Tension-Compression Fatigue Behavior of Plain Woven Kenaf/Kevlar Hybrid Composites

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The applications of hybrid natural/synthetic reinforced polymer composites have been rapidly gaining market share in structural applications due to their remarkable characteristics and the fact that most of the components made of these materials are subjected to cyclic loading. Their fatigue properties have received a lot of attention because predicting their behavior is a challenge due to the effects of the synergies between the fibers. The purpose of this work is to characterize the tension, compression, and tensile-compression fatigue behavior of six layers of Kevlar hybridized with one layer of woven kenaf reinforced epoxy, at a 35% weight fraction. Fatigue tests were carried out and loaded cyclically at 60%, 70%, 80%, and 90% of their ultimate compressive stress. The results give a complete description for tensile and compression properties and could be used to predict fatigue-induced failure mechanisms.

Keywords: Plain woven kenaf; Kevlar fabric; Mechanical; Cyclic loading; Morphological; Fatigue properties

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INTRODUCTION

Designing hybrid composites requires an understanding of their failure mechanisms, especially under cyclic loading. Durability (fatigue) testing evaluates the performance of materials in severe environments, establishes their acceptable economic life cycles, and identifies failures in hybrid composites (Hochard and Thollon 2010). Adequate fatigue tests find potential fatigue critical areas and investigate crack growth behavior (Thollon and Hochard 2009). In composites, the fatigue damage due to repeated mechanical loads usually initiates as cracks in the matrix, laminate edges, notches, or stress discontinuities; they may progress as interlaminar delaminations (Mortazavian and Fatemi 2015; Salman *et al.* 2015c). Fatigue resistance is a significant property for many applications in the automotive, marine, and aircraft industries (Milne *et al.* 2003).

Over the past decade, natural/synthetic fiber reinforced composites have attracted substantial attention as potential structural materials for their low cost, low density (light weight), reasonable mechanical properties, and environmental benefits, including sustainability and a lower carbon footprint (Nunna *et al.* 2012; Salman *et al.* 2015b). However, in structural applications, such materials are often subjected to cyclic loads, which cause progressive damage and may lead to long-term failure of the structure

(Petrucci *et al.* 2013; Swolfs *et al.* 2014). Hence, the knowledge of the fatigue behaviors including damage mechanisms and stress levels *versus* the number of cycles to failure is required for designing hybrid structures and estimating their fatigue life.

The fatigue behavior of hybrid natural/synthetic fiber-reinforced polymers under various types of cyclic loading has been examined (Dong *et al.* 2014; Fotouh *et al.* 2014). Several fatigue schemes have been proposed to overcome the scatter issue; resin cracking, interfacial debonding, fiber pull out, and breakage are the main failure mechanisms noticed under fatigue tests (Salman *et al.* 2015a). Thwe and Liao (2003) compared the fatigue behavior of bamboo fiber (BFRP) with hybrid bamboo/glass reinforced polypropylene composites (BGRP). In a comparison of S-N curves, BGRP showed a better fatigue resistance than BFRP when tested at various load levels of their ultimate tensile stress. In another study, a tension-tension fatigue test was carried out on hybrid oil palm/carbon-reinforced epoxy composites with two different values of fiber volume ratios, 35% and 55% (Kalam *et al.* 2005). When Wu *et al.* (Wu *et al.* 2010) compared the tensile fatigue behavior of carbon, glass, and basalt fiber composites with hybrid composites, hybrid composites lowered the scatter of the fatigue life because the addition of carbon fiber shifted the S-N curves of basalt composites to a higher number of cycles. This result was clarified by the lower tensile modulus of basalt fiber compared with that of carbon fiber. In contrast, Bagheri *et al.* (Bagheri *et al.* 2014) found the opposite result in their investigation of the fatigue properties of the carbon/flax/epoxy hybrid composites as a substitute for the metallic materials for orthopedic long bone fracture plate applications. Their results suggested that the fatigue strength of the hybrid composite was high enough to carry clinical-type cyclic forces that occur in normal daily activities, and thus, they are appropriate for applications that require specific mechanical properties in a given period of time.

