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Research paper

Fire behavioural and mechanical properties of carbon fibre reinforced aluminium laminate composites for aero-engine

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Abstract

Two different properties of fibre-metal laminate composites (FML), including the fire behaviour and mechanical properties, were experimentally studied in this paper. The fibre-metal laminate composites studied were made of aluminium alloy 2024-T3, carbon fibre, flax, kenaf and epoxy resin/hardener arranged in different forms. The aims of the study are to assess the fire behaviour of the composites using ISO2685 standard and mechanical properties of the composite after withstanding the burn-through according to the standard. The fire test was carried out using ISO2685 standard using a propane-air burner, whereby the propane gas and air serves as the fluid to the system. The universal testing machine of the 100 kN load cell and gun tunnel were used for the mechanical properties test according to each test standard. The fire results showed that three of the FML composites considered in the study are fireproof composites while carbon fibre kenaf reinforced aluminium laminate (CARALL4) is a fire resistant composite. Carbon fibre reinforced aluminium laminate with aluminium alloy at the front and the rear face (CARALL2) withstood higher flame temperature than the other FML composites with 14.4%, 49.0% and 82.8% greater than CARALL1, CARALL3 and CARALL4 in terms of thermal conductivity. In terms of mechanical properties, it was also CARALL2 that has higher tensile, compressive, flexural and impact strength. Therefore, the study showed that carbon fibre flax reinforced aluminium laminate (CARALL3) which is the hybrid composite with green fibre can compete with fibre-metal laminate composites of pure synthetic fibre in terms of their properties.

Keywords: *composite; fibre metal laminate; fire designated zone; high temperature; mechanical properties*.

1. Introduction

The fire designated zone of an aircraft requires a fire blanket composite that can withstand a high temperature for a specific time, as well as having properties such as low density, high corrosion resistance, good fatigue resistance, good impact resistance , lower degradation, high strength and stiffness, and also highly resistant to moisture [1]. Nowadays, many researchers use an advanced method of using a thin sheet of metal alloy such as titanium, aluminium, magnesium etc. with high reinforced fibres such as carbon, Kevlar, glass among others to fabricate a composite using high strength polymers such as epoxy, polyester, polypropylene etc. called fibre metal laminate (FML) composite. FML composite combines the properties of the materials used to produce a high-quality component that can be used in aerospace and automobile industries [2-9]. FML composite has been used in aerospace industry for over seven decades, where the FML was used in F-27 for the bonding in Fokker aircraft due to its lightweight and damage tolerance properties [10]. Among the FML composites developed and used in an aerospace industry in the past few decades were aramid fibre reinforced aluminium laminate composite (ARALL), glass fibre reinforced aluminium laminate (GLARE) and carbon fibre reinforced aluminium laminate (CARALL). Among these FML composites, some were used as secondary component of aircraft due to their brittle properties and used in military aircraft, while others were used in the primary structure due to their improved properties such as high compressive strength, tensile strength and excellent adhesion between the fibres of the composite and high resistance to loading on compression [10-15].

The FML composite that is most used in an aircraft is carbon fibre reinforced aluminium laminate (CARALL); this type of FML comprises aluminium alloy and carbon fibre with the polymer matrix. Different types of aluminium alloy are used in aerospace industry, but the most common type used is 2024 and 7075 due to their good fatigue resistance, impact resistance, high strength and a good level of machinability [16]. The alloy can be used in different layering pattern in fibre reinforced composite such as in alternating pattern or in front and the rear face of the reinforced composite. Aluminium alloy produces high resistance to impact in the FML composite. Likewise, carbon fibre can be used in FML in a different form; the carbon fibre prevents aluminium alloy from crack, as it also has high strength and stiffness [17, 18]. The CARALL has applications in aerospace industry due to its excellent properties including corrosion resistance, lightweight, and resistance to moisture absorption. These properties allow CARALL to replace the metal used as a component in aircraft [19-21]. The FML composite has the dual benefit of carbon fibre reinforced as well as aluminium alloy; these benefits provided CARALL with excellent damage tolerance to fatigue crack growth and impact damage to the component [22, 23].

