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Non-metallic lightning strike protection coating for wind-turbine blades

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Abstract. The increasing use of Carbon Fiber Reinforced Polymer (CFRP) composites in the wind energy industry presents a challenge concerning lightning strike protection (LSP). Due to their low electrical conductivity, these materials are inferior to metals in dissipating electrical currents generated by lightning strikes, potentially leading to catastrophic damage. The current LSP system for wind turbine blades involves metallic lightning arrestors, which may only sometimes be effective due to the accumulation of debris and salt on other parts of the blade. Other commercially available products, such as diverter strips and nano-filler coatings, are expensive and impractical for use throughout the entire blade. Recently, researchers have proposed using electrically conductive polymeric coatings as a potential solution. These coatings are easy to apply and can be spray-coated, painted, or manufactured via automation. In this study, newly developed polymeric coating solutions were experimentally tested and compared to traditional metallic-based LSP systems. The experiments showed promising results in dissipating the current generated by lightning strikes. In addition, the thicker coatings reduced catastrophic damage, including puncture, fiber breakage, and resin evaporation, compared to thinner coatings. Overall, the study highlights the potential of polymeric coatings as a viable solution for lightning strike protection in the wind energy industry.

1. Introduction

In recent years, fiber-reinforced polymer (FRP) composites have gained popularity and are already dominating the aerospace and wind energy industries. Carbon FRP incorporation in future wind turbine blades is also growing [1]. Although FRPs can replace their metal counterparts in applications where specific strength is desired, but not in applications where other properties, such as high electrical conductivity, are required. Due to low electrical conductivity, CFRP structures are inferior to their counterpart metal structures in the event of a lightning strike [2]. Lightning strikes on wind turbine structures are severe due to substantial repair costs and downtime associated with lightning strike damages. The location of installed wind turbine blades (areas with the most probability of strong winds) also makes them highly vulnerable to lightning strike damages [3]. During a lightning strike, Carbon/Glass Fiber Reinforced Polymer C/GFRP structures can be destroyed due to the extreme heat produced by resistive heating or Joule's heating.

Wind energy has been a great source of clean, renewable energy; therefore, the United States of America is expected to increase wind turbine blade deployment by 5X. The target for offshore energy production is 30 GW by 2030, which will pay the path for 110 GW of total energy production via offshore wind turbines. The offshore turbine will deliver 10% of the USA's energy need by 2050.

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With this exponential expansion, it has become critical to safeguard these tall structures from extreme weather and increase their credibility. Keeping these wind farms running without properly mitigating weathering problems will cost significantly. Therefore, a new lightning strike protection system is needed. Many research groups and industries are investigating novel LSP systems as the current LSP systems are inadequate.

The current lightning strike protection system of wind turbine blades includes a metallic lightning arrestor, which creates a lightning attachment point on the tip of the blades and is connected to a metal rod (down conductor) placed underneath the C/GFRP structure [4]. However, the current technology has yet to be effective during a lightning strike, as the accumulation of debris and salt on the other blade areas can also act as the lightning attachment points. In such events, there is no down conductor available to dissipate the current safely to the ground, and the C/GFRP structure suffers potentially catastrophic damage in the form of puncture, fiber breakage, resin evaporation, etc. Some of these damages grow over time and can ultimately put the blade out of commission [5]. Diverter strips and nano-filler coatings are other commercially available products for lightning strike protection of wind turbine blades. Both technologies depend on the arc jumping mechanism, where a dielectric material separates the two closely placed conductive electrodes. These expensive diverter strips cannot be used throughout the blade, leaving many unprotected surfaces exposed.

A promising solution being extensively researched is the development of a nano-engineered multifunctional coating of polymer/ceramic composite that could create an in-situ 3D conductive network to dissipate the lightning current. Painting or advanced automation manufacturing techniques can apply the coating to the wind turbine. In addition, it can operate under harsh conditions of lightning strikes and severe wear during the operation of onshore/offshore wind turbine blades.