The fiber and resin type, textile structure, fabrication process, laminate composition, load type, and environmental conditions are parameters that influence the fatigue life of a hybrid composite structure (Sharba *et al.* 2015a). Because these mechanisms are difficult to model, extensive testing is needed to define the service life of structures that are fabricated from these materials. It was reported that the most suitable natural fibre to be used with Kevlar in hybrid laminated composites is kenaf fibre; such fiber is expected to contribute significantly to the development of hybrid laminated composites for many applications (Yahaya *et al.* 2014). In this work, the tension-compression fatigue behavior of plain-woven kenaf/Kevlar fibers reinforced with epoxy composites was examined. The fatigue resistance property of the hybrid composites was investigated by fatigue curve analysis. The fracture surfaces of the hybrid composites at both high and low stress levels were examined under scanning electron microscopy (SEM) to investigate the nature of failure under fatigue.

EXPERIMENTAL

Kenaf and Kevlar fabric were supplied by ZKK Sdn Bhd, Kuala Lumpur, Malaysia (Fig. 1a, b). The kenaf fiber in a plain weave pattern ($0^{o}/90^{o}$) and the Kevlar 129 fibers were prepared and cut to manufacture hybrid composite panels according to ASTM D3039/D3039M-10 (2010) and ASTM D695-10 (2010). Epoxy resin was utilized to produce the hybrid composite samples. The physical and mechanical properties of the materials are shown in Table 1.


(a) (b)

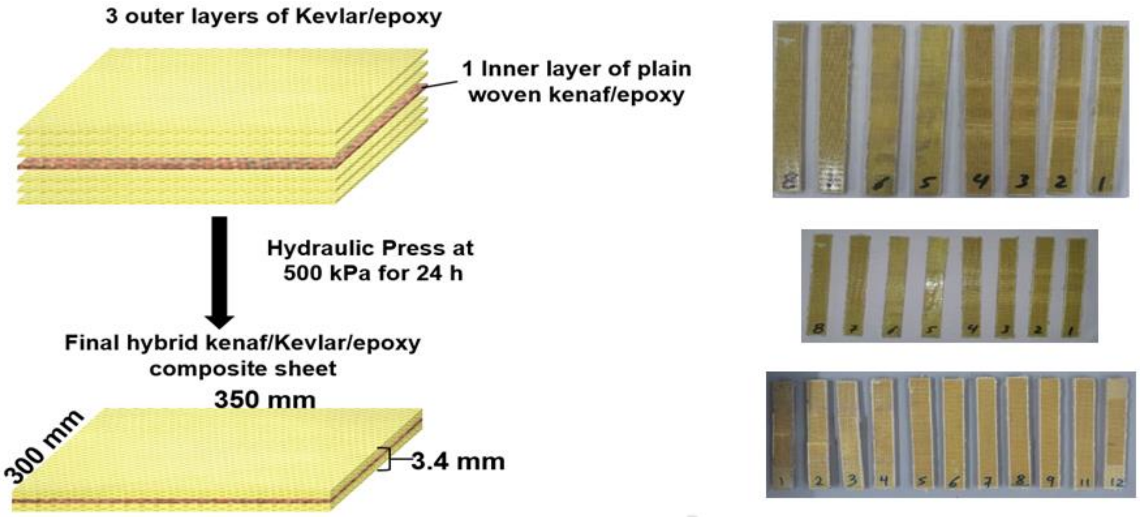
Fig. 1. (a) Plain woven kenaf fabric, (b) Kevlar fabric

Table 1. Physical and Mechanical Properties of the Materials (as in data sheet)

Materials	Density (g/cm^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation at Break (%)	Thickness (mm)
Kevlar 129	1.43	3400	99	3.3	0.3
Plain woven kenaf	1.2	100.64	-	17.3	2
Epoxy LY556 1:2 Hardener [HY951]	1.14	73.3	3.470	4.5	-

Fabrication of the Composite Sample

The plain woven kenaf/Kevlar/epoxy composite plates were manufactured by using one layer of woven kenaf for every six layers of Kevlar-reinforced epoxy resin, with a resin weight fraction of 35% (Fig. 2).



