Pertanika J. Sci. & Technol. 31 (1): 425 - 436 (2023)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Failure Behavior and Mechanism of Pultruded Kenaf/Glass Hybrid Composite Under Compressive Impact Loading

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ABSTRACT

A substantial amount of kenaf fiber research has been carried out recently to incorporate more sustainable materials into the production process. For many years, scientists have studied the properties of kenaf and the hybrid composites it may form. Composites made from kenaf and synthetic fibers were the focus of the majority of the study. Similarly, the researchers discovered mechanical characteristics as a fundamental truth. Despite this, earlier research on particular properties has not permitted using kenaf composites for load-bearing purposes. Nevertheless, kenaf composites can significantly influence car exteriors and other vital applications, even if their impact characteristics are only studied in other materials science disciplines. Due to this, dynamic failure behavior and mechanism of unidirectional kenaf and kenaf/glass hybrid composite compressive response were examined. Therefore, both composite specimens were loaded compressively under static and dynamic loading at a strain rate range of 0.1/s to 1700/s. The results showed that the failure behavior and mechanism of kenaf and kenaf/glass hybrid composite were different under static and dynamic loadings. Shear banding failure occurred at 60 degrees for kenaf composites. In contrast, kenaf/glass composites were fractured longitudinally along the fiber direction under static loading. Glass fibers in hybrid composites were more vulnerable to damage under microscopic analysis because they carried most loads. Consequently, the kenaf fibers in hybrid composites were less damaged than those in kenaf composites, which had fiber breakage, fiber splitting, and fiber-matrix debonding.

Keywords: Compressive loading, failure behavior and mechanism, high strain rate, kenaf/glass composite

ARTICLE INFO

Article history:
Received: 26 January 2022
Accepted: 22 April 2022
Published: 09 November 2022

DOI: https://doi.org/10.47836/pjst.31.1.25

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ISSN: 0128-7680
e-ISSN: 2231-8526

INTRODUCTION

The usefulness of composite structural material, such as a hybrid combination of synthetic and natural fibers, is greatly enhanced because natural fibers are abundantly available and significantly less expensive. Furthermore, the growth in the market for hybrid fiber composites is encouraging research and development to provide even better utilization of natural fiber resources by improving its mechanical properties. However, the mechanical properties of natural fiber composite are significantly lower than synthetic fiber composite, which limits the application of natural fiber composite for structural purposes. Nevertheless, natural fibers are preferable when applied to improve composite materials since their lower manufacturing costs help to reduce the overall cost of composite fabrication while maintaining material properties.

Since the 1990s, the use of natural fiber composites has been the subject of a number of research investigations, most notably in the automobile (Ravishankar et al., 2019), household, and construction industries (Onuwe et al., 2018). The problem with natural fiber is that it is not as strong or as water-resistant as synthetic fiber. So, mixing natural and synthetic fibers to boost mechanical performance and repel moisture is highly beneficial. Several experiments with different combinations of natural and synthetic fibers are being conducted in the automotive, packaging, aerospace, and sports industries to apply secondary structures in their respective fields (Safri et al., 2018).

The mechanical properties of hybrid composite materials have been researched extensively using various research methodologies. For example, Zhang et al. (2013) studied the response of flax/glass composite under tensile loading. The tensile properties of the composite improved as the proportion of glass fiber rose. In a similar study, Sanjay and Yogesha (2018) found that mechanical characteristics strengthened when glass fiber was partially incorporated into the woven jute/kenaf/glass fiber hybrid composite.

Mishra et al. (2003) examined the tensile properties of glass/sisal and glass/pineapple leaf fiber reinforced polyester composites. Tensile strength was improved by hybridization in these composite materials. Using a woven combination of kenaf and glass fibers, Subramaniam et al. (2019) explored the characteristics of tension and quasi-static indentation in composite metal laminate made of metal woven fabric with similar fiber weight fractions and diverse fiber stacking sequences. Composites with glass fiber in the topmost layers showed great resistance to indentation and tensile strength when compared to composites that were not hybrid.

