Ballistic impact velocity response of carbon fibre reinforced aluminium alloy laminates for aero-engine

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Abstract. Aerospace and other industries use fibre metal laminate composites extensively due to their high specific strength, stiffness and fire resistance, in addition to their capability to be tailored into different forms for specific purposes. The behaviours of such composites under impact loading is another factor to be considered due to the impacts that occur in take-off, landing, during maintenance and operations. The aim of the study is to determine the specific perforation energy and impact strength of the fibre metal laminates of different layering pattern of carbon fibre reinforced aluminium alloy and hybrid laminate composites of carbon fibre and natural fibres (kenaf and flax). The composites are fabricated using the hand lay-up method in a mould with high bonding polymer matrix and compressed by a compression machine, cured at room temperature for one day and post cure in an oven for three hours. The impact tests are conducted using a gun tunnel system with a flat cylindrical bullet fired using a helium gas at a distance of 14 inches to the target. Impact and residual velocity of the projectile are recorded by high speed video camera. Specific perforation energy of carbon fibre reinforced aluminium alloy (CF+AA) for both before and after fire test are higher than the specific perforation energy of the other composites considered before and after fire test respectively. CF +AA before fire test is 55.18% greater than after. The same thing applies to impact strength of the composites where CF +AA before the fire test has the highest percentage of 11.7%, 50.0% and 32.98% as respectively compared to carbon fibre reinforced aluminium alloy (CARALL), carbon fibre reinforced flax aluminium alloy (CAFRALL) and carbon fibre reinforced kenaf aluminium alloy (CAKRALL), and likewise for the composites after fire test. The considered composites in this test can be used in the designated fire zone of an aircraft engine to protect external debris from penetrating the engine shield due to higher values of impact strength and specific perforation energy as highlighted by the test results.

1. Introduction

Due to demands for lightweight body in aircraft construction, the need for improved fibre reinforced laminate composites has been progressively increasing. Fibre metal laminates play an important role in protecting the aircraft components against foreign objects and providing an excellent ballistic impact penetration resistance on them. Improvement in the performance of impact properties, lightweight and
toughening of aircraft engine nacelle materials has become necessary to protect the components from cracking after collision with debris, birds, rain and/or hail. Fibre reinforced composite is among the materials with excellent properties of impact loading. In aircraft industry, this material type has been produced with different fibre types that uses different types of matrix, formed using different methods, and can have various shapes with different thickness [1]. Carbon fibre reinforced plastic (CFRP) has superior properties of high strength, stiffness and also resistance to impact loading [2]. However, the most frequently identified constraints of fibre-reinforced plastics are their poor resistance to localized impact loading and their load bearing properties [3, 4]. The study of hybrid laminate composites has become necessary due to limitation of each constituent. For instance, when they are considered alone, carbon fibre reinforced composite has the disadvantages of poor impact and residual strength whereas poor fatigue strength affects the performance of aluminium alloy. Combination of these two materials can overcome these problems and increase the cost effectiveness of the composite [5].

There are several factors to be considered in the hybridization of natural fibre with synthetic fibres, which include availability, lightweight, cost and environmental factors. Bast fibre has been reported to be the most suitable hybridized natural fibre [6, 7]. Furthermore, some advantages of Kenaf hybridized with synthesis fibre have also been highlighted [8]. An investigation on ballistic impact of synthetic fibre hybridized with natural fibre laminates has also been conducted. Different layers of aramid and kenaf are hybridized, and the resultant laminate composites that are used for protective helmet showed the same performance in high impact penetration as that of aramid only [9]. In addition, it is found that improved thickness and epoxy ductility of the composites will produce excellent impact properties and improve energy absorption of the material (in this study, kenaf is hybridized with glass fibre) [10]. In the meantime, it has been found out in a study on the effect of stacking a sequence of Kevlar fibres on failure mechanism and residual velocity, where the ballistic limit of coir yarn and Kevlar/epoxy hybrid composite are determined, that the main failure on a high velocity impact test is based on fibre fracture and delamination of the metal part of the composite [11].