(a) (b)

Fig. 2. (a) Drawing of the plain-woven kenaf/Kevlar/epoxy composite laminates and (b) the test specimens after failure

A combination of the hand lay-up and hydraulic cold press methods was used to fabricate the hybrid composite laminates. These laminates were inserted into a stainless-steel mold and pressed into a compression-molding machine at 500 kPa pressure and room temperature (20 °C) for 24 h. The final hybrid composite material sheet was 300 mm in length, 300 mm in width, and 3.4 mm in thickness. To completely cure the hybrid interior, the laminates were stored at room temperature in the open air for 15 days before being cut into specimens using a table saw according to ASTM D3039/D3039M-10 (2010) and ASTM D695-10 (2010).

Mechanical Properties of Composites

Tensile and compression strength testing were carried out according to ASTM D3039/D3039M-10 (2010) and ASTM D695-10 (2010). The tensile specimens were cut to a 250 mm × 25 mm × 3.4 mm rectangular sectional area flat strip, with the gage length at 170 mm. Four tab plates with the dimension of 40 mm× 25 mm were attached to the two sides of both ends of the samples by an adhesion agent. The compression specimens were cut to a 150 mm × 15 mm × 3.4 mm rectangular sectional area flat strip. Both tests were replicated 8 times on an Instron 3382 universal testing machine (Instron Company, USA) with a capacity of 100 kN and a crosshead speed of 2 mm/min (Figs. 3a, b). These tests were conducted until specimen fracture to measure the ultimate tensile strength and ultimate compression strength of the hybrid samples, and the average value of five specimens was recorded. Generally, the minimum value of the maximum of either the tension or a compression stress is used to do the fatigue test.

The tension-compression fatigue tests were carried out on a servo-hydraulic MTS test machine (Instron Company, Norwood, MA, USA) equipped with a 100 kN load cell capacity (Fig. 3c). The fatigue experiments were conducted in accordance with the BS ISO 13003 standard (International 2003) at ambient temperature and 10 Hz frequency. The tests were loaded cyclically at 60%, 70%, 80%, and 90% of their ultimate compressive stress. For each load level, three specimens were tested, and the selected sample was examined under a scanning electron microscope (SEM) to observe the damage and failure characteristics. The fatigue tests were stopped if the specimen broke or one million cycles was reached, whichever occurred first. During the fatigue tests, the maximum, minimum, mean load, the load amplitude, and the number of cycles to failure were recorded by a computerized data acquisition system (Instron model 8874 with wave matrix fatigue software).

(a) **(b)** **(c)**

Fig. 3. Mechanical test setup: (a) tension test (b) compression test, and (c) tension-compression fatigue test

Morphological Observation

After tension-compression fatigue testing, the mechanisms of specimen failure were characterized using a HITACHI S-3400N scanning electron microscope (Tokyo, Japan) operated at 10 kV to 15 kV. All fractured specimens were sputter-coated with a thin layer of gold by a low-vacuum apparatus (model EMITECH K550X, Quorum Technologies Limited Company, Laughton, UK) to avoid electron charge accumulation.

