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Research Article

Development and Mechanical Characterization of Light-Weight Fiber Metal Laminate Using Jute, Kenaf, and Aluminium

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ABSTRACT

This research focuses on the development and mechanical characterization of a lightweight sustainable fiber metal laminate (FML) using jute, kenaf, and aluminium. The objective is to investigate the feasibility of utilizing natural fiber composites in combination with aluminium to create a sustainable and lightweight material for various engineering applications. The mechanical behavior of metal laminates reinforced with jute and kenaf, with fiber concentrations ranging from 10% to 50%, is evaluated in this work. FMLs were fabricated using composite in the place of core and skin made up of metal. The mechanical behaviour of the developed FMLs was evaluated when they were subjected to tensile, flexural, and impact loading. The results showed that when the fiber percentage was set at 30 wt%, both jute and kenaf-based FMLs exhibited the best mechanical properties. Furthermore, kenaf-based FMLs (KFML) outperformed jute-based FMLs (JFML) in terms of mechanical properties. KFMLs had tensile and flexural strengths that were 4.76 and 10.2 percent higher than those of JFMLs with 30 weight percent fiber content. Kenaf-based FMLs exhibited an impact strength that was 8.19% more than that of jute-based FMLs.

1. Introduction

Modern materials called FMLs have been extensively used in the aerospace sector. By using an adhesive at the interface to bond metallic layers to a composite material, FMLs are produced. FMLs have been shown to have sandwich structures that provide better resistance when subjected to impact load as well as fatigue load in comparison with conventional alloys [1,2]. FMLs also offer exceptional sound absorption, high specific strength, and stiffness [3,4].

Due to their small weight and large specific strength, FMLs are been suggested in the automotive sector to improve energy economy without compromising safety [5]. In fact, over the past few decades, addressing the poor fatigue characteristics of metals has been a top objective for FML research. The process of fiber bridging in FMLs considerably slows the rate of fatigue fracture formation, hence extending their life against fatigue loading. Following the initiation of a crack, fibers prefer to maintain the load behind the crack tip opening. Fibers' rigidity helps to reduce the amount of stress present, which in

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turn slows the pace at which cracks spread. These FML-based sandwich composites have fracture propagation rates that are 100 times lower than those of alloys belonging to aluminium, according to a study [6]. The crack closure phenomenon is important to study as it estimates the fatigue life of the components. It becomes even more complex under low-cycle fatigue (LCF) since under LCF high amount of plasticity is induced within the material near notches or defects [7].

Nowadays, synthetic fibers including carbon, aramid, and glass fibers are used to create commercial FMLs [8,9]. In truth, the sandwich construction introduced by TU Delft in 1978 was what produced the initial generation of FML [10]. After that, aramid fiber was replaced with glass fiber in FMLs to improve the materials' fatigue resistance. These FMLs consisting of polymers nevertheless have a significant flaw, though, in that the thermoset polymer must be processed for a long period, which reduces material productivity. In this situation, the thermoplastic matrix has proven to have a desirable benefit in that the production process may be greatly sped up by merely heating to the processing temperature and then cooling to ambient temperature. Interest in utilizing natural resources to make composite materials has increased in recent years due to growing environmental awareness and conscience. FMLs might be included in the initiative to use environmentally friendly materials available naturally. As a replacement for synthetic fibers in FMLs, natural fibers have shown a lot of promise in this area [11-14]. It is important to note that, when compared to glass fiber, due to its lightweight nature, the utilization of natural fiber composites may boost efficiency, especially in the field of transportation [15-17]. The improvement in mechanical properties of biodegradable and sustainable materials like natural fibers turns out to be exceptionally appealing from financial and biological perspectives [18]. However, they also have some drawbacks in terms of mechanical properties such as moisture absorption, lower strength and stiffness, variability and inconsistency, limited temperature resistance, and so on. Through advancements in fiber treatments, hybridization strategies, processing techniques, and composite design, the overall performance of these composites continues to improve [19-21]. Jute-based green composites are emerging materials due to their certain attractive properties like appropriate strength-to-weight ratio, high damping ratio, low price, and corrosion resistance [22].

