Mechanical Properties of Fibre-Metal Laminates Made of Natural/Synthetic Fibre Composites

Ibrahim Mohammed,[a,b] Abd Rahim Abu Talib,[a,c,]* Mohammed Thariq Hameed Sultan,[a,c] Mohammed Jawaid,[c] Ahmad Hamdan Ariffin,[c] and Syamimi Saadon [a]

Mechanical properties are among the properties to be considered in designing and fabricating any composite to be used as a firewall blanket in the designated fire zone of an aircraft engine. The main focus of this work was to study the tensile, compression, and flexural strengths of the combination of natural/synthetic fibres with metal laminates as reinforcement in a polymer matrix. The materials included flax fibres, kenaf fibres, carbon fibres, aluminium alloy 2024, and epoxy. The two-hybrid fibre metal laminate composites were made from different layers of natural/synthetic fibres with aluminium alloy of the same thickness. The composites were made from carbon and flax fibre-reinforced aluminium alloy (CAFRALL) and carbon and kenaf fibre-reinforced aluminium alloy (CAKRALL). Based on the results obtained from the mechanical tests, the CAFRALL produced better mechanical properties, where it had the highest modulus of elasticity of 4.4 GPa. Furthermore, the CAFRALL was 14.8% and 20.4% greater than the CAKRALL in terms of the tensile and compressive strengths, respectively, and it had a 33.7% lower flexural strength. The results obtained in the study shows that both composites met the minimum characteristics required for use in the fire-designated zone of an aircraft engine due to their suitable mechanical properties.

Keywords: Mechanical properties; Natural fibres; Synthetic fibres; Tensile strength; Compressive Strength; Flexural strength

Contact information: a: Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor; b: Department of Mechanical Engineering, College of Engineering, Hassan Usman Katsina Polytechnic, Katsina, 2052 Nigeria; c: Aerospace Manufacturing Research Centre, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor;
** Corresponding author: abdrahim@upm.edu.my*

INTRODUCTION

The combination of natural and synthetic fibres produces a new composite that is lightweight with good mechanical properties and can be used in aircraft engine nacelles. Different types of composites are used when constructing aircraft structures used in different locations that have different purposes. Natural fibre composites are now attracting more attention from researchers because they are lightweight, environmentally friendly, have a high availability, and are cost-effective (Sivakumar *et al*. 2017). The mechanical properties of flax fibre are very close to that of synthetic fibres, such as glass fibres. Therefore, natural fibres could potentially be used to replace synthetic fibres in the near future in aerospace applications. Synthetic fibres, such as carbon fibre, glass fibre, and aramid, combined with natural fibres are used to make hybrid structures with good mechanical properties (Prabhakaran *et al.* 2013).

Natural/synthetic fibre composites offer a high strength and stiffness to weight ratio, corrosion resistance, and good fatigue properties, among other properties. In the development of aircraft materials for future use, improved composite properties must be achieved, such as an impeding crack growth and resistance to corrosion (Asundi and Choi 1997). Another advantage of combining synthetic and natural fibres is the reduction in skin irritation and respiratory problems caused by synthetic fibres such as glass and carbon fibres (Ashori 2008). Different types of natural fibres are used today to replace existing synthetic fibres. Kenaf fibre (bast and core) is among the many natural fibres that are being used worldwide to make bio-composites for structural applications, such as in the aerospace, automobile, building, food packaging, furniture, and other industries (Saraswati and Mahanum 2008). Kenaf fibre is able to reinforce polymers because of its high strength properties (Aji *et al.* 2009).

Corrosion, fatigue, low strength, poor impact, health issues, and water absorption are among the issues that need to be overcome for each material so that they can be used in the fabrication of composites. The health issues associated with synthetic fibres is related to ecological and environmental degradation because they are non-biodegradable (Souza *et al.* 2011), while the natural fibres are hydrophilic in nature, which results in a lower mechanical strength for composites. The problem of health issues can be reduced by sandwiching the synthetic fibre with natural fibre and that of moisture absorption can be mitigated by using a metallic layer on the front and rear faces of the composites (Botelho *et al.* 2006). Composite structures have been used in aircraft structures for the past few decades because of their different advantages in aircraft structures, including high strength and stiffness, remarkable structural weight reduction, good fatigue resistance, and resistance to corrosion (Beumler *et al.* 2006). Improvement of the moduli and strength of the composite would yield a better structural component (Liu *et al.* 2009).