RESULTS AND DISCUSSION

Tension and compression tests were conducted to define the stress levels for fatigue testing and to determine the ultimate tensile strength (UTS) and ultimate compressive strength (UCS) of the hybrid kenaf/Kevlar reinforced epoxy composites. The stress *versus* strain plots for the hybrid composites are shown in Figs. 4 and 5. Notably, the tension stress curve showed linearity in the first phase, followed by non-linearity up to fracture, while the compression stress curve was characterized by four regions. The first region was a straight line from 0% to 0.25% strain, while the second region from 0.25% to 0.5% exhibited quasi-linear behavior. The third region had a “staircase” behavior up to 5% strain, and then the fourth region corresponded to the initiation of cracks in the matrix, which led to the sudden rupture of the specimens. The maximum stress amplitude that was applied for each fatigue test was defined as a percentage of the minimum value of the maximum of either the tension or the compression results. The ultimate tensile strength was 216.94 MPa, and the ultimate compressive strength was 36.22 MPa.

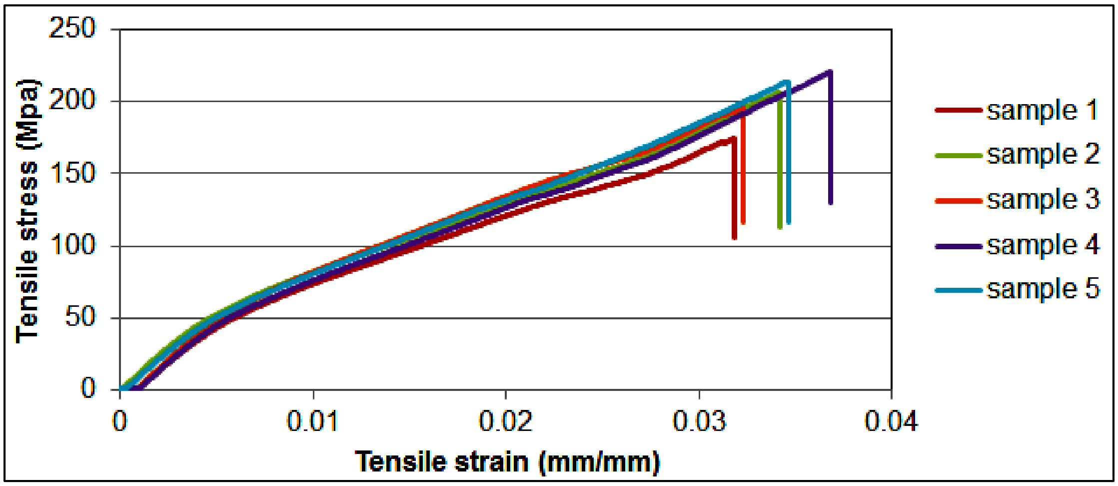


Fig. 4. Tensile stress curve

The tensile strength value of the hybrid kenaf/Kevlar-reinforced epoxy composites was much higher (approximately 70%) than that the compressive strength value. As a result, the ultimate compressive strength value was used as the maximum stress amplitude in the fatigue test. Under compression load, the interfacial adhesion characteristics of the fibres have an important effect on the load carrying capacity; the progressive debonding leads to weaken the composites. A similar trend was reported by Nosbi *et al.* (Nosbi *et al.* 2010) in a study on pultruded kenaf fiber-reinforced composites. Generally, variation in the load-distribution properties increases the tensile strength and modulus of hybrid materials. This is in agreement with Sreekala *et al.* (2002), which reported similar trends for hybrid oil palm and glass fibers.