In-depth research has recently been done on these cellulosic fiber-reinforced composites to see whether they might eventually replace synthetic fiber-based composites. There are numerous well-known benefits of natural fibers over synthetic ones [23-25]. Natural fibers offer several benefits, including being affordable, having a minimal carbon impact, being lightweight, and being widely available [26,27]. Natural fibers have several advantages, but their light weight is particularly appealing in the transportation sector to reduce energy use. Despite the many benefits, natural fibers' drawback of hydrophilic behaviour has restricted their use in structural applications. There have been attempts to overcome this drawback of natural fibers, and chemical treatment may be a different way to do it [28,29].

On the other hand, the addition of skin layers made of aluminium to composites reinforced with natural fibers is thought to be a direct and efficient method of lowering moisture sensitivity. FMLs are far less sensitive to moisture than comparable polymer metric composites (PMC) [30].

In-depth studies on several natural fibers have been conducted to produce bio-composite materials that are both sustainable and affordable. The most extensively studied reinforcements have been revealed to be those made of plant fibers, including flax, jute, hemp, sisal, ramie, and Kenaf [31]. Researchers have examined the use of jute-reinforced composites using a variety of natural and synthetic resin components [32,33]. Additionally, the behavior of jute-reinforced composites that have been alkali-treated is evaluated under various loads at various temperatures [34]. Automotive components have successfully utilized jute-reinforced composites [35]. Jute and glass fiber were hybridized, and a thermo-mechanical analysis provided an outcome in favor of hybridization [36]. Kenaf fiber has lately attracted a lot of interest because of its rather good mechanical qualities and affordability [37].

Mechanical characterization of glass and jute fiber-based hybrid composites fabricated through compression moulding technique has been studied [38] and it was found that damage area decreases with increasing jute percentage in glass/jute hybrid composites, showing that jute fiber contributes more towards the composites' impact strength than glass fiber. Therefore, jute fiber can replace glass fiber in the glass/jute hybrid composite as a natural and eco-friendly constituent.

Several researches have been published in the literature to describe the mechanical characteristics of FMLs. The impact of fiber orientation was investigated in Kevlar and glass-reinforced PMC-based FML. Regardless of fiber type, they discovered that 0°, 45°, and 90° orientations of FMLs had the best tensile strengths. We investigated the tensile and impact characteristics of self-reinforced polypropylene, basalt, flax, hemp, and other FMLs. The results showed that the laminates' tensile and impact capabilities were enhanced by using aluminium as the skin layers [39]. Tensile testing was done on metal laminates made of polypropylene and reinforced with aramid fibers. The results showed that FMLs' tensile strength was on par with that of composite laminates and aluminium [40]. The mechanical characteristics of FMLs manufactured from carbon along with flax fibers and carbon along with Kenaf fibers were experimentally investigated and it was found that FML containing carbon along with flax fibers presented better strength when subjected to tensile loading but flexural strength of this combination was low [41]. The effect of the anodizing process on the interlaminar shear strength of GLARE composite was studied and it was found that anodizing makes the aluminium surface porous and improves glass fiber's adhesion with the aluminium surface [42].

The loading conditions also play a vital role in determining the strength of the composites. The effect of On-axis and Off-axis loading on the strength of carbon/epoxy, glass/epoxy, and jute/epoxy composites was studied and it was found that glass/epoxy composite showed improved failure strain, by 90%, without much loss in tensile strength in off-axis loading than on-axis loading. The jute fiber revealed limited tensile strength and failure strain in both loading conditions [43].

The mechanical properties of potential FMLs have been demonstrated by the aforementioned study. However, there aren't many studies that concentrate on FMLs made from natural fibers. When compared to FMLs constructed of synthetic fiber, it is believed that using natural fibers will have a good environmental impact. Jute fiber and kenaf-reinforced epoxy-based FMLs have not yet been mechanically characterized. As a result, the objective of this study is to investigate the behaviour of FMLs manufactured from jute and kenaf with different fiber weight ratios when subjected to mechanical loading.

2. Materials and Methods

The present section describes the selection of materials, manufacturing methods used, and characterization techniques.