Serbescu et al. studied the silver-based conductive coating as a scalable lightning strike protection for composite aircraft. Silver-coated carbon fibers (SCCF) with various binders were used, including epoxy and PEDOT:PSS conductive ink. All SCCF-based LSP exhibited around 45% - 50% retention of flexural strength, which was lower than the commercial Cu-mesh LSP, which exhibited an 83% retention of flexural strength [6]. Zhang et al. studied the thin, flexible graphene surface coating as lightning strike protection of carbon fiber epoxy prepreg laminate. They reported that the damaged area and volume in the graphene-coated laminate were reduced by 94% and 96%, respectively, compared to the laminate without the coating [7]. In another study, Zhu et al. applied a dual conductive network of nickel-coated carbon fiber woven fabrics (Ni-CFWF) on CFRP. They investigated both the indirect and direct lightning strike protection response of the composites. This study showed that the maximum lightning strike-induced damage depth and area-protected composites were reduced by 21.59% and 6.11% under a simulated lightning current of 100 kA, respectively [8]. Wang et al. designed a film reinforced by nickel-coated carbon fibers/carbonyl iron powders to provide a conductivity framework (NCF/CIPCF) for lightning protection of CFRP laminates [9]. Yokozeki and his group have been working on intrinsic conductive polymer, i.e., Polyaniline (PANI) based polymer, to make lightning strike protection coatings [10–12]. Their multiple studies focused on the coating performance at various lightning intensities and on optimizing the thickness of the coatings for optimal performance. The current work is also inspired by PANI based system.

In the current work, we embedded conductive PANI in the polyurethane-based system to represent the coatings used in wind applications. For the reference, expanded metal (Cu) foils were also tested for comparison.

2. Materials and Method

2.1 CFRP substrate

A commercial CFRP specimen (230 mm × 230 mm × 3.17 mm, McMaster Carr) was used as a substrate control specimen, and various conductive coatings were applied on top of it to prepare a PANI-PU LSP coating on top of the CFRP. Coated and uncoated CFRP panels were compared against lightning strikes. The following information about the CFRP was provided by the supplier (PAN-based woven fabric, tensile strength ≈ 827-1200 MPa, compressive strength ≈ 517-880 MPa, flexural strength ≈ 613-1200 MPa, and service temperature up to 82.2 °C).

2.2 Synthesis of conducting coating solution

The flow chart below shows a detailed experimental procedure to make the PANI-coating.

