Enhanced Lightning Strike Protection using Vertically Oriented Carbon Fiber Melded with Conventional Carbon Fiber-Reinforced Composite and its Validation Through Damage Analysis

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ABSTRACT

Lightning strike protection (LSP) is one of the prime factors in aerospace and wind industries concerning safety, enhanced service life, and reduced downtime. To ensure better LSP, high electrical conductivity is required to dissipate the current, which is always a challenge for polymer composites due to the inherent insulating nature of the polymer matrix. Conventional carbon fiber-reinforced composites (CFRP) offer electrical conductivity in the planar direction while the vertical i.e. through-thickness conductivity still remains a challenge. Having been motivated by this fact, we have fabricated CFRP interleaved with vertically oriented CF (Z-fiber) for the lightning strike test (100 kA). A paint was applied to mimic the actual service condition of the composite laminates. We have prepared two Z-fiber composites: (a) Z-1 containing one Z-fiber layer on the top along with conventional CF layers and (b) Z-5 containing five interleaved Z-fiber layers and compared the properties with conventional CFRP (Z-0). Interestingly, even a single Z-fiber layer (Z-1) showed lower damage (visual damage diameter 22 mm) than Z-0 (visual damage diameter 26 mm). Z-5 displayed the lowest damage (visual damage diameter 16.7 mm), which was further confirmed by cross-sectional optical microscopy. Improved LSP was attributed to the higher through-thickness electrical

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conductivity in the case of Z-5 (9 times with respect to Z-0) reflecting a lower electrical anisotropy for Z-fiber composites. The residual mechanical property after the lightning test was analyzed through the flexural test, and the retention of flexural strength and modulus was 66% and 86%, respectively for Z-5 showing a significant improvement in comparison to Z-0 (>40% for both).

INTRODUCTION

Lightweight fiber reinforced polymer (FRP) composite materials are now inevitable in modern society replacing heavy metals which are challenging in terms of materials handling, processing, etc. In aerospace and wind industries, where the reduction of weight is the major challenge, composite materials play a significant role. The use of carbon fiber (CF) laminates drastically improves the specific strength, and unlike metals, these composites are corrosion free. However, the major obstacle in aerospace and wind industries are extreme weather conditions, and lighting strike is one of them [1, 2]. During the lightning strike, the electrical discharge reaches from a few hundred amps to over 200,000 Amps [2]. Therefore, high electrical conductivity is required to dissipate such a huge electrical discharge which would otherwise cause severe structural damage. CF laminates fall behind in this respect despite containing an ordered hexagonal carbon allotrope of CF [3]. The conductivity is impaired as the inter-fiber spaces are occupied by the insulating polymer matrix [4]. The through-thickness conductivity of the composite, i.e. perpendicular to the fiber direction, is significantly weakened as compared to along the length direction. The current strategy to improve electrical conductivity is by introducing metal-based protection layer on the top of the CFRP structures to safeguard against lightning strikes [5, 6]. The mesh can be made of copper, aluminum, or bronze wire [7]. These wires can either be co-woven with the carbon fiber in a prepreg fabric form or bonded separately to the laminate layer. However, attaching metal meshes or foils notably increases the weight of the structural parts [8]. This causes a higher consumption of fuel as well as subsequent CO_2 emission in the case of the aerospace industry. Whereas the increase in weight enhances rotational hindrance for the wind blades which cuts down the energy production. Moreover, metallic meshes are prone to corrosion deteriorating their performance. Therefore, an alternative technology needs to be developed to improve the conductivity of the CFRP without enhancing the weight.

During the last few decades, several attempts have been reported on alternative technologies to replace metal-based liners [8-10]. Improving through-thickness (TT) conductivity is found to be an effective way to enhance lightning strike protection [11]. The use of nanofillers, like carbon nanotube (CNT), graphene or graphene oxide (GO), silver nanoparticles, etc. are investigated by many researchers to improve the through-thickness conductivity [11]. Lin et al. reported the effect of CNT-grafted CF on the through-thickness electrical conductivity of CFRP [12]. The CNT was grown on the CF surface by the tedious Chemical Vapor Deposition method. Senis et al. investigated the TT electrical conductivity of GO modified epoxy based CFRP. The TT electrical conductivity was reported as 0.18 $S.cm^{-1}$ at 6.3 vol% of GO loading [13]. Qin et al. measured the TT electrical conductivity of graphene nano-platelets coated CF/epoxy CFRP which was found to be 0.07 $S.cm^{-1}$ [14]. Kandare et al. described the synergistic effect of graphene nano-platelets and silver nanoparticles/nanowires on the TT electrical conductivity of epoxy carbon fiber laminates [15]. Note that, the usage of nanofiller increases the overall cost and the dispersion of the nanofiller is challenging due to their high surface energy. On the other hand, the incorporation of vertically oriented CF (or Z fiber) could be a promising alternative route to reduce electrical anisotropy. Recently, a few research works have been published on the vertically oriented CF to improve the TT properties, e.g. thermal conductivity [16, 17]. Uteni et al. showed the vertical orientation of CF using electrostatic flocking in the fluorinated rubber and its effect on the TT thermal conductivity [16]. However, so far, no research article has been reported to the best of our knowledge on the lightning strike damage of vertically aligned CF-based CFRP composite. For the first time, our research group has shown the impact of interleaved vertically aligned short CF (Z-fiber) on reducing the damage during the simulated lighting strike test by enhancing the TT electrical conductivity [18]. This is the continuation of the previous work. Herein, we have compared the effect of a single Z-fiber layer and five Z-fiber layers with conventional CFRP. An aerospace-grade paint was also applied to mimic the actual service condition of the composite laminates. A detailed study of the cross-sectional morphology has been done after the lightning strike test to understand the depth of damage at varying CF configurations.

