Low cost carbon fiber as potential lightning strike protection for wind turbine blades

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Abstract
Until recently, glass fiber composites (GFRP) were the preferred choice to prepare wind turbine blades due to their low cost compared to their counterpart carbon fiber composites (CFRP). However, to harvest the maximum wind energy, ever larger wind turbine blades are being manufactured. To support such a large structure carbon fiber composites CFRP have become the integral part of load bearing structures in the blade. In this work, we are proposing to utilize the low cost carbon fiber (LCCF), manufactured at Carbon Fiber Technology Facility (CFTF) of Oak Ridge National Laboratory (ORNL) as not only the cost effective alternative to the currently used CF but also as the lightning strike protection of the wind turbine blades. Wind turbines often get hit by lightning strikes due to their operating locations. LCCF can provide structural integrity to these gigantic structures and mitigate the effect of lightning strike on them by effectively dissipating the current. Two composite panels made of LCCF were tested against artificial lightning strikes of 100 kA and 200 kA (component A of lightning waveform SAE ARP 5412-B). The results showed very high resilience of LCCF composite due to their high electrical conductivity both in-plane and in through-thickness directions. There was no significant damage (fiber breakage, resin evaporation or delamination) in both the cases.

Keywords: Low Cost Carbon Fiber, Lightning Strike Protection, Wind Turbine, Electrically Conductive.

Introduction

Lightning strike protection of composites is one of the biggest challenges to incorporate them in aerospace or wind energy industry [1,2]. Due to very low electrical conductivity of the CFRP structures compared to their metal counterpart structure, they perform poorly in an event of getting struck by a lightning strike [3]. Engineers have utilized a range of protecting methods to make

CFRPs safe against lightning strikes. Copper (Cu), aluminum (Al), Nickel (Ni) Metal-based foils/film/meshes are the most traditional lightning strike protection (LSPs) [4]. However, in recent years, researcher came up with modern solutions based on recent development in materials and processing advancement in the scientific world [5].

Carbon nanomaterials are the most studied alterative lightweight solution to current metallic LSPs due their inherent high electrical, thermal and structural properties [6,7]. However, novel material such as intrinsically conductive polymer, “polyaniline (PANI)” also performed exceptionally well against artificial lightning strikes under laboratory setups [8,9]. However, commercialization of these new LSP systems is yet to be realized.

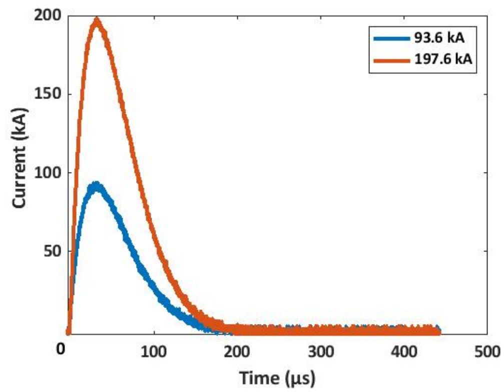
Although all these efforts required to have additional LSP system on top of the CFRP structure, which eventually add to a parasitic weight. The additional LSP do not contribute to other structural functionalities and therefore, the ideal way is to make CFRPs electrically conductive itself so that it doesn’t require any additional conductive layer. This can be done by modifying the type, content, properties of fiber, matrix or interphase (sizing) respectively, to achieve the highest electrical conductivity in the CFRP laminate structures. Some reports on changing matrix type and interphase are available in literature. Additional electrically conductive fillers into the matrix and growing carbon nanofillers or metal-coating on fibers are some of the studied methods to increase the electrical conductivity of CFRPs and their effect on CFRP performance against lightning strikes. However, the effect of carbon fiber type on lightning strike damage behavior has not been studied.

In the present work, the effect of carbon fiber type on the LSP performance is studied. A textile grade PAN based precursor was utilized to manufacture low cost carbon fiber at the Carbon fiber Manufacturing Facility or Oak Ridge National Laboratory. The fundamental study on the mechanical performance of the composite prepared by LCCF has been studied by other researchers. However, the electrical conductivity and its effect on LSP performance of LCCF composite is being presented for the first time.