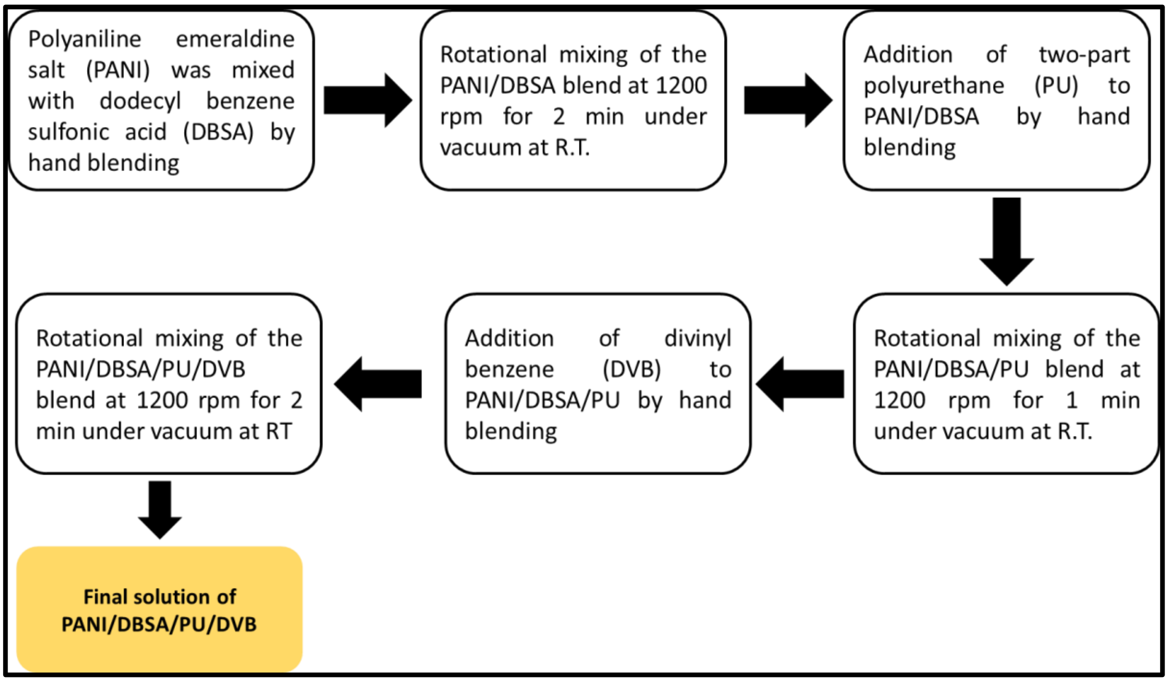
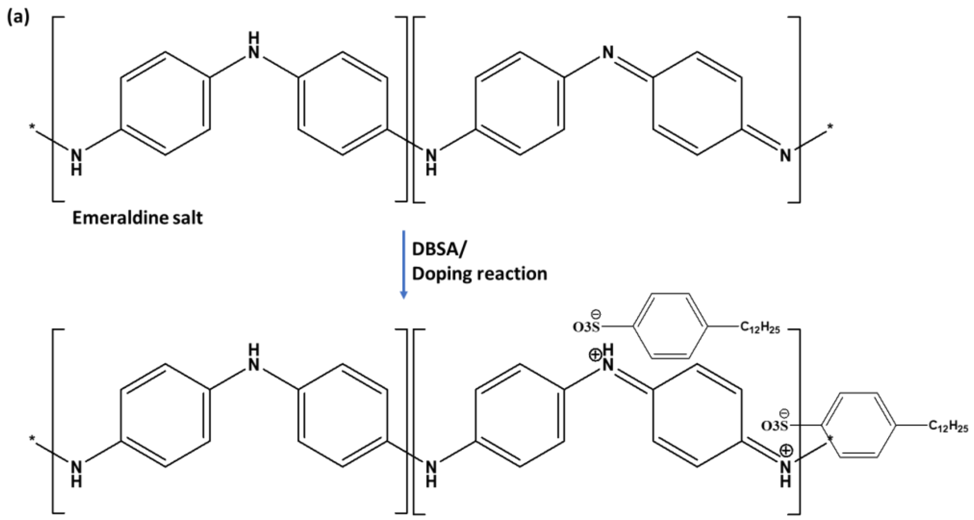


Figure 1. Synthesis of PANI/DBSA/PU/DVB blend for conductive coating layer

2.3 LSP- coating on CFRP

Before applying a coating, the specimen's outermost layer was lightly sanded for better bonding between the PANI-based LSP system and composites. Further, different PANI-based resin weights were applied over the composite panels to achieve the different thicknesses of LSP coating. Finally, the PANI-based LSP coating was cured in the oven. The heating rate was 10˚C/min, from 23 to 115˚C, followed by 5 mins of a dwell period at 130˚C.

2.4 Reaction mechanism



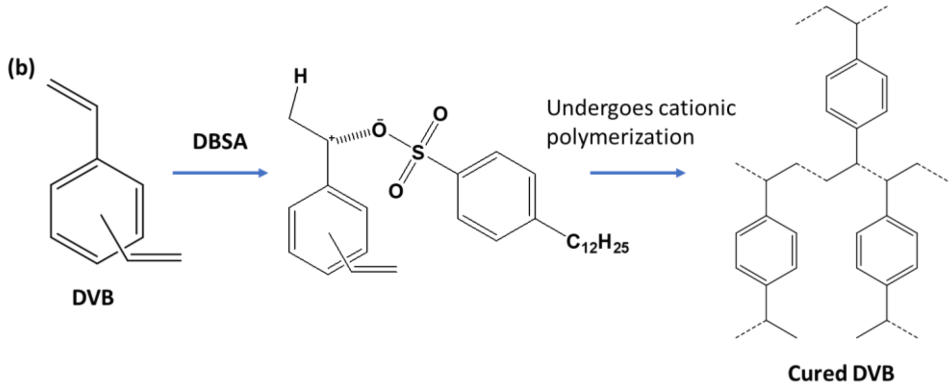


Figure 2. (a) PANI-DBSA doping and (b) DVB curing mechanism.