Fibre-metal laminates (FMLs) are the combination of a composite and metallic skin layer with an adhesive agent. Fibre-metal laminates have been used over the last few decades in many industrial sectors. The compound combines the excellent properties of fibres and metals to yield a better component. These laminates are applied in the aircraft and automotive industries because of its high fatigue resistance and lightweight properties. Additionally, the hardness strength of the composite increases as the composition of reinforced fibre increases in the composite (Sivakumar *et al.* 2017). Skhabovskyi *et al.* (2017) reported new techniques to produce FML panels reinforced with metal pins deposited by cold metal transfer welding. The method improved the mechanical properties (compression and buckling test) of the aluminium alloys and composite materials. The composites have an excellent impact resistance and fatigue crack resistance that was restrained by the fibre content because of its stiff nature, which led to the limiting stress intensity factor. The crack growth rate of the FML was decreased to almost one-tenth to one-hundredth of that of monolithic aluminium alloy (Homan 2006; Vogelesang and Vlot 2000).

In this study, the composite included a thin sheet of aluminium alloy 2024 on the top and bottom of the natural/synthetic fibre composites. The techniques of FML production integrate the benefits from metallic materials and natural/synthetic fibres-reinforced matrix applications. Therefore, the composites will have the advantages of high strength and stiffness with a good fatigue resistance. In contrast, aluminium alloy is subject to corrosion and fatigue (Chang *et al.* 2008), carbon fibre-reinforced composites have a poor impact and residual strength properties, and natural fibres absorb water (Vogelesang and Vlot 2000). The FML composite was first developed in 1978 at Deft University of Technology. The composite consists of aluminium alloy 2024-T3 sheets, an epoxy as a polymer, and aramid as the reinforcement (Sinmazçelik *et al*. 2011), but this type of FML has the disadvantage of being brittle. Therefore, it can only be used in secondary structures (Jumahat *et al.* 2015). Carbon fibre-reinforced aluminium alloy (CARALL) and glass fibre-reinforced aluminium were later developed to improve the mechanical properties of FMLs, where the carbon and glass fibres serve as reinforcement to the composite that contains a thin aluminium sheet (0.3 mm to 0.5 mm) (Marissen and Vogelesang 1981; Sadighi *et al.* 2012). This composite is mainly used in aircraft applications, such as fuselages, cargo doors, and wings (Li *et al*. 2017).

Because of the flammability of fuel and combustible products, there is a need to develop a new fire blanket that can be used in designated fire zones in aircraft engines. The DMA test measure the visco-elastic properties of FML fabricated having a transition of temperature between 70 and 72 °C, dynamic damping (tan δ_{max}) of the range between 0.46 and 0.53 with a mass residue that ranges between 30 and 40% and inflection temperature between 390 and 400 °C after undergoing a thermogravimetric test. The main objective of the study was to examine the mechanical properties of two different composites of aluminium alloy and natural/synthetic fibres. Testing was conducted according to ASTM standards for tensile, compression, and flexural properties using a universal testing machine (UTM) with different crossheads and a constant crosshead speed of 1 mm/min. This paper presented the properties testing results of the hybrid composites with natural/synthetic fibre and aluminium alloy 2024-T3, where the aluminium alloy was placed on the top and bottom of the composites.

EXPERIMENTAL

A hand lay-up method was used in the fabrication of both FML composites and compressed using a compression machine.

Materials

Table 1 shows the number of layers in the materials used and their thickness. All of the samples for the two composites were 300 mm x 300 mm, arranged unidirectionally.

Table 1. Specifications of the Materials used in FML

Material	Specifications of Layers	Thickness (mm)
Aluminium alloy	4	0.3
Carbon fibre	9	0.2
Kenaf fibre	1	1.4
Flax fibre	2	0.6

The weight ratio of resin to hardener used was 2:1, and the ratio of fibre to polymer matrix in terms of their volumetric ratio was 50:100.