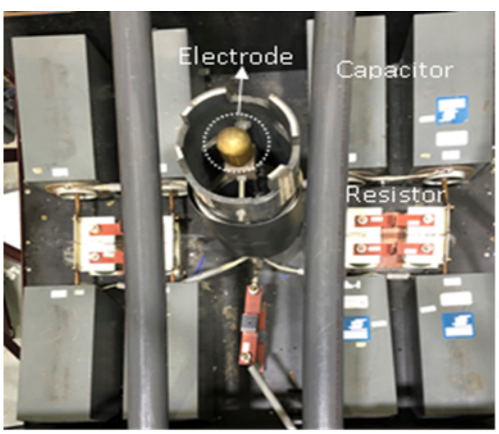
Experimental

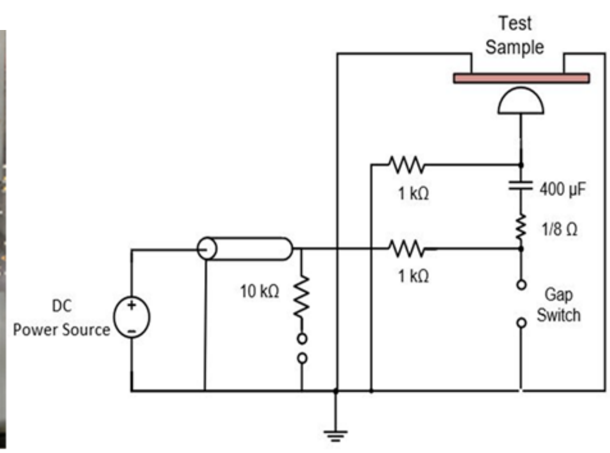
LCCF-CFRP preparation: LCCF composites were fabricated using a hand lay-up method followed by a compression molding (CM) technique. Epon 862 and Epikure Curing Agent were used to impregnate the LCCF fibers. A continuous LCCF tow with 450 K filaments was spread and taped to produce 76 mm - 102 mm wide TCF sheets. Sixteen layers of LCCF were arranged in $[0/90]_{8S}$, and epoxy resin (resin to hardener ratio 3:1) was poured and spread on each layer. A perforated release film was placed on the top of the fabric lay-up, and the entire setup was sealed with the bagging material. An Aluminum caul plate was positioned on the sealed setup to achieve a good surface finish. The assembly was placed in the compression molding press (Carver hot press (model 3895), located at FCMF, UTK, USA) at 180 °C and 0.6 MPa pressure for 60 mins. The panel were trimmed to 200 × 200 mm^2 for lightning strike test.

Lightning Strike Test Setup: The impulse current generator at high voltage lab of Mississippi State University was used to simulate the lightning strike tests on prepared LCCF composites. The high voltage lab located at Mississippi State University (HVL-MSU) can produce components A and D of SAE standard lightning waveform as shown in **Fig. 1**. Eight 47 μF capacitors are connected in parallel and the capacitance of the circuit is 376 μF. In this setup, the capacitors were discharged by triggering the spark gap, and the discharged current penetrated through the test article. The generator is charged by a DC power source up to 44 kV for each capacitor that can store 50 kJ electrical energy to vary the current amplitude of the strike and generating the standard waveform of lightning. In this study, component A of the lightning strike waveform was generated, and current discharges of 93.6 kA and 197.6 kA were used as shown in the figure. The simulated lightning current is in accordance with component A of the SAE standard lightning waveform which can be up to 200 kA and should be less than 500 µs. So, it is suitable for lightning strike damage analysis. The samples were grounded to a steel plate with copper strips, steel strips, and braided wires. The braided wires were wrapped around the edges and the copper and steel strips were tight into the sheet of steel with nuts and bolts to hold the sample and make a path for discharged current to the ground. The test apparatus was placed face down on the top of the impulse generator's discharge electrode and struck by simulated lightning strike [10].



(a)





(b) (c)

Fig. 1. Simulated lightning strike test setup (a) applied component A of lightning waveform (b) current discharge electrode (c) circuitry for the artificial lightning generation.

Ultrasonic Inspection: Ultrasonic inspection imaging was conducted using the OmniScan SX ultrasonic flaw detector (*i.e.,* a 16:64PR phased array unit) from Olympus IMS to examine the damage of the two composite laminate specimens inflicted by the simulated lightning strike. In particular, C-scan images were obtained both before and after the simulated lightning strike test to identify the locations of any potential delamination caused by lightning strike in the in-plane direction of the composite specimens, while B-scan images were only obtained after the lightning strike test to identity the delamination locations across the thickness direction of the composite specimens.