2.5 Lightning testing

LSP testing was conducted at Wichita State University's National Institute for Aviation Research Center as per SAE ARP 5416 standard. The actual waveform varies for various specimens, but the standardized waveform is shown below. The benchmarking (unprotected and Cu-mesh) samples were tested for all the three waveforms, while thin-PANI and Thick-PANI were tested only for the waveform A. This research aimed to understand the PANI-based coating performance against lightning strike, rather than the full certification, therefore only the modified waveform A was used for PANI-based samples.

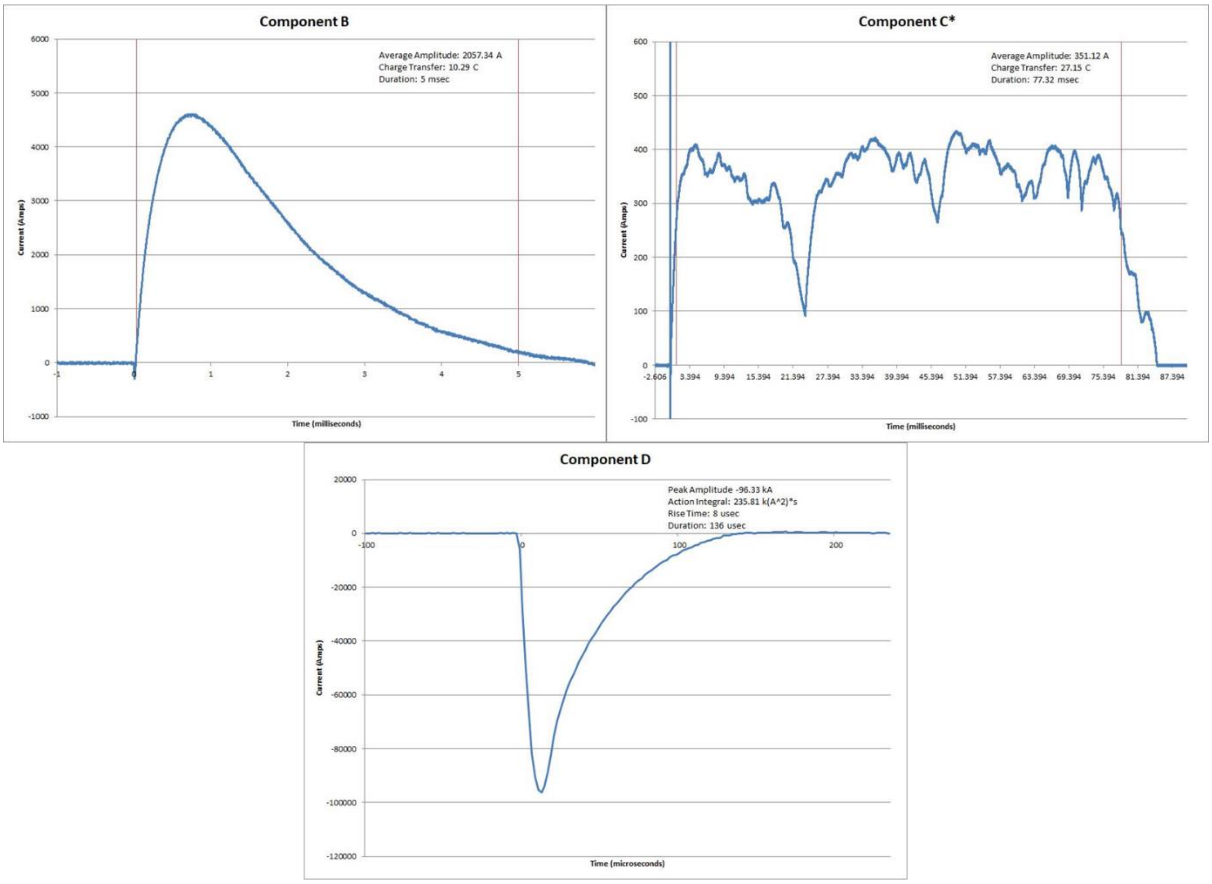


Figure 3. Applied current waveforms as per SAE ARP 5416 standard.