Carbon/flax fiber reinforced epoxy hybrid composites were analyzed by Sarasini et al. (2016) to find out the characteristics of low-velocity impact damage. Regarding the enhanced energy absorption capabilities of flax fibers, the hybrids showed to have greater fracture propagation resistance because of it. Kenaf/X-ray/epoxy hybrid composites also possess a surprisingly good energy absorption when impacted by hemispherical projectiles, as discovered by Azmi et al. (2019). However, an impact force of 800N and an energy of 135 Joules are no match for this hybrid composite's impressive shock resistance.

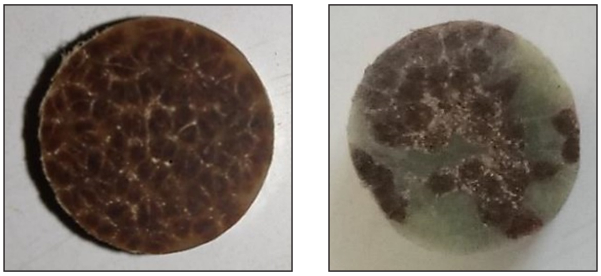
Composites made from kenaf/glass and kenaf/epoxy, when impacted at 9J, had significant crack lengths of 52.92 and 100.61 millimeters, respectively. Kenaf/glass hybrid composites were resilient to impact because of the incorporated woven glass and kenaf. In the meantime, 16.02 mm damage to the glass/epoxy composite was measured (Majid et al., 2018). Other studies have shown that 25% kenaf and 75% glass fiber composites perform nearly identical to 100% glass fiber composites in terms of mechanical properties. Under low-speed testing, the kenaf/glass fiber hybrid composite, stacked up to 10 layers, could absorb 40J (Ismail et al., 2019).

Matrix cracking, delaminations, fiber fracture, and infiltration have all been observed due to low-velocity impact (Ahmad Nadzri et al., 2020). In all laminate kenaf/epoxy and hybrid composites studied by Majid et al. (2018), matrix cracking was found to be the primary source of damage. Woven kenaf fibers showed an interesting behavior as they acted as a mechanism to arrest the spread of matric cracking and to confine its propagation through the weft and warp directions, as opposed to crack propagation along the radial direction under low-velocity impact loading.

Despite significant effort, little is known about the hybridization effect of glass fibers in the pultruded natural/synthetic fiber reinforced hybrid composites in the face of high impact loading, and much less about the specific failure behavior and mechanism. It is, therefore, necessary to investigate the static and dynamic mechanical responses of pultruded kenaf/glass hybrid composites to comprehend their potential application range.

METHODOLOGY

The pultruded kenaf and kenaf/glass hybrid composites in this study were made of kenaf fiber with tex number 1400, E-glass unidirectional glass fibers and unsaturated polyester were produced through a pultrusion process with a diameter of 12.7 mm. Benzoyl peroxide (BPO) was utilized as an initiator, calcium carbonate ($CaCO_3$) was used as a filler, and a powdered release agent was used in the resin combination. As a result, kenaf composite was produced with 80% fiber volume fraction. In contrast, the kenaf/glass hybrid composite was produced with a kenaf to glass fiber ratio of roughly 1:1 (Figure 1).



(a) (b)

Figure 1. Pultruded specimens: (a) kenaf; and (b) kenaf glass hybrid composites

For dynamic and quasi-static uniaxial compression tests, kenaf and kenaf/glass hybrid composite cylindrical specimens with a diameter of 12.7 mm were utilized. Abu Seman et al. (2019) employed the ideal slenderness ratio of 0.5 for the split Hopkinson pressure bar (SHPB) test. According to ASTM standard E9–89, a slenderness ratio of 1.5 was preferred for static tests, which resulted in the specimen in Figure 1. The lubricant was added to the contact field to help reduce the end friction between the sample and compression plates. The surface was ground to achieve maximum contact and remove any possible additional stress.