2.1. Materials

The present study makes use of Lapox L12 epoxy (manufactured by ATUL India Ltd.) along with K6 hardener in the ratio 10:1. The addition of hardener ensures proper bonding and curing. Jute and kenaf obtained from local suppliers in India are used as fiber reinforcement in the proposed composite. Aluminium 2024-T3 is used as the skin material. The properties of Jute, Kenaf, and Aluminium 2024-T3 are presented in Table 1.

2.2. Manufacturing

In this work, the compression moulding approach is used used to create composites and FMLs. Composite was made before FML processing since it is the foundation of FMLs. Kenaf and jute fibers of a short length of about 3 mm were dried using the oven to remove the content of water from them, which helped in the reduction of voids.

Following that, the fibers were reinforced in polymer-based epoxy. The fiber weight compositions of kenaf/epoxy and jute/epoxy ranged from 10% to 50% by weight. To eliminate residual stress, 0.5 mm aluminium sheets were annealed in a furnace for 2 hours at 345°C following ASTM B918. After the annealing procedure, the aluminium sheets were allowed to cool naturally. To improve the bonding level of aluminium alloys and composites, the surface of the aluminium was mechanically treated with an 80-grit SiC abrasive. It was discovered that mechanical surface treatment results in a rough surface of aluminium, which improves bonding [44]. The schematic of the manufacturing of FMLs is presented in Figure 1.

Table 1. Properties of materials used in the preparation of FMLs

Properties of fiber	Jute	Kenaf	Properties	Aluminium 2024-T3
Density (g/cm^3)	1.4 to 1.5	1.2	Density (Kg/m^3)	2650
Elongation (%)	1.8	1.6 to 4.3	Young's Modulus (MPa)	72000
Elastic modulus (GPa)	10 to 30	11 to 60	Yield Stress (MPa)	340
Tensile strength (MPa)	300 to 700	223 to 1191	Poisons Ratio	0.31
Cellulose content	50 to 57	37 to 49	Failure Strain	0.175

