40% of the kenaf stem contribute to the useful fibers, which are approximately twice compared to other fibers.[11,12] Previous studies have shown the potential of using kenaf fiber as the reinforcement in composite as well as FMLs. Feng et al.[13] have demonstrated the high potential of utilizing kenaf fibers in FMLs for those applications that involve fatigue loading. Ramesh et al.[14] concluded the kenaf fibers can be used in the hybrid composites as an alternate material for the replacement of conventional fiber reinforced composites.

Despite the several advantages offered by natural fibers, the limiting factors such as high moisture sensitivity, relatively low mechanical strength, and poor thermal stability of natural fibers have retarded the usage of natural fibers as reinforcement. However, hybridization with synthetic fibers is considered to be one of the techniques used to improve the mechanical strength and reduce the water uptake in natural fiber reinforced composites. Hybrid composites are formed by combining two or more types of reinforcement within a single matrix. The advantages of one type of fiber in the composites could offset the disadvantages of the other fiber. Numerous literature studies have shown hybrid composites demonstrated an improvement in mechanical strength compared to single fiber reinforced composites.[15–18]

Thus far, there are numerous literature studies which emphasized on the mechanical properties of FMLs. Reyes and Kang[19] compared the tensile properties of FMLs based on self-reinforced polypropylene (Curv) and glass fiber polypropylene prepreg (Twintex). They revealed that the tensile properties of Twintex-based FMLs are higher than Curv-based FMLs. Twintex-based FMLs showed brittle failure behavior compared to Curv-based FMLs, which exhibited ductile failure characteristic. A recent study has been carried out by Vieira et al.[20] who investigated the mechanical properties of FMLs based on sisal fibers and epoxy matrix. Mechanical properties of FMLs were also compared to their corresponding composites. The findings showed that FMLs exhibited higher tensile and impact properties than their respective composites. When the density was considered, FMLs significantly demonstrated better specific properties than composites. Li et al.[21] made a comparison between the mechanical properties of conventional GLARE and glass fiber reinforced aluminum–lithium laminates (NFMLs) using epoxy matrix. The results showed the tensile strength of NFMLs was slightly higher than conventional GLARE. When comparing the tensile modulus, NFMLs showed tremendous improvement over conventional GLARE. Ali et al.[22] characterized the mechanical properties of titanium-based carbon fiber reinforced epoxy FMLs under moisture effect. Reduction in the longitudinal and transverse tensile strength was noticed in FMLs. However, the decrease in the tensile strength of FMLs was lower than their respective composite materials due to the lower water uptake in FMLs. Kuan et al.[23] compared the tensile properties of thermoplastic FMLs based on hemp, flax, and basalt fibers. They demonstrated that basalt reinforced FMLs have the highest tensile properties among the natural fiber-based FMLs. Vasumathi and Murali[24] investigated the mechanical properties of carbon/jute reinforced FMLs based on aluminum and magnesium skin layers. They noticed that the FMLs with aluminum as the skin layers exhibited better mechanical properties than FMLs with magnesium as the skin layers. The mechanical properties of FMLs improved with the increase in fiber layers regardless of the types of FML skin layers. Farsani et al.[25] had shown the Charpy impact energy absorption of basalt fiber reinforced aluminum and steel FMLs to be superior compared to their corresponding composites. Sivakumar et al.[26] conducted Charpy impact test for oil palm fiber reinforced aluminum FMLs with different fiber compositions, ranging from 10 to 60 wt%. The findings depicted FMLs with 30 wt% of fiber composition exhibited the highest energy absorption.

The fiber configurations and orientations are among those of parameters that determine the mechanical properties of the materials. The balance between the environmental friendliness and mechanical properties can be achieved by obtaining the proper fiber configuration and orientations in the FMLs. Notably, most of the studies are limited to thermoset-based nonhybrid composite reinforced FMLs. The mechanical properties of thermoplastic-based hybrid composites reinforced FMLs are still unexplored. Therefore, this study aims at investigating the tensile and Charpy impact response of thermoplastic-based kenaf/glass fiber reinforced aluminum laminates with different fiber stacking configurations and orientations.

