Research Article

Drop-weight Impact Responses of Kenaf Fibre-Reinforced Composite-Metal Laminates: Effect of Chemical Treatment and Fibre Composition

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Abstract
Recently, fiber-metal laminates have gained high attention from material scientists and engineers, particularly when it comes to impact-critical applications. When compared to metallic alloys and composite materials, fiber-metal laminates offer several distinguishing advantages. This work intends to evaluate the low-velocity response of kenaf fiber-reinforced polypropylene metal-composite laminates with various fiber compositions, in line with the current trend of using natural fiber as possible reinforcement in composite materials. In addition, a comparison was made between the low-velocity impact response of non-treated and chemical-treated kenaf fiber-reinforced composite-metal laminates. A hot molding compression technique was employed to fabricate the laminates. Low-velocity impact tests were performed based on ASTM D7136 to determine the peak force, maximum displacement, and energy absorption of the materials. The results confirmed that NaOH treatment and increased fiber content resulted in a higher peak force of NaOH-treated kenaf-based metal laminates. For NaOH-treated laminates, the peak force of laminates with 70 wt% was found to be 11.20% higher than laminates with 50 wt% at the impact energy of 60 J. At fiber content of 70 wt%, the peak force of NaOH-treated laminates is 2.14% greater than that of untreated laminates when subjected to low-velocity impact with an energy level of 60 J. However, laminates with low fiber content and without NaOH treatment manifested higher maximum displacement and energy absorption due to the ductile behavior of such materials.

Keywords: Chemical treatment, Energy absorption, Fiber-metal laminates, Fracture behaviors, Kenaf fiber, Low-velocity impact, Natural fiber

1 Introduction

The development of advanced composite materials has been fueled by the rising need for sustainable and lightweight materials. In recent years, composites have been successfully utilized in the automotive, aircraft, and marine sectors. It can be speculated that the composite industry will be subjected to continuous growth in the future. Some remarkable characteristics of composite materials are their strength, modulus, fatigue, and wear. In addition, fiber-reinforced polymers have been identified to have a high strength-to-weight ratio over metallic alloys. Concurrently, fiber-reinforced polymers have also been proven to have better fatigue resistance than metallic alloys [1]. Nonetheless, it has been shown that composites exhibit poor impact strength compared to metallic alloys. Thus, fiber-metal laminates (FMLs), which inherit the advantages of composite materials and metallic alloys, have been created to address the drawbacks of these two competing materials. FMLs are categorized as a hybrid composite structure comprising alternate layers of metal and composite material. FMLs have high mechanical properties, superior fatigue behavior, and good fire resistance inherited from their constitutive materials [2]–[5]. Today FMLs, such as glass fiber-reinforced aluminium laminate (GLARE), aramid fiber-reinforced aluminium laminate (ARALL), and carbon fiber-reinforced aluminium laminate (CARALL) are commercially available. All of the above-mentioned FMLs are based on different types of man-made fibers.

The rising environmental consciousness has prompted researchers to look for ecologically acceptable and sustainable materials to replace man-made fiber-reinforced composites. The integration of cellulosic fibers in polymers is seen as an alternative method of improving the environmental friendliness of composites. Cellulosic fibers have become essential for industrial applications, such as paper making, textile, and building materials. At this stage, composites based on cellulosic fibers have been utilized in automotive, aerospace, construction, packaging, electrical, and household applications [6]–[9]. Cellulosic fibers are gaining popularity because of their numerous benefits, such as high strength/density ratio, non-abrasive, low energy consumption for production, environmentally friendly characteristics, and cheap [10]–[12]. It is estimated that cellulosic fibers can reduce the weight of composite materials by 15% compared to glass fiber-reinforced composites [13]. Thus the lightweight characteristic of cellulosic fibers is promising in reducing energy consumption in the transportation sectors. In 2016, cellulosic fibers accounted for approximately 11% of the total reinforcement volume in composite materials [14]. Among the cellulosic fibers, kenaf fiber is regarded as one of the most economical fibers with relatively high mechanical strength. The high aspect ratio of kenaf fiber makes it an excellent reinforcement for composite materials [15]. In Malaysia, kenaf has been widely cultivated through the founding of the National Kenaf and Tobacco Board.

