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Enhanced through-thickness electrical conductivity and lightning strike damage response of interleaved vertically aligned short carbon fiber composites☆

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ABSTRACT

Through-thickness electrical conductivity of carbon fiber reinforced polymers (CFRPs) is a key characteristic that determines the severity of lighting strike-induced damage. Carbon Fibers (CFs) are inherently electrically conductive and therefore provide high conductivity in the direction of the fiber orientation. However, electrical conductivities through the thickness and orthogonal to the CF orientation in CFRPs are governed by the insulating polymer matrix present between CFs. In this work, through the thickness alignment of short CFs in between layers of CFRP laminates is demonstrated to improve the through-thickness electrical conductivity. Composites with interleaved vertically aligned short CF fibers (<150 μm) will be referred as V-fiber composites hereafter. The effect of the V-fiber on the lightning strike damage is evaluated against an artificial lightning strike of 100 kA (modified waveform A of SAE ARP-5412B standard). The improved through-thickness electrical conductivity of CFRP laminates (1.15 S/cm) through vertical alignment of short CFs was compared to reference CFRP laminates (0.13 S/cm) and was found to dissipate the artificial lightning strike current more efficiently. The surface damage after the artificial lightning strike in the V-fiber composites was reduced to 12.69 cm^2 compared to the reference CFRP surface damage of 57.67 cm^2, a 78% reduction. It was also demonstrated that Joule heat generated due to lightning strike on the composites was significantly less than the reference sample using infrared (IR) thermography. A high retention (up to 78%) of flexural properties (modulus and strength) was observed in V-fiber composites post lightning strike impact as compared to only 47% retention in the reference panel.

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1. Introduction

Decarbonization has been identified as most needed in technological advancements to counter global warming and climate change. Researchers world-wide are investigating ways to reduce the carbon dioxide (CO_2) emission in the transportation industry which includes aerospace, automotive, marine, etc. [1]. One way to reduce CO_2 emissions is to reduce fuel consumption which is directly proportional to the weight of the vehicles bringing forth new classes of lightweight structural materials. The growing market forecast for urban air mobility (UAM), such as drones and unmanned aerial vehicles (UAVs)/electrical vertical take-off and landing (eVTOL) is focusing on lightweight materials [2]. Therefore, reducing the weight of vehicles will reduce the energy consumption in transport.

Carbon fiber reinforced polymers (CFRPs) are a class of materials known for their high specific strength and stiffness. In many cases, CFRPs have been employed in applications where weight savings is critical without sacrificing mechanical performance. Although CFRP has many advantages over metallic counterparts, it has a few disadvantages, one of which being low electrical conductivity [3]. Low electrical conductivity of CFRPs can be catastrophic for a structure in the event of a lightning strike [4]. Aerospace and wind energy industries have predominantly adopted CFRPs and glass fiber reinforced polymers (GFRPs) structures which are extremely vulnerable to lightning strikes due to their operating locations. Catastrophic damage and failure is imminent if these structures are not protected from a potential lightning strikes [5]. The current state-of-the-art in aerospace sector utilizes metal-based lining or coatings on top of CFRP structures to provide safety against lightning strikes. The metal-based lightning strike protections (LSP) are primarily available in the form of metal-meshes or foils, which are bonded to the outer most layer of the CFRP structures [6]. Using metal based lightning protection adds significant weight (1065 kg to a Boeing jumbo jet [7]) to the CFRP structures. This results in greater fuel consumption and more CO_2 emission for the aerospace industry. Moreover, it is also known that each kg of extra payload on an aircraft leads to 0.2 kg extra fuel consumption [8]. Therefore, advancements in lightning protection systems that do not add parasitic weight to the structures are needed to reduce CO_2 emissions in the transportation industry.

In the last few decades, there have been many attempts to replace metal-based lightning strike protection systems with alternative technologies [9,10]. Making CFRP structures electrically conductive has been studied as the most common way to improve LSP protection without the need for additional components or materials. Carbon-based electrically conductive fillers have been studied with various combinations of matrices to create conductive composites [11–15]. These have included graphene, carbon nanotube (CNT), carbon black, etc., along with intrinsic conductive polymers such as polyaniline. Previous methods attempt to improve current (charge) dissipation through tailored fiber orientation through-thickness (TT), orthogonal to the fiber direction and/or in-plane (IP) or fiber directions of the composites without the need for additional metallic conductors.

From these previous studies, researchers have identified critical factors that affect the response of CFRPs against lightning strike. The effect of TT electrical conductivity is a major influencing factor [16,17]. Therefore, recent efforts to create advanced LSP systems revolve around the concept of improving TT conductivity. CFRPs typically have anisotropic mechanical and electrical properties governed by the orientation and alignment of carbon fibers (CFs) in the structure [18,19]. CFs possess high strength and conductivity in the longitudinal direction, an attribute that can be utilized to design a CFRP structure for tailored mechanical and electrical performance. Attempts have been made to align CFs in the Z-direction or TT direction to create composites with reduced anisotropy. In recent years, several researchers have demonstrated that aligning fibers in the Z-direction of the composites can create enhanced thermal, electrical, and mechanical properties in the out-of-plane direction [20–23].