2 | EXPERIMENTAL METHOD

2.1 | Materials

Aluminum 5052-H32 sheets with a thickness of 0.5 mm were obtained from Novelis Inc., United States. Polypropylene granules with a density of 0.95 g/cm^3 were supplied by Basell Asia Pacific Ltd, Malaysia. The adhesive films with a density of 0.91 g/cm^3 were obtained from Collano Adhesives AG, Switzerland. Plain weave kenaf fabrics with an areal weight of 295 g/m^2 were provided by National Kenaf and Tobacco Board, Malaysia, while plain weave E-glass fabrics with an areal weight of 600 g/m^2 were purchased from ZKK Sdn. Bhd, Malaysia. Figure 1(a) and (b) shows the kenaf and glass fabrics used in this study. The physical and tensile properties of kenaf, glass, PP, and annealed aluminum 5052 are depicted in Table 1.

2.2 | Fabrication of fiber reinforced polymer and FML specimens

Hybrid composites and FMLs were fabricated through hot press molding compression method using picture frame mold. Hybrid fiber reinforced polymer composites with a nominal thickness of 3 mm were manufactured before the FML fabrication. PP granules were firstly formed into PP films with a nominal thickness of 1 ± 0.2 mm using sheet extrusion machine. Kenaf (K) and glass fabrics (G) were cut according to the dimension of frame mold (250 × 250 mm). Fiber was dried at a temperature of 105°C for 24 hr to remove the excessive moisture content in the fibers. PP films were stacked in between each layer of fabric in the frame mold for optimum fiber impregnation. The stack was then compressed at a temperature of 210°C and pressure of 5 MPa for 10 min. This was followed by the cooling process at the same pressure until room temperature was reached. The composites consist of three layers of fiber reinforcement. Nonhybrid glass and kenaf fiber reinforced FMLs are referred to GGG and KKK FMLs. GKG and KGK FMLs represent a substitution of middle glass fiber with kenaf fiber and replacement of outer glass fibers with kenaf fibers in FMLs. Aluminum sheets were annealed at a temperature of 345°C, which was followed by natural cooling to room temperature. The surfaces of the aluminum sheet were then mechanically treated with 80-grit sandpaper to create a rough aluminum surface for better mechanical interlocking to the composite laminates. The surfaces of aluminum were degreased with ethanol to remove the impurities to improve the adhesion level. FML fabrication was carried out by stacking composite laminate in between two aluminum layers, and the adhesive agents were incorporated at the interfaces of aluminum and composite. The stacking configuration for FMLs is shown in Figure 2. FMLs with a total thickness of 4 mm were compressed at a temperature of 155°C and pressure of 0.4 MPa for 10 min. Subsequent rapid cooling was conducted for the FML panels until room temperature. FML panels were then cut to the desired dimensions with reference to the ASTM E8 and ASTM E23.

2.3 | Material characterization

Tensile and Charpy impact tests were performed to evaluate the properties of the FMLs under static and dynamic conditions. The tensile test was performed at room temperature and quasi-rate of loading using Instron 5969 universal testing machine with a 50 kN load cell. The crosshead displacement rate for the tensile test was fixed at 2 mm/min in accordance with ASTM E8. The data from the tensile test were recorded for subsequent evaluation and analysis. Charpy impact test was conducted at room temperature according to ASTM E8