Although cellulosic fibers have shown plenty of attractive features, they are not demerit-free materials. High moisture absorption, less durability, and poor mechanical strength compared to synthetic fibers are often the challenges when using natural fibers as reinforcement for composites. These limitations have retarded the use of cellulosic fibers in structural applications. On this note, chemical treatment is commonly applied to cellulosic fibers to tackle their weaknesses. In particular, it is a critical step to eliminate the impurities to promote a strong fiber-matrix adhesion. It has been proven that natural fiber-reinforced composites have greater mechanical properties and lower water absorption after the natural fiber is subjected to chemical treatment [16]. Apart from chemical treatment, adding filler to the composites has also been found to improve Young's modulus, thermal stability and compressive and impact strengths [17]. However, a more straightforward and effective technique to tackle the disadvantages of natural fiber-reinforced composites is coalescing cellulosic fiber-based composites with metallic skin layers. It has been demonstrated that the moisture sensitivity of FMLs is tremendously lower than their composite counterparts [18]. At present, FMLs are primarily dominated by man-made fibers instead of cellulosic fibers. Since cellulosic fibers have shown great potential to supersede man-made fibers, it is worth investigating the feasibility of incorporating cellulosic fibers in FMLs. Several studies have unveiled the high potential of cellulosic fiber-based FMLs based on their mechanical performance [11], [19]–[22].

The impact properties of FMLs have been reported in several literature studies. Ferrante *et al.*, [23] investigated the impact response of FMLs based on plain weave basalt fiber-reinforced epoxy prepreg. They found that the basalt fiber-based FMLs exhibited higher impact energy absorption than monolithic aluminium. Jakubczak *et al.*, [24] performed a low-velocity impact test on the FMLs based on carbon fiber-reinforced epoxy composites with different fiber orientations. The findings showed that the fiber orientations did not significantly influence the impact behaviors of FMLs. However, the unidirectional FMLs evidenced slightly higher maximum energy absorption than other orientations. Malingam *et al.*, [25] conducted an experimental investigation on the impact responses of FMLs based on kenaf/glass fiber-reinforced polypropylene composites with varying fiber stacking sequences. Hybridizing kenaf with glass fiber was proven that could enhance the impact properties of FMLs. However, the improvement was more prominent when the glass fiber was situated in the outermost layers of composites. Vieira *et al.*, [26] evaluated the effect of surface treatment and fiber orientations (0°/90°, ±45°, random mat) on the impact properties of FMLs based on sisal fiber-reinforced epoxy composites. They reported that surface-treated FMLs with a fiber orientation of ±45° showed the highest energy absorption and deflection properties. Mirzamohammadi *et al.*, [27] studied the effect of hybridization on the impact properties of FMLs based on jute/basalt fibre-reinforced epoxy composites. It was found that FMLs exhibited the highest impact properties when basalt fibre was placed as the outermost layers of the composites.

To date, the low-velocity impact responses of FMLs based on kenaf fiber-reinforced polypropylene composites remain unexplored. Since kenaf fiber exhibits high economic value and decent mechanical strength, it is vital to explore the impact properties of kenaf fiber-based FMLs to show their potential for impact-critical applications. This research study aims to evaluate the low-velocity impact response of untreated and chemical-treated kenaf fiber-based FMLs with different fiber compositions. The fracture behaviors of FMLs after the low-velocity impact are analyzed.

2 Methodology

2.1 *Materials*

Homopolymer polypropylene (PP) granules with a density of 0.91 g/cm^3 were provided by the Al Waha Petrochemical Company, Saudi Arabia. Sodium hydroxide (NaOH) pellets were purchased from Merck KGaA, Germany. Kenaf fiber was obtained from Innovative Pultrusion Sdn. Bhd, Malaysia. 5052-H32 aluminium sheets were supplied by Novelis Inc., United States. The properties of kenaf fiber and PP are summarised in Table 1.

Table 1: Properties of kenaf fiber and PP [28], [29]

Properties	Kenaf Fiber	PP
Density (g/cm^3)	1.4	0.91
Elongation (%)	1.5–2.7	15–700
Elastic modulus (GPa)	14.5–53	0.95–1.77
Tensile strength (MPa)	223–930	26–41.4

2.2 *NaOH treatment*

The NaOH treatment was performed by soaking kenaf fiber in the 5% NaOH solution. The fiber was immersed in the NaOH solution for 4 h at room temperature to alter the fiber surface structure. Generally, NaOH concentration of 5% and a soaking duration of 4 h are fixed to attain greater mechanical properties of composite materials [30]–[34]. Thereafter, the fiber was washed thoroughly using distilled water to purge the inordinate NaOH solution on the fiber surface. The fiber was then allowed to dry naturally for 72 h before being dried in an oven for 24 hours at 80 °C.

