Effect of Fiber Misalignment on Mechanical and Failure Response of Kenaf Composite under Compressive Loading

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ABSTRACT

The use of kenaf fibres has grown unexpectedly in the world as they help to establish green materials in automobile, sports and food packaging industries. Over the past few decades, unidirectional fiber-reinforced composites have been extensively used in industry due to their high specific strength characteristics. During manufacturing process, several defects especially fiber misalignment might exist in the unidirectional composite structure. This kind of deviation from its optimal parallel packing in a unidirectional fibre reinforced composite would influence its overall load-bearing efficiency. Performance data of kenaf composite due to this imperfection, however, is very limited in the literature. In this regard, the effects of fibre misalignments on the unidirectional kenaf composite compressive reaction have been studied. For this reason, pultruded kenaf composite specimens with different fibre alignment from 0^0 to 2^0 at 2.1 and 8.4 mm/s strain rates were subjected to a range of compression measures. The findings revealed that, the failure strain seems to be almost constant at value of 0.05 and 0.063 while the failure stress decreases from 140Mpa until 120MP when the fibre alignment increases when loaded within a range of 2.1~8.4s^{-1}. Additionally, under increased fiber misalignment and strain rate, fibre plastic microbuckling, fibre breakage, fibre splitting and fibre matrix debonding was progressively formed on the specimen.

Keywords: *Kenaf composite; Fiber misalignment; Damage behavior*

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Introduction

The researchers have been especially interested in kenaf fibre composite in recent years and are becoming popular in a variety of applications including construction [1, 2], sports and the car industry [3, 4] due to its overall results, recyclability and sustainable properties [5]. More recently, the rising need for light-weight vehicles that meet strict fuel economy and safety criteria has encouraged the application in the automotive industry of the kenaf composite [6]. Low manufacturing costs and rapid production processes, resulting in small angle fibre misalignments within any structure, are important to compete in this industry [7, 8]. Worse still, it may be the greatest hurdle in this industry for kenaf composite widespread use.

In unidirectional (UD) high-performance composites, misaligned fibres are inevitably present. The fibre misalignment in UD composite is used to express the deviation of the fibres, which is not totally in parallel. This production-related imperfection [9] would control the mechanism of compressive failure, as it was loaded, called the localised plastic microbuckling [10] which is generally accepted as the dominant failure mode in UD fiber composite [11].

Composite material should have no flaws in order to serve the particular application well, especially fibre misalignment that govern during the production process, as it affects the structure's overall performance [12, 13]. The mechanical properties of the carbon fiber composite laminates with fibre misalignment angles of 0 to 40° in single ply samples and of 0 to 90° in one ply for two-ply samples have been investigated by Yang et al. [14]. They have observed that fibre misalignment noticeably reduces strength and elastic modulus of the carbon fiber composite.

Werken et al. [15] has also studied the fibre-alignment effects on the mechanical properties of recycled carbon fibre composites. The degree of alignment has been shown to have the most important effect on the composite strength and elastic modulus. The aligned composite showed an improvement of 100% and 137% in normalised tensile strength and module of recycled carbon fibre composites.

Several finite element analyses (FEA) have also been conducted to understand the effect of fiber misalignment on composite performance. For example, carbon fibres composite, although the angles of 0.25° were small, were predicted to decrease from 2720 MPa to 1850 MPa as reported by Wisnom [16]. Song et al. [17] performed a comparison between experiments and the FEA to study the influence of the original fibre alignment on the mechanical characteristics of GMT composites. The findings demonstrate that the initial orientation of the fibres in the first GMT sheets plays an important role on the finished part's structural properties.

In addition, the presence of fiber misalignment on composite material may lead to some damage such as fiber breakage and fiber-matrix debonding when loaded [18]. Hillig [19] stated that high-fibre misalignment regions of glass fibre composite can serve as nucleation points for instability-failure processes, for example buckling and shear-induced delamination. To date, there are only a few researches on the effects of fibre misalignment on kenaf composite. Static compression tests for kenaf composite material were therefore conducted to detect the effect of fiber misalignment on mechanical properties, in particular on failure stress and failure strain as well as subsequent damages.