Many researchers have studied the impact velocity of composite used in aircraft components. It is reported that the energy absorption of Kevlar-29/epoxy and Kevlar 29/epoxy-Al₂O₃/Al with different stacking sequences using a cylindrical steel projectile increases with increase of composite thickness [12]. The elastic, petaling and dishing work are all ingested in perforation energy [13]. Moreover, the relationship that exists between thickness of the composites and ballistic impact velocity of cylindrical bullet has been established, whereby the total loss of kinetic energy of the cylindrical bullet projectile is assumed to be equal to total work done in the deformation of the plate 14]. The energy dissipation of the component depends on the types of polymer used and the high impact strength of the composites is dependent on bonding adhesions that exists between the fibre and matrix, and the delamination of the composites, whereas the brittle matrix dissipation energy is suppressed [15]. The hybrid composite of synthetic fibre (Kevlar, glass fibre and carbon fibre) for constructing armour are studied and the result indicates an increase in ballistic impact performance, likewise on Kevlar and polypropylene (PP) [16, 17]. Fibre is the material responsible for crack in fibre reinforced composite. It controls the elongation of the composite during breakage by reducing impact energy absorption. Agglomeration also occurs on it at high fibre loading, causing fibre-to-fibre contact that reduces the stress transfer between the fibre and the matrix, resulting in composite failure [18-20].

Different modes are used in determining the level of damages in the composites during impact. There are various internal damages after the impact on the composites such as delamination, matrix cracking, fibre breakage and others, especially when they are impacted with low velocity. Ultrasonic image or radiography and backlighting are some of the equipment used to detect the internal damage made from impact [21-27], matrix crack for each ply of fibre are determined by Bar-Cohen and Crane [28] and also detect some of the defects that affect the fibres such as misalignment. In this study, four types of laminate composites are fabricated to withstand a high temperature in fire designated zone of an aircraft engine using fibre metal laminate of aluminium alloy 2024-T3, carbon fibre, natural fibres (kenaf and flax) and epoxy resin/hardener. Two of the composites are consisted only of carbon fibre and aluminium alloy: one with aluminium alloy at front and rear face of the composite only, and the
other composite consists of alternating layer of aluminium alloy. Two other composites consist of hybrid synthetic and natural fibres with aluminium alloy at the front and rear face of the composites: one consists of carbon fibre and kenaf at the centre whereas the other consists of carbon fibre and flax.

The main purpose of this study is to investigate the impact strength resistance and the specific perforation energy of the fibre metal laminate composites. The test is performed in a fire designated zone of an aircraft engine, using propane-air burner according to ISO 2685 standard. The temperature range and heat flux range of the standard are 1100±80°C and 116±10kW/m². The materials used in fire test are affected by the impact velocity based on the external forces that affect the aircraft engine nacelle during take-off and landing. Hybrid composites of synthetic/natural fibre and synthetic fibre with aluminium alloy 2024-T3 have been developed with varying proportion of materials layers, so that different effect of hybridization of the materials used in the composites are evaluated. Ballistic impact velocity of each composite is determined using gun tunnel system machine, and the impact and residual velocities each composite before and after fire test are evaluated using the high-speed video camera. Four main results are presented: the impact and residual velocity, potential energy, impact strength and the specific perforation energy before and after fire test of the composites considered.

2. Experimental Setup
Four composite samples have been prepared for the ballistic impact velocity target using fibre metal laminates of aluminium alloy 2024-T3, woven carbon fibre and natural fibres with the epoxy resin/hardener of different numbers of layers, with 0°-90° orientation. The plate area used for the impact is 100mm x 100mm and the target area is at the centre of the plate of around 15±2mm with the thickness is 3.5±0.2mm. Table 1 gives the summary and stacking configuration of the composites.

Table 1: Composites and their stacking configuration

| S/No. | Composite Type | No. of layers | Stacking Configuration | Density (kg/m³) |
|-------|----------------|---------------|------------------------|-----------------|
| 1     | Carbon fibre kenaf reinforced aluminium alloy with aluminium alloy at the front and rear face of the composite (CAKRALL) | 7 | Al/2CF/KF/2CF/Al | 1483 |
| 2     | Carbon fibre flax reinforced aluminium alloy with aluminium alloy at the front and rear face of the composite (CAFİRİALL) | 9 | Al/2CF/FF/CF/FF/2CF/Al | 1506 |
| 3     | Carbon fibre reinforced aluminium alloy with alternating aluminium alloy (CARİALL) | 11 | Al/2CF/Al/CF/Al/CF/Al/2CF/Al | 1414 |
| 4     | Carbon fibre reinforced aluminium alloy with aluminium alloy at the front and rear face of the composite (CF+AA) | 13 | Al/11CF/Al | 1240 |