2.3 *The fabrication process of FMLs*

The hot molding compression technique was used to fabricate both composites and FMLs. Composites were fabricated prior to the preparation of FMLs since composites are the core constituent of the laminate structures. A film stacking technique was employed to arrange the PP layers and kenaf fiber to ensure the maximum impregnation of the fiber. The PP granules were firstly compressed at 175 °C and 5 MPa to form PP films with a nominal thickness of 0.3 mm. Then, the random kenaf fiber with a length of 30 mm was also compressed to form fiber mats. Four layers of kenaf fiber mat and three layers of PP film were stacked alternately in a frame mold with a thickness of 3 mm. The stack was then heated at 175 °C without applying pressure for 2 min to ensure heat was dispersed uniformly throughout the composite panel.

The composite panel was then completely compressed at a pressure of 5 MPa and the same temperature for 8 min. The 3 mm thick composite panel was cooled to room temperature before being removed from the frame mould. Table 2 lists the fibre weight and volume percentages of the kenaf fibre-reinforced composites. The fiber volume fraction of the composite cores with varying fiber content is computed using Equation (1).

Table 2: Fiber weight and volume fraction in composite laminates

Fiber Weight Fraction (wt.%)	PP Weight Fraction (wt.%)	Fiber Volume Fraction (vol.%)
50	50	40
60	40	50
70	30	60

$$V_{fiber}(\%) = \frac{\dfrac{w_{fiber}}{\rho_{fiber}}}{\dfrac{w_{fiber}}{\rho_{fiber}} + \dfrac{w_{PP}}{\rho_{PP}}} \times 100 \quad (1)$$

where w_{fiber} is the weight of kenaf, w_{PP} is the weight of PP, ρ_{fiber} is the density of kenaf and ρ_{PP} is the density of PP.

Aluminium sheets with a thickness of 0.5 mm were subjected to an annealing process with the aims of reducing residual stress and enhancing the formability of the materials [35], [36]. The annealing process was conducted on the aluminium sheets at a temperature of 345 °C for 2 h in accordance with ASTM B918. After heating, the aluminium sheets were naturally cooled down to room temperature. Then, mechanical surface treatment was performed to roughen the aluminium surface using silicon carbide abrasive paper

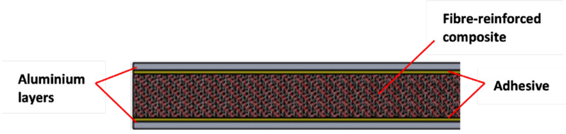


Figure 1: Schematic illustration of the FMLs with a 2/1 configuration.

with 80 grit-size. The literature study reported that mechanical surface treatment using 80 grit-size abrasive paper is able to improve the bonding level of FMLs [37]. Following the surface treatment, ethanol was used to degrease the aluminium sheets in order to remove any contaminants that had adhered to the aluminium surface. Later, 2/1 configuration FMLs were prepared by alternately stacking the composite panel and aluminium layers in a 4 mm thick frame mold. The stack was rapidly cooled to room temperature after being hot compressed at 175 °C and 1 MPa for 8 min. Finally, FMLs were taken out of the hot press machine to check for any flaws visually. The FMLs in a 2/1 configuration are shown in Figure 1. Figure 2 shows the flowchart of the fabrication process of FMLs.