A Universal Testing Machine (UTM) was used to conduct the static compressive tests that identified the mechanical properties of the kenaf composites. In order to ensure that the moving head center is vertically above the specimen center, the specimen is positioned centrally between the two compression plates. A correct preload was provided at the crosshead location, where the device's loading mechanism arrives to prepare the specimen for a certain value before a test may be confirmed. The specimens were put under load until they reached a certain level of strain, and their load-bearing ability was measured. The displacement data points for each specimen were then calculated into stress-strain curves.

An SHPB constructed of steel bar (diameter of 12 mm) at the School of Aerospace Engineering, Universiti Sains Malaysia (USM), was used for the dynamic characterization of kenaf and kenaf/glass composites. The SHPB compression test setup is shown in Figure 2. SHPB functions on the elastic wave theory principle. The incident bar, transmission bar, and striker bar make up the SHPB. Compressed air moves the striking bar inside the barrel up to 2 bars. The cylindrical composite sample is placed between the transmission bars during the test. When the striking bar hits the incident bar, a rectangular compressive wave with continuous amplitude is generated. The incident bar, specimen and transmission bar then propagate that wave. Wave propagation partially reflects the tensile pulse at the boundary between the specimen and the incident bar. The data acquisition system (DAQ) collects and calibrates the voltage pulses generated by pressure gauges. The stress and strain generated by a dynamic equilibrium in the specimen at different times were then estimated with the elastic wave theory.

Figure 2. Split Hopkinson pressure bar

The specimen's strain rate, strain, and stress histories can be derived from a one-dimensional stress-wave analysis performed on the bars as shown in Equations 1 to 3:

$$\dot{\varepsilon} = \frac{C_0}{L_s}[\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] \quad [1]$$

$$\varepsilon = \frac{C_0}{L_s}\int_0^t [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] \quad [2]$$

$$\sigma = \frac{A_0}{2A_s}E_0[\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] \quad [3]$$

ε_i (t), ε_r (t), and ε_t (t) are incident, reflected, and transmitted strain pulses,
A_0, E_0 and C_0 are bars cross-sectional area, Young's modulus and wave speed,
A_s and L_s are the specimen' initial cross-sectional area and length.
Under conditions of homogeneous stress in the specimen, pulses become Equation 4:

$$[\varepsilon_i(t) + \varepsilon_r(t) = \varepsilon_t(t)] \quad [4]$$

Equations 1 to 3 can be simplified as Equations 5 to 7:

$$\dot{\varepsilon} = -2\frac{C_0}{L_s}\varepsilon_r(t) \quad [5]$$

$$\varepsilon = -2\frac{C_0}{L_s}\int_0^t \varepsilon_r(t)\, dt \quad [6]$$

$$\sigma = \frac{A_0}{A_s}E_0\varepsilon_r(t) \quad [7]$$

As a result, the stress-strain data can be extracted from the collected strain gauge signals in an SHPB experiment.

With the Hitachi S-3700N scanning electron microscope (SEM), microscopic images of all specimens that suffered damage are captured at resolutions of up to 500 µm to uncover different post-compression failures. Prior to SEM analysis, a carbon layer was applied to the samples using a sputter coater. For macroscopic pictures, a standard camera was used to document the damage behavior of the kenaf and kenaf/glass composites at low and high strain rates.

RESULTS AND DISCUSSION

In the fiber direction of both composites, uniaxial static and dynamic compressive experiments have been carried out. Strain data captured by the strain gauge mounted on the incident and transmitter bars of SHPB during high strain rate testing of kenaf and kenaf/glass composite is shown in Figure 3. The incident reflected and transmitted strain pulses are denoted as I, R and T, respectively. Those pulses have been extracted and used in Equations 5 to 7 to calculate the stress-strain curves of both composites. Stress-strain curves of kenaf and kenaf/glass composites were then compared under static and dynamic loadings (Figures 4 and 5).