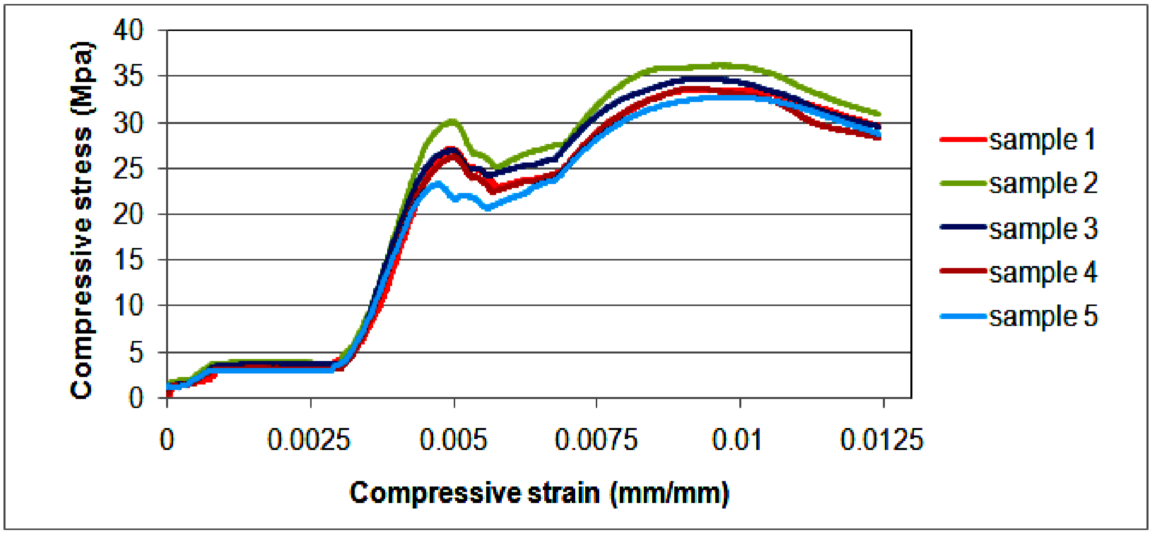


Fig. 5. Compression stress curve

To investigate the formation and propagation of microdamage in the hybrid composite laminates, the fatigue stress ratios were determined at 60%, 70%, 80%, and 90% of the UCS. The selection of the maximum stress level was based on the compression stress response of the UCS results, and the number of cycles was limited to one million or until final rupture, whichever occurred first. A minimum of three test specimens was used for each test at different stress levels, which are shown in the S-N curve (Fig. 6).