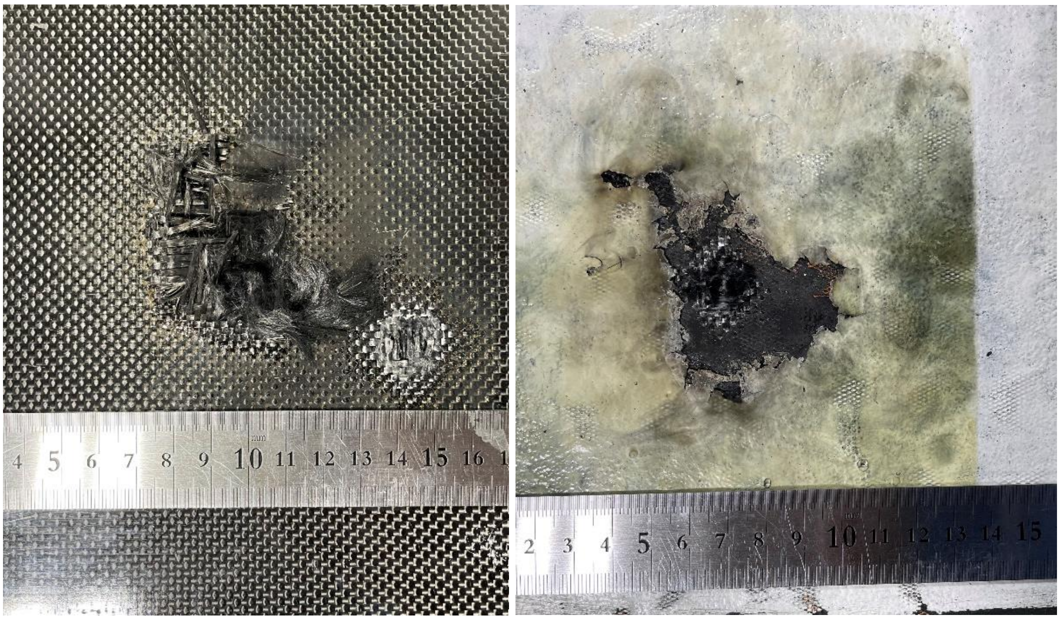
Table 1. Applied lightning waveforms on the CFRP samples.

Sample	Component A/D				Component B			Component C		
	Peak Amplitude (kA)	A/I (AAs)	Rise Time (μs)	Duration (μs)	Average Amplitude (kA)	Charge Transfer (C)	Duration (ms)	Average Amplitude (kA)	Charge Transfer (C)	Duration (ms)
Unprotected	-96.33	2.36E+5	8	136	2.06E+3	10.29	5	351.12	27.15	77.32
Cu-Mesh	-93.60	2.14E+5	8	128	2.06E+3	10.29	5	336.02	28.47	84.72
Thin-PANI	-59.47	7.6 E+4	10	94	-	-	-	-	-	-
Thick-PANI	-58.27	7.2 E+4	8	90	-	-	-	-	-	-