Under static loading, for the kenaf composite, 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 behavior, where the curve displays stress hardening before its maximum stress is reached. The highest stress on the graph was the ultimate stress when the specimen collapsed after the maximum load-bearing capacity was surpassed. Strain

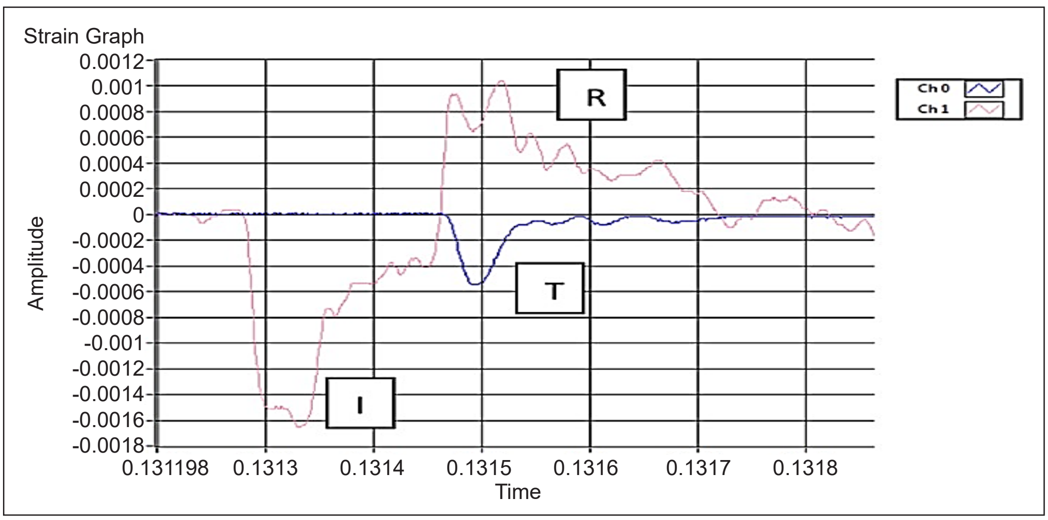


Figure 3. Incident, reflected and transmitted data obtained from SHPB

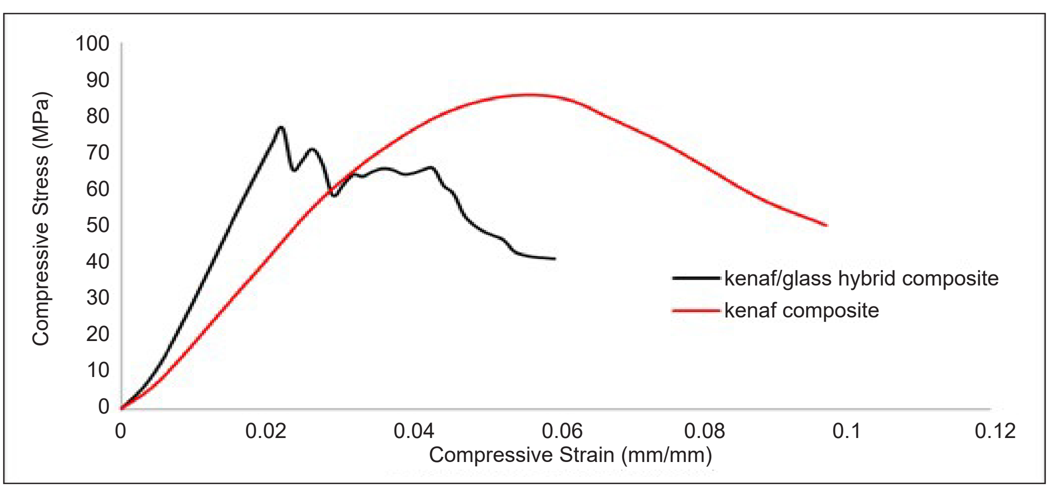


Figure 4. Stress-strain curves of kenaf and kenaf glass hybrid composite under static loading

