Effect of Layer Structure on Dynamic Response and Failure Characteristics of Carbon Fiber Reinforced Aluminum Laminates (CARALL)

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Abstract The effect of placing carbon fiber reinforced composite layers exterior or interior to the aluminum layers on the low-velocity impact performance of CARALL FMLs was investigated in this research study. In this study, CARALL laminates having 3/2 configuration, with aluminum in the outer layer for the first case (CARALL A) and one with carbon fiber composite (CFC) layer in the outer layer (CARALL B) were prepared using a vacuum press without using any adhesive film. In addition, CARALL-A FML was modified with a thin veil cloth layer between CFC and aluminum layers (CARALL-C). Force–displacement histories, damage morphologies and energy absorption capabilities of these laminates in relation to different energy levels are presented and discussed. The influence of resin rich layers (veil cloth) at the interfaces of aluminum and carbon fiber/epoxy layers on the impact behavior and damage size is also investigated. CARALL-A FMLs absorb the energy mainly through plastic deformation and delamination initiation and propagation whereas CARALL-B absorbs the impact energy through penetration and perforation of the laminate. The introduction of resin rich layers (veil cloth) affects the overall dynamic response with higher contact forces, smaller ultimate central deflections, reduced delamination damage area, and provides hindrance to the growth of cracks in the non-impacted aluminum layer and thereby increasing the impact resistance of CARALL-C FMLs.

Keywords Fiber metal laminates · Drop weight impact test · C-scan · CARALL · Layer structure · Dynamic response · Failure characteristics

Introduction

Fiber Metal Laminates (FMLs) are ultra-light weight hybrid structural materials made with the combination of alternating thin metallic sheets and fiber reinforced composite layers, developed at the Delft University of Technology [1, 2]. FMLs are great materials for aerospace and shipbuilding applications due to their high resistance to crack propagation and improved damage tolerance characteristics [3, 4]. GLAss-REinforced aluminum laminates (GLARE), is the most common type of FMLs which consists of S2 glass/epoxy composite layers stacked alternatively to 2024-T3 aluminum sheets. It has found application in many primary components of various aircraft such as Airbus A380 [5, 6] and Boeing 777 [7] due to its excellent damage tolerance properties. CARALL FML still being a novice, is not widely used in the industry. Carbon fiber reinforced aluminum laminates offers additional benefits of improved safety and cost reduction in addition to weight reduction and resistance to cumulative damage from the other materials available for aircraft structures [8, 9]. CARALL FMLs can be used as structural material for a potential application in the different automotive vehicle structures due to their excellent stiffness and strength combination [10].

Impact damage to composite aircraft structures can occur during preflight and taxing operations, due to runway debris, hail or bird strikes, tool drop during maintenance of aircraft, collisions of the structure with service cargo or cars, engine debris, tire rupture and ice dropping on fuselage from

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propellers [11]. According to Vogelesang and Vlot [11], impact damage is the reason behind the major structural repairs of Boeing 747 aircraft. Impact damage tolerance is one of an essential property for choosing and designing these materials. Therefore, the knowledge of impact behavior of these materials is required in finding the methods for predicting the impact resistance of these FMLs. In the past years, many researchers have conducted experiments and performed numerical simulations to study the low-velocity impact behavior of FMLs. The majority of these studies are focused on studying the impact behavior of GLARE and Aramid Reinforced Aluminum FMLs. Ardakani et al. [12] investigated the influence of interfacial adhesive bonding on impact behavior of several glass-fiber reinforced aluminum (GLARE) laminates with different bonding adhesion. They reported that laminates with poor interfacial adhesion had greater damage size as compared to that of laminates with strong adhesion between aluminum and glass layers. Rajkumar et al. [13] experimentally investigated the effect of repeated low-velocity impacts on the tensile strength of glass fiber-reinforced aluminum FMLs using drop weight impact tester. Their test results indicated that ultimate tensile strength, failure strain, and ductility of all specimens initially decrease with an increase in a number of impacts and then remain constant. Seo et al. [14] presented a finite element model used to simulate the impact response of a FML. Two and three-dimensional failure criteria in ABAQUS are used to model stiffness degradation of the glass-fiber-reinforced composite layers and the load time history, maximum deflection, and damage progression was examined using an explicit finite element model. The FE simulation results showed good agreement with experimental results. Jeremy Laliberté et al. [15] investigated the low-velocity impact behavior of GLARE FMLs to study the damage modes and mechanisms through which the panels absorb the energy of impact. They reported that the fundamental damage modes change and the relative amount of absorbed energy also change with the increase the level of impact energy. Having more fibers in one direction leads to a more predictable and gradual onset of panel penetration. Jeremy Laliberté et al. [16] developed a continuum damage mechanics based material model using a user-defined material subroutine to predict the impact response GLARE panels. They reported that the model with the tiebreak-interface delamination model showed some sensitivity to the mesh density giving over-prediction of the delamination damage for lower mesh densities and under-prediction of the dent depth. Guocai Wu et al. [17] investigated the impact properties and damage tolerance of glass fiber reinforced aluminum laminates with cross-ply glass prepreg layers. They showed that both GLARE 4 and GLARE 5 laminates had better impact properties than those of 2024-T3 solid aluminum alloy. Taheri-Behrooz et al. [18] studied the effect of stacking