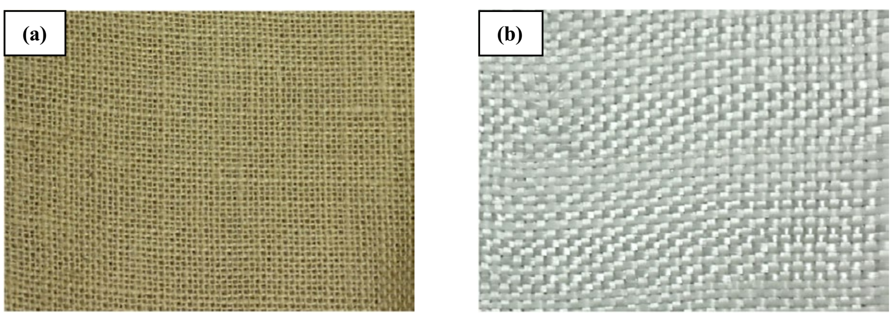

FIGURE 1 Plain weave fabrics used in this study (a) Kenaf (b) Glass

TABLE 1 Properties of kenaf, glass, polypropylene, and annealed aluminum 5052

Properties	Kenaf[27]	Glass[28]	PP[29]	Aluminum[30,31]
Tensile strength (MPa)	930	2000–3500	26–41.4	193
Elastic modulus (GPa)	53	70	0.95–1.77	70.3
Elongation (%)	1.6	2.5	15–700	25
Density (g/cm^3)	1.45	2.5	0.91	2.68

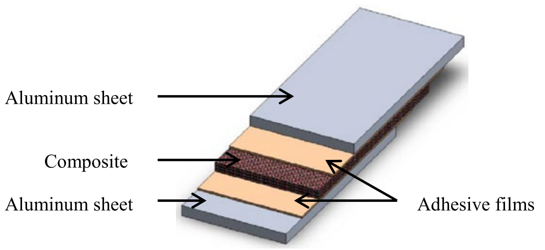

FIGURE 2 Stacking configuration of fiber metal laminates

using Gotech pendulum impact machine with the maximum energy capability up to 50 J. Both edgewise and flatwise orientations of unnotched FMLs were subjected to the impact loading.

3 | RESULTS AND DISCUSSION

3.1 | Tensile properties of FMLs

The tensile properties of FMLs with different fiber configurations and fiber orientations were evaluated at a quasi-static rate of loading. Stress–strain curves were plotted to determine the tensile properties of each FMLs. Figure 3 depicts the stress–strain curves for hybrid and nonhybrid FMLs with fiber orientation of 0°/90°. It was noticed that the curves show the transition from the elastic region to plastic region without showing significant kink for FMLs with fiber orientation of 0°/90°. Overall, nonhybrid glass fiber reinforced FMLs showed the highest tensile strength compared to hybrid FMLs and kenaf fiber reinforced FMLs. The tensile strength of hybrid FMLs with GKG and KGK fiber configurations was in the intermediate of nonhybrid GGG FMLs and KKK FMLs. The tensile strength of GGG FMLs was 101.62 MPa, which is 57.43% higher than KKK FMLs at 64.55 MPa. When a certain amount of glass fibers were incorporated in the hybrid FMLs, the tensile strength of hybrid FMLs showed a significant improvement over KKK FMLs. The tensile strength of hybrid FMLs was increased by 16.83% when glass fibers substituted the middle layer of kenaf fiber. However, the improvement was more prominent when glass fibers replaced two outer layers of kenaf fibers. Approximate 39.44% improvement in tensile strength was observed in GKG FMLs compared to KKK FMLs. When the outer layers of composite are incorporated with stronger fibers, the improvement in tensile properties is more significant. This is due to the outer layers of fiber contributing more in sustaining the tensile load compared to the middle layer. The same observation was observed in numerous literature studies where the substitution of outer layers with stronger fibers results in better enhancement.[32,33] Positive hybrid effect is shown in the tensile strength of hybrid FMLs due to the addition of stronger glass fibers. In the case of hybrid FMLs, the tensile strength is governed by the lower elongation fibers. The loads are bridged by the high elongation fibers once the low elongation fibers start to break, thus resulting in a positive hybrid effect. The high elongation fibers carry the load after the breakage of the low elongation fibers causing a pseudo yielding effect which improves the overall tensile properties. As the tensile properties of the laminates are governed by the fiber properties, the incorporation of glass fibers improves the overall tensile properties of the laminates.