Methods

The first FML was fabricated using two sheets of aluminium alloy located on the top and bottom of the composite; four layers of carbon were arranged in unidirectional (0°/90°), and one layer of kenaf at the centre. The layers were laid accordingly and epoxy was used to bond them together. Figure 1 shows the FML arrangement.

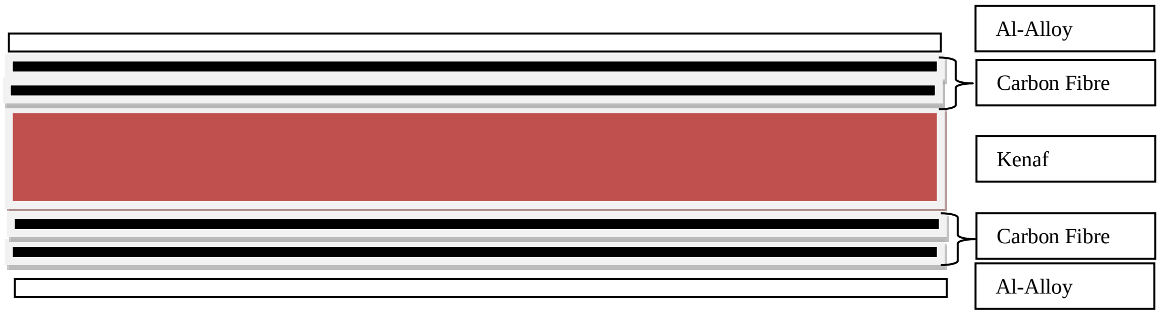

Fig. 1. FML of the aluminium alloy with carbon and kenaf fibres

The second FML was fabricated using two sheets of aluminium alloy 300 mm x 300 mm on the top and bottom of the composite, five layers of carbon, and two layers of flax in between the carbon fibres. The layers were laid accordingly and epoxy was used to bond them together. Figure 2 shows the FML arrangement. A carbon layer was placed at the centre of the composite in between the two layers of flax in unidirectional orientation. Two layers of carbon fibre were in between the flax and aluminium layers.

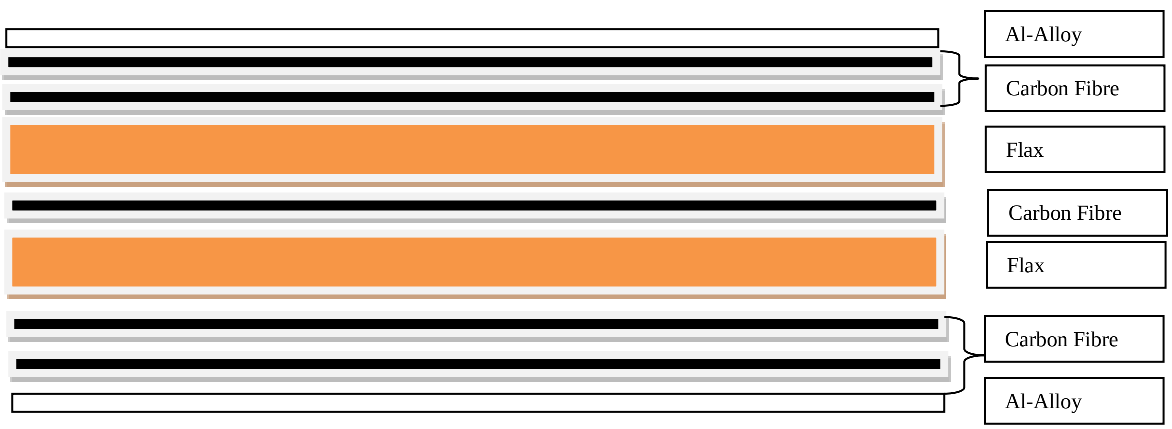

Fig. 2. FML of the aluminium alloy with carbon and flax fibres

The FMLs were fabricated in a mould of dimensions 300 mm x 300 mm x 3.5 mm by the oldest method. They were compressed with a compression machine LHDC-50, LI CHIN (SEA) SDN BHD. Perak, Malaysia at a compression pressure of 100kN/m^2 and allowed to cure for 24h at room temperature. The fabricated FML composites were then subjected to mechanical testing (tensile, compression, and flexural properties).

Mechanical Properties of the FMLs

The mechanical tests performed studied the tensile, compression, and flexural properties.