sequence on the impact behavior of fiberglass–aluminum FMLs under the drop weight impact test. They reported that $[Al-(\pm 45)_8-Al]$ layups has higher load-bearing capacity before failure of the outer aluminum layer than the specimens having $[Al-(0/90)_8-Al]$, $[Al-(0/90)_4-(\pm 45)_4-Al]$ and $[Al-(\pm 45)_4-(0/90)_4-Al]$ layups.

Very few research studies have been conducted in recent years to study the behavior of CARALL FMLs [19–26]. Song et al. [10] studied the impact performance of CARALL laminates with the drop weight impact tests and dynamic non-linear transient simulations. The experimental results of this study verify that the specimen impacted by 2.35 J shows no critical damage but there were significant fiber and matrix failures in CFRP layers and a shear crack on the aluminum surface of specimen impacted by 9.40 J. Kim [27] studied the low velocity impact damage characteristics of aluminum/composite hybrid drive shaft whose composite layer was stacked inside of the shaft. They have reported that when the thickness of the aluminum tube was larger than the 3 mm, the damaged area of the composite layer decreased significantly. Rajkumar et al. [28] investigated the repeated low-velocity impact behavior of glass fiber reinforced aluminum laminates and carbon fiber reinforced aluminum laminates at the same location using drop-weight tester. They observed that monolithic aluminum plates, GLARE, and CARALL FMLs exhibited different behavior for load bearing capacity and damage pattern. Bienias Jaroslaw [29] conducted a comparative study on the low-velocity impact resistance of aluminum/carbon and glass FMLs investigating the influence of fiber orientations on the load–time response, damage size and damage depth in relation to various energy levels. They observed that carbon fiber laminates showed a higher tendency to a perforation in comparison to laminates containing glass fibers.

However, the relationship between the damage mechanisms and layer structure of carbon fiber/epoxy layers and aluminum layers in CARALL laminates is not explained. In this research work, the influence of placing carbon fiber/epoxy layers exterior and interior with respect to aluminum layers on the impact damage morphologies, load–displacement histories, and energy absorption are presented and discussed. Also, the effect of resin rich layers (veil cloth) which were added to the interfaces of the aluminum and carbon fiber layers on the impact response of CARALL laminates is studied.

Specimen Preparation

The FMLs, which are subject to examination in this research work, are composed of 5052-H32 aluminum alloy and VTM264/CF302 woven carbon fiber/epoxy layers.