2.4 *Experimental works*

The effects of fiber weight composition and chemical treatment on the impact properties of FMLs based on kenaf fiber-reinforced composites were examined through a low-velocity impact test. In this research investigation, a low-velocity impact test was performed in compliance with ASTM D7136-20 utilizing a CEAST 9250 drop tower impact. A waterjet cutter was used to cut the FMLs into dimensions of 100 × 100 mm. The schematic representation of the

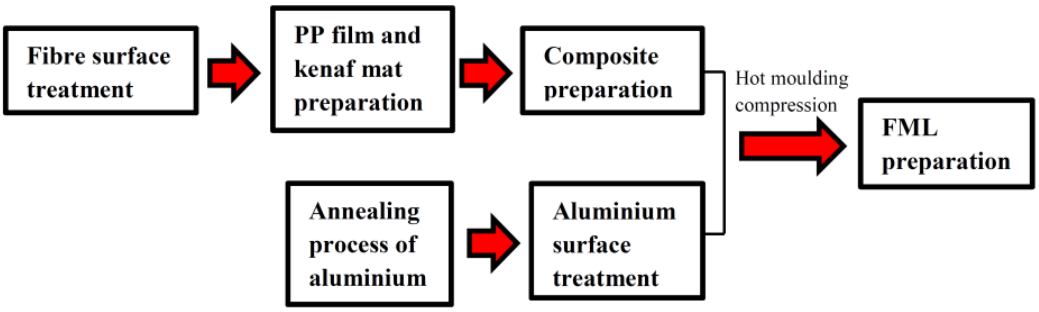


Figure 2: Flowchart of composite and FML preparation

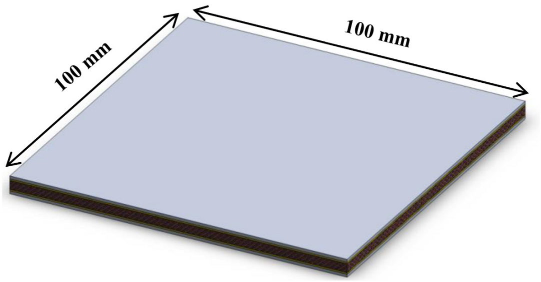


Figure 3: Schematic illustration of the FML specimen for low-velocity impact.

FML specimen for low-velocity impact is shown in Figure 3. Three different impact energy levels were fixed to study the impact damage threshold: 20, 35 and 60 J. During the impact test, FMLs were clamped in the fixture with a 76 mm diameter opening and subjected to impact loading using a hemispherical impactor with a diameter of 12.7 mm. Five specimens were tested for each fiber composition and energy level. The maximum force, displacement and energy absorption of FMLs with different fiber weight compositions were recorded for analysis and evaluation. The fracture behaviors of post-impact specimens were then assessed through the optical micrograph to relate the fracture modes to the impact properties of FMLs.

3 Results and Discussion

3.1 *Low-velocity impact responses*

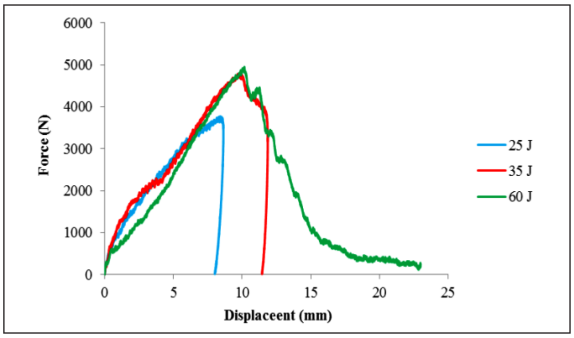
The low-velocity impact test was performed to determine the impact properties of the materials at different impact energy levels. In this research work, the energy levels were fixed at 20, 35 and 60 J. The impact damage of a material is commonly associated with the impact and absorbed energies. The impact energy can be defined as the kinetic energy of the impactor before it contacts with the specimen, whereas the absorbed energy is the energy that dissipates within the materials through several mechanisms such as elastic deformation, plastic deformation, friction, fiber pull-out, fiber breakage, matrix cracking and debonding [38]. The impact properties, including the peak force, maximum displacement and absorbed energy of untreated and chemically treated FMLs with different fiber weight compositions, are recorded in Table 3 and Table 4.