It is reported that, one order variation in the TT electrical conductivity can be the difference between a catastrophic failure or minimal damage [24]. As a result, many studies have focused on improving the TT electrical conductivity of CFRPs. Cano et al. used a metal-wire braided system coupled with traditional CFRP structures for LSP of the full-scale cockpit [25], and Rehbein et al. employed metal toughening/stitching for similar reasons [26]. Guo et al. used the silver nano-wires as interleaves to improve the through-thickness electrical conductivity of the CFRP structures [27]. Yet another method to overcome poor TT electrical conductivity in CFRP laminates is to insert highly conductive layers, such as interleaved CNT-buckypaper replacing the polymer-rich layers [28,29]. Some of these methods showed improvement in TT electrical conductivity to help reduce lightning strike damage extensively; however, these additional conductive layers and fillers can be costly and complicated for integration in a manufacturing process. In a study, Rajesh et al. summarized the electrical properties of recent lightning strike protection (LSP) solutions utilizing buckypaper, metalized fibers, and more [30]. They tabulated that LSP using nickel-coated single-walled nanotubes resulted in sheet resistance of 2-4 x 102 Ω Square-1 and less damage than unprotected specimens. Additionally, they reported that carbon nanofiber paper had a conductivity of 341 S/cm for a panel composed of 6.94 g nanofibers and 19.55 g nickel nano-strands. Only 1% of the buckypaper was damaged in a zone 2A lightning strike test. They also cited the work, where LSPs made with Indium Tin Oxide (ITO) coated carbon fiber composites prepared with 40% ITO in colloidal suspension were better protected than those with lower or no ITO. Another study by Kumar et al. highlighted the intrinsic conductive polymer, Polyaniline based composites as an LSP solution with volumetric electrical conductivity in the range of 0.8–1.1 S/cm [31]. In addition, they demonstrated the high residual mechanical properties of the CFRP substrate after 100 kA tests. The impact of thermal conductivity on the damage mechanism due to lightning strike on the composite panels is still unclear. There are multiple articles supporting conflicting conclusions [32–34]. Therefore, this work did not cover the impact of thermal conductivity. Nevertheless, any dedicated effort to use the vertically aligned CFs (V-fiber) for improving the electrical properties and imparting LSP to CFRPs has not been extensively explored.

In this paper, vertically or Z-direction aligned short CFs are used to improve the TT electrical conductivity in CFRP laminates and illustrate their effectiveness in reducing lightning strike damage. Furthermore, the vertically aligned carbon fibers are shown to provide multiple entry points for the incident lightning arc reducing the energy entering the CFRP laminate at any given location.

2. Materials and methods

2.1. Materials procurement

Vertically aligned CFs in the form of prepreg mats were donated by an Oak Ridge National Laboratory's industry partner (Boston, MA). A magnetic field was used to align the nickel-coated carbon fibers in the Z-direction, then consolidated them using a proprietary binder material [35]. The entire prepreg manufacturing process is propriety so further information about the process is not provided. Vertically aligned CFs in the mat had an average length of 150 μm and ~55% volume fractions. Plain woven fabric (T300, 3K × 3K) coated with 150 μm milled carbon fibers aligned in the Z-direction pre-impregnated with epoxy (Newport NB 301) were used to produce CFRP laminates of 25 cm × 25 cm in size. The total CF volume fraction was maintained around ~55% in the overall laminate. The total ply thickness of V-fiber composites 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.

2.2. Sample preparation

Two CFRP panels were fabricated to investigate the benefits of vertically aligning CFs for lightning strike protection. One panel consisted of 8 layers of woven prepreg while the other panel consist of 5 layers of V-fiber prepreg. V-fiber mat on woven fabric was provided in the form of prepreg and could be processed in the same way as a traditional prepreg. The methodology to control the vertical alignment of the V-fiber is the company's propriety information, but some information about it is mentioned in the reference [35]. During manufacturing, the V-fiber mat thickness reduced during the molding processes from the original 0.42–0.48 mm to 0.39–0.41 mm after compression, as seen in the SEM images in Fig. 1. Schematics of the woven prepreg and V-fiber prepreg are shown in Fig. 1 (a) with the woven prepreg stack-up shown in Fig. 1 (b) and the V-fiber prepreg stack-up shown in Fig. 1 (c). The SEM image in Fig. 1 (d) shows the actual cross section of a V-fiber prepreg (as received), Fig. 1 (e) shows the fully consolidated V-fiber composite laminate, with close-up shown in Fig. 1 (f).

Both (reference and V-fiber) panels were manufactured in a Carver hydraulic press (model: 3895.4NE1000, serial number: 130,181) which were pressed at 690 kPa and held for a dwell time of 1 h at 135 °C.

2.3. Electrical conductivity test

Electrical conductivity was measured using the 4-probe method. A Keithley multi-meter (KEITHLEY 2110-120) coupled with banana clips were employed to measure the electrical resistance. For in-plane electrical conductivity, test specimen with size of 25 mm in length, 10 mm in width and "t" in thickness were used. For TT conductivity test, specimen with size of 25 mm in length, 25 mm in width and "t" in thickness were used. Where "t" was 1.6 mm for the reference CFRP sample and 2.1 mm for the V-fiber sample. A thickness difference after the compression molding was noted between reference CFRP and V-fiber laminates due to the presence of vertically aligned fiber, which hindered the compressibility of the latter one during the molding process. We reported volumetric electrical conductivity in this work to nullifies the thickness difference. The TT electrical conductivity was measured from the z-direction faces while the in-plane electrical conductivity was measured from the y-directional faces. We have tested three samples for each composition. The surfaces of the samples were polished and cleaned before applying silver epoxy (Dotite-500) for reduced contact resistance. Conductive aluminum tape was used as the attached electrode to the surfaces with silver epoxy [36,37]. The silver epoxy went through a 24-h cycle to ensure it was dried entirely before performing resistance measurements. Resistance values were recorded, and the electrical conductivity was calculated using the formula, $\sigma = \frac{L}{RA}$, where σ is the electrical conductivity (S/cm), L (cm) is the length of the samples, R (Ohm) is the resistance values obtained from multi-meter, and A (cm^2) is the cross-sectional area of the sample.