Commercially available 5052-H32 aluminum alloy sheets was utilized in the fabrication of these FMLs. The as received aluminum alloy sheet was strain hardened and had stabilized H32 temper. It was a bare aluminum alloy sheet without having any textured surface and have an average grain size of 19 μm . A microstructure grain analysis was performed to study the size shape and distribution of material grains as the grain structure can largely influence the mechanical response of FMLs. The small sample strips were cut from the received aluminum alloy sheet. These small sample strips were highly polished and etched with Keller's reagent (2.5 ml HNO_3 , 1.5 ml HCL , 1 ml HF , and 95 ml water) to reveal the grain structure of aluminum alloy. The thickness of aluminum alloy layer and woven carbon fiber/epoxy prepreg was 0.5 and 0.22 mm, respectively. The chemical composition of 5052-H32 aluminum alloy layers used in this research study is given in Table 1.

A viewgraph of received aluminum alloy sheet along with its grain structure is shown in Fig. 1. The fiber volume fraction in carbon fiber/epoxy prepreg utilized in this study is 42 %. The synthetic surface veil cloth used in this research is a non-woven fabric manufactured from Dacron[®] 106 homopolymer, and it is commercially known as Nexus[®]. The surface of aluminum layers was slightly made rough with the help of grit paper # 60/P60 so as to improve the adhesion between aluminum and carbon fiber/epoxy layers. The specimen's layers were stacked in desired stacking sequence by utilizing hand layup method.

The layered specimens were cured in autoclave vacuum press under 0.35 MPa pressure and 130 °C temperature for 60 min. The curing cycle utilized for consolidation includes the cooling of specimens by passing mist and water over the platten for 15 min each. The schematic illustration of stacking sequence of carbon fiber/epoxy

layers, aluminum layers and resin rich layers (veil cloth) in CARALL FMLs studied in this research is shown in Fig. 2.

Experimental Procedures

The low-velocity impact experiments were performed according to ASTM standard D7136 [32] using the drop weight impact test equipment. The weight of the hemispherical impactor employed to conduct impact experiment was 1.819 kg and a tip diameter of 28.39 mm. A 20 mm thick aluminum plate having a 125 mm $\times$ 75 mm cutout located at the center was used to clamp the rectangular specimens having dimensions of 152.4 mm $\times$ 101.6 mm with the help of four toggle clamps. The tips of clamps were made of neoprene rubber, and minimum holding capacity of these clamps was 1100 N. The specimen was positioned centrally over the cutout with the help of guide pins. The entire fixture was aligned to the rigid base using bolts. The height of the hemispherical impactor was adjusted to obtain the designated impact energy. The accelerometer was positioned on the top of the impactor to measure the velocity of the impactor nose. The contact force–time signal was recorded by the acquisition system with the help of the load cell located underneath the rigid support fixture.

The displacement–time signal was obtained by integrating the acceleration–time signal measured by the acquisition system. Different types of CARALL FML specimens were experimentally tested at three different impact energies of 14, 21 and 31 J by utilizing the impact tower shown in Fig. 3b. To gain the profound understanding of the behavior these CARALL FMLs, five samples from each FMLs category were tested at different impact energy levels. The mechanical behavior of these FMLs showed excellent repeatability. The minimal each impact energy deviation in the peak force, ultimate central displacement, delaminated area and absorbed energy is shown in respective figures through errors bars. The experimental test matrix used in the research is shown in the Table 2. In the calculation for contact force between

Table 1 Chemical composition of 5052-H32 aluminum alloy

Element	AL	Fe	Mg	Mn	Si	Cr	Cu	Zn
%	96.85	0.25	2.5	0.07	0.11	0.2	0.01	0.01

Fig. 1 Aluminum 5052-H32 sheet along with its grain structure used in making FMLs

Fig. 2 CARALL FML systems studied in the current research [30, 31]

Fig. 3 Impact test tower utilized in this research study. **a** Close view of striker impact the specimen. **b** Impact tower [30]

Table 2 Experimental test matrix

Impact energy (J)	Number of FMLs sample tested		
	CARALL A	CARALL B	CARALL C
14	5	5	5
21	5	5	5
31	5	5	5

Fig. 4 Force–displacement plots for CARALL FMLs **a** 14 J, **b** 21 J, **c** 31 J

striker and specimen, an assumption of no energy loss was made during an impact event.