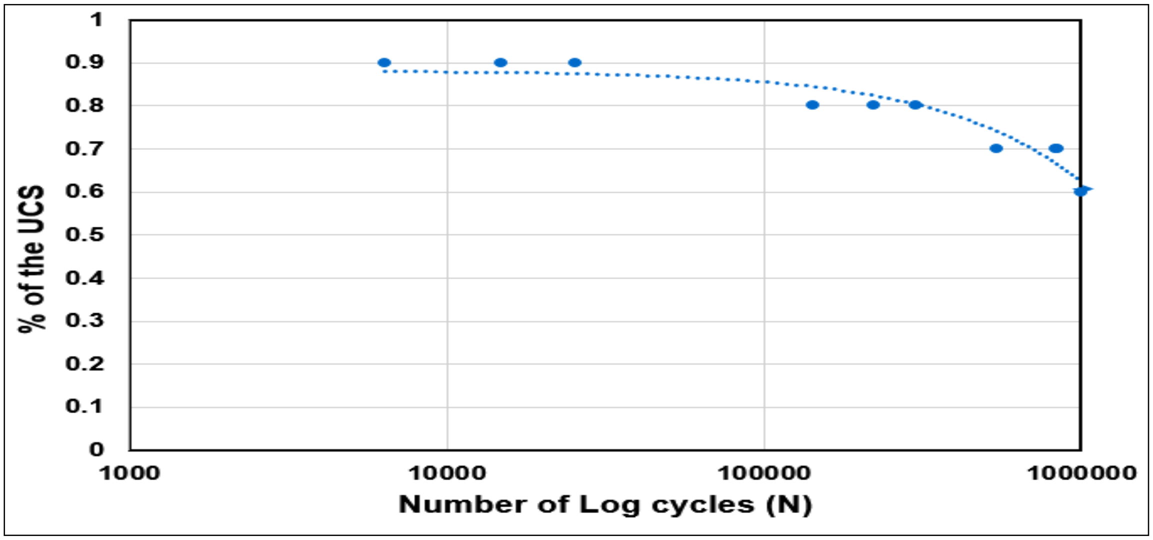


Fig. 6. S-N curve of tension-compression fatigue

The hybrid sample results with a 50% UCS level indicated that the samples did not fail at 6 million cycles. For low loading levels, the fatigue behavior of the composite is the same, which means a long term life (Liang *et al.* 2012). The hybrid fatigue failure appears to be highly dependent on the loading level imposed (Silva *et al.* 2009). At high loading levels of 90% UCS, the failure of the specimen occurred between 9 × 10^3 and 12 × 10^3 cycles, while for loading levels lower than 90% UCS, failure was observed after 10^5 cycles. These results suggested a high fatigue resistance of the hybrid Kevlar/kenaf fiber-reinforced epoxy resin. At 80% UCS, the hybrid fatigue life difference was not as significant when compared with 70% UCS, which ranged between 10^5 and 10^6 cycles for both levels. Limited data scattering, related with fatigue life, is common for a sandwich composite structure due to the arranged nature of the damage accumulation process (Shahzad 2011). Even though no visible points of damage were found in the samples loaded at 60% and 70% UCS, microcracks of various length that were transverse to the load direction were observed in the samples tested at 90% UCS. An increase in the load cycles increased the density and size of these microcracks; thus, more fatigue cracks occurred inside the composite in order to reduce the stress concentration.

In composite materials, fatigue damage always reduces the stiffness as opposed to the strength of the composite (Liang *et al.* 2012). The stiffness degradation (F/F_0) is calculated by dividing the maximum load (F) for the imposed displacement level on the load that was obtained at the first cycle (F_0), to estimate the progression of damage under cyclic loading. The stiffness degradation (F/F_0) *versus* the number of log cycles for different loading levels (r) is shown in Fig. 7. The stiffness degradation rapidly decreased to 15% of the initial load F_0 after 5 cycles, followed by a slow stiffness decrease lasting for the majority of the fatigue life of the specimen. For the loading levels 0.7 and above, a short and sudden growth of damage of the stiffness degradation curve was observed. The composite fatigue failure seems to be very sensitive to the load imposed level (Bezazi and

Scarpa 2007), and this depends on several interrelated modes of failure (Bezazi *et al.* 2007). For up to 10^3 cycles, the F/F_0 loss was 12.2%, 15.8%, and 19.3% for r = 0.7, 0.8, and 0.9, respectively. The failure of the specimen occurred between 7000 cycles and 25000 cycles at loading level 0.9, but failure was observed after 10^5 cycles for loading level 0.8. The fatigue life was up to a million cycles for r = 0.6, while for r = 0.7, the fatigue life approached 10^6.