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Various research had been conducted on the types and procedure of fire test on aircraft components such as those reported by Neely *et al.* [24] based on certification and airworthiness regulations. The two types of flame fire test that are most often used on aircraft components were AC20-135 and ISO2685 propane-air burner. The standard temperature and heat flux stated by the two standards are almost the same, where AC20-135 states 1093 ± 85 °C and 106 kW/m^2, while ISO standard states 1100 ± 80 °C and 116 ± 10 kW/m^2 respectively. Also, a new next-generation burner has been introduced with almost the same function as that of ISO2685 propane burner but with a small difference; the test using this burner uses jet-A as the fuel and tabs were added to tabulator [25, 26]. Different devices were used to measure the flame temperature and heat flux such as those reported by Mohammed *et al.*, [27], and convective and radiative heat transfer were also measured using different devices as reported by Balland *et al.*, [28]. The flammability nature of some composites such as carbon reinforced epoxy was among the issues that have grabbed the attention of researchers to find the solution, whereby research on flame retardant polymers was undertaken to reduce the flammability of the composite, and also to come up with the most suitable reinforced fibres (carbon, glass and Kevlar) to be used in aircraft components [29-31].

Mechanical properties were among the properties to be considered when determining the aircraft components to be used in fire designated zone of an aircraft engine. The FML composite can withstand crack failure when there is a crack on the metal surface layer; due to the stresses acting on the fibres and polymer, the stress will be distributed along the polymer and fibres layer [22]. The fibres of FML composite can be either made of synthetic fibre only, natural fibre only, hybrid of synthetic fibre (e.g. carbon and glass), hybrid of natural fibre (e.g. flax and kenaf) or a hybrid composite of synthetic with natural. The composite with synthetic fibre only produces higher values of mechanical properties than the hybrid composite, while hybrid composite produces higher mechanical properties than natural fibre composite [15, 20, 32, 33].

The FML composites used in this study were made of four types of FML which are carbon fibre reinforced aluminium alloy with alternating aluminium alloy (CARALL1), carbon fibre reinforced aluminium alloy with aluminium alloy at front and rear face (CARALL2), carbon fibre flax reinforced aluminium alloy with aluminium alloy in front and rear face (CARALL3) and carbon fibre kenaf reinforced aluminium alloy with aluminium alloy at front and rear face (CARALL4). The main aims of the investigation are to study the flame fire properties using the ISO2685 standard as well as the mechanical properties of the four FML composites. Flat panels of 300 x 300 x 3.5 mm were used in fire tests at 3-inches distance from burner face, the samples were burnt as stated in the ISO2685 standard [34], and propane gas and air with compressed air were used as the test fluid. Meanwhile, universal testing machine and gun tunnel were used for mechanical properties test, where each test sample was cut according to the standard of the test. The study is intended to contribute in the proposed future components to be used in an aircraft fire designated zone and other high-temperature zones of other machinery by providing an experimental result on the properties (flame fire and mechanical) of the four different types of FML composites.

2. Material and methods

The section covers the materials and the methods used in this study for the properties test of fibre metal laminate (FML) composite. The materials used were aluminium alloy 2024-T3, carbon fibre, kenaf and flax as the reinforcement fibres bonded by an epoxy. Also propane burner, propane gas, air gas, compressed air, R and K type thermocouple, heat flux meter (SBG01), data logger, computer and gas lighter for fire behavioural properties test where used, while universal testing machine (UTM), gun tunnel, helium gas, flat cylindrical projectile, spotlight and high-speed camera were used for mechanical properties tests.

The four composites were fabricated by hand lay-up method in a mould of 400 x 400 x 3.5 mm compressed with cold compression machine and cured between 22 to 24 hours at a room temperature. Table 1 and Table 2 show the materials used in fabricating the four FML composites used in the study and the layered arrangement.