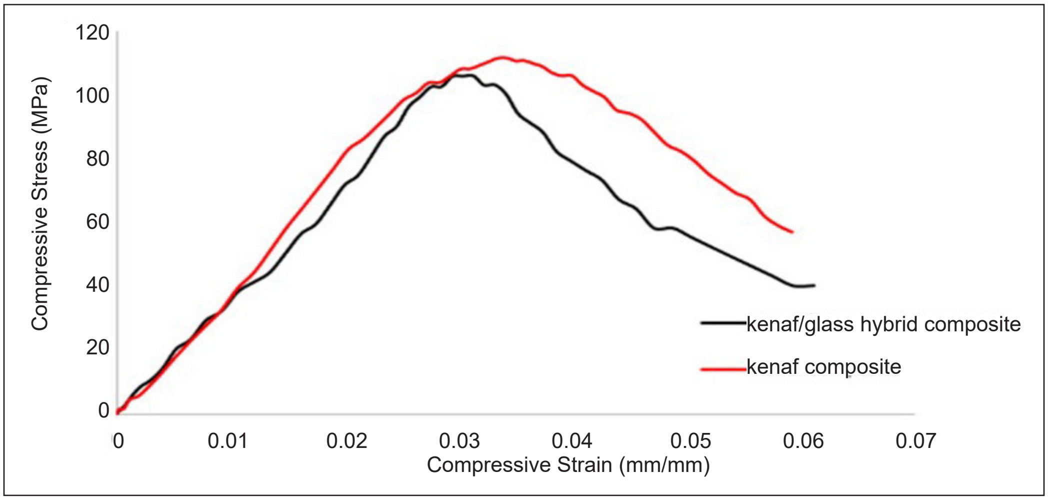


Figure 5. Stress-strain curves of kenaf and kenaf glass hybrid composite under dynamic loading

softening then takes place up to the residual strength of the specimen. Dewan et al. (2013) also observed similar stress-strain curves showing elastic-plastic behavior for a natural jute/polyester composite.

The kenaf/glass hybrid composite demonstrated different stress-strain curve behavior. After the initial straight section of the curve up to the yield point, no stress hardening region is observed. Nonetheless, after the maximum load-bearing capacity was surpassed, the specimen fractured brittlely, especially by the glass fibers. However, as shown in the stress-strain curves (Figure 4), even though some glass fibers failed, kenaf fibers could carry the applied load until the second maximum stress was achieved. Ashraf et al. (2021) also reported a similar stress-strain curve for a flax/glass hybrid composite that demonstrated elastic-brittle and dual fracture site behavior.

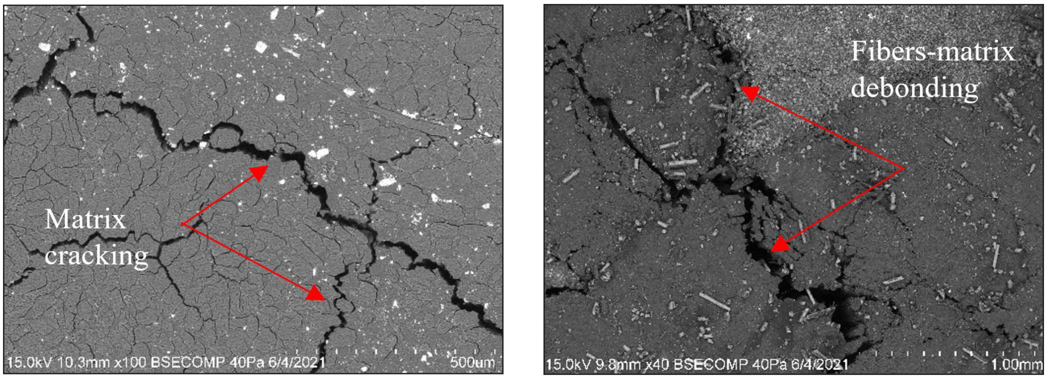
Under dynamic loading, the shape of stress-strain curves for kenaf and kenaf/glass composites are just slightly different. It is because loads were applied instantaneously on the fibers, and all fibers have deformed uniformly throughout the specimens. Nonetheless, for the kenaf/glass composite, it did not show any strain hardening region before maximum stress was reached. It happened because the glass fibers in the hybrid composite handled most of the load when subjected to dynamic loading (Figure 5).