The stress–strain curves for hybrid and nonhybrid FMLs with a fiber orientation of ±45° are shown in Figure 4. In contrast to the stress–strain curves of FMLs with fiber orientation of 0°/90°, the curves of FMLs with ±45° showed an obvious kink. A linear elastic region was observed at the initial stage which is followed by a nonlinear region until the total fracture of FMLs. On average, the general trend of tensile properties of FMLs with a fiber orientation of ±45° is similar to those of FMLs with a fiber orientation of 0°/90°. However, it is interesting to note that the tensile strength of GKG FMLs is comparable to those of GGG FMLs at a fiber orientation of ±45°. When comparing the

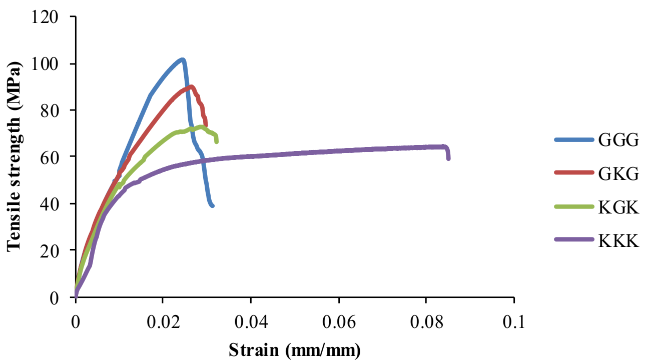

FIGURE 3 Stress–strain curves of FMLs with different fiber stacking configurations at the orientation of 0°/90°

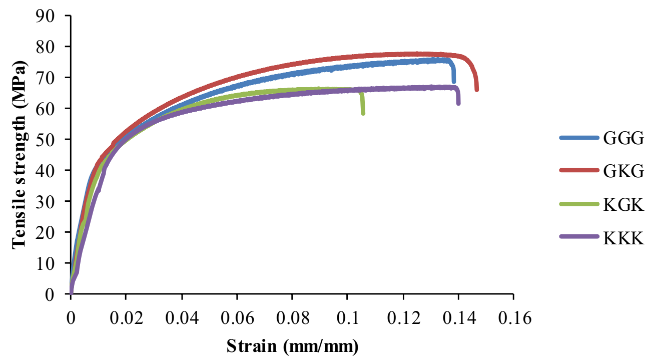

FIGURE 4 Stress–strain curves of FMLs with different fiber stacking configurations at the orientation of ±45°

tensile properties of FMLs with fiber orientation ±45° to those of 0°/90°, FMLs with fiber orientation ±45° showed relatively lower tensile properties. Fiber orientation, which is parallel to the loading direction, has higher load carrying capacity compared to those of fiber orientation with an off-axis angle. When the fibers are aligned at an off-axis angle, the shear at the fiber–matrix interface tends to induce damage in the composites and thus reducing the tensile properties. Figures 3 and 4 show a steeper decline in tensile strength in glass fiber dominated FMLs with a fiber orientation of ±45° compared to 0°/90°. The drop in tensile strength of GGG FMLs is 26.13%, while only 4.15% decrease was observed in KKK FMLs. The reduction in tensile strength of hybrid FMLs is in between the nonhybrid FMLs. Therefore, it can be concluded that kenaf fibers are less sensitive to the orientation effect in comparison with glass fibers. This could be attributed to the better adhesion level between kenaf fiber and matrix. Because of the shear deformation during the tensile loading at an off-axis angle, the fiber–matrix adhesion level becomes more vital in sustaining the load. Due to the better adhesion level between kenaf fibers and matrix, thus the decrease in tensile strength at an off-axis angle is less in comparison with glass fibers. The fiber–matrix adhesion level of kenaf and glass fibers was further confirmed using SEM in the following section.

Nevertheless, higher elongation was noticed in FMLs with a fiber orientation of ±45° in comparison with 0°/90° due to the trellis effect of the fabrics at an off-axis angle. The lateral contraction of the fabric with an orientation of ±45° during tensile loading allows the elongation of the composite laminates to a greater extent. At fiber orientation of 0°/90°, the elongation of the laminates is limited by the yarn system. In comparison with other FMLs, KKK FMLs with the fiber orientation of 0°/90° showed the highest elongation. As the kenaf fabrics were formed by twisted yarn, the yarn became untwisted during the tensile loading, resulting in higher elongation as evidenced in Figure 3.