2.4. Simulated lightning strike testing

A high-current impulse generator designed and built by Dr. Park's team [38] was used to perform lightning strike experiments on the prepared CFRP composites. The high-current impulse generator set up shown in Fig. 2 (a) can produce components A and D of Society of Automotive Engineering (SAE) standard lightning waveform, as shown in Fig. 2 (b). In this setup, at least seven 44 kV-rated 47 μF capacitors were connected in parallel and reach 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

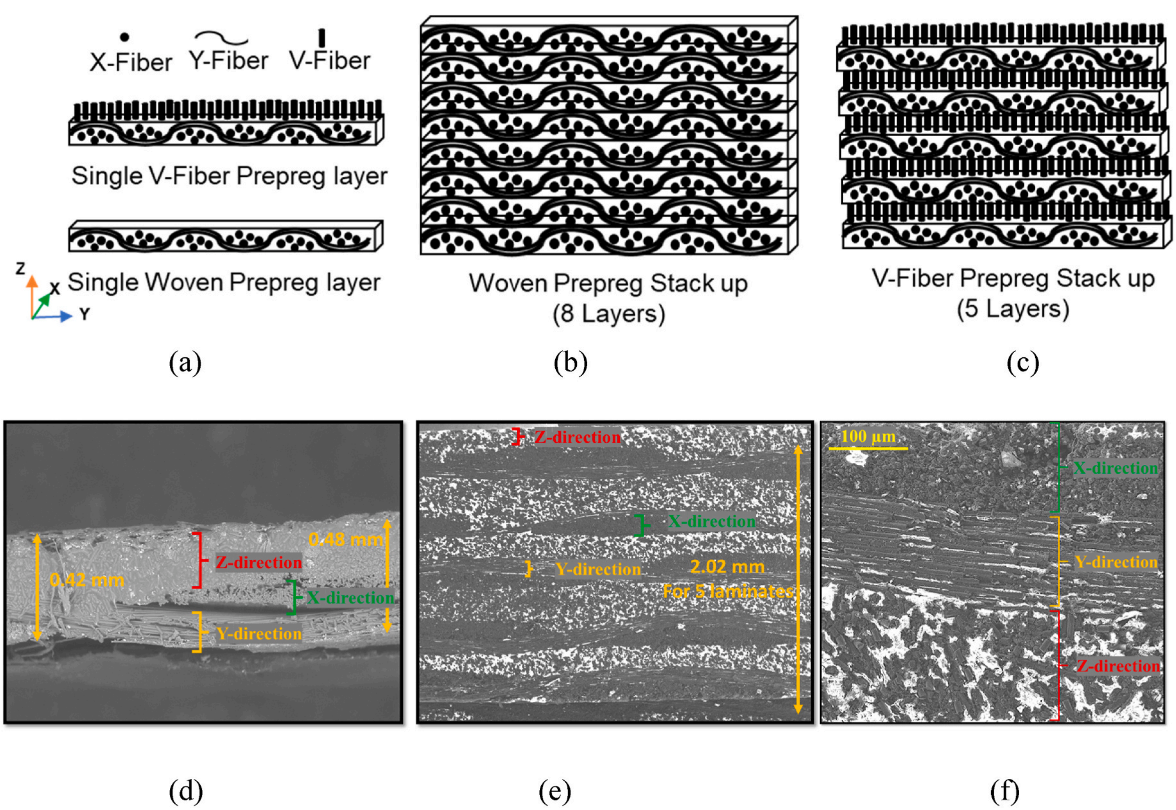

Fig. 1. (a) Schematic of woven prepreg and V-fiber prepreg (b) Stacking sequence of woven prepreg to prepare composite laminates (c) Stacking sequence of V-fiber prepreg laminate (d) Actual cross section of a V-fiber prepreg (as received), (e) Fully consolidated V-fiber composite laminate, (f) close-up SEM image of CFRP laminate with fibers aligned in X, Y and Z directions.

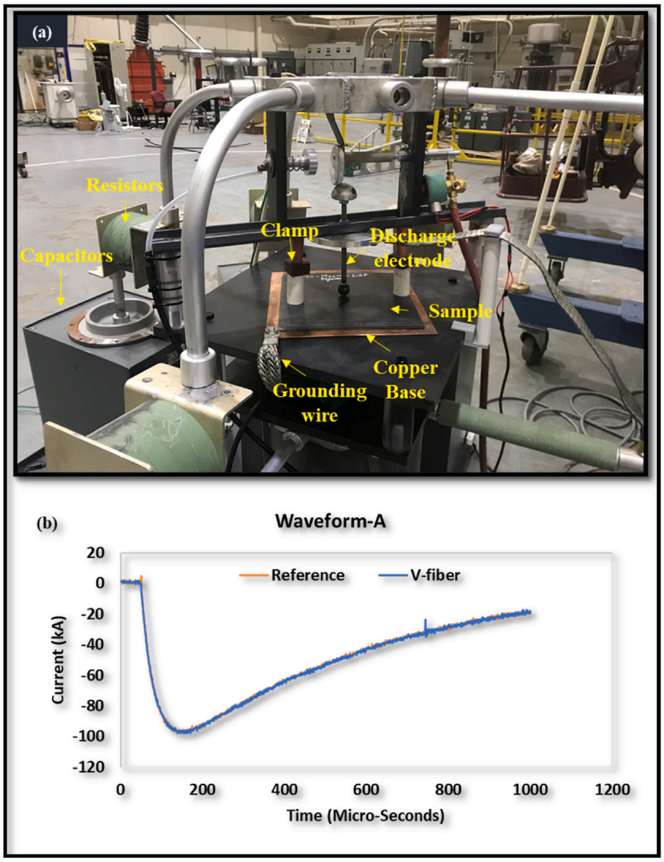

Fig. 2. (a) The artificial lightning strike test setup. (b) The current vs. time plot of Waveform-A of 100 kA applied to both samples.