Table 3: Impact properties of untreated kenaf-based FMLs at different impact energy levels

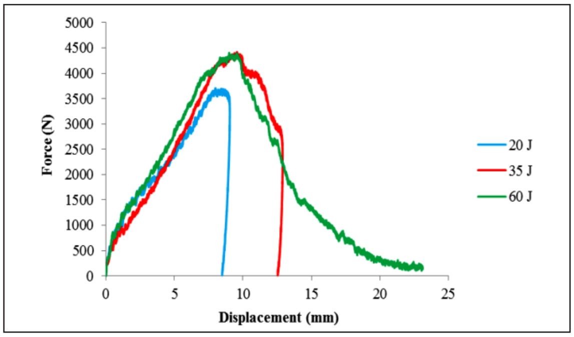
Fiber Composition (wt.%)	Impact Energy (J)	Peak Force (N)	Maximum Displacement (mm)	Absorbed Energy (J)
50	20	3704.49 ± 98.77	8.48 ± 0.71	19.60 ± 0.19
	35	4403.78 ± 104.03	12.54 ± 0.14	31.88 ± 0.04
	60	4421.12 ± 81.95	-	58.78 ± 0.17
60	20	4005.01 ± 81.43	7.97 ± 0.29	18.74 ± 0.18
	35	4970.14 ± 45.52	11.39 ± 1.15	30.76 ± 0.01
	60	5155.08 ± 102.27	-	57.58 ± 0.21
70	20	4334.43 ± 40.46	6.58 ± 0.26	17.69 ± 0.05
	35	5172.42 ± 104.94	10.10 ± 1.19	29.25 ± 0.38
	60	5392.03 ± 128.18	-	56.05 ± 1.63

Table 4: Impact properties of NaOH-treated kenaf-based FMLs at different energy levels

Fiber Composition (wt.%)	Impact Energy (J)	Peak Force (N)	Maximum Displacement (mm)	Absorbed Energy (J)
50	20	3773.84 ± 40.45	8.02 ± 0.52	17.52 ± 0.04
	35	4790.99 ± 69.87	11.45 ± 1.09	30.67 ± 0.21
	60	4952.81 ± 46.23	-	57.72 ± 0.13
60	20	4293.97 ± 113.83	7.85 ± 0.45	16.87 ± 0.11
	35	4993.26 ± 86.62	11.12 ± 0.54	29.68 ± 0.07
	60	5345.80 ± 112.60	-	56.56 ± 1.49
70	20	4652.29 ± 90.72	6.41 ± 0.12	15.88 ± 0.06
	35	5472.94 ± 110.85	9.46 ± 0.19	28.77 ± 0.13
	60	5507.61 ± 167.60	-	54.60 ± 0.76



(a)



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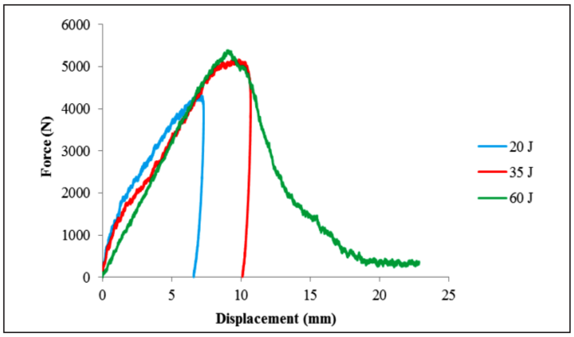
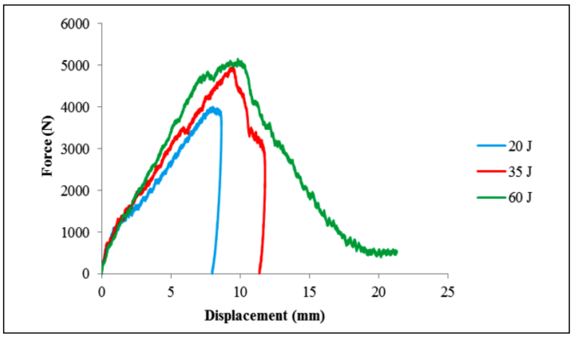
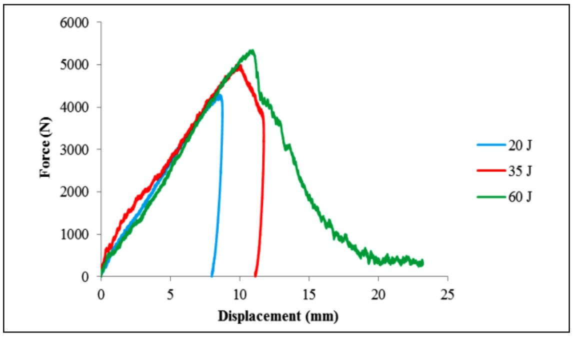


(c)

Figure 4: Force-displacement curves of untreated kenaf-based FMLs at different energy levels (a) 50 wt% (b) 60 wt% (c) 70 wt%.