The comparison between tensile and specific tensile strength of FMLs with fiber orientation of 0°/90° and ±45° was presented in a bar chart in Figures 5 and 6. As can be seen from Figures 5 and 6, the specific strength of FMLs shows similar trend to the tensile strength where the GGG FMLs at fiber orientation of 0°/90° showed the highest specific strength compared to other FMLs. At fiber orientation of ±45°, GKG FMLs exhibited the highest specific tensile strength, which is 3.77% greater than GGG FMLs. The difference in specific strength of hybrid FMLs in comparison with GGG FMLs becomes less significant when the density is being considered. This is due to the intrinsic lower density of natural fibers, which can be considered as one of their greatest advantage.

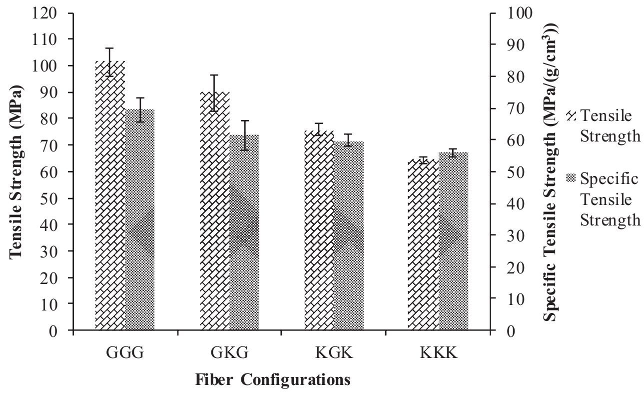

FIGURE 5 Tensile and specific tensile strength of FMLs with fiber orientation of 0°/90°

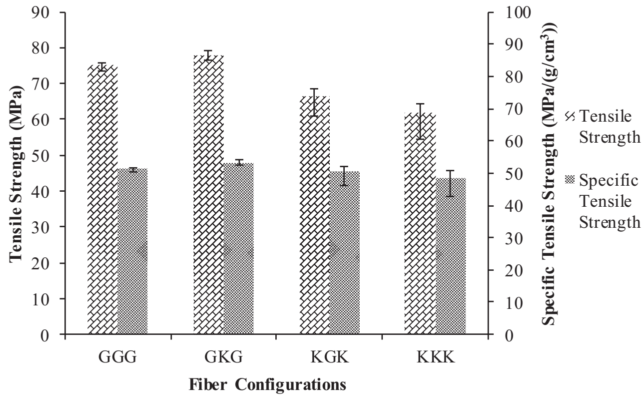

FIGURE 6 Tensile and specific tensile strength of FMLs with fiber orientation of ±45°

3.2 | Impact properties of FMLs

Impact strength of FMLs can be defined as the capability of the materials to absorb energy when subjected to impact loading until the deformation or rupture of the materials occurs. In comparison with the metallic alloys, which absorb energy through the elastic–plastic deformation, the composite core exhibits several fracture mechanisms such as debonding, fiber fracture, and fiber pull-out to absorb impact energy. Figure 7 depicts the impact strength of FMLs with fiber orientation of 0°/90° in both flatwise and edgewise directions. The impact strength of FMLs at flatwise direction demonstrated a different trend compared to the tensile properties of FMLs as shown in Figure 5. Even though the tensile elongation at break of the KKK specimen with 0°/90° orientation is the highest, but the impact strength value of this specimen is the lowest among the 0°/90° orientation specimens. The tensile elongation of the KKK specimen is due to the yarn untwisting along the fiber direction during tensile loading. Effect of yarn untwisting is not significant in the impact direction as it is acting

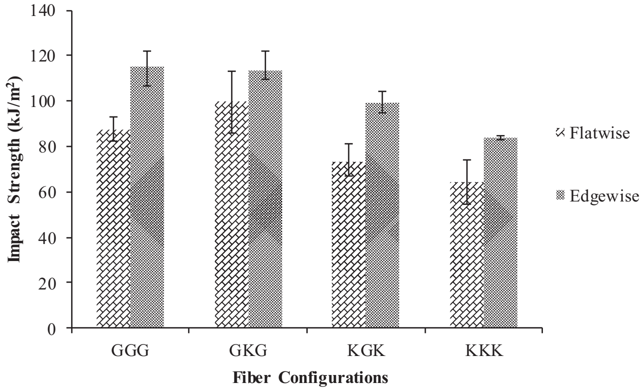

FIGURE 7 Impact strength of FMLs with fiber orientation of 0°/90° in flatwise and edgewise directions