EXPERIMENTAL

Materials

Vertically aligned CFs in the form of prepreg mats were donated by Boston, MA. A magnetic field was employed to align the carbon fibers in the Z direction (vertical), then consolidated them using a proprietary binder material [19]. The prepreg manufacturing process is proprietary, so further details are not given herein. The average length and volume fraction of the Vertically aligned CFs were 150 μm and ~55%, respectively. Plain woven fabric (T300, 3K × 3K) coated with 150 μm milled carbon fibers aligned in the Z-direction was pre-impregnated with epoxy (Newport NB 301). The total CF volume fraction was maintained around ~55% in the overall laminate. The total ply thickness of Z-fiber layer was around 0.38 mm with a total areal weight of 370 $g.m^{-2}$, where in-plane fiber contributed to 200 $g.m^{-2}$ and V-fiber to 170 $g.m^{-2}$.

Preparation Of Composites

Three CFRP panels, one composed of conventional CFRP and two of them containing Z-fiber layers, were developed to investigate the simulated lightning strike test (figure 1). The conventional CFRP composite (Z-0) contained eight layers of woven prepreg while two Z-fiber composites were composed of either one or five Z-fiber layers, respectively. The composite panel containing one Z-fiber prepreg (Z-1) was developed by placing the Z-fiber prepreg on the top of the seven conventional woven prepreg stacks. The other Z-fiber composite (Z-5) was prepared by stacking five Z-fiber prepregs without using conventional woven prepregs. All the stacked prepregs were subjected to compression molding to prepare the final composite panels. The molding process was conducted in Carver hydraulic press (model: 3895.4NE1000, serial number: 130,181) operated at temperature and pressure of 135 °C and 690 kPa, respectively for 1 h.

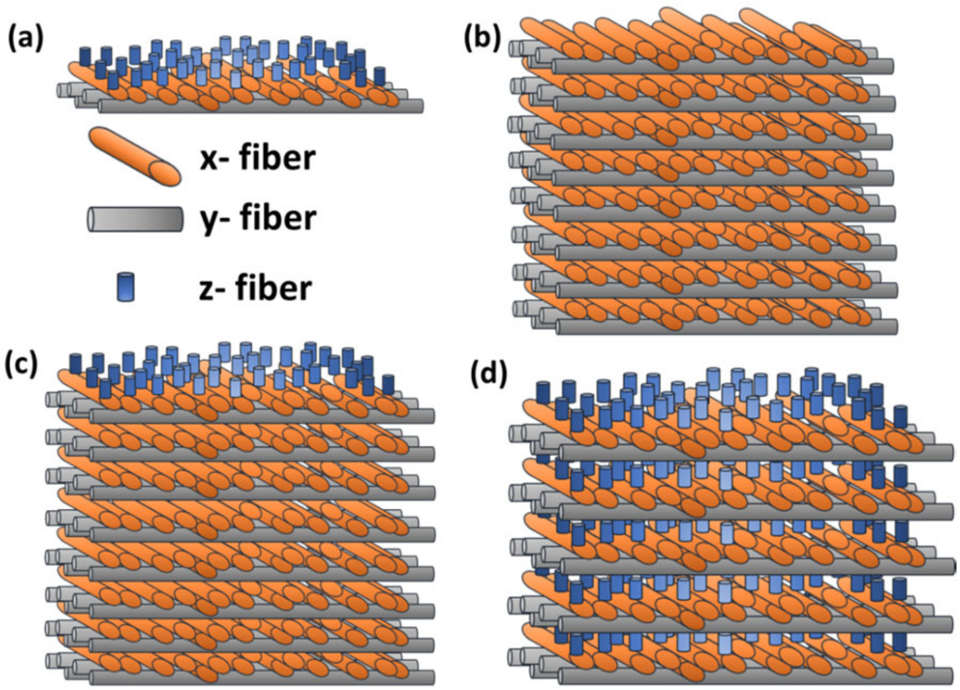


Figure 1. Schematic of the carbon fiber alignment in (a) each Z-fiber prepregs; stacking sequence of (b) eight layers of conventional woven prepregs (Z-0), (c) one Z-fiber prepregs on the top of the seven woven fiber prepregs (Z-1), and (d) five layers of Z-fiber prepregs (Z-5).