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 were adjusted [39]. In this study, component A of the lightning strike waveform was generated, and the current discharge magnitude of 100 kA was achieved as shown in Fig. 2(b). The rise (T1)/tail (T2) times of the current waveform as well as the specific energy or action integral were calculated using the equations provided in the literature [40–42]. T1, T2 and action integral values for the applied current waveform are found to be 6.8 μs, 54.9 μs, and 3.24e5 A^2•s, respectively. The values are within the range of acceptable waveform to represent actual lightning strike that are reported in literature [42,43].

The waveforms generated satisfied component A lightning waveform criteria as defined in the SAE standard: 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 [44]. The CFRP samples were fixed on a copper plate that was grounded by a braided wire. The braided wire was wrapped around the edges of the copper plate into the ground of the lab floor while the copper plate and the CFRP sample was clamped together to make conductive paths for the discharge current. The testbed allows lightning discharge current to hit the center of the CFRP samples and exit the sample through the edges of the grounded copper plate.

2.5. Optical microscope imaging

A Hirox KH-8700 digital microscope was used to capture the cross-sectional microscopic images of the tested specimens. The auto 3D tiling function was used to enable the continuous imaging across the entire length of the extracted specimen.

2.6. Thermal imaging

FLIR T420 Infrared camera, capable of monitoring temperatures from - 20 °C to 150 °C, was employed to observe the Joule's heating effect due to lightning strike on the CFRP samples. The frame rate for the camera was limited to 10 fps, which was fast enough to record heat dissipation characteristics after a lightning strike.

2.7. Ultrasonic inspection

An Olympus OmniScan SX system with a corresponding immersion tank was used to scan the panels, providing a 1.0 mm scan resolution. A 5 MHz, 64-element phased-array probe (Olympus 5L64-SNW1-0L) was used in a pulse/echo (P/E) method at the normal incident [45]. All inspections followed the ASTM E2580 standard by classifying defected locations by a 6 dB change in amplitude [46]. Each panel was scanned before and after the artificial lightning strike. The damage was inspected from the backside of each panel to allow the waveform penetration. The lightning strike imparted out-of-plane damage, which caused scattering and attenuation of the ultrasonic waveform.

2.8. Three-point bend testing

Three-point bend tests were conducted to determine the flexural strength and flexural modulus of the specimens after the artificial lightning strike tests. Tests were conducted according to the ASTM D7264 standard, which specifies a support span to thickness ratio of 32:1 [47]. The support span for the specimens with and without V-fiber were 64 mm and 76 mm, respectively. The flexural tests were conducted with constant displacement rate of 1 mm/min on an MTS testing system with a 90 kN load cell calibrated at 5 kN.

3. Results and discussions

3.1. Visual damage assessment

A clear difference in the lightning strike induced damage in the reference and V-fiber samples was observed using digital photographs taken post simulated lightning test (Fig. 3 a-1 and b-1). The reference sample showed circular and propagating damage from the lightning entry location radially. The circular damage was due to plain-woven fabric architecture, where current dissipated in two major directions (i.e., 0° and 90°), equally. From the photographs, delamination of the top plies, fiber fracture, and decomposition of matrix were identified. The surface damage was estimated to spread across an area of 59.17 cm^2 (calculated based on circular damage with 8.67 cm diameter) based on optical images (see Figs. 3 a-1). The V-fiber composite showed minimal surface damage and only the top ply was delaminated as shown in Fig. 3 a-2 and b-2. The surface damage obtained from the optical images in V-fiber composite was around 7.07 cm^2, an 88% reduction compared to the reference CFRP panel. No fiber breakage, fracture, or resin degradation was observed. The visual damage assessment confirmed that the V-fiber composite successfully reduced the lightning-induced damage compared to the reference CFRP composite.

The cross-sectional microscope images of the extracted specimens at the center of the lightning strike entry points clearly showed the delamination depth of the specimens (Fig. 3 a-2 and b-2). For the reference specimen, the delamination reached the interface of the second and third ply with nearly complete removal of the first ply, whereas delamination in V-fiber specimen was observed only between the first and second ply while rest of the plies remained intact.

3.2. Ultrasound damage assessment

Ultrasound inspection was used to evaluate the damage caused by the artificial lightning strike. Fig. 4 shows the ultrasound C-scans before

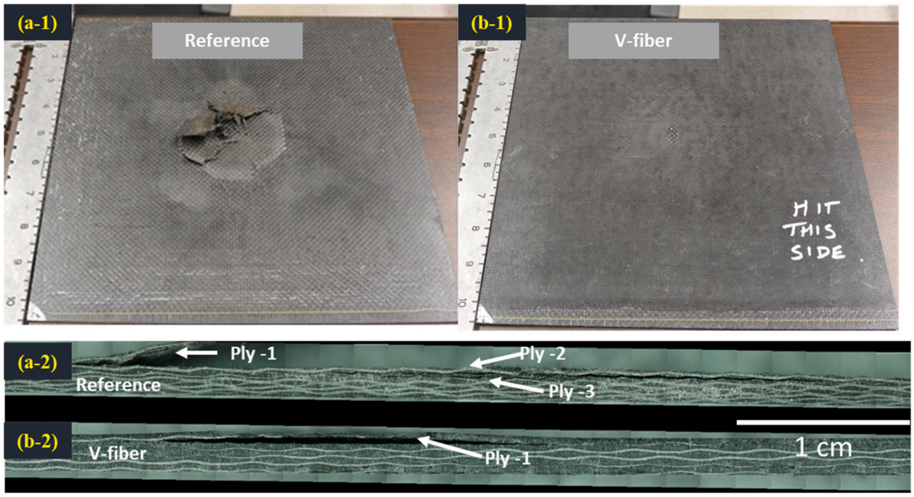

Fig. 3. Visual damage assessment of reference and sample after the lightning strike of 100 kA intensity. (a-1) and (b-1) images of the whole sample, (a-2) and (b-2) are the images of the cross section at the lightning entry point.