perpendicularly to the yarn and at higher strain rate. Apart from the fiber properties, the impact properties of the laminates are generally influenced by the fiber–matrix adhesion. The fiber–matrix debonding increases the impact properties of the laminates as the energy can be further dissipated. In this case, GKG FMLs exhibited the highest impact strength instead of GGG FMLs. The addition of a limited amount of kenaf fibers in the hybrid composites was observed to be beneficial to the impact resistance. This is possibly due to the improved bonding capacity of kenaf fibers, which results in an increase in impact strength. Figure 7 shows the impact strength is higher when glass fibers substituted the outer layers of the composite core. This has been expected as the glass fibers have higher strength and modulus that can efficiently sustain the initial impact load. In contrast, the placement of kenaf fibers at the outer layers of the hybrid composites reduced the impact resistance as the fiber–matrix debonding occurs once the outer kenaf layer breaks, and thus the bridging mechanism between kenaf fiber and glass fiber is less efficient. Apart from that, kenaf fibers also possess lower impact resistance compared to glass fibers. Overall, KKK FMLs showed the lowest impact strength in both flatwise and edgewise directions. The impact strength of GKG FMLs in flatwise and edgewise directions is 99.73 kJ/m^2 and 113.25 kJ/m^2, which are approximately 55% and 37% higher than the KKK FMLs. When comparing the impact strength of FMLs in the two different orientations, it is noticeable that the impact strength of FMLs at edgewise orientation was higher than the FMLs at flatwise orientation. This is most probably due to higher fracture energy is required for the crack initiation, and failure at edgewise direction as the width of FMLs, which is parallel to the impact loading, is larger in this direction.

Figure 8 elucidates the impact strength of FMLs with fiber orientation of ±45° in flatwise and edgewise directions. The overall trend is very similar to the impact strength of FMLs with a fiber orientation of 0°/90°. However, it was found that the impact strength of FMLs with fiber orientation of ±45° was apparently higher than FMLs with a fiber orientation of 0°/90° irrespective of impact orientation and fiber stacking configurations. This is due to the pseudo-ductile behavior of fibers at an angle of ±45°, which is resulted from the shearing effect.[34] The impact load is well distributed to the fibers and matrix. Due to the higher strength of fibers compared to the polymer matrix, the failure mode is mainly dominated by fiber–matrix debonding rather than fiber fracture. As reported by Wong et al.,[35] this failure mode indeed enhances the energy dissipation and thus improving the impact strength.

3.3 | Morphological characterization

The fracture surface of FMLs with different fiber configurations due to tensile failure is depicted in Figures 9 and 10. The interlocking mechanism in both kenaf and glass fabrics plays the main role in resisting load applied. In the woven fabrics, the cracks start at the transverse direction, which is followed by longitudinal crack and fiber–matrix debonding at the interface. From Figures 9 and 10, it is clearly shown that the adhesion level between kenaf fibers and the polymer matrix is good as there is only limited fiber–matrix debonding for kenaf fibers. In contrast, prominent fiber–matrix debonding and fiber splitting were noticed in glass fibers dominated FMLs, indicating that the adhesion level between glass fibers and the polymer matrix is weak. This apparently demonstrates the decline in the tensile strength of glass fiber dominated FMLs was higher than kenaf dominated FMLs when comparing the tensile strength of FMLs with fiber orientation of 0°/90° to ±45°. The better fiber–matrix adhesion for kenaf fibers could be due to the fiber surface morphology as Wu et al.[36] revealed the rougher surface of natural fibers could results in better fiber–matrix adhesion level. The fiber breakage during the tensile loading is clearly shown in Figures 9 and 10. The fiber breakage indicates that the fibers indeed have a major contribution in carrying the tensile loading. In overall, the incorporation