Simulated Lightning Strike Test

The lightning strike experiment on all the three CFRP composite panels was performed by a high-current impulse generator designed by Dr. Park's team. Waveform-A according to the Society of Automotive Engineering (SAE) standard was generated by the high-current impulse generator setup to mimic the lightning strike situation. In this setup, at least seven 44 kV-rated 47 μF capacitors were connected in parallel and reached the total capacitance of 329 μF. To safely control the high voltage and high energy circuit, capacitors were charged and discharged via pneumatically actuated sphere gaps. A 60 kV-rated high-voltage DC power supply was used to charge the capacitors of the generator up to 44 kV, which translates to each capacitor storing 45.5 kJ of energy. To vary the current amplitude and the waveform of the lightning strikes, either the charging voltage or the number of parallel connected capacitors was adjusted [20]. The current discharge magnitude of 100 kA was achieved. A detailed description of the simulated arc discharge is given in our previous article [18].

According to the SAE standard of waveform A, the lightning discharge current magnitude should be lower than 200 kA and the time required to reach 50% of the current peak should be shorter than 500 μs. The CFRP samples were attached to a copper plate which was grounded by a braided wire. During the test, the lightning discharge hit the center of the CFRP samples and exited through the edges of the grounded copper plate.

Optical And Scanning Electron Microscopy

A Hirox KH-8700 digital microscope was used to capture the damaged surface and the cross-sectional area after the lightning test. The cross-section morphology of the composite panels was also analyzed by field emission scanning electron microscopy (FESEM) in a Zeiss Merlin FE-SEM with a Gemini column, at an acceleration voltage of 1.0 kV. The morphology was analyzed before as well as after the lightning strike test.

Flexural Properties

Three-point flexural tests were conducted at room temperature on an electro-mechanical load frame (Model 45, MTS Systems Corporation, Eden Prairie, MN, USA) using a 10 kN load cell. Testing was conducted according to ASTM D7264 using a standard crosshead speed of 1 mm/min. A standard span-to-thickness ratio of 32:1 was used for all tested samples, so that failure occurs at the outer surface of the specimen under excessive bending moment. The samples were cut from the composite panels after the lightning strike test by a waterjet cutter (OMAX 2626 JetMachining Center, OMAX Corporation, Kent, WA) into a dimension of 88.9 x 13 mm x 2.1 mm. Prior to flexural testing, all the specimens were vacuum-dried at 100 °C for 1 hour to remove any residual moisture. The damaged surface (front side) was placed in compression during the flexural test. The location of the waterjet cut samples is shown in figure 2.

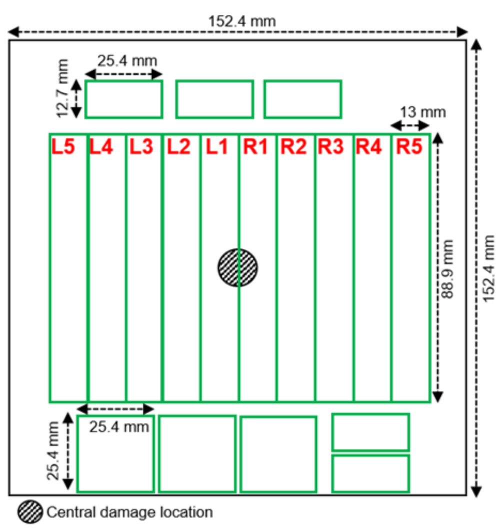


Figure 2. Schematic illustration showing the locations and dimensions of specimens cut from the damaged CFRP sheets.

Electrical Conductivity

The electrical conductivity of the CFRP composites was measured by Keithley multi-meter (KEITHLEY 2110-120) coupled with banana clips using the 4-probe method. A square shape sample of length 25 mm was used for TT conductivity measurement. The surface of the samples was cleaned before applying silver epoxy (Dotite-500) in order to reduce contact resistance. Conductive aluminum tapes were used as electrodes which were attached to the surface by silver epoxy. The sample was left for 24 h for complete curing of the silver epoxy. Resistance values were recorded, and the electrical conductivity was calculated using the formula,

$$\sigma = L/(R.A) \quad (1)$$

Where, σ is the electrical conductivity ($S.cm^{-1}$), L (cm) is the thickness of the samples, R is the resistance (Ohm) obtained from the multimeter, and A is the cross-sectional area of the sample (cm^2).