Table 1: Composites material with their layers

S/No.	Composite	Number of Layers			
		0.3 mm Aluminium Alloy	0.2 mm Carbon Fibre	1.4 mm Kenaf	0.6 mm Flax
1	CARALL1	5	6	-	-
2	CARALL2	2	11	-	-
3	CARALL3	2	4	1	-
4	CARALL4	2	5	-	2

Table 2: Composites layers arrangement

S/No.	Composite	Layers Arrangement
1	CARALL1	1LAl, 2LC, 1LAl, 1LC, 1LAl, 1LC, 1LAl, 2LC, and 1Lal
2	CARALL2	1LAl, 11LC, and 1Lal
3	CARALL3	1LAl, 2LC, 1LK, 2LC and 1Lal
4	CARALL4	1LAl, 2LC, 1LF, 1LC, 1LF, 2LC and 1Lal

Note: 1LAl means 1 layer of aluminium alloy, 1LC means 1 layer of carbon fibre, 1LK means 1 layer of kenaf, and 1LF means 1 layer of flax.

The cured composites were cut according to the standard of each test. For the fire test, the composites were cut 300 x 300 x 3.5 ± 0.2 mm for each composite. For the mechanical tests, the composites were cut as follows: for tensile test 120 x 20 x 3.5 ± 0.2 mm [34], compression test 12.75 x 12.75 x 3.5 ± 0.2 mm [35], flexural test 67 x 20 x 3.5 ± 0.2 mm [36] based on the Eqn. 1, and for impact test 100 x 100 x 3.5 ± 0.2 mm, where L is the length and d is the thickness of the composite.

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

The fire behavioural test begins with burner calibration according to the ISO2685 standard [33] where 7 thermocouples were used to calibrate the flame temperature and SBG01 calibrate the heat flux at a distance of 3-inches from burner face. The ISO2685 standard states the standard flame temperature of 1100 ± 80 °C and a heat flux of 116 ± 10 kW/m^2, whereas the supply gas, primary and secondary air should be maintained at 45 mm H_2O, 435 mm H_2O and 300 mm H_2O respectively. Fire test was conducted on the four composites according to ISO2685 standard for 15 minutes, whereby fireproof and fire resistant composites were determined after the test. Three K-type thermocouples were used at the rear face of the composite, at the centre, 1-inch above the centre and 1-inch right to the centre, to measure the rear face temperature of each composite. Figure 1 shows the propane-air burner.

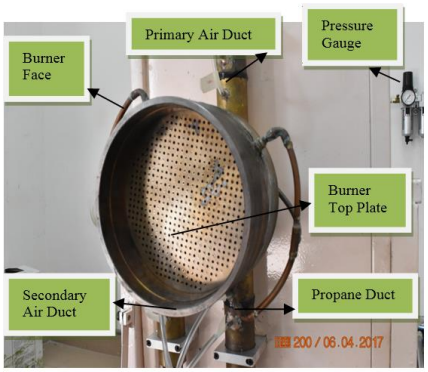


Fig. 1: Propane-air burner

Also, the thermal conductivity of the composites was determined using Eqn. 2, where k is the thermal conductivity, δ the thickness of the composites in metre, W is the heat flow in Watt, A is the

area of the plate in metre square and ΔT is the temperature difference between the hot and cold face of the plate in Kelvin.

$$k = (W_x \delta)/A_x \Delta T \quad (2)$$

Four properties were examined for a mechanical test that includes tensile, compression, flexural and impact tests. Three of these tests (tensile, compression and flexural test) were carried out using a universal testing machine, using 1 mm/min as the crosshead speed for the entire test, while the other test was carried out using a gun tunnel system as shown in Figure 2, where the projectile was fired using a helium gas for low-velocity impact test of 30 ± 5 m/s. Five samples of each composite were cut according to their standard and the average result of each composite was recorded. Also, the absorbed energy and impact strength was evaluated using Eqn. 3 and Eqn. 4, where E_{Abs} is energy absorption by the specimen (J), m_p is the mass of projectile (kg), V_i is the impact velocity (m/s), V_r is the residual velocity (m/s), QI is the impact energy, A is the area of the plate and I_s is the impact strength.

$$E_{Abs} = ½\ m_p\ (V_i^2 - V_r^2) \quad (3)$$

$$I_s = QI/A \quad (4)$$



Fig. 2: Impact test rig

3. Result and discussion

This section deals with the results and discussion of the two properties considered in this study namely the fire behavioural and mechanical (tensile, compression, flexural and impact test) properties. The section is divided into two sub-sections.