Tensile test

The tensile test for the two FML was performed and recorded using the standard ASTM D3030/D3039M-14 (2014) for both the carbon and kenaf fibre-reinforced aluminium alloy (CAKRALL) and carbon and flax fibre-reinforced aluminium alloy (CAFRALL). Five samples from each specimen were cut to the dimensions 120 mm x 20 mm x 3.5 mm. The average values of the tests were calculated for both FML. The crosshead speed of the machine was maintained at 1mm/min.

Compression test

The compression test for the two FML composites was performed and recorded using ASTM D3410/D3410-16 (2016). Five samples from each specimen were cut to the dimensions 12.75 mm x 12.75 mm x 3.5 mm. The average values of the tests were calculated for both FML. The crosshead speed of the machine was maintained at 1mm/min. The axis of force application that runs through the centreline of each sample was loaded correctly and accurately to avoid sample bending or buckling during the test.

Flexural test

The interface bond between fibres in composites influences the results of flexural tests. The cut samples from the two FML were tested according to ASTM D790 -10 (2010). Five specimens from each composite were subjected to the flexural test. The length (*L*, mm) of each sample depended on the depth of the specimen, which was determined by the following equation (Ning *et al.* 2015):

$$L = 16d + 20\% \text{ of the length} \quad (1)$$

where *d* is the thickness of the composite (3.5 mm).

Five specimens were cut to the dimensions 67.2 mm x 20 mm x 3.5 mm from both FMLs (CAKRALL and CAFRALL). The three-point bending method was used in the flexural test, where two supports were placed at 10% of the length from the end of the specimen. The load was applied to the top surface of each sample, and the crosshead speed was maintained at 1 mm/min. The flexural strength of FML composites was obtained using a modified theory of Kennedy *et al.* (2011) whereby the stress/strain relationship was expressed from the theory as reported by Zal *et al.* (2017). Therefore, the calculation of the stress, strain and flexural strength was carried out using Kennedy's modified developed theory.

RESULTS AND DISCUSSION

This section presents the mechanical test results obtained from the experimental work and the analysis and discussion of the result based on the previous work on FML composites. Three properties were considered in this study, which is tensile, compression and flexural.

Tensile test

The average tensile test results for the five specimens for both CAKRALL and CAFRALL were obtained and analysed. The tensile load increased with an increasing extension up to a certain level, where it reached the maximum extension, and then it fell slightly. This characteristic was also reported by Tamilarasan *et al*. (2015), where CARALL 6061-T6 sandwich laminates were found to have a maximum load of 40kN and extension of 9.25mm. The result of this study shows lower load values due to a sandwich between synthetic and natural fibre.

Table 2 shows the average results of the tensile test for CAKRALL and CAFRALL with the maximum load that each composite could withstand. It was found that the CAFRALL composite withstood a higher load of 26.2 kN and had the highest tensile stress (375 MPa) and strain (18.8%) at the maximum load. The results obtained in this study were almost the same as the results obtained by Tamilarasan *et al.* (2015), where pure synthetic fibre was used and a higher maximum load was obtained. It was observed that a laminate composite with synthetic fibre yielded a better tensile strength than a hybrid FML composite that consists of synthetic and natural fibre materials. Furthermore, the same result was obtained, but with lower loads and stresses applied when using only natural fibres in the laminate, as well as with glass and bamboo fibres (Zikre and Bhatt 2016).

Table 2. Average Results of the Tensile Test

Properties	Unit	CAKRALL	CAFRALL
Maximum Load	kN	21.7	26.2
Modulus (Automatic)	MPa	2650	2680
Tensile Stress at Maximum Load	MPa	310	375
Tensile Strain at Maximum Load	%	14.6	18.8
Load at Break (Standard)	kN	0.31	0.29
Tensile Stress at Break (Standard)	MPa	4.55	4.18
Tensile Strain at Break (Standard)	%	22.9	20.0
Tensile Stress at Yield (Zero Slope)	MPa	316	371

Based on the results obtained from the tensile testing, a tensile stress and strain graph was used to obtain the tensile strength. Results are shown in Fig. 3.