The composite of fibre metal laminates are fabricated by stacking the proper number of plies of the fibre materials and aluminium alloy sheets in a mould using the appropriate volume of epoxy resin/hardener (of ratio 2:1) by hand lay-up method and then placing the stack into a compression machine. The laminates composites are then cured at room temperature for 24 hours and post cured in an oven for three hours at 80°C. Figure 1 illustrates the laminate composite of the plate in a fixed position and
Figure 2 depicts the picture of the sample after impact. A plate of square edge of length 100 mm is clamped in a steel support and it is bolted to the steel block. Two sets of composites are tested: first set are composites before the fire test while the second set of composites are those after the fire test.

Figure 1: Composite laminate plate

Figure 2: Picture of a sample after impact

A flat cylindrical mild steel bullet of mass 5g, diameter 8.5mm and a length of 13.5mm are used in the test. In addition, a gun tunnel system, high speed video camera and a spot light are also used. The set up picture of the test is as shown in Figure 3, where the gun reservoir is pressurised at 20bars with helium gas and is fired by fast active valves. The flat cylindrical bullet accelerated horizontally in the barrel to impact chamber where the composite samples are fixed. The amount of the air in the barrel is ejected prior to the firing test by evacuating 100 mbar from the barrel.

The experimental impact velocity tests of the four composites are carried out using the test rig. The rig is 365mm length with nominal bore of 20mm. The composites to be tested are clamped between two steel constraining plates and are firmly tightened. During the test, the velocity before hitting the target and the residual velocity after hitting the target are measured by high speed video camera, which is set to record the incident impact at 30,000 frames per second with an image size of 277.3 pixels per image. The velocities of the flat cylindrical bullet before and after penetration of the composites, and the horizontal distance are recorded and the travel projectile time is calculated.

Figure 3: Ballistic impact test facility setup
Impact and residual velocities are obtained from different types of laminate composites before and after hitting the target, and also before and after the fire test. The ballistic impact test is performed on the composites for a range of impact energies until the complete perforation of the composite.

3. Results and Discussion

During the test, it has been observed that penetration occurs on all composite samples under study that are subjected to a velocity of 214±2m/s. The debris is pulled out from the front and rear faces of the composites, consisting of the matrix and fibre components, and delamination of the aluminium alloy. A bulge is observed on the rear face of the composites with much debris, while the front face takes the shape of a flat cylindrical projectile. Meanwhile, perforation at the front face has the same diameter with the projectile as shown in Figure 4. The bulge at the rear face shows that the projectile ceased at the exit of the composites with continuous crack development. As the fibre is fractured due to impact, the polymer matrix of that area will no longer hold the fibre (no stress acts on the area), therefore the matrix undergoes shear stress which in turn leads to failure of the panel. This situation agrees with a previous work in Ref. [29]. The flat cylindrical bullet has penetrated all composites during the impact, with increasing hole diameter from the front face to the rear face. Due to different materials used in each composite, the immensity of frictional force affects the impact energy absorption of the samples owing to much delamination that occur on the composite as reported by Ref. [30].

![Figure 4: Front and rear faces of the samples after penetration](image)

The lay-up of the samples are unidirectional and the impact damage is very extensive, especially in the delamination on the fibre axis leading to fragmentation of the fibre on the rear face. This is shown by the different shapes on different composites, which looks like rhombo-hedral and a cone shape, but the front face shows the same circular shape. Similar observation has been made in Ref. [31, 32], with a little bit higher deflection of the composites as reported in Ref. [33]. Before the fibre is fractured, the crack grows through the matrix inside the plies of the fibre up to the inter-laminar region where the composites are weakened and then failed as seen in Ref. [1]. The composites absorbed and dissipated the energy under the impact condition due to nature of composite constituents, as also observed in Ref. [34]. As the applied force has exceeded the fibre-matrix interfacial bond, de-bond occurs and the fibre breaks. The ductile tearing of the fibres and the delamination of the aluminium alloy of FML are in agreement with Ref. [35] and the mode of failure comes before the delamination as those observed in Ref. [36], which leads to plate deformation.