Characterization: Specimens were cut from the panels for electrical conductivity Direct Current (DC) measurement in through-thickness and in-plane directions. Electrodes made of aluminum tape were attached to the longitudinal side faces via conductive silver adhesive. The silver adhesive was dried completely before measurement. Electrical resistance was measured using a HP Hewlett Packard 34401A multi-meter. At least three specimens were tested for both the through-thickness and in-plane directions. Mechanical properties were measured using Test Resources frame with a 50 kN load cell fitted Universal Testing Machine (UTM) machine. A flexural bending test (ASTM D790) was performed in a 3-point bending configuration. For each material, at least three specimens were tested, taken from panels before and after lightning strike tests.

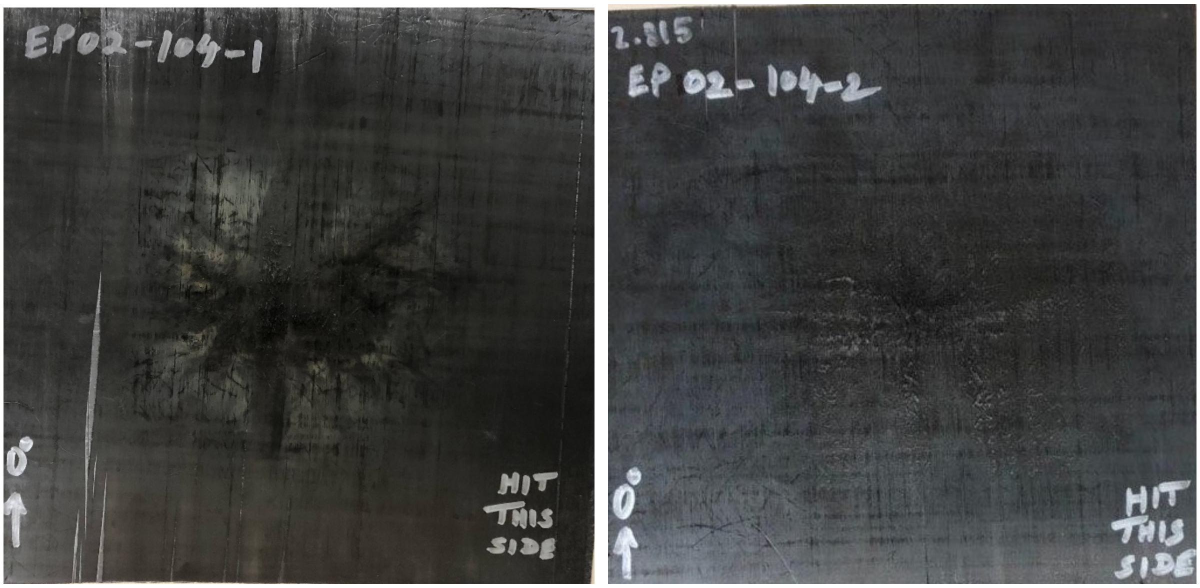
Results and Discussion

Electrical Conductivity of LCCF-CFRP: The electrical conductivity of the prepared LCCF-composite panels was measured in through-thickness and in in-plane directions as shown in the Table 1. As electrical conductivity is also a function of CF volume fraction, the CF volume fraction of both panels was also measured and reported in the Table 1. The through-thickness electrical conductivity of LCCF-composite was around 0.26 S.cm, which is almost 4 times higher than that of the epoxy composite prepared by Eight layers of prepreg "F6343B-05P" consist of T300-3K plain woven fabric and #2500 epoxy obtained from Toray Industries, Inc. explained in the literature [11]. Similarly, in-plane electrical conductivity of LCCF-composite is also found to be around 4 times compared to reference composite panel. The electrical conductivity of LCCF-composite panels is significantly high compared to most of the conventional epoxy-based CFRP without any modification. Even with addition of highly electrically conductive fillers into the matrix, the highest through-thickness electrical conductivity reported is around 1 S/cm. High electrical conductivity of the LCCF-composite could be assigned to the higher carbonization of the fibers and due to the higher CF volume fraction.

Table 1. Thickness, CF volume fraction and electrical conductivity (through-thickness and in-plane) value of LCCF-composite samples.