RESULTS AND DISCUSSION

Cross-sectional View of the Laminates as Prepared

The cross-sectional morphology of the laminates clearly displayed the different orientations of the fiber along the thickness (figure 3). In the case of Z-0, the fibers were oriented horizontally along the x and y directions in a successive manner. On the other hand, the vertical alignment of the fiber is visible in the case of Z-1 at the uppermost layer (inset in figure 3c). The thickness of the Z-fiber layer in the prepreg was 0.42-0.48 mm which reduced to 0.39-0.41 mm in the laminate after compression molding; however, the vertical orientation of CF remained. For Z-5, the alternative vertical (z-direction) and horizontal (x and y directions) orientations of the fiber were noticeable in the cross-sectional morphology. Note that the thickness of the Z-5 laminate was 2.1 mm, which was marginally higher than the Z-0 and Z-1 (both cases ~1.78 mm). The higher thickness of Z-5 resulted from the restriction offered by the vertically aligned fibers to compress the laminates during the molding process.

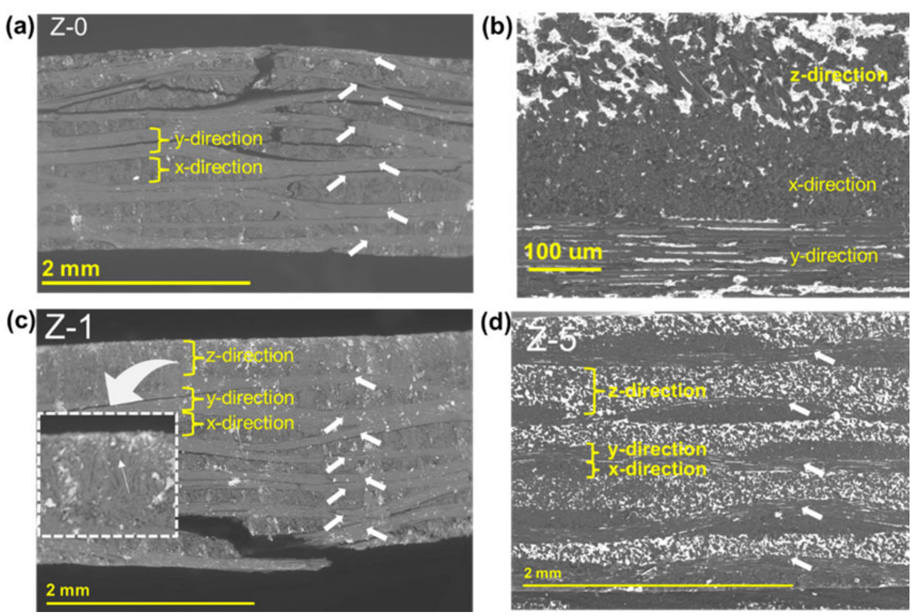


Figure 3. Cross-sectional SEM image of (a) Z-0 (showing 8 prepreg layers by white arrow), (b) Z-fiber prepreg (stacking sequence of Z-fiber composite), (c) Z-1 (showing 8 prepreg layers by white arrow), and (d) Z-5 (showing 8 prepreg layers by white arrow).

Visual Damage Analysis

After the lightning strike test, the optical images of the top and bottom surfaces of the laminate are shown in figure 4. In all cases, no fiber damage was noticed on the bottom surface. However, a distinct difference was observed on the top surface where the electrical arc was applied for all three cases. For Z-0, the paint was completely removed from a large rectangular-shaped area and the fiber damage was noticed at the center. The width of the fiber damaged area was around 26 mm. In contrast, the paint came off from the Z-1 laminate in a dendritic manner indicating an improvement as compared to Z-0 where a large chunk of paint burnt off from the surface. The width of the fiber damaged area was around 22 mm for Z-1. The lowest damage was noticed in the case of Z-5. The burning of the paint was minimum, and the width of the fiber damaged area was only 16.7 mm.