(a)



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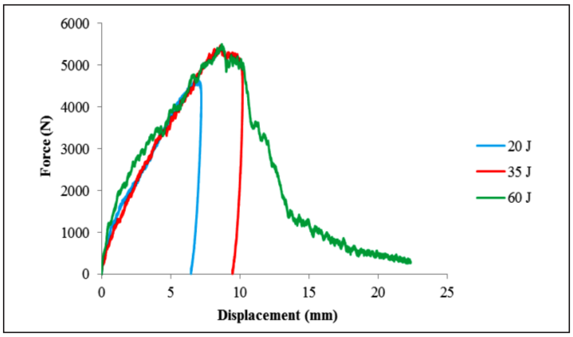


(c)

Figure 5: Force-displacement curves of chemical-treated kenaf-based FMLs at different energy levels (a) 50 wt% (b) 60 wt% (c) 70 wt%.

Figures 4 and 5 show the typical force-displacement curves of untreated and chemical-treated kenaf-based FMLs with different fiber weight compositions. These force-displacement curves of FMLs displayed a similar feature regardless of fiber weight composition and chemical treatment. It can be seen that the curves indicated an increasing trend of force with increasing displacement until a maximum force was obtained. Beyond the maximum force, a sudden force drop in these curves was observed. As reported in the previous literature studies, the sudden force drop in the curves of the fracture materials implies the damage of the materials with the loss of structural integrity and major fiber fracture [39], [40]. From the curves, it can also be observed that the maximum force of FMLs increases with the increase of impact energy. Furthermore, the maximum displacement of FMLs also showed an increment with an increase in impact energy level. As visible in the force-displacement curves of untreated and treated FMLs, the curves can be either open- or closed-ended. The closed-ended curves imply that the materials exhibited an elastic deformation and had minimum or no damage during the impact loading. Moreover, the closed-ended curve is also associated with the rebound of the impactor during an impact event. When the materials were subjected to high-impact energy levels, excessive damage was exerted on the materials, and this phenomenon resulted in an open-ended force-displacement curve. By referring to Figures 4 and 5, the curves are closed-ended when the energy levels were 20 J and 35 J. At these energy levels, FMLs showed minimum or no damage, which can be referred to as an elastic response. However, open-ended curves can be seen when the energy level was further increased to 60 J. At this stage, complete penetration or excessive damage was observed in FMLs irrespective of fiber weight composition and chemical treatment.

When comparing the peak force of kenaf-based FMLs with different fiber weight compositions, the highest peak force was found in FMLs with 70 wt%, whereas the lowest can be noticed in FMLs with 50 wt%. Overall, the increase in fiber weight composition increased the peak force of FMLs, implying that a higher force is required to puncture the FMLs. In other words, the incorporation of fiber indeed improves the strength and resistance of FMLs against impact load. For untreated kenaf-based FMLs, the peak force of FMLs with 70 wt% was found to be 21.96% higher than FMLs with 50 wt% at the impact energy of 60 J. Besides, the chemical-treated FMLs with 70 wt% also exhibited a peak force of 5507.61 N, which is 11.20% greater than FMLs with 50 wt% at the impact energy of 60 J.

However, the maximum displacement of kenaf-based FMLs showed a different trend in which increasing the fiber weight composition reduced the maximum displacement irrespective of chemical treatment. Kenaf-based FMLs demonstrated the highest maximum displacement when the fiber weight composition was fixed at 50 wt%, while the lowest was observed in FMLs with 70 wt%. Although the increase in fiber content of FMLs improved peak force, it deteriorated the maximum displacement of the materials. These results confirm that the impact properties of FMLs with high fiber composition are dominated by fiber rather than matrix properties. Based on Table 1, the elongation of PP is greater than kenaf fiber, indicating that PP is more ductile than kenaf fiber. Reducing the PP composition in FMLs may lead to a reduction in ductility. Therefore, FMLs with high fiber content are more brittle and have high peak force but low maximum displacement. Due to the brittleness of FMLs with high fiber content, the energy absorption of such materials was also lower than those FMLs with low fiber content. According to Table 3, the energy absorption of untreated kenaf-based FMLs with 50 wt% was slightly higher than the FMLs with 60 wt% and 70 wt% at all energy levels. The energy absorption of chemical-treated FMLs demonstrated a similar trend where the FMLs with 50 wt% evidenced the highest energy absorption, whereas the lowest was found in FMLs with 70 wt%.