Methodology

Specimen preparation

The pultruded kenaf composites with 60% fiber volume fraction used in this study were made of kenaf fiber with tex number 2200 and unsaturated polyester that were produced through pultrusion process with a diameter of 14 mm. Kenaf composite with a combination of 60% fiber volume fraction and tex number 2200 has been chosen as it has a good compressive strength as reported by Zamri et al. [20]. Other mixtures for resin such as benzoyl peroxide (BPO) as initiator, calcium carbonate (CaCO3) as filler and the release agent powder were also used.

Based on ASTM E9-89a (2000) designation, 18 specimens were produced using the metallurgical specimen cutter and miling machine with length/diameter (L/D) of 1.5 and 3 different alignment angles of 0°, 1° and 2° as illustrated in Figure 1. For each strain rate and fiber misalignment tested, 3 samples have been used. The fiber angle was selected between $1\text{-}2^0$ because it was the most commonly reported misalignment angle for pultruded parts as reported by Yurgartis [21]. The fiber alignment was examined in which specimens were cut into two separate parts through the fiber direction and then placed below the SEM. During the cutting process, lubricant which act as coolant was used to help the dissipate heat in order to prevent over heating which might cause changes in morphology of kenaf fiber composite material. Parallel contact surfaces were prepared by grinding for maximum contact and removing possible bending moment.

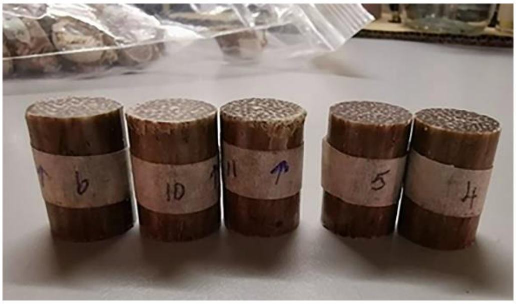


Figure 1: Specimens with different angles.

Mechanical testing

The static compressive tests were conducted to identify the mechanical properties of the kenaf composites using the universal testing machine (UTM) at two different strain rates of 2.1 s^{-1} and 8.4 s^{-1}. This strain rate which corresponds to crosshead speed of 1mm/s and 2.5mm/s was appropriate to show the effect of strain rate on compressive properties and failure behaviour of kenaf composite under low strain rate range. The specimen is positioned centrally between the two compression plates, so that the travelling head centre is vertically above the specimen centre as shown in Figure 2. During the compression testing, the end friction between the sample and compression plates was reduced by means of a lubricant in the contact field. An appropriate preload was added where the crosshead travels to load the specimen to a specified value before a test becomes reliable. The specimens were tested until failure up to a maximum load of 17 kN to attain strain values and load carrying capacity. Stress-strain curves for each of the specimens were then plotted based on the data obtained as shown in Figure 3 and Figure 4.

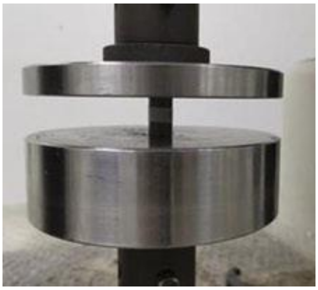


Figure 2: Position of specimens during compression test using UTM.

Failure observations

Microscopic photographs of all damage specimens have been taken with the Hitachi S-3700N scanning electron microscopic (SEM) to achieve resolution of up to 500 μm in order to find various post-compression failures. Before the SEM process was carried out, the specimens were covered with carbon layer using the sputter coater. For macroscopic images, the damage behaviour of the kenaf composite was identified in three different fibre alignments value and strain rates using an optical camera.

Results and Discussion

Mechanical properties

In the fibre direction of the composites, uniaxial compressive experiments have been carried out. Stress-strain curves with a strain rate of 2.1/s and 8.4/s are shown in Figure 3 and Figure 4 for the specimens with 3 different degree of alignment. Based on Figure 3 and Figure 4, as the fibre misalignment increased from 0^0 to 2^0, it did not generally affect the form of the stress-strain curves. The initial straight section of the curve up to the yield point represents the specimen's elastic responses. The yield point signals the beginning of inelastic behaviour, where the curve then displays stress hardening before its maximum stress is reached. The highest stress on the graph is the ultimate stress when the specimen collapsed after the maximum load-bearing capacity was surpassed. Strain softening then took place up to the residual strength of the specimen. Similar stress-strain curve which showed elastic brittle behavior has also been reported by Dewan et al. [22] for natural jute/polyester composite.