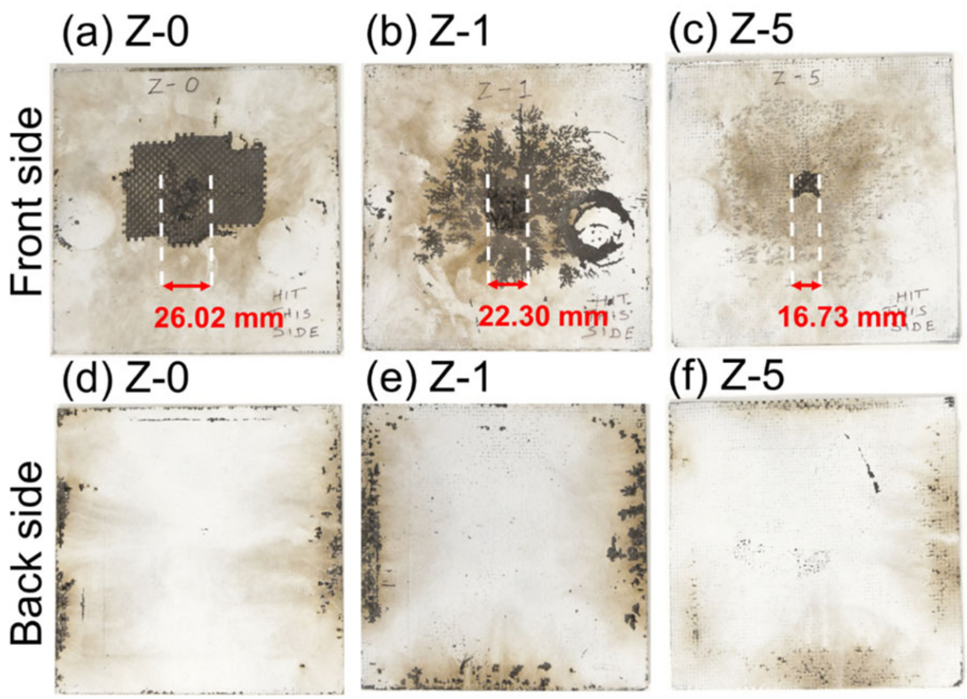
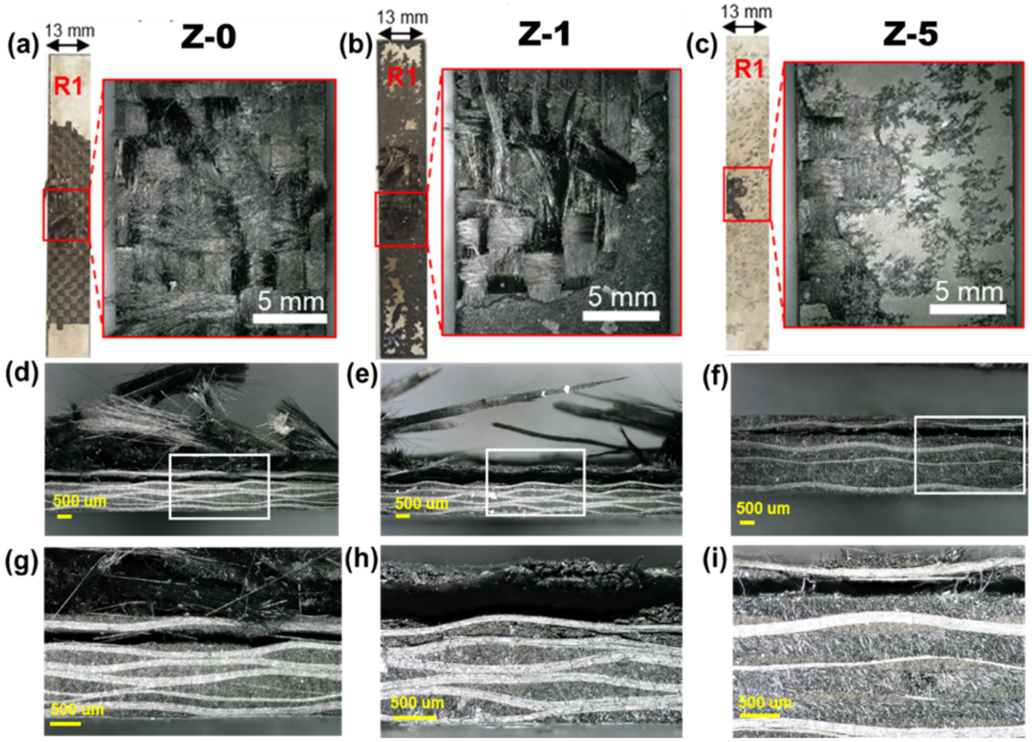


Figure 4. (a-c) Front and (d-f) back sides of the CFRP sheets after the lightning test with the varying CF configurations: Z-0, Z-1, and Z-5, respectively.