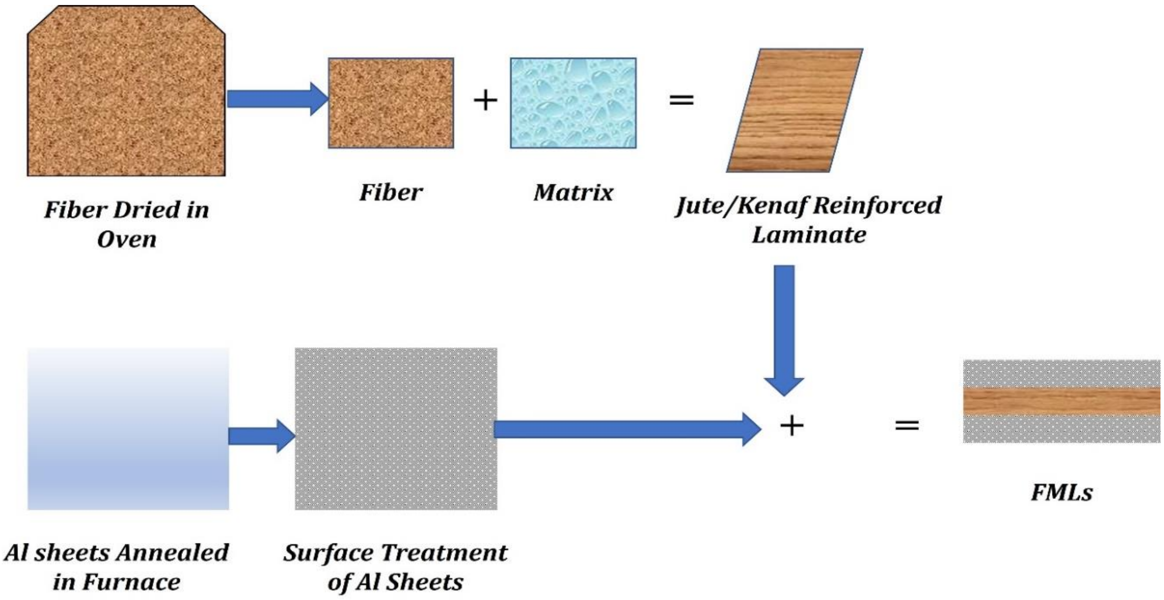

Fig. 1. Schematic of FML manufacturing

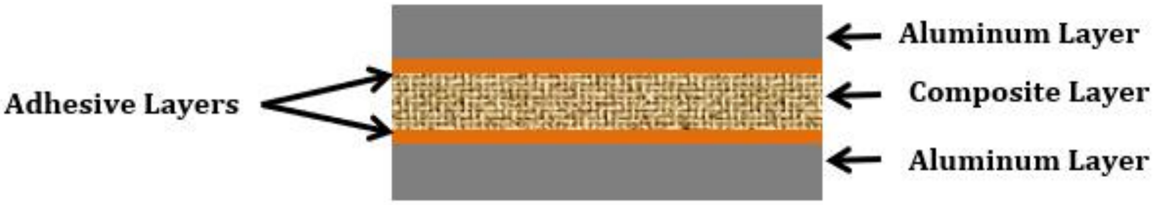

Fig. 2. FMLs with a 2/1 structure

FMLs with a 2/1 structure, as illustrated in Figure 2, were created by joining metallic skin layers to a core made up of composite.

To connect the structure, adhesive chemicals were introduced at the metal composite contact. The aluminium sheets and composite were then assembled in a 4 mm thick picture frame mould. Finally, FML was visually inspected and sliced into the proper specimen size.

2.3. Characterization

FMLs were created using different fiber kinds and weight percentages of fiber (10, 20, 30, 40, and 50 wt%). A universal testing device was used to conduct the tensile and flexural test according to ASTM 3039 and ASTM 790 respectively at 2 mm/min speed of cross-head movement. According to ASTM D6110-18, a Charpy impact testing was executed.

Five specimens of each configuration in each test are tested and their average value is reported as a result along with their standard deviation. After performing the mechanical characterization, the fractography of fiber-reinforced plastics is studied using a scanning electron microscope (SEM).

3. Results and Discussion

3.1. Tensile Test

Tensile tests were performed on developed FMLs to ascertain the impact of fiber type and content on the tensile strength of the materials. Table 2 displays the characteristics of tensile loading of jute and kenaf-incorporated metal laminates with varied fiber concentrations ranging from 10% to 50%. Each tensile parameter's standard deviations are displayed in parentheses. Figure 3 shows the comparison of tensile strength between JFML and KFML with a varied weight percentage of fibers.

Table 2. Tensile characteristics of an FML-based composite made of jute and kenaf (standard deviation)

Weight percentage of fiber (%)	Tensile Strength in Mpa		Tensile Modulus in GPa	
	JFML	KFML	JFML	KFML
10	54.23 (1.18)	56.73 (0.76)	18.56 (0.78)	20.15 (0.65)
20	56.89 (1.05)	58.92 (1.15)	20.31 (0.48)	21.78 (0.75)
30	65.41 (0.75)	68.53 (1.1)	21.82 (0.65)	22.96 (1.05)
40	62.12 (0.65)	65.66 (0.85)	21.15 (0.62)	21.81 (0.91)
50	60.91 (0.61)	62.84 (0.62)	20.45 (0.3)	20.54 (0.22)