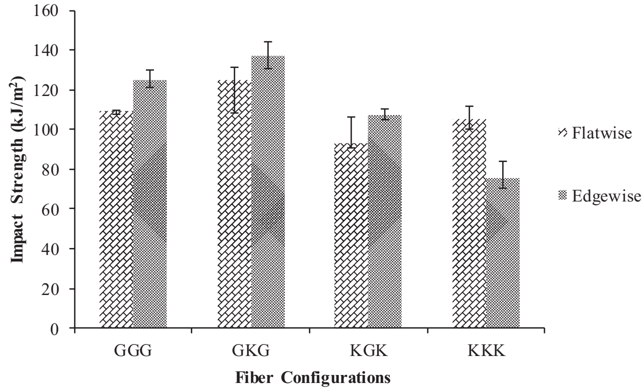

FIGURE 8 Impact strength of FMLs with fiber orientation of ±45° in flatwise and edgewise directions

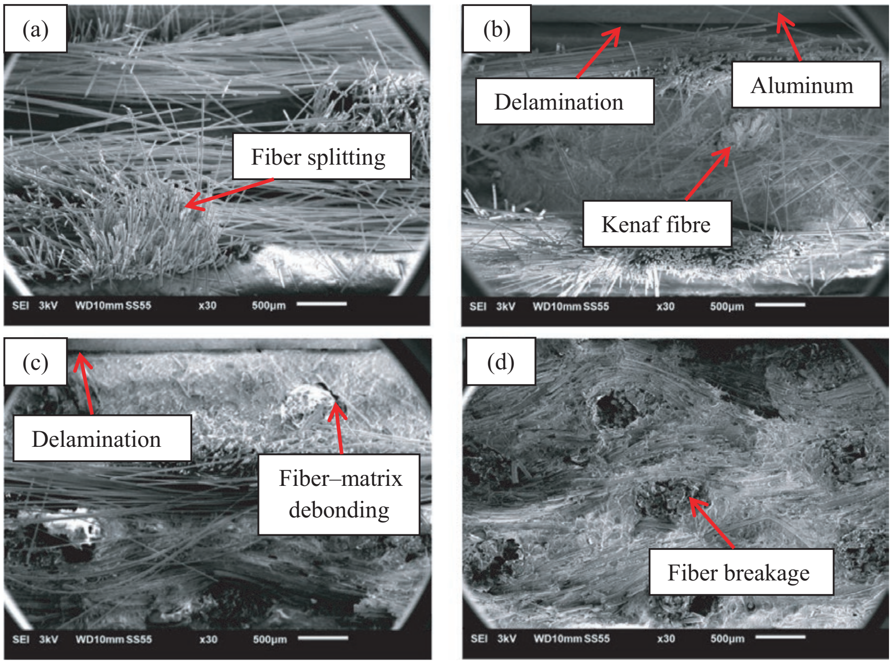

FIGURE 9 SEM micrograph of the FML fracture surface with fiber orientation of 0°/90° due to tensile loading (a) GGG (b) GKG (c) KGK (d) KKK