3.1. Fire behavioural test result

The average results of fire test among the four fibre metal laminate (FML) composites are presented in the first sub-section. Table 3 shows the results of the four composites considered in the study.

Table 3: Fibre-metal laminate composites fire test result

S/No	Composites	Burn-through Time (min)	Comments
1	CARALL1	>15	Fireproof
2	CARALL2	>15	Fireproof
3	CARALL3	>15	Fireproof
4	CARALL4	10:22	Fire resistant

The results obtained in the fire test shows that three of the composites were fireproof and the other composite was fire resistant. The FML composite with kenaf natural fibre burnt before the stated standard time for fireproof material but showed fire resistant property since it withstood the fire longer than the stated standard time of fire resistant property (5 minutes). At around 1½ minutes, a layer of aluminium alloy sheet bonded to the main fibre composite started to melt, allowing the flame to reach the fibre composite. At this point, the fibre composite yielded by carbonising on the thickness of the composite, therefore delamination of the fibres layer occurred that allowed air to pass through it which then insulate the composite for some time from the flame. This insulation caused the rear face aluminium alloy to have a lower temperature than the front side of the composite. The rear face temperature was measured using three K-type thermocouples as indicated in Figure 3, the result obtained was in agreement with the result reported by Hooijmeijer and Vlot [38]. As the flame continued to impinge on the fibre composite smoke and flaring were observed from the fibre composite, with time the smoke and flaring reduced while a crack started to appear on the fibre composite that allowed more flame to penetrate the composite. Char was formed as a result of an epoxy and reinforced fibre decomposition and oxidisation. As more fire impinges with time, one of the composites that was hybridized with kenaf fibre burnt through at about 10 minutes 22 seconds, while the other three composites withstood the flame for 15 minutes according to the standard including the other composite hybridized with flax fibre, the result obtained was in agreement with the result in Sikoutris *et al.* [30].

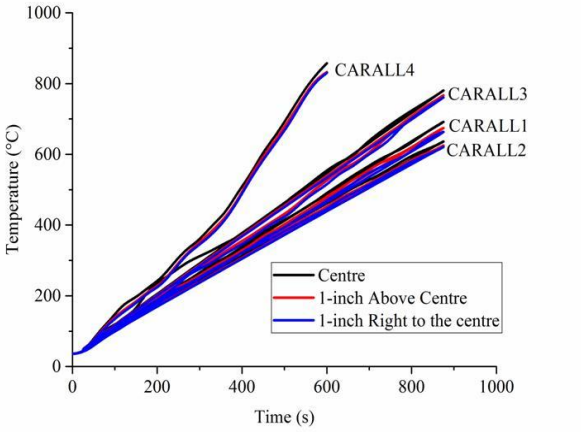


Fig. 3: Rear face temperature of fibre-metal laminate composites

The FML composites fabricated showed good fire resistance; therefore, these composites can be used in fire designated zone of an aircraft engine since they withstood the flame temperature of about 1100 ± 80 °C for the stated time according to the standard. From the result obtained, it was clearly observed that CARALL2 withstood more flame temperature than the other composites being studied. The thermal conductivity of each composite was calculated using Eqn. 2 and the result is presented in Table 4.