After the impact test, the extent of damage through the thickness was examined carefully by slicing some samples

Fig. 5 Variation of peak force for CARALL FMLs at different impact energies **Fig. 6** Variation of ultimate central deflection for CARALL FMLs

through the center of laminate with the help of a diamond cutter. The damage area was measured by utilizing nondestructive (C-scan) testing. The damage size was calculated from the C-scan images by image analysis, using ImageJ software.

Results and Discussions

Force–Displacement Histories

The results of CARALL-A specimens are taken from our previous publication [30] so that the effect of stacking sequence and the addition of resin rich layers (veil cloth) on the low-velocity impact performance of these FMLs can be compared. A comparison between averaged force–displacement results of CARALL-A, CARALL-B & CARALL-C samples is made by plotting their results simultaneously on one scatter plot as shown in Fig. 4. The solid line describe the F–D curves of CARALL-C FMLs

Fig. 7 Damage morphologies of CARALL-A, B & C FMLs

whereas dashed lines are used to show plots of CARALL-A & B FMLs at different impact energies as shown in Fig. 4a–c.

CARALL A FMLs showed higher peak forces as compared to CARALL B FMLs at all impact energies. With the increase in impact energy, more fiber, and matrix damage

was observed in CARALLB FMLs resulting in larger permanent central deflection as compared to CARALL A FMLs at all impact energies. The variation of peak force with respect to impact energy for CARALL FMLs is shown through a line plot described by Fig. 5. The peak forces increase with an increase in impact energy for CARALL-A

FMLs, but there was not a significant increase in peak force for CARALL-B FMLs as the impact energy increases from 21 to 31 J due to more penetration and perforation of specimens. However, the closed type Force–Displacement (F–D) curves of CARALL FMLs for all impact energies implies that complete penetration of specimens was not observed in this research work.

The effect of the addition of resin rich (veil cloth) layers at the interfaces of aluminum and carbon fiber layers so as to improve the adhesion is studied by comparing the results of both CARALL-A and CARALL-C. It can be observed from the comparative plot described in Fig. 4 that the addition of epoxy rich veil cloth layers led to much higher peak forces and smaller permanent central deflections as compared to CARALL-A FMLs which were cured without using these cloth layers at all impact energies.

Force–Displacement curves of CARALL-A and C differ in both loading and unloading sections which can be observed in comparative plots described in Fig. 4. CARALL-C showed a much stiffer response in loading and unloading region resulting in more rebound and smaller central deflections as compared to CARALL-A FMLs. The variation of ultimate central deflection for CARALL FMLs with respect to impact energy is shown in Fig. 6. Comparing the response of all CARALL FMLs, it is clear that stacking the carbon fiber/epoxy layers exterior to aluminum layers resulted in more damage as compared to standard CARALL-A FMLs. As a consequence, of which the peak forces were lower and, ultimate central deflection was larger than CARALL-A FMLs. The addition of resin rich layers with the use of veil cloth resulted in much stiffer FMLs showing high peak forces and smaller central deflection as compared to standard CARALL-A FMLs.

Impacted and Non-Impacted Sides Damage Morphologies

The impacted and nonimpacted side's damage morphologies of CARALL-A, B and C are compared in Fig. 7. Minor cracks were observed in non-impacted aluminum and carbon fiber/epoxy layers of CARALL-A and CARALL-B FMLs, respectively at the lowest impact energy. For the lowest energy, the indentation-induced damage was observed on the impacted side of CARALL-A FMLs whereas minor fiber fracture along with delamination was observed on the impacted side of CARALL-B FMLs. CARALL-B FMLs showed larger delamination at all interfaces as compared to CARALL-A FML at lowest impact energy in the cross section images presented in Fig. 8. Fiber fracture was also observed in CARALL-A FMLs at lowest impact energy. Increasing the impact energy to 21 J resulted in larger crack lengths on the non-impacted side of both CARALL-A and B FMLs.