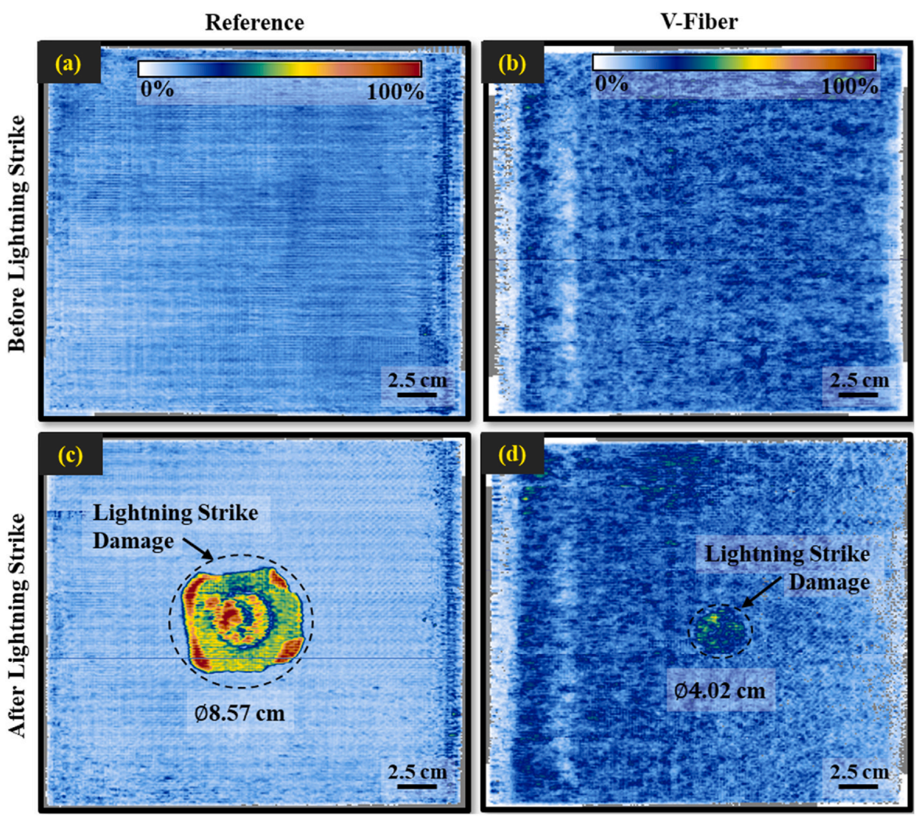

Fig. 4. Ultrasound response between the reference CFRP and V-Fiber composite panels (a) and (b) before and (c) and (d) after lighting strike test. The C-scan displays the ultrasound reflections of damaged locations.

(Fig. 4 a-b) and after (Fig. 4 c-d) lightning strike for both the reference and V-fiber panels. The areal damage for the reference and V-fiber panel was measured from the C-scan and found to be 57.68 cm^2 (calculated based on circular damage with 8.57 cm diameter) and 12.69 cm^2, respectfully, which is a 78% reduction in areal damage. The ultrasound inspection matches with the visual inspection as shown in Fig. 3. Compared to the visual inspection, the ultrasonic inspection indicated larger damage area for the V-fiber panel. This indicates that the lightning strike spread below the surface of the panel affecting other plies, but by only 5 mm radially. The amplitude response within the damaged location for the reference panel varied between 50% and 100%, where higher amplitudes typically indicate higher levels of damage. The V-fiber amplitude response was relatively low compared to the reference panel varying between 40% and 60%. According to ASTM E2580, a 40%–60% amplitude response through the 6 dB damage threshold signifies minimum damage.

The volumetric damage of the reference and V-fiber panels was measured from the ultrasound C-scans according to the procedure explained in the previous work [48]. The volumetric damage assessment (refer Fig. 5) revealed a maximum depth-of-damage of 0.72 mm and 1.30 mm for the reference and V-fiber panels, respectively. For the reference panel, most of the damage occurred near the surface of the