On top of that, under different strain rates loading, the initial straight section of the stress-strain curves up to the yield point was not significantly changed. However, rate of strain softening which took place up to the residual strength of the specimen was fairly decreased as strain rates increased. Strain softening which is deterioration of material strength with increasing strain was decreased since the cumulative damage at certain stresses was much smaller under a slightly high stain rate. Hence, the residual stress of the specimen can withstand considerably more load at high strain rates and deform much longer.

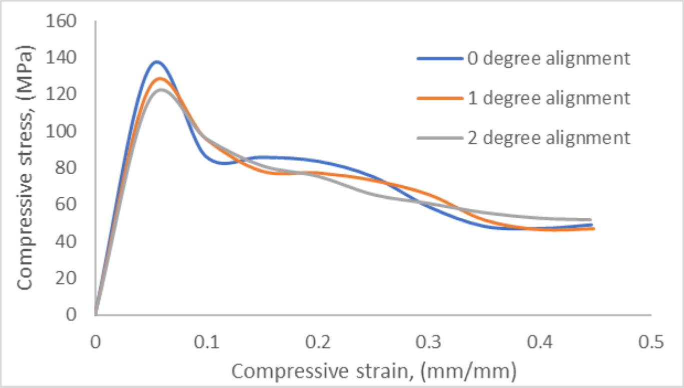


Figure 3: Stress-strain curves of kenaf composite under strain rates of 2.1/s.

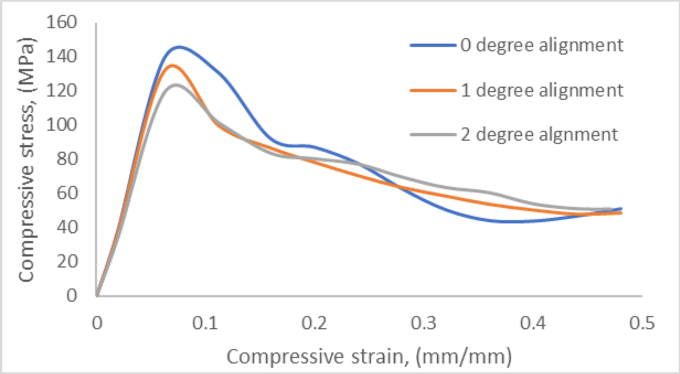


Figure 4: Stress-strain curves of kenaf composite under strain rates of 8.4/s.

The mechanical properties for sets of samples of kenaf composite materials are presented in Figure 5, Figure 6 and Table 1. Figure 5 shows the average failure stress of the kenaf composite as a function of fibre alignment under two different strain rates. Generally, as the fibre alignment increased from 0^0 to 2^0, a maximum of 14% reduction in compressive failure stress was observed. However, under difference strain rates, the percentage of reduction was different. At strain rate of 2.1/s, failure stress was decreased from 140 Mpa to 120 MPa while at 8.4/s, failure stress was decreased from 136 Mpa to 119 MPa. Similar reduction in performance has also been reported by Yang et al. [14] and Werken et al. [15] when fiber alignment introduced in the carbon fiber composites.

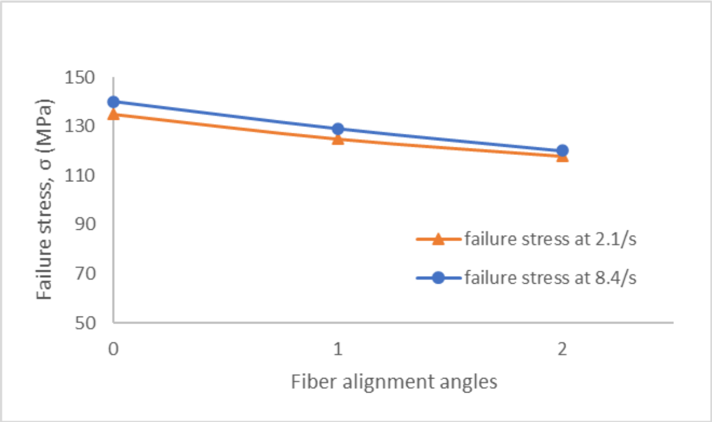


Figure 5: Failure stress vs fiber alignment angles.

