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Lightning strike response of composite structures: A review

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Abstract

Wind turbines and aircraft are generally made of less conductive carbon/glass composites. Significant damages may occur to these materials if they are struck by high energy lightning strikes. Damage and structural response of composites is essentially a multiphysics domain, involving thermal, electrical, magnetic and structural analysis. In this article, the fundamental physics of lightning, multiphysics analysis, numerical implementation and experimental studies about composite materials are reviewed. The relevant international standards and possible characterization methods of lightning strike damage are also reproduced in this article. In addition to this, the current and prospective technologies, to protect composite from lightning strikes are also provided.

1. Introduction

Lightweight composite materials are replacing metals as preferred materials for wind turbines blades and aircraft structures. Metals generally are a good conductor of electricity, so lightning strike gets quickly discharged, and the damage is minimal. Composite materials like CFRP, GFRP, Aramid fibers, are susceptible to lightning strike damage due to low electrical conductivity. Researchers are now trying to enhance the electrical conductivity to the density ratio of CFRP/GFRP without any big disadvantage.

Wind turbines are generally situated on hilltop or offshore, where a lightning strike is widespread. Rotating blades of wind turbines made them even more prone to lightning strike, compared to other tall earthbound objects. Most of the Lightning damages in wind turbine blades are reported several meters away from the tip. Blade damages occupy 75% of the total damages for large wind turbine generators over 1000 kW. The damages to the blades warrant additional expenses in terms of replacement and transportation of blades [1].

Airplanes are often exposed to the charged cloud during in-flight 'airborne' or even lighting may strike at landed planes, rockets, or nuclear weapons. During a lightning strike, a substantial current passes through the airplane structure and parts. It may cause ablation of the surface of airplanes, delamination of composite parts, embrittlement of matrix, fiber breakage, dielectric punctures, and also sparking near the fuel tank, vaporization of electrical wiring may happen due to variation in electric and magnetic fields [2,3]. Aluminum and its alloys had been safely used for aircraft structures. These materials are sufficiently conductive to protect the aircraft from lightning strikes. Composite structures are now replacing most of the metallic frames and parts because of their high specific stiffness and strength with accompanying fuel savings. However, the fiber-reinforced composites (CFRP/GRFP) are not electrically very conductive to protect aircraft from lightning strikes.

The obvious solution to protect composite structures is by covering it with metal meshes of aluminum, copper, nickel, or phosphor bronze. However, it will again hamper the weight savings offered by composites. To address this problem, better solutions in the form of metallic coatings, metal nanowires, nanocomposites, CNT, and graphene are being proposed by researchers [1,3-5]. The response of composites under lightning strike and its protection for wind turbine and aerospace application is reviewed in this article.

2. Background of lightning strike

2.1 Physics of lightning strike

Lightning can occur in the atmosphere between the two clouds (inter-cloud), within the cloud (intra-cloud), or between the cloud and ground. Lightning is created from the breakdown of the air gap between clouds (or between cloud and ground) by the electric fields. These electric fields are not strong enough to cause lightning; however, the local electrical field's upsurge within a cloud can initiate the growth of leaders (channels of ionized gas). This local electrical field's upsurge is supposed to be because of the rubbing of graupels (ice, hail, and semi-frozen water particles) and water drops. During this rubbing, graupels become positively or negatively charged. Once leaders (often fork-shaped) are generated, they propagate towards the region of the opposite charge. There are two major consecutive steps in lightning strike, first leader propagation and then return stroke. Preliminary breakdown due to electrical field upsurge causes leader propagation. In the case of cloud and ground lightning strike, when the downward leader of cloud and upward streamers of ground meets then a conducting path is formed. Once a conducting path between cloud and ground is formed the second step, i.e., return stroke occurs with a bright flash and thunder. Return stroke neutralizes all

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of the incomplete leader branches, which appears as a classic forked lightning pattern [6].

Airborne aircraft can move relative to the lightning channel. Therefore flash attachment point on the aircraft surface moves relative to the channel, causing it to sweep back along the aircraft surface. It happens to be discontinuous, with dwell times depending on the surface, geometry, and lightning waveform [7].

2.2 Standard and practices

IEC 61400-24 (International Electro-technical Commission) standard defines the lightning environment for wind turbine generators. Requirements for the protection of structural parts, blades, and electrical systems against both indirect and direct effects of lightning strikes are addressed in this standard [8]. American and European aircraft lightning standards are shown in Table 1. Aerospace companies also have their own internal practices to cater safety and economic needs. Lightning waveforms and levels are significantly varied in nature, so a standardized lightning waveform is used for testing in the lab. SAE ARP 5412/EUROCAE ED-84 standards have defined this test waveform, and the same is shown in Figure 1. This standard test waveform is comprised of four current components named as component A-D. Among short duration fast components, component A is associated with the first return stroke; component D is associated with a re-strike. components B and C are long duration slow components and are associated with the sweeping action of the lightning arc on the airplane surface. The peak current of component A is double to that of component D, but energy associated (action integral) with component A is eight times higher than component D. This happens because of the different rise and fall times of the two components. Fast component (A & D) causes joule heating, magnetic forces, changing magnetic fields, acoustic shocks, arcing and sparking in joints of CFRP structure. Long duration slow components (component B & C) of test waveform causes heating of CFRP surface [7]. Delamination in CFRP is predominant when short duration fast components (component A & D) of the test waveform is applied [2,9-11], whereas thermal ablation is significant damage when all components (A-D) are applied to CFRP specimen [12]. These different waveform components (A-D) cause different type of damages; moreover, the probability of lightning flash attachment and flash sweep is different for different regions of aircraft. Therefore aircraft is classified in different zones and the same is shown in Figure 2. Zone 1 shows regions, where there is a high probability of lightning flash attachment, and Zone 2, shows regions where there is a high probability of lightning swept. Other areas, except Zone 1 & Zone 2 are assigned in Zone 3. Based on simulated lighting waveforms test results leading to non-uniform currents on body of aircraft, this zoning is carried out by SAE ARP 5412 & 5414 standards.