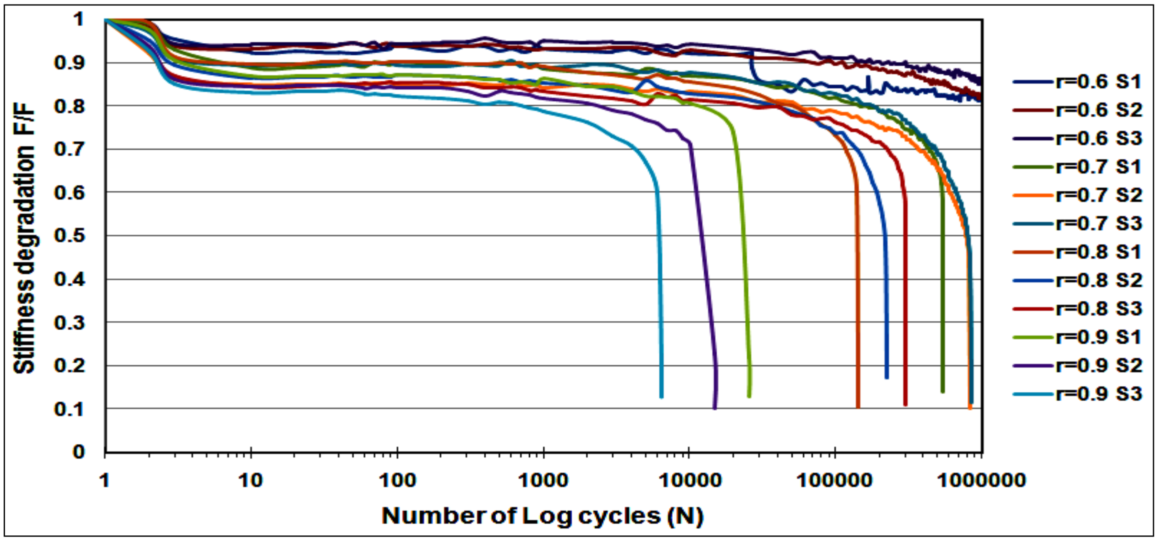


Fig. 7. Stiffness degradation *versus* the number of cycles for different loading levels

Figure 8 clearly shows the initiation and subsequent evolution of fatigue damage at different numbers of cycles and tension-compression loading conditions. Up to the 0.7 loading level, similar behavior was noticed for the maximum forces, and the log cycle decreased significantly with increasing fatigue cycle numbers that are accompanied by higher displacements.

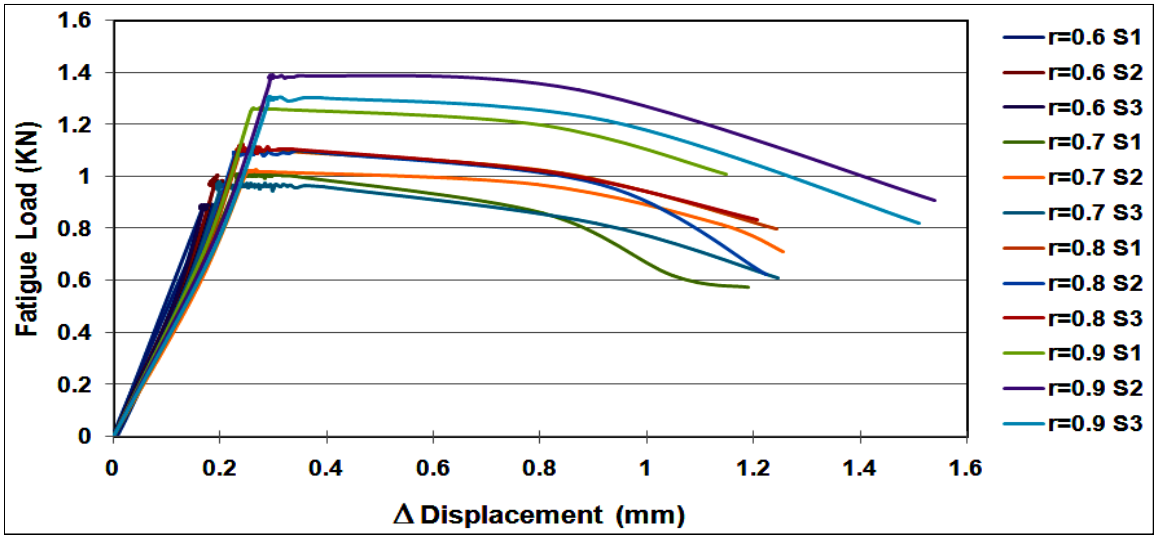


Fig. 8. Variation in the fatigue load with the change in displacement for different loading levels