Samples	Thickness (mm)	CF volume fraction (%)	Through-thickness (S/cm)	In-Plane (S/cm)
EP02-104-1	2.47	70.0	0.27	30.1
EP02-104-1	2.81	63.3	0.26	38.3
Reference [11]	1.86	55.2	0.07	9.27

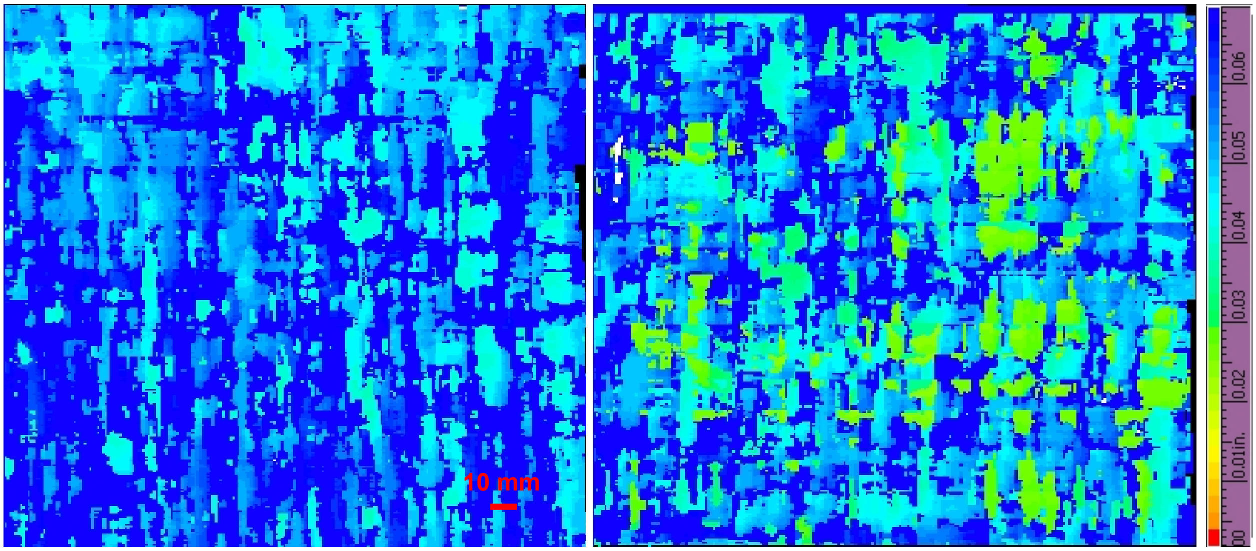
Visual Damage Inspection: The visual inspection of the panels after lightning strike confirmed that there was no fiber breakage, resin evaporation or delamination in the composite panels after the lightning strike test. Small discoloration and some fiber fuzziness around the lightning attachment location (center of the panel) was observed. This is significant finding as without any additional LSP these panels exhibited remarkable resilience to the lightning damage. In the literature, there is no report of epoxy based CFRP composites surviving such a high lightning currents without undergoing any visual damages. This behavior can be assigned to the inherent high electrical conductivity of LCCF-composites compared to the other traditional epoxy-composites.



(a) EP02-104-1 (b) EP02-104-2

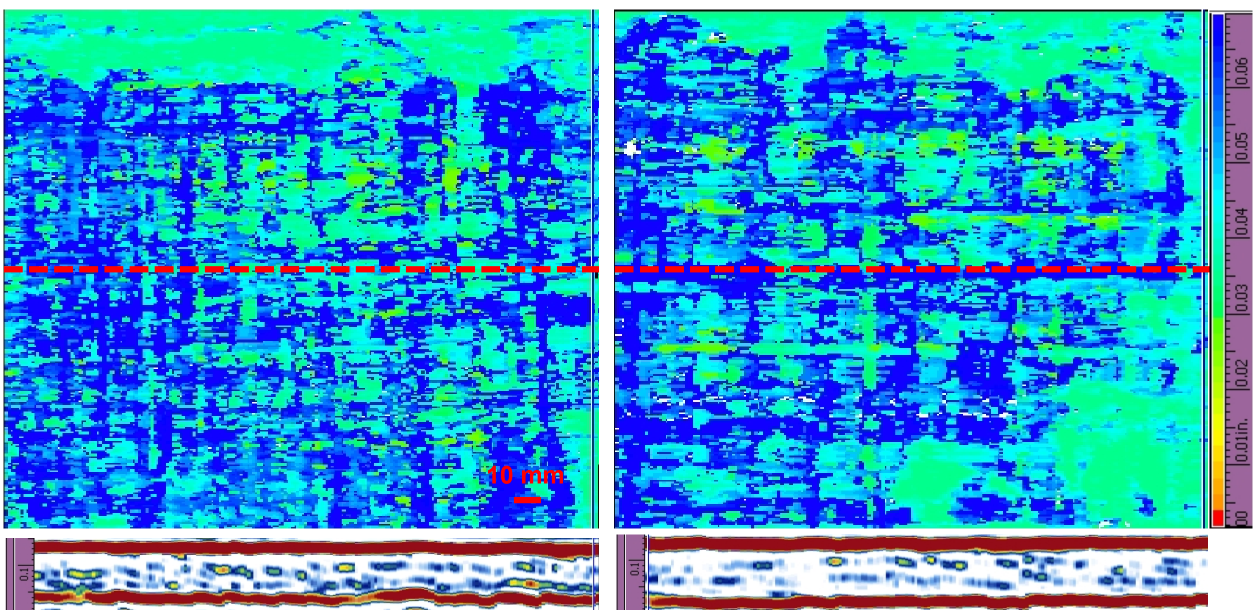
Fig. 2. Visual damage inspection of LCCF-composite panels after lightning strike test of (a) 100 kA and (b) 200 kA.