Fig. 8 Cross-section images of CARALL-A, B & C FMLs impacted at different energy levels

The failure of the interior aluminum layer was observed in CARALL-B FMLs, which can be seen in non-impacted side damage morphology image shown in Fig. 7. Indentation-induced damage was observed on the impacted side of CARALL-A FMLs at 21 J energy level whereas CARALL-B FMLs showed fiber breakage and failure of the interior metallic layer along with increased indentation depth. Increasing the impact energy to 21 J, results in the higher delaminated area in CARALL-A FMLs and less fiber fracture, whereas more penetration resulting from the failure of interior metallic and the fibrous layer was found in CARALL-B FMLs, which can also be seen in cross-section images shown in Fig. 8. A minor cohesive delamination between the middle carbon fiber/epoxy layers was also observed in CARALL-B specimens.

Fig. 9 C-scan results for delamination area of CARALL FMLs

Further increasing the impact energy to 31 J resulted in the failure of all metallic and fibrous layers of CARALL-B FMLs but the complete penetration of specimen by striker was not observed. At this impact energy, the indentation-induced failure of the top aluminum metallic layer was also found in CARALL-A specimens as shown in Fig. 7. The failure of interior metallic aluminum layers and carbon fiber/epoxy layers to a much larger extent can also be observed in cross section images for CARALL-A FMLs. Excessive adhesive delamination along with increased penetration was observed at all interfaces for this energy level in CARALL-B specimens. The addition of resin rich layers (veil cloth) reduces the crack lengths on the non-impacted sides of CARALL-C specimens as compared to CARALL-A FMLs at all impact energy levels. In addition to this, there was no failure of aluminum layer on the impacted side at 31 J impact energy.

The major effect of the addition of epoxy resin rich layers was that the delamination between successive layers reduced to a great extent which can be seen in cross-section images shown in Fig. 8. The failure of interior metallic layers was also not found with the addition of these layers at all impact energy. Fibrous layers also showed less rupture damage with the addition of these layers as can be seen in cross-section images of CARALL-C FMLs described by Fig. 8. Penetration depth was also reduced as compared to CARALL-A FMLs with the addition of these resin rich veil cloth layers.

Delamination Area Results

The delamination area results were obtained by scanning the impacted samples with the help of C-scan equipment. The C-scan results obtained by establishing a data collection gate on A-scan and recording the amplitude of the

signal at regular intervals as the transducer scanned the specimens is shown in Fig. 9. The 100 and 0 % values describe the fully delaminated and no delamination regions in the C-scan results. The delamination area increases with increase in the impact energy for all three types of FMLs.

Comparing the results of CARALL-A and C FMLs, it is clear the addition of resin rich layers (veil cloth) has a significant effect in reducing the delamination area. CARALL-B FMLs showed the higher delamination area as compared to CARALL-A for 14 and 21 J impact energies but impacting the CARALL-B FMLs at 31 J resulted in less delaminated area than CARALL-A FMLs due to the dominance of perforation failure over the delamination at this impact energy. The calculations of delamination area obtained through the image analysis, using the ImageJ software is shown in Fig. 10.

Absorbed Energy and Energy Restitution Coefficient Results Comparison

A comparison between the energy absorption capabilities of all CARALL FMLs is shown in Fig. 11. Similarly, the energy restitution coefficient (ERC) of all CARALL FMLs is compared in Fig. 12. Equation 1 was employed to calculate the ERC for each impact energy.

Fig. 10 Delamination area versus impact energy

Fig. 11 Absorbed energy versus impact energy comparison for all CARALL FMLs

Fig. 12 ERC versus impact energy comparison

Energy restitution coefficient (ERC)

$$= 1 - \frac{\text{Absorbed energy}}{\text{Total Impact energy}} \quad (1)$$

The absorbed energy values also increase as the impact energy level is increased for all CARALL FMLs. The outer impacted and non-impacted carbon fiber epoxy layers in CARALL-B FMLs suffered significant damage due to the enormous stiffness and brittle nature of carbon fibers. Thus, it can be implied from the ERC and absorbed energy plot that the impact resistance of CARALL A specimens is more than CARALL B FMLs due to less damage area and slightly high metal volume fraction. The addition of epoxy rich layers (Veil cloth) resulted in more absorption of impact energy as compared to CARALL-A FMLs, which were cured without using these cloth layers.