Damage Analysis by Optical Microscopy

The optical images of the top surface and corresponding cross-sectional morphology of the damaged laminates cut from the R1 area (as shown in figure 2) are depicted in figure 5. In the magnified image of the top surface, the damage of both resin and fiber due to excessive heating was observed at the center of the arc discharge area. The damaged area was the minimum for Z-5. The cross-sectional view of the damaged laminates illustrated the depth of the damage, i.e. the number of plies burnt off during the lightning strike. In the case of Z-0, the damage penetrated up to the third layer. The first two stacks were completely delaminated or burnt off within the damaged area, and the third layer was partially detached from the rest of the five layers. Whereas for Z-1, the first layer was burnt off and completely delaminated, and the second ply was partially delaminated keeping the



rest of the six plies intact after the lightning strike test. In the case of Z-5, only the first ply was partially delaminated without complete burning of any layer.

Figure 5. Representative optical micrographs after the lightning strike test for R1 cut specimens (as shown in figure 2) with varying CF configurations: (a) Z-0, (b) Z-1, and (c) Z-5 showing the top surface and the corresponding cross-sectional micrographs are shown in (d) and (g) for Z-0 (low and high magnification, respectively), (e) and (h) for Z-1 (low and high magnification, respectively) and (f) and (i) for Z-5 (low and high magnification, respectively).

Scanning Electron Microscopy Analysis

High magnification SEM images of the cross-sectional morphology also supported the optical microscopy results. The R1 cut surface of the laminates after the lightning strike test was displayed in figure 6. In the case of Z-0 (figure 6a), the total of eight ply-stacks was reduced to five after the lightning strike similar to the observation from the optical microscopy. At the top surface, an unwetted ply layer was noted (marked by yellow arrow) indicating the complete burning of the resin from the upper three layers. Whereas, for Z-1, the upper two layers were completely delaminated and the third layer (i.e. the top layer in figure 6b) was partially detached; however, the resin was not completely burnt off from the third layer of the laminates exposed to the lightning strike. For Z-5, only the top layer was delaminated and the other four stacks beneath the top layer remained completely intact including both the vertical and horizontal fibers layers.

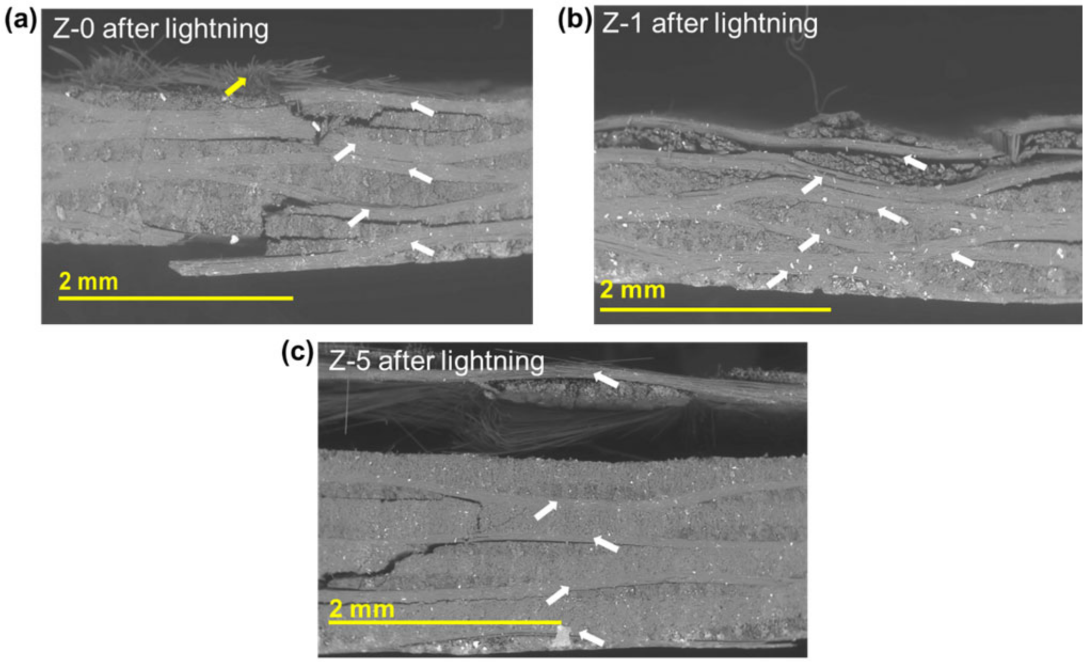


Figure 6. Cross-sectional SEM image of (a) Z-0, (b) Z-1, and (C) Z-5 after the lightning strike test. (White arrow shows the remaining ply-stacks)