In the context of chemical treatment, the findings revealed that NaOH treatment influences the impact properties of kenaf-based FMLs to a certain extent. The peak force of FMLs was enhanced regardless of impact energy level and fiber composition. Nonetheless, the maximum displacement and energy absorption of chemical-treated kenaf-based FMLs were slightly lower than their respective untreated FMLs. A significant portion of the lignin, pectin, wax, and impurities are removed during the NaOH treatment, altering the fiber surface structure and creating a rough, clean fiber surface that is essential for increasing the bonding strength between the fiber and matrix. The mechanical strength of the materials improved because of the enhanced fiber-matrix bonding level. In this regard, the improved bonding between the fiber and matrix, which enables the impact force to be efficiently distributed between the fiber and matrix through the shear stress at the fiber-matrix interface, is responsible for the higher peak force of NaOH-treated FMLs compared to untreated FMLs. Nevertheless, once the fiber-matrix bonding level was improved, NaOH-treated FMLs became more brittle than the untreated FMLs, resulting in a drop in the maximum displacement and energy-absorbing capacity of the materials. In addition, a weak fibre-matrix adhesion can dissipate more energy than a strong interfacial adhesion [41]. Consequently, better energy dissipation of untreated FMLs makes them have a higher impact strength.

3.2 *Damage assessment*

After the low-velocity impact test, the damage assessment of both untreated and NaOH-treated kenaf-based FMLs was performed. The evaluation was conducted to show the damage progression of kenaf-based FMLs at varying impact energy levels. Both the front and the rear surfaces of the FMLs were evaluated after the impact tests at various energy levels. Essentially, the damage behaviors of FMLs in response to low-velocity impact include plastic deformation, fiber breakage, fiber-matrix debonding, fiber pull-out and delamination. Undoubtedly, the damage behaviors of FMLs are highly dependent on the applied energy level. However, it is clear that each constituent of FMLs also has a significant influence on the impact of damage behaviors.

Low-velocity impact damages can be grouped into indented, partially perforated, fully perforated and penetrated laminate. Table 5 depicts the fracture surfaces of the untreated kenaf-based FMLs with a fiber weight composition of 50 wt% at various energy levels. Minimum damages were detected on the front and rear surfaces of FMLs at the energy level of 20 J. The front surface of FMLs was indented, whereas the first crack was noticed at the rear surface of FMLs. The increase in energy level resulted in severe damage to the front and rear surfaces of kenaf-based FMLs. The fracture was observed in the aluminium skin layers of FMLs at the energy level of 35 J. When the energy level was further increased to 60 J, FMLs were fully penetrated by the impactor, implying the final fracture of such materials. When observing the damage behaviors of kenaf-based FMLs at the energy level of 60 J, the fracture surfaces of FMLs show fiber pull-out and inter-ply delamination. Moreover, the composite-metal delamination can also be noticed at the rear surface of FMLs at the energy level of 60 J.

Table 6 elucidates the fracture surfaces of NaOH-treated kenaf-based FMLs with a fiber weight composition of 50 wt%. The overall damage behaviors of NaOH-treated FMLs were similar to those of untreated FMLs. Nevertheless, it was found that the NaOH-treated FMLs had less damage than the untreated FMLs. At the energy level of 20 J, no visible crack was detected at the rear surface of NaOH-treated FMLs. When the energy levels were increased to 35 and 60 J, it was noted that the untreated FMLs had more damage at the front and rear surfaces than NaOH-treated FMLs. When comparing the damage behaviors of untreated with the chemical-treated FMLs after being impacted with an energy level of 60 J, it can also be seen that fiber-matrix debonding and fiber pull-out are more severe in untreated FMLs. In fact, fiber pull-out is actually favorable to the impact properties of FMLs since it helps disperse impact energy more effectively. Hence, fiber pull-out eventually increases the impact performance of the materials. Al-Maharma and Sendur [42] stated that fiber pull-out is the main source of energy dissipation which could improve the impact strength of the materials. Javanshour *et al.*, also revealed that fiber pull-out in composites can enhance energy dissipation due to interfacial sliding [43]. Aside from fiber pull-out, the plastic deformation of the aluminium skin layers also significantly contributes to the impact strength of FMLs. The inclusion of aluminium layers in FMLs allows global deformation to a greater extent, leading to higher energy absorption [44].