Table 4: Thermal conductivity of the composites

Composite	CARALL1	CARALL2	CARALL3	CARALL4
Thermal Conductivity (W/mK)	1.048	0.916	1.365	1.674

The heat flux of each composite was calculated during the fire test using a steady-state version of 1D Fourier's law of conduction as indicated in Eqn. 5, where q_{diff} represents the differential heat flux, and T_s, T_b are the temperature at the surface and at the back respectively. Table 5 shows the calculated values.

$$q_{diff} = k(T_s - T_b)/\delta \quad (5)$$

The result obtained shows the same result as the stated by the standard. The composites experienced re-radiation heat flux ($q_{re\text{-}radiation}$) and the value of each composite was evaluated using Eqn. 6, as the highest temperature absorbs by each composite was used in calculating the values as shown in Figure 4.

$$q_{re\text{-}radiation} = T^4 \quad (6)$$

Table 5: Differential heat flux during fire test

Composites	Heat Flux (W/M^2)
CARALL1	116,013
CARALL2	116,050
CARALL3	115,959
CARALL4	115,973

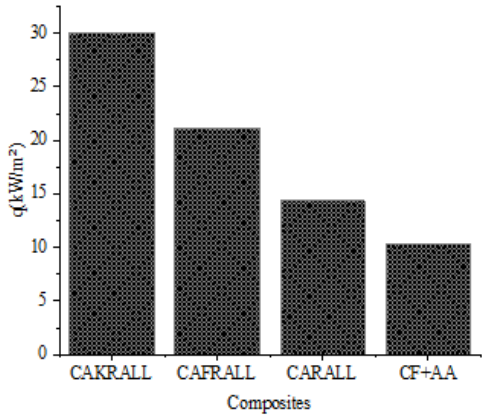


Fig. 4: Re-radiated heat flux for each composite

The burner and flame position were retained throughout the test according to the standard; therefore the stability of the jet flame was affected by the circulating air and buoyancy in the enclosed area. Some other factors that had also affected it were incomplete combustion, char formation, fibre enlargement and early melting of the metal used with some other abnormal physical etiquette. The time relation with the heat of conduction is linear; these factors observed during the test were also reported by Quintiere [39]; Tewarson [31]; Bartlett and Stratford [42].

3.2. Mechanical properties

Four mechanical properties result are presented and discussed in this section, namely tensile, compression, flexural and impact tests. Figure 5 shows the average result of the tests for the four properties.

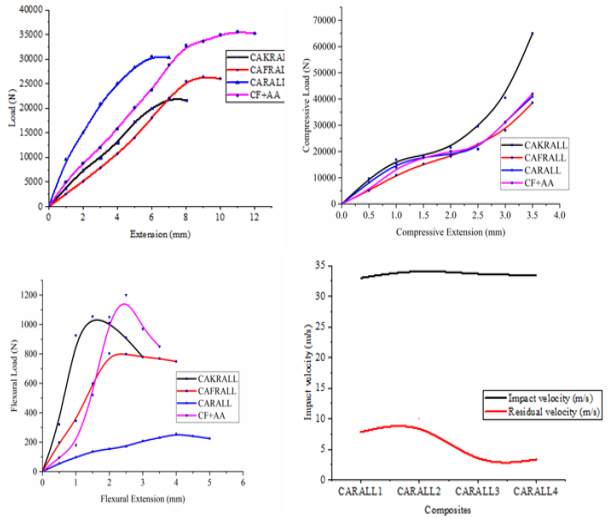


Fig. 5: Mechanical test results

The results from the mechanical tests for the three properties (tensile, compression and flexural) showed an increase in extension as the load increases till a certain point where the composite failed. The characteristic of the curves for the tensile and flexural tests were also observed in Tamilarasan *et al.* [20], in which the mechanical properties of FML composite of aluminium alloy 6061-T6 sandwiched with carbon reinforced fibre laminates were used, while the compressive curve characteristic was reported by Zikre and Bhatt [32] where glass fibre was used.