Residual Flexural Properties

The residual mechanical strength after the lightning strike test was analyzed by measuring the flexural properties across the damaged area as described in figure 2. Five specimens were cut from the left-hand side of the damaged area and labeled as L1 to L5. Another five specimens were cut from the right-hand side which were labelled as R1 to R5. The flexural strength and modulus of these ten specimens (L1-L5 and R1-R5) were plotted with respect to the specimen labeling (figure 7). Flexural properties were lowest either at L1 or R1 for all the three composites which were located at the center of the electrical arc discharge area followed by a gradual increase in the properties on both left and right directions forming a crater-like profile. The retention in the properties after the lightning strike was estimated from the ratio of the average obtained from the center cavity region with respect to the average obtained from the peak region at both edges. Both flexural strength and modulus at the edge region, considered to be the initial flexural properties, were maximum for the conventional CF composites, i.e. Z-0. The lowest initial flexural properties were noted for Z-5. This is because the vertically oriented Z-fibers did not contribute to load bearing when the in-plane flexural load was applied. In addition, the total number of stacks in Z-5 was five whereas the Z-0 and Z-1 contained eight in-plane layers which was also responsible for the lowest mechanical properties of Z-5. The flexural properties of Z-1 were in between Z-0 and Z-5, as the top layer of Z-1 contained the Z-fiber. On the other hand, the average flexural strength and modulus at the center cavity region were maximum (319 MPa and 27 GPa) for Z-5. In this case, the retention of the flexural strength and modulus were ~67.6 and ~86%, respectively after the lightning strike. The retention in properties for Z-0 and Z-1 were almost similar. The flexural strength and modulus retained after the lightning strike were ~37% for both the cases for Z-0 and ~37% and ~39%, respectively, for Z-1. Figure 7 also revealed that the drop in flexural modulus after the lightning strike was detected over a narrower region in the case of Z-5 (L1 to R1, i.e. 26 mm, marked by a red dotted arrow in figure 7b) which was similar to the visual observation. Whereas, the drop occurred over a wider area (L-2 to R-3, i.e. 65 mm marked by a black dotted arrow in figure 7b) for Z-0. In the case of Z-1, the decrease in flexural modulus was noted from L2 to R2, i.e. within the range of 52 mm (marked by a blue dotted arrow in figure 7b).

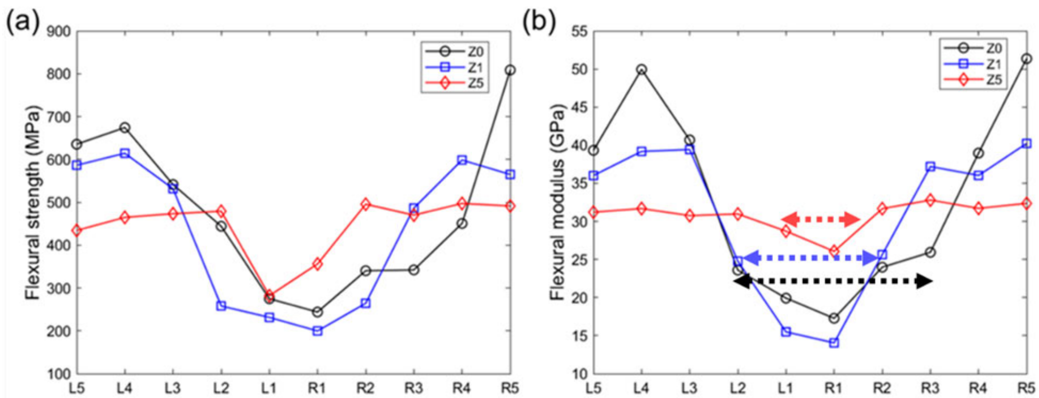


Figure 7. Residual mechanical properties of the CFRP composites with varying CF configurations after the lightning strike test: (a) flexural strength and (b) flexural modulus.

TABLE I. RESIDUAL FLEXURAL STRENGTH AND MODULUS OF THE CFRP COMPOSITE AFTER THE LIGHTNING STRIKE TEST

LSP sheet	**Flexural strength (MPa)**									
	L5	**L4**	**L3**	**L2**	**L1**	**R1**	**R2**	**R3**	**R4**	**R5**
Z-0	635.5	674.4	541.5	444.1	274.9	244	340.2	342.3	450.6	808.7
Z-1	586.5	614.4	531.7	258.1	231.4	199.8	264.3	486.6	598.6	564.9
Z-5	434.3	464.8	473.4	479.1	282.1	356.1	495.5	470.1	497.3	491.4

LSP sheet	Flexural modulus (GPa)									
	L5	L4	L3	L2	L1	R1	R2	R3	R4	R5
Z-0	39.32	49.94	40.68	23.59	19.92	17.27	23.97	25.94	38.95	51.36
Z-1	36.02	39.18	39.43	24.77	15.50	14.05	25.63	37.19	36.03	40.22
Z-5	31.20	31.68	30.75	30.96	28.71	26.06	31.66	32.79	31.71	32.35