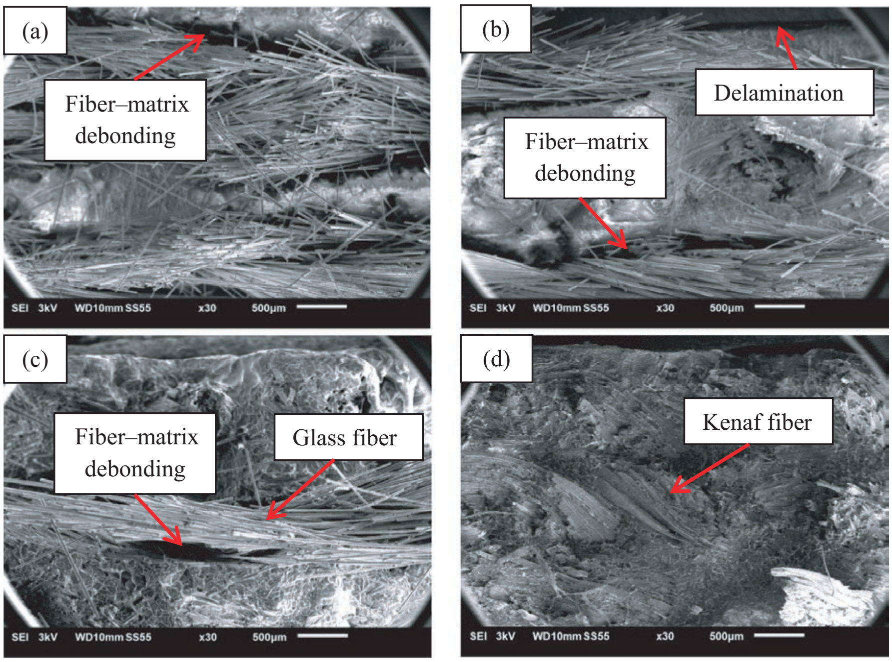

FIGURE 10 SEM micrograph of the FML fracture surface with fiber orientation of ±45° due to tensile loading (a) GGG (b) GKG (c) KGK (d) KKK

of glass fibers in FMLs does not have any significant effect on the fracture behavior of FMLs. The typical failure mechanisms were observed, such as fiber–matrix debonding, aluminum-composite delamination, fiber splitting, and fiber breakage.

4 | CONCLUSIONS

Tensile and impact properties of kenaf/glass FMLs with different fiber configurations and orientations have been investigated in this study. The tensile and impact properties of hybrid FMLs were compared with those of nonhybrid FMLs. Based on the findings obtained, several conclusions can be drawn:

1. The nonhybrid glass fiber (GGG) reinforced FMLs showed the highest tensile strength, which is 57.43% greater than kenaf fiber (KKK) reinforced FMLs. The tensile strength of hybrid FMLs was in between the glass and kenaf fiber reinforced FMLs. Improvement in tensile strength was observed when a certain amount

of glass fibers were incorporated in the hybrid laminates. 16.83% and 39.44% improvement were observed in KGK and GKG FMLs in comparison with KKK FMLs. When the density is being considered, the difference in tensile strength of nonhybrid GGG FMLs as compared to hybrid FMLs becomes negligible due to the lower density characteristic in kenaf fibers.

2. The tensile strength of FML with fiber orientation at an off-axis angle was lower than in the principal direction. However, the kenaf fibers were identified to be less sensitive to this effect due to the better fiber–matrix adhesion level compared to glass fibers. GKG FMLs exhibited the highest tensile strength, which was approximately 3.65% higher than GGG FMLs when the fiber orientation was at ±45°. When comparing the elongation of FMLs, tensile loading at fiber orientation of ±45° showed higher elongation compared to fiber orientation of 0°/90° due to the trellis effect that allows free lateral contraction in fiber with an off-axis angle.
3. FMLs with GKG fiber configuration demonstrated the highest impact strength compared to other fiber configurations regardless of impact orientations. However, KKK FMLs still showed the lowest impact performance in both impact orientations. The impact strength of GKG FMLs in flatwise and edgewise orientation was 55% and 37% higher than KKK FMLs, respectively. The substitution of outer kenaf layers with glass fibers is beneficial in overall impact resistance as the glass fibers have higher potential to sustain the initial impact loading compared to kenaf fibers. Furthermore, it is noticeable that the impact strength in edgewise orientation was higher than flatwise orientation due to the larger energy required for crack initiation in edgewise orientation.
4. FMLs with fiber orientation of ±45° have outstanding impact resistance compared to FMLs with fiber orientation of 0°/90°. At an off-axis angle, the impact loading is well distributed among fibers and matrix. Because of the higher strength in fibers, the failure mode was mainly governed by fiber–matrix debonding rather than fiber breakage, which results in efficient energy dissipation and thus improving the impact strength.

Based on the results obtained, hybrid kenaf/glass-based FMLs with replacement of middle glass fabric with kenaf fabric have demonstrated an excellent tensile and impact properties. Therefore, hybrid kenaf/glass-based FMLs show an excellent potential in developing a more environment friendly and less costly structures compared to those of conventional thermoset-based nonhybrid FMLs. This research suggests alternative materials in the replacement of synthetic fibers especially for transportation sectors such as aerospace, marine, and automotive fields.

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