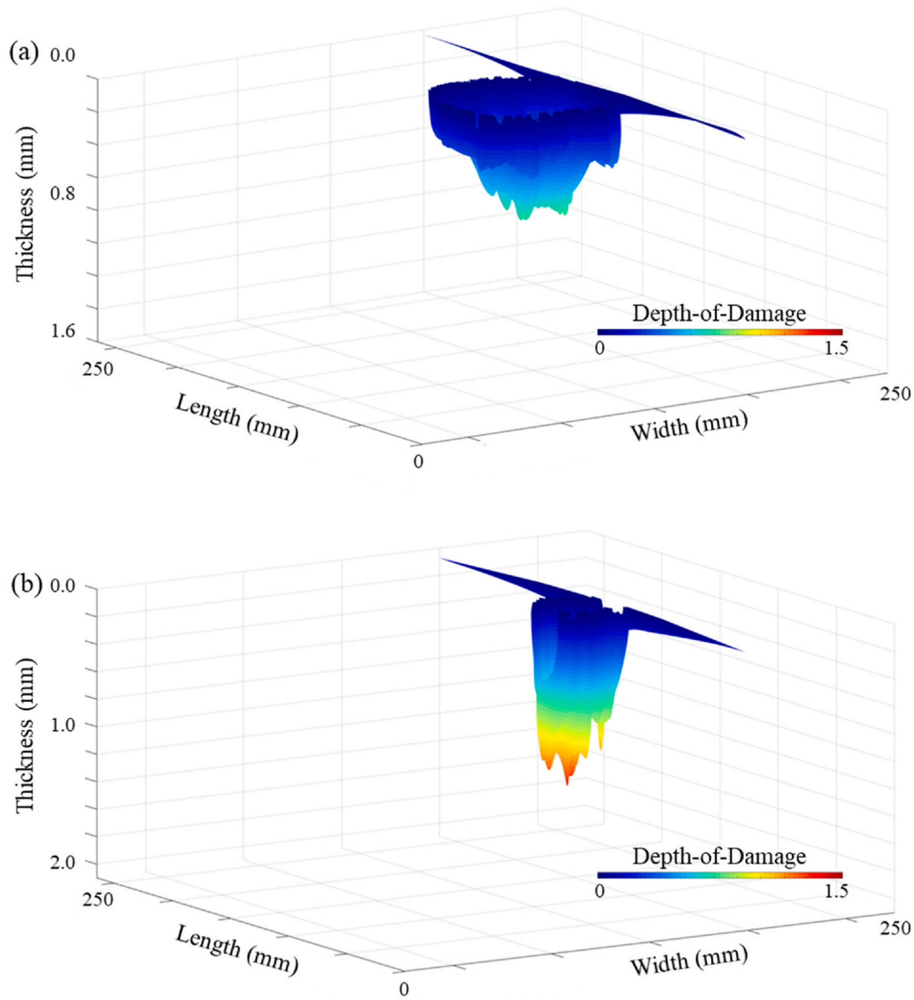

Fig. 5. Volumetric damage assessment of the (a) reference and (b) V-fiber CFRP panels. The depth-of-damage for the reference and V-fiber are 0.72 mm and 1.30 mm, respectively, while having a volumetric damage of 1696.1 mm3 and 762.1 mm3, respectively.

panel within 0.4 mm depth, confirming the current was not able to dissipate efficiently through the panel leading to a higher resistive heating, which is confirmed by the IR thermography. The damage becomes smaller with depth evident by a smaller damage diameter of 3.67 cm at 0.4 mm depth and penetrating to only 0.72 mm. The V-fiber damage flared outwards below the surface, but then concentrated down to a depth of 1.30 mm. Due to the high TT conductivity the current caused a deeper damage in the specimen before exiting the laminate through the in-plane layers. The damage was also concentrated at the penetrated depth of 1.30 mm due to Joule heating. The volumetric damage of 1696 mm^3 and 762 mm^3 was measured for the reference and V-fiber panels, respectively. The depth-of-damage was greater in the V-fiber, but overall, the vertical fibers reduced the volumetric damage by 55%. Depth-of-damage analysis from NDE and cross-sectional optical images show damage in all three orthogonal dimensions and confirms that ultrasonic NDE captured the damage which were invisible to the 2D microscopic images.

3.3. Electrical conductivity

The electrical conductivity of V-fiber composite in the TT direction was found to be 1.15 S/cm, which is almost nine times higher compared to the reference CFRP panel (0.13 S/cm). However, the in-plane electrical conductivity of both samples was not significantly different, where the V-fiber composite (50.38 S/cm) showed only 1.25 times the electrical conductivity compared to the reference CFRP sample (40.16 S/cm). The results of the TT and in-plane electrical conductivity testing are shown in Table 1.

As discussed in the Introduction, the TT conductivity is the primary factor that determines the performance against lightning strikes. In V-fiber composites, the vertically aligned short carbon fibers provided the preferable conduction path from the top ply to the bottom CF plies causing the current to bypass the insulating resin and dissipate in the TT direction. Each layer in the laminate contributed to the lightning current discharge as the current needs a continuous path through the thickness for effective dissipation. Such a dissipation of lightning strike in the TT direction was confirmed by smaller damage area and higher depth of damage illustrated in Fig. 4-d and 5-b. Whereas for the reference CFRP panel, a higher damage area and lower depth of damage were observed as shown in Fig. 4-d and 5-b. This could be assigned to the presence of the insulating epoxy at the interface between each layer hindered the

Table 1
Through-thickness and In-plane electrical conductivities of reference CFRP panel and V-fiber CFRP panel.

	Reference (S/cm)	Standard Deviation	V-fiber (S/cm)	Standard Deviation
Through-Thickness	0.13	0.03	1.15	0.1
In-Plane	40.16	4.53	50.38	0.6

charge transfer between layers, forcing the current to stay on the top layers of the CFRP laminate. As a result, the hindered current dissipation led to the generation of larger resistive heat or Joule heat confirmed through IR thermography (see Section 3.4). The thermal degradation of the material from Joule heating was likely a main factor for the significant damage observed in the reference sample compared to the V-fiber sample.

3.4. IR thermography

IR thermography was utilized to capture the real-time thermal history of the CFRP samples during lightning strike testing. As discussed previously, Joule heating is the primary reason for catastrophic damage to CFRP composites from lightning strikes. Therefore, IR thermography provides quantitative data to understand the response of the CFRP samples under such extreme circumstances. Fig. 6 reveals the temperature profile of the CFRP samples during and 1 s after the artificial lightning strike test. The lightning strike event lasted roughly 500 microseconds, so the lightning arc's heat flux and radiation temperature that can exceed 20,000 °C could not be captured [49]. Although the IR camera couldn't quantify the temperature at the exact moment of the artificial lightning strike, the V-fiber panel surface temperature 1 s after the strike was only 67.4 °C while the CFRP reference panel had a surface temperature of greater than or equal to 150 °C. The maximum temperature that can be recorded by the camera was 150 °C, but the V-fiber panel dissipating heat more efficiently than the reference panel is clearly shown by the 67.4 °C measured value 1 s after the artificial lightning strike.