Electrical conductivity

TT electrical conductivity of Z-0 and Z-5 was analyzed before and after the lightning strike test to understand the effect of vertically oriented fiber. The TT electrical conductivity of Z-0 was 0.13 $S.cm^{-1}$ and it reached 1.15 $S.cm^{-1}$ in the case of Z-5, showing a nine-time increment. After the lightning strike, the TT electrical conductivity of Z-0 and Z-5 reduced to 0.01 and 0.1 $S.cm^{-1}$ respectively; however, the conductivity of Z-5 remained ten times higher than that of Z-0. The significant increase in electrical conductivity of Z-5 resulted from improved interlayer connectivity through the vertically oriented fiber. The electrical conduction through the thickness direction involved all the plies to dissipate the arc discharge during lightning strike instead of concentrating the current on the top layers. Thus, minimum damage was noticed in the case of Z-5. Still, the top layer of Z-5 was partially delaminated which was responsible for the reduction in the conductivity after being subjected to the lightning test.

DISCUSSION

The effect of vertically oriented CF on the lightning strike protection of CFRP is described here through the damage analysis after the lab scale simulated lighting strike test. To safeguard the composite structure, each fiber layer of the laminate needs to contribute to dissipating the higher electrical current descended during lightning strike. The interleaved vertical fiber provided an electrical conduction path between the layers which would otherwise be interrupted by the insulating polymer matrix. Thus, a lower electrical current was accumulated on the surface (where the electrical arc was applied) of Z-fiber composites, as compared to the conventional CFRP. Consequently, Z-5 showed the lowest surface damage during the lightning test. While greater Joule heating occurred in the Z-0 composite since current dissipation was hindered exhibiting a larger surface damage area. The burning and removal of paint from the top layer can be used to infer the electric or heat conduction path. In the case of Z-0, a large chunk of paint was burnt off indicating the accumulation of the electrical current on the top surface causing resistive heating. While the dendritic burning pattern of Z-1 illustrated multiple entry points of the electrical current through an interconnected conduction path. The burning of paint was drastically lower for Z-5 describing a high TT conductivity which was in line with the TT electrical conductivity results. Although the electronic conduction was improved, the mechanical properties were reduced by the incorporation of interleaved Z-fiber. This is because the Z-fiber did not contribute to reinforcing the structure through a load transfer mechanism. At the same time, the Z-fiber and horizontal fiber interface might act as stress concentration point. The lower number of laminate layers in the case of Z-5 to maintain the thickness might also be a reason for lower mechanical properties. In order to minimize these effects, Z-1 composite was prepared which contained only one Z-fiber laminate at the top layer. The surface damage was marginally lower; however, the mechanical properties were also slightly lower than Z-0. Therefore, further studies are required in the future to investigate the method of incorporating the Z-fiber layers to enhance the TT electrical conductivity of CFRPs without compromising the in-plane mechanical properties. For example, the effect of more than one Z-fiber layer in combination with conventional horizontal plies and the sequence of adding these layers, the effect of mold pressure on reducing the gaps between the ply layers as well as fiber orientation, etc. needs to be exhaustively investigated.

CONCLUSION

A unique approach to improving the lightning strike protection of CFRP composites by introducing vertically oriented Z-fiber was studied herein. Two laminates containing five vertically oriented Z-fiber stacks (Z-5) only and one Z-fiber stack at the top in combination with seven conventional horizontal plies (Z-1) were prepared. The damage due to lightning strike was compared with conventional laminates containing eight horizontal plies (Z-0). The surface damage of Z-5 was only 16.7 mm wide, while for Z-1 and Z-0, the damages were 22 and 26 mm, respectively. The burning of paint occurred in a dendritic pattern in the case of Z-fiber composite describing a better dissipation of electrical charge whereas the paint was completely removed from a wide area in the case of Z-0. Only the first ply was partially delaminated for Z-5 as observed from the cross-sectional morphology. On the other hand, it penetrated to the third layer for both Z-1 and Z-0. The retention of flexural strength and modulus after the lightning strike were found to be 67% and 86% respectively for Z-5, whereas the retention of flexural properties was less than 40% for both Z-1 and Z-0. The higher TT electrical conductivity was the prime factor for the lesser damage in the case of Z-fiber composites. It is interesting to note that the vertical Z-fiber, despite improving the lightning strike protection, impaired the flexural properties. In essence, the current study described a strategy to enhance the TT conductivity to protect the CFRP composites from the lightning strike damage, however further investigation is needed to improve mechanical properties.

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