The results indicated that CARALL2 produces the highest tensile and flexural load, which is due to the high number of reinforced fibre used and more bonding exists between the fibre and epoxy. While CARALL3 and CARALL4 produce the highest compressive load, it shows that natural fibre plays a good role in resisting the compressive load. CARALL1 and CARALL2 have nearly the same impact load. The impact result showed that all four composites can withstand a low-velocity impact with the highest residual velocity in CARALL2 and the lowest on CARALL3. The result was in agreement with the result reported by Mohammed *et al.* [9]. Also, the result showed that the FML composite of synthetic fibre yielded better mechanical properties than composites that were sandwiched with greener fibre material, as observed in glass fibre and bamboo composite [32]. The strength of the composites (tensile, compressive and flexural) obtained from the analysed stress and strain as well as the curves were shown in Figure 6.

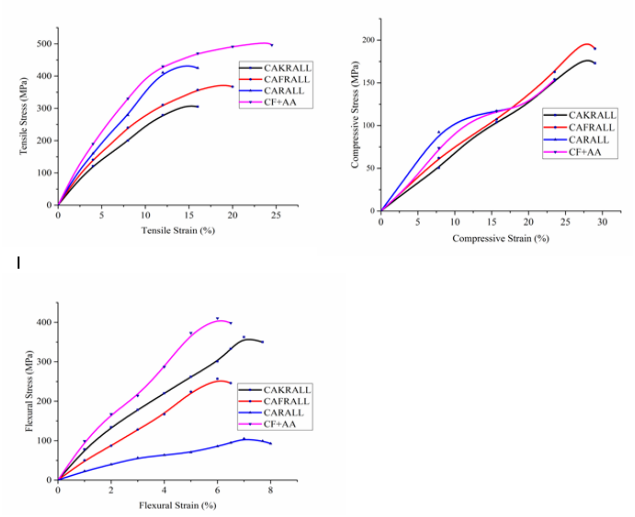


Fig. 6: Stress vs strain

There was an elastic behaviour on the tensile stress/strain curve between 300-400 MPa, where the highest elastic behaviour was observed on the composite of synthetic fibre, whereas the curve changes to plastic behaviour that resulted to the failure of the composites (indicating the shape changing in composite under load). Meanwhile, on the compression stress/strain curve, the composite of natural fibre sandwiched with synthetic fibre produced higher compressive stress values, the composite showed a premature failure and delamination before final failure, as reported by Botelho *et al.* [42]. It was also observed from the flexural stress/strain, that the composite with aluminium alloy at the top and bottom of the composite yielded a better strength than the composite with alternating aluminium alloy. Table 6 shows the calculated strength of the four composite being studied.

Table 6: Tensile strength of the FML composites

Composites	Tensile Strength (GPa)	Compressive Strength (GPa)	Flexural Strength (GPa)
CARALL1	4.80	0.56	0.08
CARALL2	5.07	0.56	0.47
CARALL3	4.40	0.56	0.27
CARALL4	3.75	0.44	0.36

The increase of tensile strength for the FML composites being studied was due to the interfacial cohesion between the polymer and fibres based on the properties of the polymer, using other types of other polymers reported the same result as in this study [43-45]. Lower flexural values obtained on CARALL1 was due to the number of metal alloy used in fabricating the composite, where there is a poor surface interaction between the alloy and polymer due to the lack of interfacial interaction. Therefore, the composite weakens at the early stage of the applied load than the composites. This reduced matrix and fibres interface, which then reduced the stress transfer materials. The mechanical properties results from the test showed excellent properties that can be used in fire designated zone of an aircraft engine. Also, the average standard deviation of the tensile test was obtained from the four different composites during the test as in Table 7.

Table 7: Standard deviation of tensile test of the FML composites

Composites	CARALL1	CARALL2	CARALL3	CARALL4
Maximum Load (N)	8634.68	6044.05	3461.47	4028.55
Modulus (MPa)	956.27	519.79	424.31	674.12
Tensile stress at Maximum Load (MPa)	67.64	86.34	40.88	57.55
Tensile strain at Maximum Load (%)	1.51	2.10	2.54	3.04
Tensile stress at Break (Standard) (MPa)	2.75	1.55	1.91	2.05
Tensile strain at Break (Standard) (%)	1.59	1.69	2.13	1.79
Tensile stress at Yield (Zero Slope) (MPa)	63.53	86.35	23.52	57.55

Absorbed energy and impact strength of the four composites were evaluated using Eqn. 3 and Eqn. 4, respectively. The results were shown in Figure 7 and Figure 8.