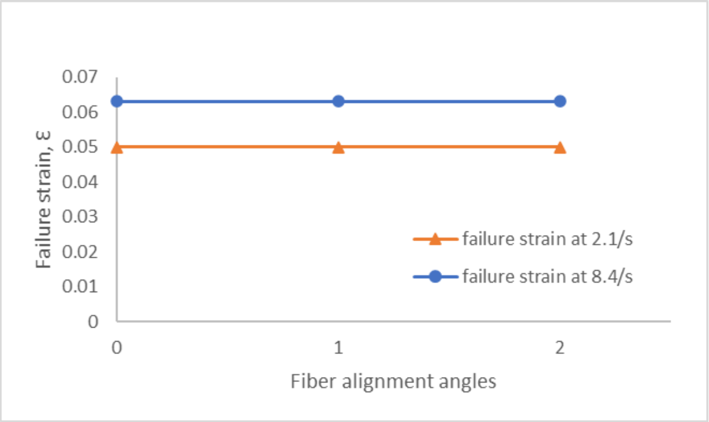


Figure 6: Failure strain vs fiber alignment angles.

Table 1: Compressive failure stress and failure strain of kenaf composite

Fiber alignment angle	Failure stress (MPa)		Failure strain	
	2.1 mm/s	8.4 mm/s	2.1 mm/s	8.4 mm/s
0^0	136	140	0.05	0.063
1^0	128	132	0.05	0.063
2^0	119	120	0.05	0.063

Figure 6 shows the failure strain of the kenaf composite as a function of fibre alignment under two different strain rates. As the fibre alignment increased from 0^0 to 2^0, the failure strain seemed almost constant at a fixed value. However, different value of failure strain was observed under different strain rates. At strain rate of 2.1/s, value of failure strain is 0.05 and when loaded under strain rates of 8.4/s, the failure strain is 0.063 which was increased by 26%.

Azizan et al. [23] explained the cause of failure stress reduction where the existence of fibre misalignment created an additional bending stress on the overall stress that broke the composite much earlier before its compressive strength was achieved. As shown in Table 1, only failure stress was affected by the change of fiber alignment. However, both the failure strain and failure stress were affected by the change of strain rate as they were slightly increased. Change of mechanical properties value even under low strain rate region was also reported by Hao et al. [24] when they tested nonwoven kenaf composite under tensile loading.

Damage behaviors

Microscopic observations showed that fibre matrix debonding and matrix cracking were observed on the top and bottom surfaces of each specimen with 3 different alignment angles tested under 2 different strain rates, without any fibre pull-out and fibres breaking as shown in Figure 7. Fiber matrix interface degradation was reported to generate considerable degradation in the composite's transverse response resulting in the premature degradation of the stress-strain curve [25], followed by other failures due to continuous compression of the specimens.

Macroscopically, the fibre misalignment played a major role in determining failure behaviours as shown in Table 2. With the degree of alignment increased, fibre breaking, fibre splitting and fibre matrix debonding were much more progressive than specimens with ideal parallel packaging. In addition, most of the failures that have been mentioned above were more noticeable at the middle region of the specimen with increasing fibre misalignment. Table 3 shows that most failure occurred only in half portion of the lower region in relation to the fibre misalignment of 1^0 and 2^0 in the top view of a failed kenaf composite, as compared with an ideally aligned specimen where a bottom zone failure was equally distributed.

Optical sample observations also show that an angle fracture plane occurred as a result of shear failure (Table 2). Generally, micro buckling of fibre was resulted from the process of shear instability in the matrix material that is caused by the plastic yielding at higher strains. The presence of fibre misalignment defects in a longitudinal direction, while compressing, is supposed to lead to kinks in a localised region. This eventually leads to the creation of fibre kink-bands and compressive kink failure [26]. It is important to note that fibre misalignment is very sensitive to kinking stresses. Outcome of this study are in line with what reported by where the 0.8–2.3° angle of misalignment was sufficient to cause a kink [27].

As shown in Table 2 and Table 3, the failure progression of the specimens with higher fiber misalignment is gradual compared to ideally aligned specimens. As previously discussed, main failure under compression loading of unidirectional composites was plastic kinking due to the existence of fiber misalignment and subsequent occurrence of matrix's shear instability. In Table 2, fiber kinking was a first failure initiated and visible prior to an inclined shear crack and fiber splitting. However, for specimens of high fibre misalignment, the gradual formation of the kink band and the associated fibre kink failure mode are more obvious.