Ultrasonic Inspection Images: Fig. 3 shows the C-scan images for composite EP02-104-1 and EP02-104-2 obtained before the simulated lightning strike test. Defects are uniformly present in both panels which could be due to the surface roughness or voids caused during the manufacturing process. For EP02-104-1, the color indicating the defects is slightly lighter than blue (see the color legend shown in Fig. 3, unit in inches), which implies that more defects are present near the laminate surface and could have been caused by the surface roughness. While for EP02-104-2, areas with more greenish color can be observed, which indicates that the defects are not only on the surface but also are generally present in more in-depth locations possibly due to voids.



(a) EP02-104-1 (b) EP02-104-2

Fig. 3. C-scan images for panels EP02-104-1 and EP02-104-2 obtained before the simulated lightning strike test.



(a) EP02-104-1 (b) EP02-104-2

Fig. 4. C-scan and B-scan images for panels EP02-104-1 and EP02-104-2 obtained after the simulated lightning strike test.

Fig. 4 shows both C-scan and B-scan images for panels EP02-104-1 and EP02-104-2 after the simulated lightning strike test. Note that the scanning parameters (e.g., focus depth) used for the C-scan before and after the simulated lightning strike test are slightly different. As one can see, the defects are still quite uniform and present almost everywhere within the composite panels. The B-scan images shown below the C-scan images in Fig. 4 were obtained by scanning along the paths in the centerline of the composite panels, as indicated by the red dashed lines in the figure. It can be observed that defects are present at multiple locations across the thickness of the panels and it appears that more defects exist in panel 1 at the centerline paths that were scanned. Overall, the C-scan and B-scan images are not enough to show any clear trends about any damage due to the lightning strikes.

Residual Mechanical Properties: NDT analysis was not able to give a good picture about the damage within the CFRP laminates after the lightning strike, therefore, destructive mechanical testing was performed to compare the mechanical properties of the LCCF-composites after the lightning strike test. Three samples from the lightning attachment location at the center of the plates and 3 samples from the side corner (undamaged location) were cut from the panels and flexural test was performed. With the assumption that the lightning current accompanied with a large amount of resistive heating and causing evaporation of the matrix, 3-point bending was chosen to capture the degradation of the matrix. However as shown in the Table 2. Flexural strength and modulus of both the composite panels from undamaged and damaged location was found to be same (within standard deviation). No reduction in the mechanical properties of the composites confirmed that the LCCF-composite panels maintained their 100% structural integrity even after struck with a 200kA lightning current.

Table 2. Residual flexural mechanical properties of LCCF-composite samples after lightning strike test.

		Avg flex strength (MPa)	Strength STD Dev. (MPa)	Avg Flex Modulus (GPa)	Modulus STD Dev. (GPa)
EP02-104-1	Before	745	72.97	58.24	5.71
	After	724	89.14	59.48	6.48
EP02-104-2	Before	704	49.21	65.01	3.74
	After	734	33.49	64.10	1.11

Conclusion

In this work, low cost carbon fiber (LCCF), manufactured at Carbon Fiber Technology Facility (CFTF) of Oak Ridge National Laboratory (ORNL) is proposed as a cost-effective alternative to the current lightning strike protection of the wind turbine blades. Two composite panels made of LCCF were tested against artificial lightning strikes of 100 kA and 200 kA (component A of lightning waveform SAE ARP 5412-B). The results showed very high resilience of LCCF composite due to their high electrical conductivity both in-plane and in through-thickness directions. There was no significant damage (fiber breakage, resin evaporation or delamination) in both the cases. High residual mechanical properties and NDT analysis confirmed no significant damage to the LCCF-composite panels after lightning strike test. This finding can help wind turbine blade manufacturers to utilize LCCF not only load bearing structure but as LSP system as well.

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