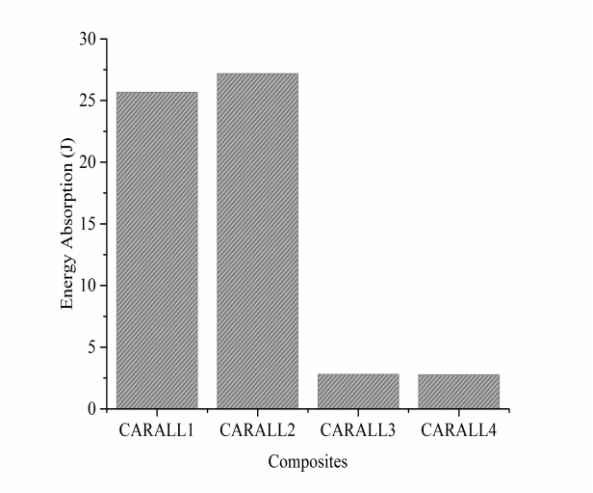


Fig. 7: Energy absorption of the composites

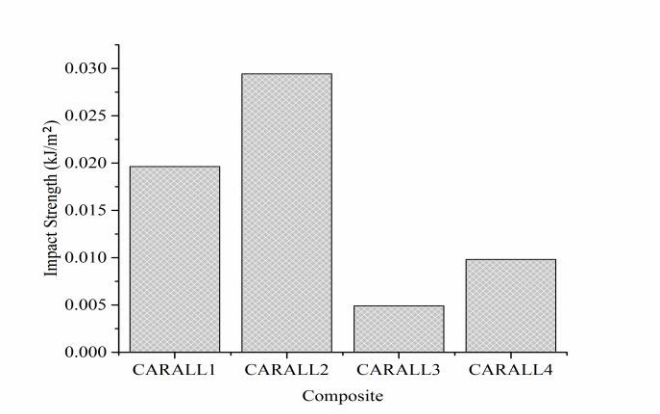


Fig. 8: Impact strength of the composites

CARALL2 was 66.67%, 83.32% and 33.33% higher than CARALL4, CARALL3 and CARALL1 respectively in terms of impact strength on low velocity, for total energy absorbed before crack begins in the composite. More delamination was observed on CARALL1 due to the number of aluminium alloy used in the composite that showed lower surface dissipation of energy, the result coincided with the results obtained using glass fibre reinforced plastic and other investigations [9, 46-48].

4. Conclusion

The study was based on developing advanced FML composites using both synthetic and hybrid synthetic/natural fibre for aero-engine applications. The objective of the study was achieved by considering the results obtained both on the fire test and mechanical properties tests, by comparing the results with the results of the existing composite used in the zone. Three out of the four FML composites considered in this study showed fireproof properties according to ISO2685 standard, while the fourth FML CARALL4 was identified as a fire resistant composite. Based on the standard, all the four FML composites can be used in fire designated zone of an aircraft engine, but CARALL4 can only be used in some location. When comparing the mechanical properties of this FML with other composites used in the fire designated zone, the results obtained was encouraging. The results for the two properties considered showed that carbon fibre reinforced aluminium laminate with aluminium alloy at the front and rear face (CARALL2) has the highest properties compared to the other three FML composites. Also, results for carbon fibre flax reinforced aluminium laminate (CARALL3) showed that the greener fibre can be used in the near future to replace the synthetic fibre due to its fireproof properties and mechanical properties as well as eco-friendly properties or can be hybridised with a synthetic fibre to reduce the health risk of synthetic fibre.

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