The temperature of the reference CFRP was concentrated at a much smaller area with much higher intensity than the V-fiber composite 1 s after the lightning strike (Fig. 6 b and d). In addition, a broader and lower temperature distribution was observed on the surface of V-fiber composites. The IR thermography confirms that the current dissipation of the V-fiber specimens was rapid and generated comparatively low amounts of heat. This behavior can be attributed to the high TT electrical conductivity of the V-fiber panel compared to the reference CFRP panel.

3.5. Residual flexural properties

To identify how the artificial lightning strike had an impact on mechanical performance, three-point bend testing was performed to measure residual strength. Specimens were extracted from the left and right sides of the center of the artificial lightning strike entry location for both the CFRP reference and V-fiber panels. Six specimens were cut from left of center and six specimens were cut from the right of center. Specimens labeled with 1 are closest to the center and specimens labeled 6 are furthest from the center with the "L" denoting the specimen was cut from the left of center and the "R" denoting the specimen was cut right of center. A schematic of the numbering and labelling of specimens for three-point bend testing is shown in Fig. 7(a). Fig. 7(b) and **(c)** show the flexural strength and modulus of the tested specimens, respectively. The specimens closest to the center of the artificial lightning strike entry location ("L1" and "R1") had the lowest flexural strength and modulus but increases as the distance from the center increases. The reference CFRP panel exhibited higher flexural strengths and moduli than the V-fiber panel at all locations except the flexural strength for R1. The V-fiber strength and modulus results are as expected due to a high percentage (46%) of short carbon fibers aligned in the vertical direction, which do not contribute to the in-plane flexural load applied. When compared to the reference panel which has all 8 layers in-plane and contribute to the applied load, the V-fiber panel only has 5 in-plane layers as can be seen in Fig. 1. This resulted in lower flexural strengths and moduli for the V-fiber panel. Another potential reason for reduction in properties is the formation of defects, such as voids at the interface of the short V-fibers and the in-plane CFs. Such a behavior has also been reported for stitched composites [50].

The flexural modulus and strength plots of extracted specimens in Fig. 7(b) and (c) form a crater-like profile with lowest values corresponding to the center damage location. The depth of the dip depicts the loss in flexural modulus and strength post lightning strike. To quantify the loss in flexural modulus and strength, the average of L5, L4, R4, and R5 was taken as the original while the average of L1 and R1 was considered as the reduced values post lightning strike. Accordingly, the flexural modulus and strength of reference CFRP specimens reduced by 56.5% and 53% representing significant losses in flexural properties due

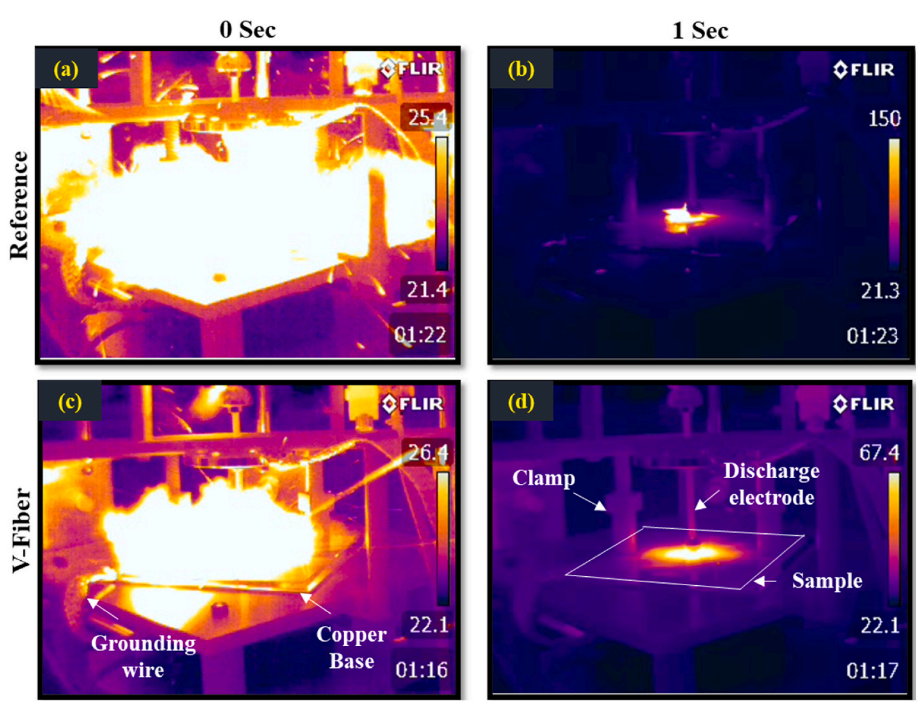

Fig. 6. The thermal responses of the reference CFRP and V-fiber panel (a and c) during the artificial lightning and (b and d) 1 s after the artificial lightning strike test.