Decohesion at the interface and shear band formation in the matrix are the two dominant damage mechanisms in controlling the composite strength [28]. In condition where decohesion is constricted, matrix's shear bands would occur at angle of $\pm 45^0$ from the compression axis [29]. The angle between the failure plane and the in-plane load direction is slightly higher than 45° and typical values are reported between 50-56° for certain composites which may be more susceptible to shear bands formation [30]. For kenaf composite's compressive strength reported here, it was controlled by the visible decohesion of fiber and matrix at the interface as no shear bands failure occurred. As fiber misalignment increased, decohesion of fiber and matrix at the interface was more obvious (Table 2 and Table 3) which contribute to the reduction of compressive strength.

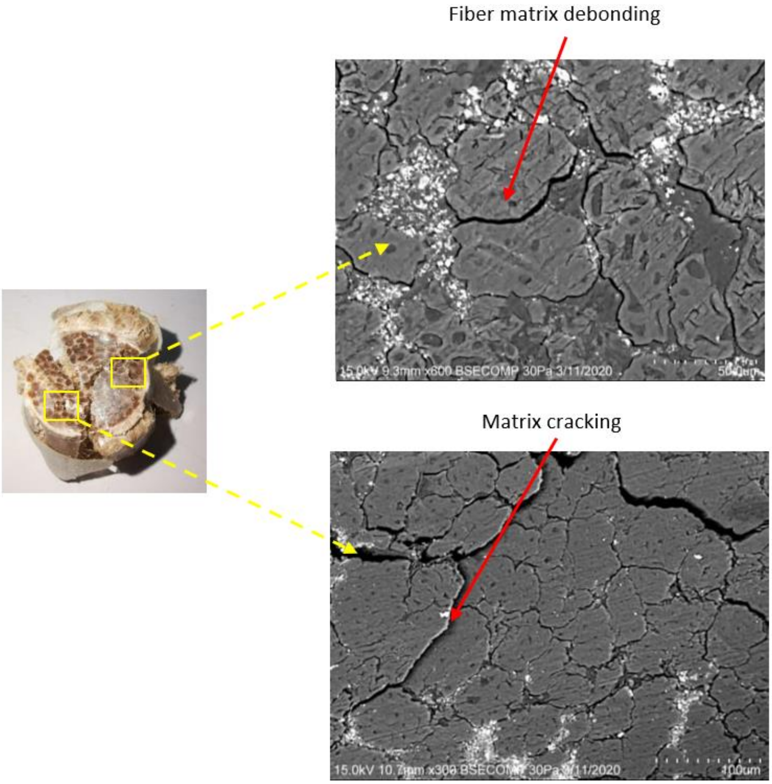


Figure 7: Top surfaces of kenaf composite.

Regarding this phenomenon, because fibre misalignment has increased, the specimen was subject to a much greater extra bending stress, thus leading to progressive damage. The kenaf composite was also gradually deteriorated as the strain rate increased, as shown in Table 2 and Table 3. This happened since the accumulated damage in certain stresses was much lower under a slightly high stress rate. Hence, the material can withstand substantially greater load with minimal damage at high strain rates and deform much longer until it fails [31].

Table 2: Side views of kenaf composite

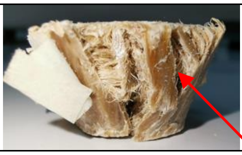
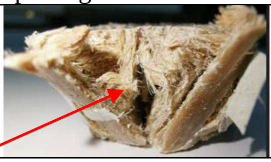
Alignment Angle	2.1/s	8.4/s
0°		
	Longitudinal splitting	
1°		
	Fibers breakage	
2°		
	Fibers plastic microbuckling	

Table 3: Top views of kenaf composite

Alignment Angle	2.1/s	8.4/s
0°		
1°		
2°		

Conclusions

This study has been performed with 3 different misalignment angles and loaded under two different strain-rate conditions to identify the effect of fibre misalignment on the mechanical properties and on the damage behaviour of kenaf composites. With a mean value of 0.05 and 0.063, the failure strain seems to be almost constant while the failure stress decreases from 140 Mpa until 120 MP when the fibre alignment increased when loaded within a range of 2.1~8.4/s. Fiber matrix debonding and matrix cracking have been typical failures, when loaded longitudinally, on top and bottom surfaces of every specimen. However, when the fibre alignment angle was increased, plastic microbuckling, fibre breakage, the fibre splitting and the fibre matrix debonding was progressively formed. In addition, the failure stress of kenaf composite was slightly increased by a maximum of 3% and a more progressive damage was observed as strain rate increased from 2.1~8.4/s.

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