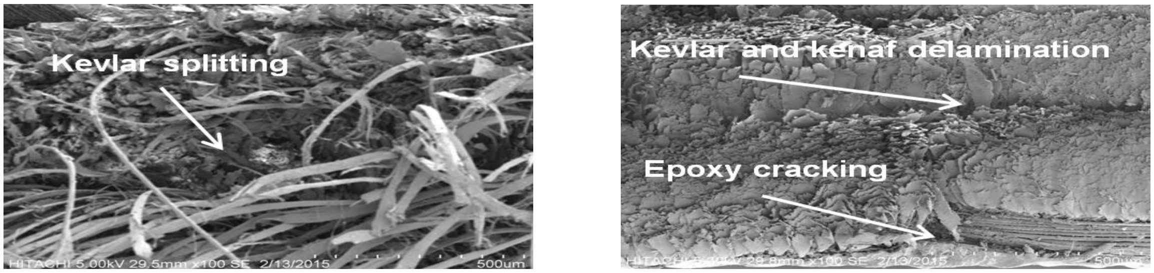
Morphological Properties

Figure 9 shows representative SEM micrographs for specimens that failed in tensile tests, where very few voids were found in the composites. The SEM micrographs confirmed that the mode of failure of Kevlar fibers was due to fiber pullout, while the mode of failure of kenaf fibers was fiber fracture. The composites displayed a cleaner failure surface, which is an indication that the damage happened in the epoxy resin, especially at the rich resin areas where the cracks had initiated and grown. Kevlar fibres pull out resulted from poor bonding between Kevlar fibers and the epoxy resin (Fig. 9b).

(a) (b)

Fig. 9. (a) The SEM images of a fractured surface of the hybrid in tension, (b) the failure caused by fiber pullout and fiber breakage

Figure 10 shows several damage modes for the specimens that failed in the fatigue test, such as the delamination at the interphase region; there is also epoxy resin cracking along both directions and connecting among the agglomerated fibers. With increasing cycle number, fatigue microcracks were generated inside the epoxy resin due to its low strength, and the microcracks expanded along and perpendicular to the loading direction. It can be observed clearly that there was delamination area as well as a high number of fibres showing pullout in the fractured surface of the samples that failed at more than 10^4 cycles (Wu *et al.* 2010). The difference in the damage modes between the Kevlar and kenaf fibers was due to irregularities in mechanical behavior. The whole failure process is first in the outer layers of the hybrid, followed by the delamination of the layers, and then the fiber breakage in the gauge section of material. Using multi layers of fibers causes delamination among layers in the case of transverse loads and off-axis (Salman *et al.* 2016; Sharba *et al.* 2015b); thus the fatigue life increases with increasing angle layers in multidirectional composite materials (Kumar *et al.* 2015).



(a) (b)

Fig. 10. (a) Fatigue fracture surface of a hybrid sample under SEM; (b) SEM image of the sample surface of the hybrid after fatigue loading for a million cycles at 80%UCS

CONCLUSIONS

1. The hybrid composite had higher mechanical properties in tension compared with compression, due to the sandwich structure effect.
2. The tensile results of the hybrid composite showed linearity in the first phase, followed by non-linearity up to fracture.
3. The fatigue life of the hybrid composite was increased with the decreasing of maximum applied stress, and there was an increase in fatigue resistance as the stress ratio was increased.
4. From the fatigue results, the damage was diffused between the kenaf and Kevlar fiber and epoxy debonding, which led to a progressive reduction in the strength and stiffness of the hybrid.
5. In cyclic loading, the fatigue damage extent was highly dependent on the loading levels applied to the specimens. The stiffness degradation was determined to evaluate the progression of damage of the hybrid under cyclic loading.
6. The 12 samples of kenaf/Kevlar-reinforced epoxy composite showed average stiffness and failure to strain characteristics that were consistent with published data.
7. Fractography studies showing the fracture behavior of the hybrid composite failed in the tensile test as brittle failure and little fiber pullout.
8. The results obtained from this study suggest that the hybrid plain-woven kenaf/Kevlar/epoxy composite has high mechanical properties that make it suitable for use in different industrial sectors.

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