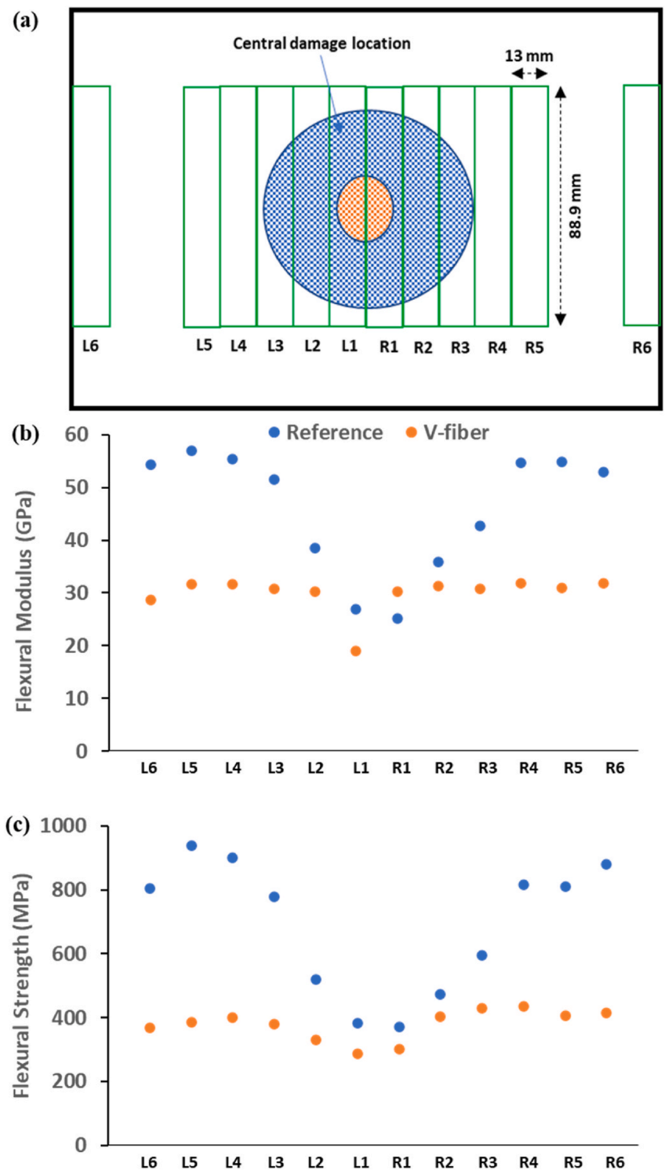

Fig. 7. Residual flexural properties of reference CFRP and composite samples after lightning strike test. (a) Schematic of specimen extraction from CFRP plate (b) flexural modulus (c) flexural strength.

to large volumetric damage. Whereas the flexural modulus and strength reduced by only 22% and 28% for V-fiber specimens exhibiting higher retention of flexural properties as compared to reference CFRP specimens. This is attributed to the overall volumetric damage being lower for the V-fiber specimens observed through the ultrasound inspection (see Fig. 5). The location of lowest flexural strength and modulus (L1 in Fig. 7) corresponds to the greatest depth-of-damage of 1.30 mm in Fig. 5.

4. Discussion

The promising response of V-fiber CFRP composites as a lightning strike protection technology has been demonstrated experimentally. The V-fibers significantly enhanced the TT electrical conductivity of the CFRP composites from 0.13 to 1.15 S/cm. Such an enhancement has led to an improved dissipation of the lightning discharge current within the CFRP composite, a reduction in the temperature caused by the resistive heating, and a lesser extent of lightning strike damage (from 57.68 cm^2 to 12.69 cm^2, a 78% reduction). Though a small extent of delamination occurred in the V-fiber composite, there was no fiber breakage nor matrix cracking, which is a significant improvement compared to the reference specimen that resulted in substantial fiber breakage and matrix degradation. Moreover, the V-fiber composite specimens exhibited 78% and 72% retention in flexural modulus and strength respectively after lightning strike impact as compared to 43.5% and 47% in case of reference CFRP specimens. These results show that enhancing the TT electrical conductivity by incorporating V-fibers is an effective and emerging method for the lightning strike protection of CFRP composites.

Mechanical characterization revealed that incorporating V-fibers in the CFRP composites reduces the flexural modulus and strength by 53% and 43%. Vertically aligned fiber layers did not significantly contribute to the load transfer. The reduction in flexural properties in case of the V-fiber composite can also be attributed to the potential formation of the defects at the interface between the V-fiber and the in-plane CFs. Therefore, future studies are required to investigate methods to enhance the TT electrical conductivity of CFRPs without compromising the in-plane mechanical properties. One such method could be incorporating V-fiber to only a few of the top layers of the laminate, rather than through-out the entire laminate thickness. The study should also be extended to understand the effect of paint on lightning damage behavior of V-fiber panels.

The V-fiber layer thickness reduced during the molding processes from the original 0.42–0.48 mm to 0.39–0.41 mm after molding, as shown in the Fig. 1. As we fabricated only two samples in this study, the impact of molding pressure during curing and its impact on the final thickness and through-thickness electrical conductivity was not studied. However, it is anticipated that the higher molding pressure will impact the final samples' thickness and the degree of V-fiber alignment, as they might lose their vertical orientation under pressure. Therefore, on the one hand, we will have a lower overall thickness of the laminate, which might improve the through-thickness electrical conductivity. But, on the other hand, losing the vertical fiber alignment will reduce the through-thickness electrical properties. A more detailed study on the process parameters for V-fiber laminate will be conducted in the future.

5. Conclusion

A unique method of using vertically aligned short carbon fibers in the TT direction within the CFRP laminates was implemented to increase the TT electrical conductivity of the laminate composite. The TT electrical conductivity was improved by almost 800% in the V-fiber composite (1.1.5 S/cm) compared to a referenced CFRP panel (0.13 S/cm). The impact of increasing the TT electrical conductivity of the laminate for lightning strike protection was evaluated by artificial lightning strike experiments at 100 kA. The V-fiber composite was found to effectively dissipate the lightning impulse current without experiencing significant damage due to Joule heat. Non-destructive test results showed that the volumetric damage reduced from 1696 mm^3 in the reference panel to 762 mm^3 in the V-fiber panel, a 55% improvement. However, the V-fiber composites exhibited reduction in flexural modulus and strength by 53% and 43%, respectively as compared to the reference CFRP specimens. Nevertheless, the TT aligned short CFs were able to effectively reduce the overall lightning strike damage compared to the reference CFRP sample.

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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