Failure stress and strain of kenaf and kenaf/glass hybrid composites are shown in Table 1. As shown in Table 1, the failure stress of the kenaf/glass hybrid composite was slightly lower than the kenaf composite under both static and dynamic loadings. The slight reduction in failure stress can be explained by the low bonding strength between kenaf and glass fibers in the hybrid composite (Figures 6 and 7). According to Goutianos et al. (2018), the inter-fiber bond density and strength would have a greater impact on both Young's modulus and strength of the fiber-reinforced composites but only a modest impact on the strain to failure. Post failure SEM images of hybrid composites after static and impact loading showed that the interface between kenaf/glass fibers would be the stress concentration area that contributed to the strength degradation. Tamrakar et al. (2021) noted a minor decline in flexural strength in their study when 12.5% of kenaf fibers were added to the kenaf/glass hybrid composite. Additionally, adding glass fibers to the hybrid composite has reduced the elongation capability, reflected in the failure strain reduction of as high as 60% when loaded statically. Sharba et al. (2016) also found similar outcomes where the addition of glass fibers in the kenaf woven hybrid composite did not significantly change the compressive strength (78MPa to 88MPa) but noticeably changed the failure strain from 1.8% to 0.8%.

Microscopically, distinct types of failure were shown between kenaf and kenaf/glass composites when compressed under static and impact loading (Figures 6 and 7). Matrix cracking was dominant for the kenaf composite, while fiber-matrix debonding was observed for the kenaf/glass composite when loaded statically. As explained before, the low bonding strength between kenaf and glass fibers would be the main culprit for the low failure strength of the hybrid composite. Glass fibers in hybrid composites were more vulnerable

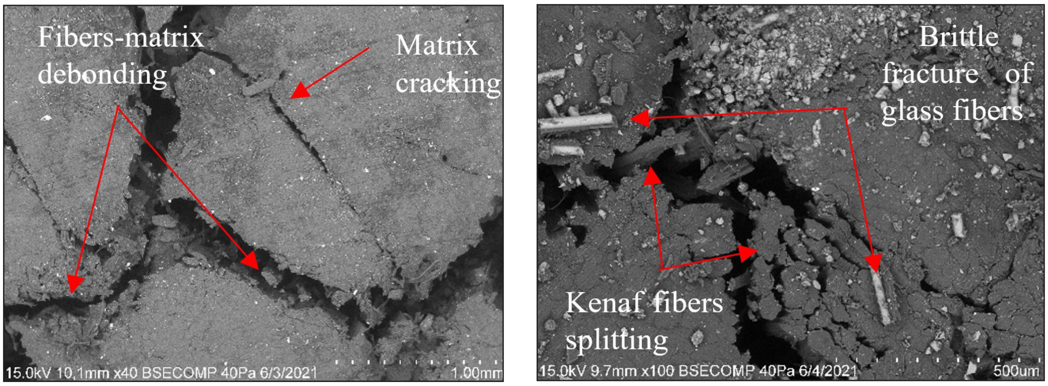
Table 1
Effect of strain rate on composites' mechanical properties and failure behavior

Loading rate	Specimen	Failure stress (MPa)	Failure Strain (mm/mm)	Type of failures
Static	Kenaf	86	0.056	Matrix cracking, shear banding
	Kenaf/glass	77	0.022	Fibres-matrix debonding, Glass fibres fracture, longitudinal splitting
Dynamic	Kenaf	111	0.034	Fibres-matrix debonding, Matrix cracking, shear splitting
	Kenaf/glass	106	0.031	Glass fibres fracture, kenaf fibres splitting, shear splitting