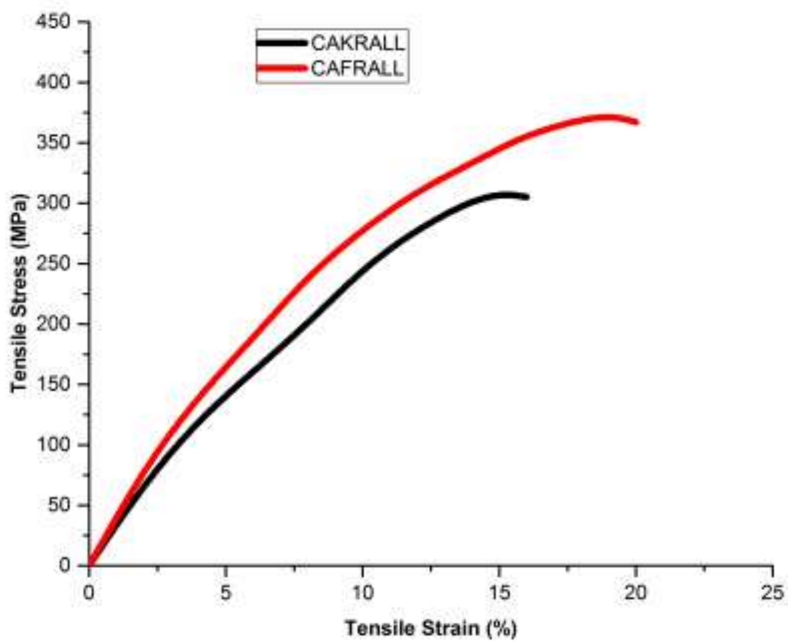

Fig. 3. Graph of the tensile stress *vs.* tensile strain

The curves clearly indicate that the CAFRALL composite had a higher ultimate stress for failure value than the CAKRALL composite. By using the graph gradient, the tensile strength of the CAFRALL was found to be 4.40 GPa, and that of the CAKRALL was 3.75GPa. The results showed that an increase in the tensile strength was because of the interfacial cohesion between the fibres and polymer matrix, and the diffusion that occurs from the polymer matrix to the fibres. Similar results were reported for different types of polymers (Mutjé *et al.* 2006; Méndez *et al.* 2007; Vilaseca *et al.* 2010).

Furthermore, the load applied affected the stresses on the FML composites, where a higher load resulted in less stress produced on the composite. The same applied to the thickness of the FML composite, as reported by Zikre and Bhatt (2016).

Compression test

The average compression test results for the five samples for both CAKRALL and CAFRALL were obtained and analysed; the compressive load increased with an increasing compressive extension up to a certain level, where it reached the maximum extension, and then it suddenly fell. The samples deform at constant strain rate until failure (crushing failure). The compression load that each composite was subjected to is shown in Table 3. For CAFRALL, the maximum load was 90 kN, while for CAKRALL it was 71.65 kN, as obtained from the test machine. The results in terms of the compressive load and stress were similar to the results obtained by Zikre and Bhatt (2016), who used glass fibre. From the maximum load and strength obtained in this study, the carbon fibre yielded more strength than glass fibre. Likewise, the epoxy resin/hardener has higher bonding strength than the polyester resin/hardener used by Zikre and Bhatt (2016). However, higher values for the compressive loads and stresses were obtained in this study, as shown in Table 3.

Table 3 shows the average results of the compression test for CAKRALL and CAFRALL.

Table 3. Compressive Test Results

Sample	Maximum Load (kN)	Compressive Strength (MPa)
CAKRALL	71.6	444.2
CAFRALL	90.0	558.0