Table 5: Fracture surface of 50 wt% untreated kenaf-based FMLs

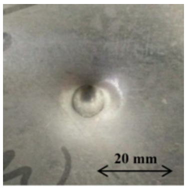
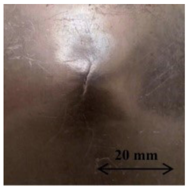
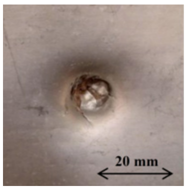
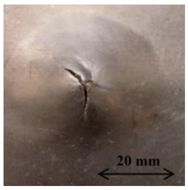
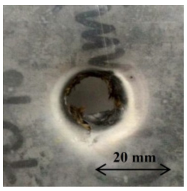
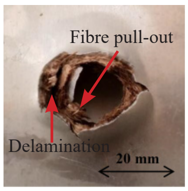
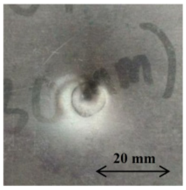
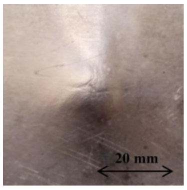
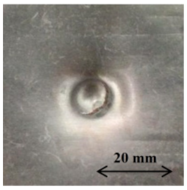
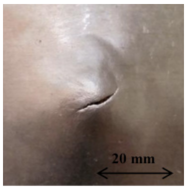
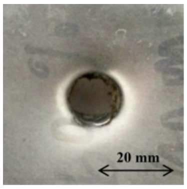
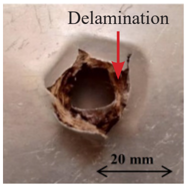
Energy Level	**Front**	**Rear**
20 J		
35 J		
60 J		

Table 6: Fracture surface of 50 wt% NaOH-treated kenaf-based FMLs

Energy Level	Front	Rear
20 J		
35 J		
60 J		

4 Conclusions

This research study aims to investigate the effects of fiber content and chemical treatment on the low-velocity impact responses of kenaf-based FMLs. In accordance with the findings obtained from the low-velocity impact test, several conclusions can be drawn. The overall findings showed that an increase in fiber content enhanced the peak force of FMLs regardless of NaOH treatment and impact energy level. At an energy level of 60 J, untreated FMLs with a fiber content of 70 wt% manifested the highest peak force, which is 21.96% higher than FMLs with a fiber content of 50 wt%. A similar observation was detected in NaOH-treated FMLs, where the FMLs with a fiber content of 70 wt% exhibited the highest peak force of 5507.61 N, which is 11.20% greater than FMLs with a fiber content of 50 wt%.

Even though an increase in fiber content improved the peak force, it deteriorated the maximum displacement and energy absorption of FMLs irrespective of chemical treatment and energy level. At an energy level of 35 J, untreated FMLs with a fiber content of 50 wt% manifested the highest maximum displacement and energy absorption of 12.54 mm and 31.88 J, which are, respectively, 24.16 and 8.99% higher than FMLs with a fiber content of 70 wt%. As for the NaOH-treated FMLs, the maximum displacement and energy absorption of FMLs with a fiber content of 50 wt% are 21.04 and 6.60%, respectively, greater than FMLs with a fiber content of 70 wt%.

The NaOH-treated FMLs showed a higher peak force but lower maximum displacement and energy absorption than untreated FMLs. At the energy level of 35 J and fiber composition of 70 wt%, the peak force of NaOH-treated FMLs is 5.81% higher than that of untreated FMLs. Nevertheless, at the same energy level and fiber content, the maximum displacement and energy absorption of NaOH-treated FMLs are 6.34 and 1.64%, respectively, lower than their respective untreated FMLs.

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Author Contributions

L. F. Ng: conceptualisation, project administration, writing an original draft; M. Y. Yahya: research design, investigation, reviewing and editing; C. Muthukumar: reviewing and editing, methodology, investigation; J. Parameswaranpillai: writing—reviewing and editing; H. Y. Leong: writing—reviewing and editing; S. M. S. A. Syed Hamzah: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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