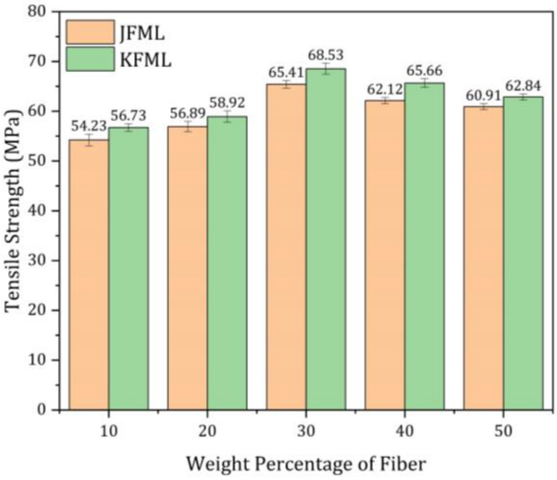

Fig. 3. Variation of tensile strength of JFML and KFML

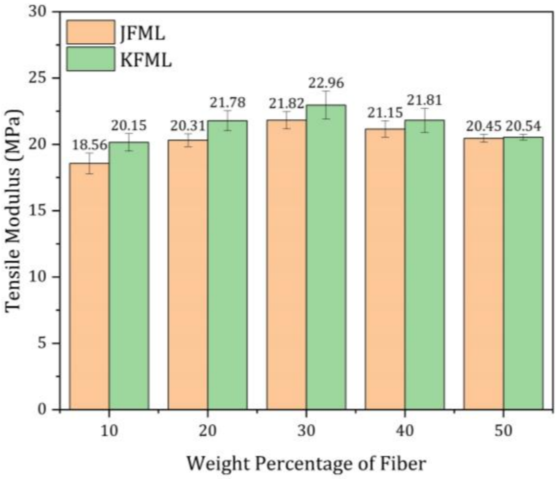

Fig. 4. Variation of tensile modulus of JFML and KFML

When the fiber weight content was raised to a crucial point, the tensile strength rose which is in agreement with the results available in the literature [45]. The outcomes demonstrated that the tensile strength of KFMLs and JFMLs rose from 10% to 30% fiber content. Regardless of the fiber type, FMLs with a 30% wt fiber mix showed the highest tensile strength. The tensile strength of KFMLs and JFMLs was found to be the lowest at a fiber concentration of 10% wt. The results for JFMLs showed that the strength of 30 wt percent JFMLs is 20.61 percent higher than that of 10 wt percent JFMLs, showing that an increase in fiber content was the cause of the JFMLs' notable increase in strength when subjected to tensile loading. However, the tensile strength of JFMLs declined after the fiber content was above 30%.

According to Table 2, JFMLs with tensile strengths of 40 and 50 weight percents of fiber had lower tensile strengths than JFMLs with a 30 weight percent of fiber. Because they make up a significant portion of FMLs, composite materials have an impact on these structures' mechanical strength. The tensile strength of FMLs decreases as the fiber content exceeds the optimal limit of 30 wt percent due to inadequate polymer matrix for fiber embedding. Due to insufficient adhesion and contact between the fibers and the matrix in composite materials without a polymer matrix, there is inefficient stress transfer over the interfacial area [21,46]. The tensile strength thus declines with the increase in fiber content beyond the threshold.

A similar pattern was seen when comparing the tensile modulus of the FMLs as shown in Figure 4, where the tensile modulus increased along with the rise in fiber content up to 30 wt% regardless of fiber kinds. KFMLs and JFMLs have a lower tensile modulus when the critical limit of 30 wt% is reached. On average, FMLs with a fiber content of 30 wt% still had the highest tensile modulus, whilst FMLs with a fiber content of 10 wt% had the lowest.

3.2. Flexural Test

FML with fiber concentration of 30 weight percent, KFMLs, and JFMLs still had the best flexural strength. As predicted, the lowest flexural characteristics were shown by KFMLs and JFMLs with a 10% fiber content. The flexural characteristics of KFML and JFML with varied fiber compositions are shown in Table 3.

Table 3. Flexural properties of jute and kenaf composite-based FML (standard deviation)

Weight percentage of Fiber (%)	Flexural Strength in MPa		Flexural Modulus in GPa	
	JFML	KFML	JFML	KFML
10	76.89 (2.17)	86.51 (2.07)	1.95 (0.4)	2.3 (0.25)
20	81.65 (1.89)	89.54 (2.04)	2.05 (0.15)	2.35 (0.31)
30	110.78 (1.77)	122.08 (1.45)	2.4 (0.21)	3.02 (0.1)
40	98.12 (2.08)	109.56 (1.95)	2.31 (0.15)	2.85 (0.25)
50	87.66 (1.75)	101.54 (1.67)	2.26 (0.12)	2.78 (0.28)

The findings in Table 3 show that as fiber content grew, so did the flexural properties of KFMLs and JFMLs. Figure 5 shows the comparison of flexural strength between JFML and KFML with a varied weight percentage of fibers.