3. Results

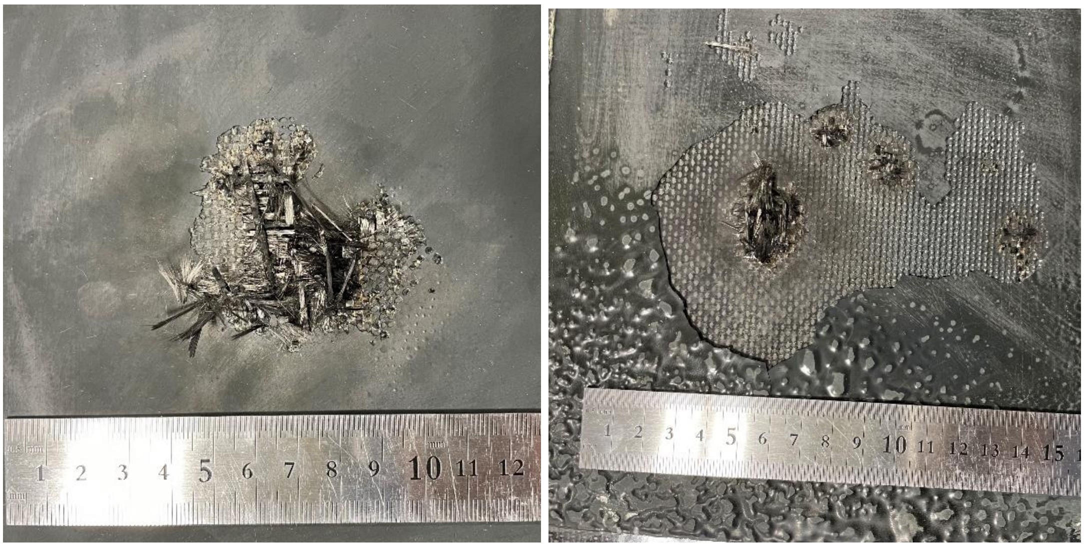
Benchmarking: In the first experiment, one bare CFRP specimen without any protection was subjected to a lightning waveform, as shown in Table 1. Lightning damaged the specimen significantly, and fiber breakage, resin evaporation, and ply delimitation were observed. The affected area of was around 150 mm in length and 140 mm in width. Secondary attachment to a nearby place was also observed.

In the second benchmarking experiment, a CFRP protected with a 76 g/m^2 weight Cu-Mesh was also tested against the lightning waveform shown in Table 1. Lightning energy evaporated the Cu-Mesh to 115 mm long and 110 in width. However, the damage to the CFRP substrate was reduced to 35 mm in length and width. The fiber damage was significantly minor compared to the unprotected CFRP specimen, confirming that the Cu-Mesh provided Faraday cage protection to the CFRP substrate until its failure (evaporation). Once the Cu-mesh is evaporated, the lightning enters the CFRP specimen damaging it. This benchmarking testing confirmed that even aerospace-grade LSP does get damaged and needs repair to be functional over a long period, which is a big challenge for wind blades, where repair cost is colossal.



(a) Unprotected (b) Cu-mesh protected

Figure 4. (a) CFRP Specimen without any protection (b) CFRP with 76 GSM CU-mesh protected LSP after waveforms (A=100 kA, B= 10 C, and D= 20C charges).



(a) Thin PANI-PU LSP (b) Thick PANI-PU LSP

Fig. 5 (a) CFRP Specimen without thin PANI-PU coating, and (b) CFRP with thicker PANI-PU LSP after waveform (A=60 kA).

In this experiment, we applied 20 gm and 30 gm of PANI-PU coating over a 280 mm × 280 mm CFRP specimen, which added roughly 255 GSM (thin coating) and 382 GSM (thick coating) of weight to the CFRF specimen. The lightning testing parameters for both panels are also shown in Table 1. The thinner PANI-PU coating showed less effectiveness against lightning, and the damaged area was around 100 mm × 100 mm. The damage is smaller than the bare uncoated CFRP specimen, but that could be due to different lightning current intensities in both cases. On the other hand, thicker PANI-PU coating showed a significant reduction in damage of around 28 mm × 25 mm in length and width, respectively. The damage is even more minor compared to the Cu-Mesh LSP. However, it is cautioned to draw a direct comparison as both samples had different lightning intensities. Nevertheless, the thicker PANI-PU coating performance is very promising for developing all-polymeric LSP solutions for wind blades. It is also worth mentioning that repairing a polymeric coating would be much more feasible than metal-mesh-type LSP repairs.

4. Conclusion

In conclusion, electrically conductive polymeric coatings have emerged as a promising solution for lightning strike protection. These coatings offer easy application methods such as spray-coating, painting, or automated manufacturing. Through experimental testing and comparison with traditional metallic-based LSP systems, newly developed polymeric coating solutions demonstrated their effectiveness. The results indicated that these coatings effectively dissipated electrical currents generated by lightning strikes and successfully safeguarded G/CFRP structures against severe damage, including puncture, fiber breakage, and resin evaporation. Consequently, polymeric coatings present a practical and cost-effective alternative for lightning strike protection in wind turbines. This study underscores the potential of polymeric coatings as a viable solution in the wind energy industry.

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