(a) (b)

Figure 6. SEM images of specimens' surfaces: (a) kenaf; and (b) kenaf glass composites under static loading

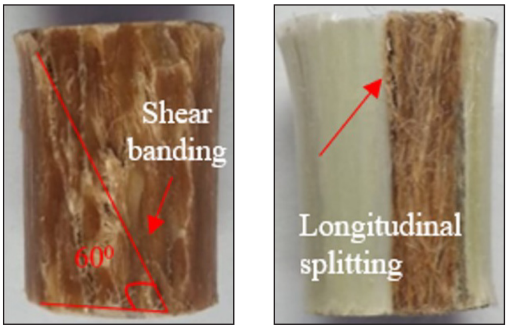


(a) (b)

Figure 7. SEM images of specimens' surfaces; (a) kenaf; and (b) kenaf glass composites under dynamic loading

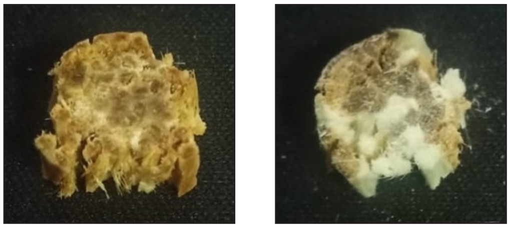
to degradation during dynamic loading because they carried most of the stresses. As a result, there were less fiber breakage, split fibers, and fiber-matrix debonding on kenaf fibers in the hybrid composites than on the kenaf composite specimens.

Different failure behaviors were observed macroscopically when kenaf and kenaf/glass hybrid compressed under static and impact loading, as listed in Table 1. Shear banding failure occurred at 60° for the kenaf composite, while the kenaf/glass hybrid composite failed with longitudinal splitting along the fiber's direction (Figure 8) under static loading. Matrix cracking is the first step of damage caused by quasi-static loading. When a greater external load is applied, the number of cracks increases, resulting in a second failure type known as shear banding. Matrix cracking was discovered to generate shear banding when strong transverse shear loads at the surrounding matrix surface affect the matrix surface and later evolve into a weak interfacial bond that leads to fiber fracture and fiber pullout. Under dynamic loading, both specimens were seen to fail, with longitudinal fibers splitting along the direction of the fibers, which occurred mostly in the outer region (Figure 9). Fiber splitting occurs when the hoop stress or normal stress in the direction perpendicular to the



(a) (b)

Figure 8. Failure of: (a) kenaf; and (b) kenaf glass hybrid composite, under static loading



(a) (b)

Figure 9. Failure of: (a) kenaf; and (b) kenaf glass hybrid composite, under dynamic loading

axis of cylindrical symmetry reaches the maximum allowed stress value. In the same way, exceeding hoop stresses can lead to fiber fracture in radial. (Rahul et al., 2019). Lee and Waas (1999) have also identified from their experiments that longitudinal fiber splitting, or brooming is the most common form of failure for glass fiber composites in the 10% to 30% fiber volume fraction range.

CONCLUSION

This study has been performed on kenaf and kenaf/glass hybrid composite under two different strain-rate conditions to identify the effect of glass fiber hybridization on the overall failure behavior and mechanism of hybrid composites. The stress-strain curves behavior was more affected by the glass hybridization when compressed statically than when specimens failed at several points before completely fracturing. Hybridization resulted in a 5% reduction in failure stress and a 60% reduction in failure strain when the strain rate ranged from 0.02 to 1400/s. Through the hybridization of glass fibers, which added some stiffness, the failure mechanism of kenaf composite has been changed from shear banding failure to longitudinal splitting, which is observed along the fiber direction. Under microscopic observation, fiber-matrix debonding and interface debonding between fibers were dominant in the hybrid composite, which would be the main cause of low failure strength.

ACKNOWLEDGEMENT

The authors want to thank the USM Short Term Grant 304/PMEKANIK/6315493 for supporting this research.

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