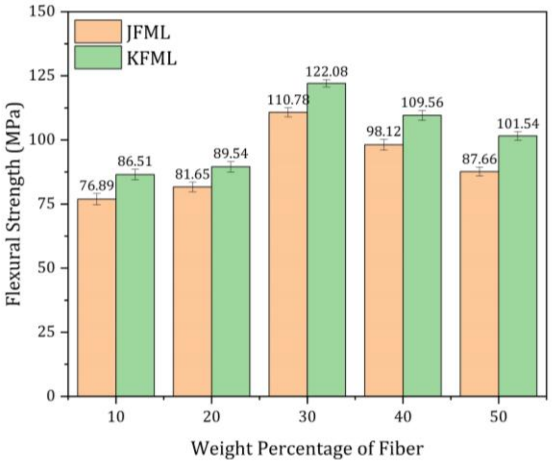

Fig. 5. Variation of flexural strength of JFML and KFML

The strength when subjected to flexural loading of the JFMLs and KFMLs at 30 wt percent was discovered to be 44.07 percent and 41.11 percent greater, respectively, than that of the 10 wt percent FMLs. As shown by a fall in flexural strength of 26.37 percent in JFMLs and a dip in flexural strength of 20.22 percent in KFMLs with 50 weight percentage of fiber, the flexural characteristics of FMLs suffered when the critical limit of 30 wt percent was exceeded. The findings of the flexural test show that the flexural properties of the FMLs may potentially deteriorate due to an insufficient polymer matrix [14,20,28]. Regardless of the fiber type, the composites at 30% wt provided the FMLs with the best flexural properties overall.

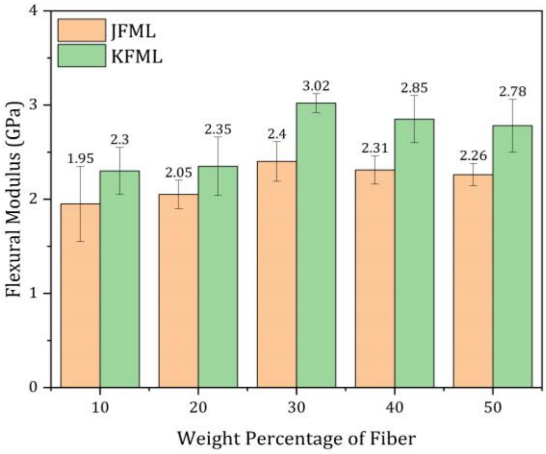

Fig. 6. Variation of the flexural modulus of JFML and KFML

KFMLs and JFMLs' flexural moduli showed a similar tendency to the flexural strength as depicted in Figure 6. Additionally, it was shown that the increase in fiber content enhanced the flexural modulus of KFMLs and JFMLs. The flexural modulus of KFMLs and JFMLs was discovered to increase as the fiber content was changed from 10 wt% to 30 wt%. However, when the fiber content of FMLs increased, the flexural modulus of KFMLs and PFMLs decreased.

3.3. *Impact Test*

The result of the impact strength is displayed in Table 4. Figure 7 shows the comparison of impact strength between JFML and KFML with varied weight percentages of fibers.

Table 4. Impact strength of jute and kenaf composite-based FML (standard deviation).

Weight Percentage of Fiber (%)	Impact Strength in kJ/m^2	
	JFML	KFML
10	42.08 (2.12)	48.77 (2.02)
20	46.71 (1.56)	53.50 (1.92)
30	62.96 (1.76)	68.12 (1.67)
40	57.67 (1.59)	61.98 (1.78)
50	53.32 (2.08)	58.65 (1.08)