Comparing the numeric values of energy absorption for CARALL-A and C FMLs, it can be concluded the CARALL-C FMLs showed approximately 13 % higher energy absorption capabilities than CARALL-A. Comparing the energy restitution coefficient for all three CARALL FMLs, it was found that the reduction in ERC values for CARALL-B FMLs is more than CARALL-A FMLs as the impact energy level is increased from 14 to 31 J. CARALL-C FMLs have not showed much reduction in ERC values as the impact energy is increased. Their ERC value remains stagnant around 0.20 as the impact energy is increased.

CARALL FML's Outer Layer Crack Lengths Comparison

The measured length of major cracks in the impacted and non-impacted sides of different CARALL FML studied in this research are compared with each other in Table 3, 4 and 5. Due to the dissimilar crack lengths in different directions on non-impacted sides of these FMLs, the major (larger) crack length (Fig. 13) was considered for making a comparison between the crack growth characteristics in outer layers of these CARALL FMLs. As previously

Table 3 Major crack lengths in outer layers of CARALL-A FMLs

Impact energy (J)	Crack Lengths (mm)			
	Impacted Side	Standard deviation	Non-Impacted Side	Standard deviation
14	0	0	20	1.3
21	0	0	24	2.4
31	18	0.7	31	3.4

Table 4 Major crack lengths in outer layers of CARALL-B FMLs

Impact energy (J)	Crack Lengths (mm)			
	Impacted Side	Standard deviation	Non-Impacted Side	Standard deviation
14	5	0.4	30	2.1
21	12	1.7	46	3.7
31	20	2.2	55	4.3

Table 5 Major crack lengths in outer layers of CARALL-C FMLs

Impact energy (J)	Crack Lengths (mm)			
	Impacted Side	Standard deviation	Non-Impacted Side	Standard deviation
14	0	0	16.2	0.7
21	0	0	21.4	1.4
31	0	0	29.1	2.1

Fig. 13 Arrow describing the major crack (*Larger*) measured in FMLs

mentioned, the length of major cracks grow will the increase in the impact energy. Due to brittle nature of carbon fibers in impacted and non-impacted carbon fiber/epoxy layers of CARALL-B FMLs, the increase in crack length was higher as compared to CARALL-A FMLs. The addition of epoxy resin rich (veil cloth) layers also helped in hindering the growth of cracks in the non-impacted aluminum layer of CARALL-C FMLs which can be observed in Table 3 and 5 by comparing the results of CARALL-A and C FMLs.

No cracks were developed in the aluminum layer on the impacted side of CARALL-C FMLs impacted at 31 J

energy, whereas CARALL-A FMLs showed the failure of impacted aluminum layer also.

Conclusions

The influence of layer structure of CFC/aluminum layers and addition of epoxy resin rich layers (veil cloth) on the low-velocity impact behavior of CARALL FMLs is studied in the present research. It was found that CARALL-A FMLs showed higher peak forces smaller central displacements at all impact energy levels than CARALL-B FMLs. The addition of epoxy resin rich layers (veil cloth) resulted in even higher peak forces and smaller ultimate central deflection as compared to CARALL-A FMLs. CARALL-A FMLs showed smaller delaminated area than CARALL-B FMLs at 14 and 21 J impact energies but showed larger delaminated area at 31 J impact energy due to the shifting of the primary failure mode in CARALL-B FMLs at this impact energy from delamination to perforation. Impact resistance of CARALL-A FMLs was found to higher than CARALL-B FMLs. With the addition of epoxy resin rich veil cloth layers, the delamination area was reduced to a great extent in CARALL-C FMLs. The addition of resin rich layers further increased the impact resistance of CARALL-A FMLs by providing improved adhesion between successive aluminum and carbon fiber/epoxy layers. The resin rich and veil cloth layers affects the

overall dynamic response with higher contact forces, smaller ultimate central deflections, reduced delamination damage area and hinders the growth of cracks in the non-impacted aluminum layer of CARALL-C FMLs. The CARALL-C laminate shows superior performance among all three systems because veil cloth layers reduces the interply shear stress, increases the stiffness of laminate and acts as spacer for aluminum layers.

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