The velocities of each composite before and after the impact are presented in Figure 5. The CF+AA composites shows more impact resistance than the other composites. CAKRALL burns during the fire test and therefore, the velocity before the impact equals to the velocity after impact since no fibre is left on the centre of the composite during the impact test. From the results obtained, the velocity for CF+AA before the fire test is 6.7%, 26.6% and 17.6% greater than that for CARALL, CAFRALL and CAKRALL, respectively. Meanwhile, after the fire test, the velocity for CF+AA is 4.9% and 10.0%
greater than that for CARALL and CAFRALL, respectively. As the fibres are pulled out from the matrix, energy is dissipated. Impact energy is calculated from the difference of the potential energy of impact before and after hitting the samples. Moreover, impact strength of each composite is estimated by dividing the impact energy with their cross-sectional area as indicated in Figure 6.

The result shows that CF+AA has the highest impact strength for both before and after fire test. It has 32.98%, 50.0% and 11.7% greater impact strength (i.e. total energy absorbed before crack begins in the composite) than CAKERALL, CAFRALL and CARALL, respectively, for samples before fire test. On the other hand, for samples after the fire test, CF+AA has 75.0% and 36.6% greater impact strength than CAFRALL and CARALL, respectively. The result for CARALL shows that alternating layers of the composites causes delamination between the inner layers, as reflected by less travelling distance of the projectile in the sample that indicates less surface energy dissipation [37, 38]. Similar result has also been observed in Ref. [39], where the impact strength of different load percentages of Roselle fibre was investigated. There are some factors that affect the impact strength of the composites after fire test, which are poor adhesion, poor interfacial bonding between the matrix and fibre, and also stress concentration at the end of fibre. These factors are in agreement with the factors identified in Ref. [40] in the study of change in impact strength with filler content of rice husk with polypropylene composites.

Figure 7, meanwhile, shows the specific perforation energy of both composites before and after fire test. The CF+AA composite before fire test has the highest value of 23.40 Jm²/kg and the least value of 3.38 Jm²/kg is observed on CAFRALL after fire test.
Specific perforation energy of the fibre metal laminates based on the type of fabrication materials increases with the increase of their tensile strength and laminate thickness. This result is in agreement with the result reported in Ref. [41]. In all the composites considered, the specific perforation energy values of the samples before the fire test are higher than those after the test. This can be contributed to the higher tensile and thickness values in the samples before the fire test. Furthermore, after the fire test, the composites lost most of adhesive bond properties between the fibre and matrix, and in some composites, there is total delamination of aluminium alloy. The specific perforation energy of CF+AA is higher than that of CARALL despite the fact that they have the same thickness. This implies that the carbon fibre plies are able to withstand more strength than a sheet of aluminium alloy and they are more bonded to epoxy resin/hardener. Therefore, the increase of carbon fibre corresponds to increase in perforation resistance in the composite. In addition, synthetic fibre (carbon fibre) is more resistant to perforation than the natural fibre (kenaf and flax). The results obtained in the specific perforation energy suggested that the fibre metal laminates that use thin sheets of aluminium alloy and reinforced fibres offer significant advantages to be utilized in the fire designated zones of an aircraft engine as a protective shield against external forces on the engine, including debris flying on the run way during landing or take-off or dropping any tools during an engine maintenance.

4. Conclusion
Moderate velocity impact performance of different types of fibre metal laminates based on reinforced synthetic and natural/synthetic fibres with aluminium alloy 2024-T3 and epoxy resin/hardener, before and after the fire test, has been studied. The results indicate that the hybrid composite laminates are able to be applied as lightweight energy-absorbing structures in the fire designated zone of an aircraft engine. The tests show that carbon fibre reinforced aluminium alloy, with aluminium alloy at the front and rear face of the composites, presents an excellent impact strength and specific perforation energy than the other considered composites due to good energy absorption behaviour of the carbon fibre. A crack growth is observed from front to rear faces of the samples, especially on the natural/synthetic hybrid fibre metal laminates, due to the de-bonding of the fibre and matrix. The lower modulus of the plies in composite makes aluminium alloy layers deform permanently by exciting remarkable energy through confined membrane stretching. The higher strain needed to break down natural/synthetic fibre with the laminate composites permits a greater amount of energy to be soaked up in the break down techniques, thereby increases perforation resistance of the composites. In terms of specific perforation energy and impact strength, the composites before the fire test have 223% and 214% higher than after the fire test, respectively. An examination on the samples shows that the composites can withstand a lower velocity impact on an external object either during take-off or landing.

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