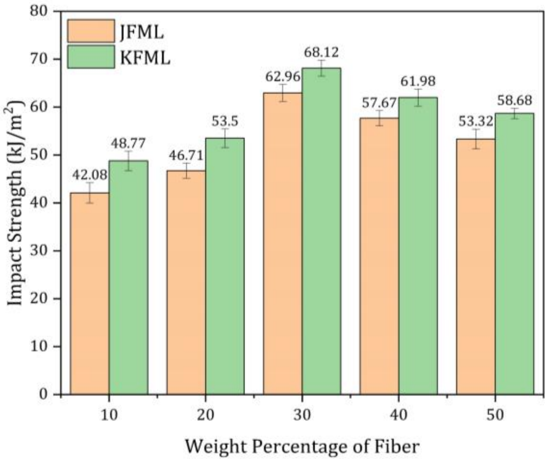

Fig. 7. Variation of impact strength of JFML and KFML

In contrast to JFMLs with lower fiber concentrations, 30 wt percent JFMLs exhibited a much higher impact strength, as indicated in Table 4. The maximum impact strengths were discovered to be 62.96 kJ/m^2 for JFMLs. On the other hand, JFMLs with 10 wt percent of fiber generated the minimum impact strengths, which were 49.61 percent lower than those made with a fiber composition of 30 wt percent. Impact strength may benefit by raising the fiber concentration in JFMLs; The capacity of JFMLs to absorb energy is negatively impacted by fiber content increases over the critical threshold. Notably, increasing the fiber content to 50% weight percent resulted in a reduction of 18.07% in the impact strengths of JFMLs. It has already been stated that the absence of a polymer matrix in FMLs with a high fiber content may impair interactions between the reinforcement and the matrix, limit stress transmission among the components of the composites, and degrade the impact resistance of FMLs [25]. High fiber concentration also causes composite materials to behave brittle, which reduces the materials' ability to absorb energy [23].

KFML impact strength followed a similar trend to JFML impact strength. At 30 weight percent, KFMLs had the highest impact strengths of 68.12 kJ/m2, whereas, at 10 weight percent, KFMLs still had the lowest impact strengths of 48.77 kJ/m2. As a consequence of the trend, the ideal fiber content of KFMLs was 30 wt percent, and as the fiber composition increased over 30 wt percent, the impact strength of KFMLs was found to have decreased. On average, KFMLs are more impact-resistant than JFMLs. KFMLs exhibited an 8.19 percent greater impact strength than JFMLs.

3.4. Morphological Characterization

SEM was used to analyze the morphological behaviors of the fracture surface of FMLs following the tensile test. Figure 8 shows the fractographic pictures of the FMLs.

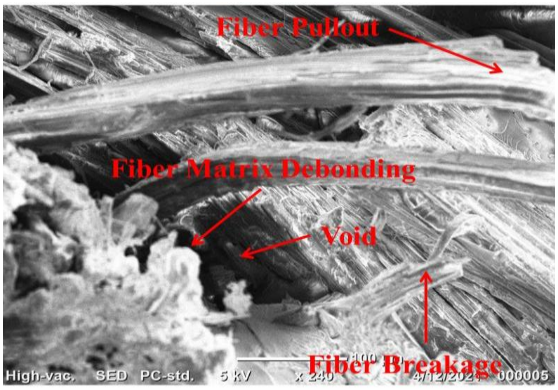

Fig. 8. Fractographic representation of FMLs

Both FMLs' morphological behaviors were quite similar. The pullout, breakage of the fiber, and debonding between fiber and matrix were observed on the fracture surface. The epoxy matrix in the composite can undergo fracture when subjected to excessive stress. This fracture can occur either by brittle fracture. In the case of brittle fracture, the epoxy matrix breaks with minimal plastic deformation, resulting in a smooth, glassy fracture surface. Fibers embedded in the epoxy matrix can experience pull-out when subjected to mechanical loading. This mechanism occurs when the stress applied to the composite causes the epoxy matrix to fail, but the fibers remain intact and are pulled out of the matrix. This results in fiber ends being exposed on the fracture surface, which can be observed as elongated fiber fragments or fibers sticking out of the matrix. Under high stress levels, the fibers themselves can undergo fracture. The fibers may break at various points along their length, resulting in fiber fragments and broken fiber ends on the fracture surface. The appearance of fiber fragments can provide insights into the strength and failure behavior of the fibers. The interface between the fibers and the epoxy matrix can experience debonding due to differential stress distribution or inadequate bonding between the fiber and matrix. Interfacial debonding can occur in the form of fiber-matrix interface separation or matrix cracking around the fibers. The presence of interfacial debonding is often indicated by voids or gaps at the fiber-matrix interface on the fracture surface. As was already said, it is believed that the presence of pull-out and breakage of the fiber enhances the impact strength. Fiber pullout and fiber breakage were visible. Interfacial shear, which occurs when stress is transferred from the polymer matrix to the fiber during tensile loading, causes the fiber to pull out and shatter. This suggests that increasing the fiber content of FMLs up to 30 wt percent might improve their mechanical qualities since the kenaf and jute fibers appear to have supported a sizable amount of weight during the tensile test. In KFMLs and JFMLs, specific voids were also found. This might be owing to the inherent hydrophilic nature of natural fibers, which results in the existence of voids in the FMLs.