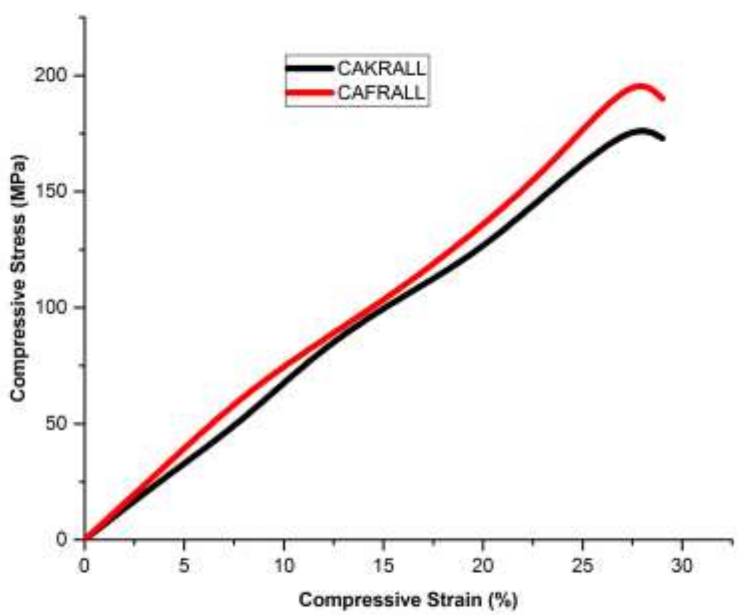

Fig. 4. Graph of the compressive stress *vs.* compressive strain

From the results obtained from the compression test, the compressive strength of the CAFRALL was 20.4% greater than that of the CAKRALL, which indicated that it had better compressive properties. The compressive strength of the CAFRALL was 558.01 MPa and that of the CAKRALL was 444.25 MPa. The compressive stress of the CAFRALL was greater than that of the CAKRALL, as shown in Fig. 4.

Flexural test

The average flexural test results for the five samples for both CAKRALL and CAFRALL were obtained and analysed. There was a variation in the flexural load with respect to the flexural extension. The flexural load increased with an increasing flexural extension up to a certain point, where the aluminium alloy delaminated and broke. The load was almost maintained at this point but then fell. It is observed from the test that delamination occurs in between the layers of the FML due to the shear stresses between them as reported by Yoshihara (2012) and Zal *et al.* (2017). The results show the flexural strength of the two different FMLs. The variation in their strength can be attributed to the variation in the materials during specimen fabrication. All of the specimens were within the limit stipulated for use in aircraft engines and a similar curve shape was also reported by Tamilarasan *et al.* (2015), where the composite reached a flexural load of 2.45kN at a flexural extension of 11mm.

Table 4 shows the average results of the flexural test for the five samples of CAKRALL and CAFRALL. The CAKRALL was 23.2%, 25.2%, and 52.4% higher than the CAFRALL for the maximum load, stress, and flexural modulus, respectively, as shown in Table 4. This meant that the CAKRALL withstood more load before it failed. The result was in agreement with the result obtained by Tamilarasan *et al.* (2015) and by Mahesh and Senthil Kumar (2013). The cited work used laminate composites of pure synthetic fibre (glass fibre) with slightly higher values than a sandwich composite of natural with synthetic fibre.

Table 4. Flexural Test Results

Sample	Maximum Load (kN)	Maximum Stress (MPa)	Flexural Modulus (MPa)
CAKRALL	1.12	314.47	45933.76
CAFRALL	0.84	235.06	21854.50

The flexural stress and strain of the composites were found using Kennedy's modified theory, and the results of analysis are shown in Fig. 5. From the results, the CAKRALL showed a higher flexural strength of 362 MPa, and the CAFRALL had a flexural strength of 271 MPa. The results of the three-point bending tests showed that the CAKRALL had higher flexural properties than the CAFRALL. The flexural strength of these composites was improved because of an organised interface between the matrix and fibres that resulted in a better stress transfer between them, as reported by Tawakkal *et al.* (2012).

In general, the tensile test specimens showed early failure in the top and bottom layer of the composites (aluminium alloy sheets) by delamination from the main component of the composites. These two layers broke first, and then the fibres gave out and broke for both composites. This phenomenon was also reported by Reyes and Kang (2007), where aluminium alloy 2024–T3 with glass fibre reinforcement and polymer polypropylene composite materials were used. Rajkumar *et al*. (2014) also reported that the same type of failure occurred for FML hybrids with carbon and glass fibres. Delamination was also observed during the compression test, which was because of the adhesive de-bonding of the link between the natural/synthetic fibres and matrix.