3.5. Comparative Study

In order to assess the practical application of the proposed FMLs, the obtained results are compared with the mechanical properties of the FMLs available in the literature [5] and presented in Table 5.

Table 5. Comparative study of mechanical properties

Parameter	Present Study		Literature [5]
	JFML	KFML	Palm Fiber Reinforced FML
Tensile Strength (MPa)	65.41	68.53	60.30
Flexural Strength (MPa)	110.78	122.08	106.86
Impact Strength (kJ/m^2)	62.96	68.12	54.02

It is found from the comparative study that the proposed FMLs outstand the Palm fiber-based FML available in literature in terms of its mechanical properties.

3.6. Future Scope and Applications

Jute and kenaf are natural fibers that offer significant potential as sustainable alternatives to synthetic fibers in composite materials. The future scope lies in further exploring and optimizing these natural fibers' mechanical properties, processing techniques, and their compatibility with other materials. The mechanical properties of the FML can be further enhanced through various strategies. Researchers can investigate different fiber treatment methods, such as chemical treatments or fiber coatings, to improve fiber-matrix adhesion and overall mechanical performance. Additionally, optimizing the fiber orientation, stacking sequence, and metal layer thickness can lead to improved strength, stiffness, and impact resistance of the FML. Future research can focus on developing FMLs with multifunctional properties. For example, integrating conductive materials or nanoparticles into the laminate can enable electrical conductivity or thermal management capabilities. This opens up opportunities for applications in the aerospace, automotive, and electronics industries. The future scope lies in developing advanced design methodologies for FMLs using jute, kenaf, and aluminium. This involves exploring numerical simulation techniques, such as finite element analysis (FEA) or computational optimization algorithms, to optimize the FML's structural performance, weight reduction, and manufacturing feasibility. Further research can focus on developing innovative and cost-effective processing techniques for FMLs. Exploring advanced manufacturing methods, such as automated fiber placement, resin transfer moulding, or additive manufacturing, can improve production efficiency, reduce material waste, and enable the fabrication of complex FML structures.

4. Conclusions

This study aims to investigate the effects of fiber types and compositions on the monotonic and dynamic properties of metal laminates reinforced with kenaf and jute. The following conclusions were drawn in light of the data:

- The best mechanical performance was shown by FMLs with a 30% wt fiber content, regardless of the fiber type. The mechanical characteristics of FMLs improved as the fiber content increased from 10% to 30%. The mechanical characteristics of FMLs are significantly influenced by the interaction between the fiber and matrix. Since the fiber content of FMLs exceeded the maximum of 30% wt, the interaction between fibers and a polymer matrix is prevented by the lack of a polymer matrix for fiber embedding. This weakens the mechanical characteristics of FMLs by limiting the amount of stress that can be transmitted from the matrix to the fibers through the interfacial area.
- In terms of fiber kinds, KFMLs outperformed JFMLs in terms of mechanical qualities. When the mechanical characteristics of KFMLs were compared to JFMLs at 30% wt of fiber, the strength against tensile and flexural loads of KFMLs was 4.76 percent and 10.2 percent more, respectively. Furthermore, it was discovered that KFMLs had impact strengths of 68.12 kJ/m^2, which is 8.19 percent greater than JFMLs.
- According to the findings of this study, jute-reinforced metal laminates show outstanding mechanical potential. Jute is currently the most widely accessible and least expensive natural fiber in India. As a result, adding jute to fiber-reinforced composites and FMLs may lower the cost of the completed product and increase sustainability, consequently improving the mechanical qualities of FMLs made from natural fibers and benefiting the environment. It is hoped that research into the mechanical characteristics of FMLs derived from the environmentally benign materials jute and kenaf will make a substantial contribution to the sector.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the authors have entirely observed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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