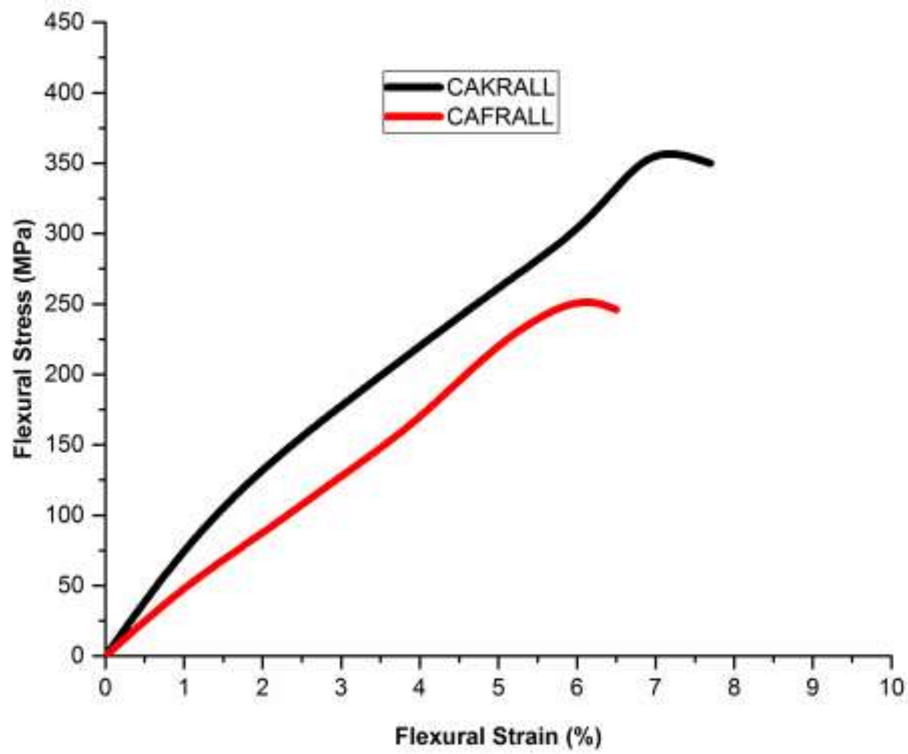

Fig. 5. Graph of the flexural stress *vs.* flexural strain

A cracking noise from the matrix was also heard and the composites became plastic. This phenomenon was also reported by Remmers and de Borst (2001), where there was a cracking noise during the compression test of the FML. In the flexural test, aluminium alloy delaminated and broke first, after some time the FML composites break at the maximum load. This was followed by the remaining layers breaking in the composites, which had a good bond between the carbon and natural fibres. The flexural strength was studied in this research; the test was performed with the three-point bending test method and measured both the compressive and tensile strengths of the composites at the same time. The fabricated FML composites overcome the problem of low strength as indicated in the result obtained from the three tests, the natural fibre was in the middle of each composite in order to avoid moisture absorption and aluminium alloy was at the front and rear face of each composite to overcome the problem of poor impact.

This study showed that carbon fibres, when combined with different types of natural fibres (flax and kenaf), differ remarkably in their flexural strengths, but both composites studied can serve as a component in the fire-designated zone of aircraft engines because of their superior properties, when compared with the mechanical properties of the existing components in the section. An investigation showed that the epoxy provided excellent adhesion, and had a superior mechanical property in between the layers of synthetic and natural fibres as reported by Kreith (1999). The main reason for the high flexural strength of the two FML composites was that a stronger chemical bond existed between the carbon and natural fibres and polymer which was evident from the thermal test (dynamic mechanical analysis) conducted on the FML composites that analyse the interface of adhesion strength.

CONCLUSIONS

1. The main objective of this study was to examine the mechanical properties of two FML composites with natural/synthetic fibres and aluminium alloy to determine their ability to be used in the fire-designated zone, by considering the mechanical properties of the existing composite in the zone.
2. The results obtained for the two composites from the tensile, compression and flexural tests were promising. The tensile and compressive strengths obtained from the experimental data showed that the CAFRALL composite had superior properties over CAKRALL composite. However, the kenaf composite had a flexural strength that was almost 33.7% higher than that of the flax composite. The flax composite had 14.8% and 20.4% higher tensile and compressive strengths, respectively than the kenaf composite.
3. The two types of natural fibres used in this study had large influences on the mechanical properties of the composites. It was concluded that both composites can be used as materials in the fire-designated zone.

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