Table 1. Lightning standards and certifications.

Standard/Regulation	Title
SAE ARP5412/ ED-84	Aircraft Lightning Environment and Related Test
SAE ARP5414/ ED-91	Aircraft Lightning Zoning
SAE ARP5416/ ED-105	Aircraft Lightning Test Methods
SAE ARP5415	Manual for Certification for the Indirect Effects
SAE ARP5577	Aircraft Lightning Direct Effects Certification
IEC 61400-24	Lightning protection of wind turbine generators

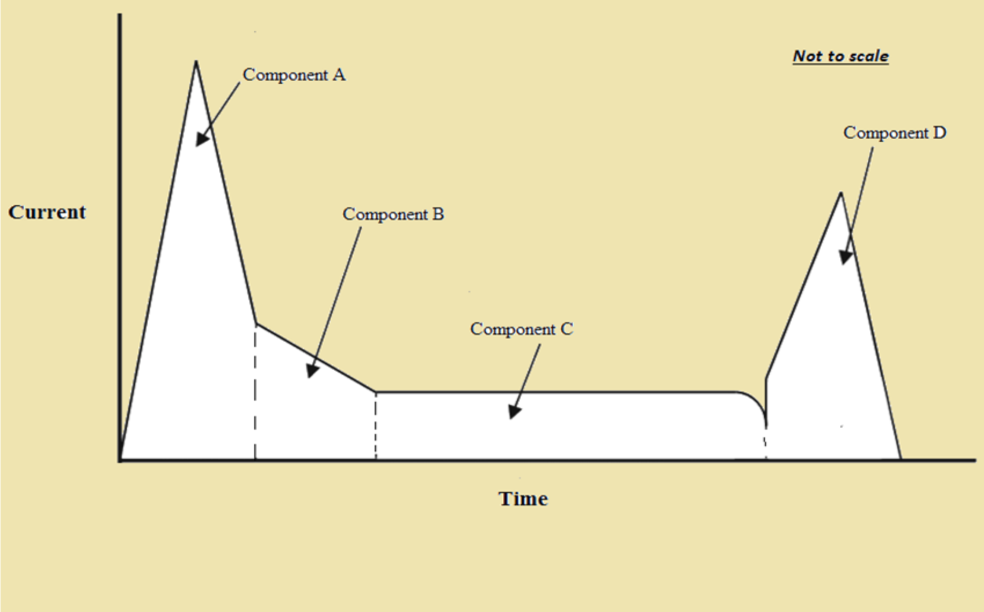

Figure 1. Standard lightning current waveform (not to scale).

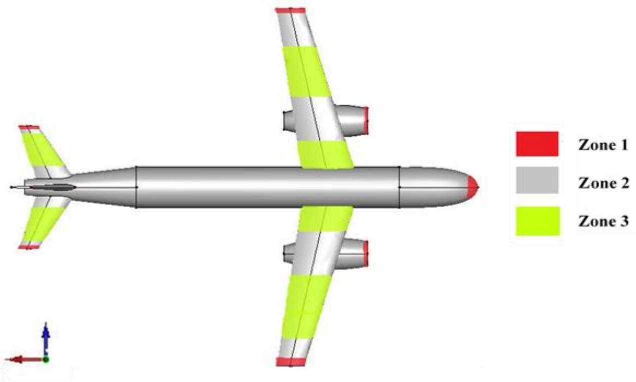

Figure 2. Lightning strike zones of aircraft [7,67].

3. Response of composite structure after lightning strike

3.1 Coupled thermo-electric analysis

During lightning strikes a high amount of electric charge impacts the composite structure and the surface of the material gets heated. Energy is transferred from lightning arc to material, which in turn rapidly heat up the material. The energy balance equation can be written as:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla.(k\nabla \mathrm{t}) \qquad (1)$$

Where ρ, C_p, k are the density, specific heat, and thermal conductivity of the composite material, respectively, all of which are temperature-dependent. Internal joule heat heating Q_J can be incorporated in equation (1):

$$\rho C_p \frac{\partial T}{\partial t} = \nabla.(k\nabla \mathrm{t}) + \mathrm{Q_J} \qquad (2)$$

Above mentioned theoretical background has been used in many damage predictive simulation studies [13-17]. Equation (1) can be written in Galerkin weak forms for numerical implementation [18].

The coupled thermo-electric problem can be numerically solved in popular FEA solvers like ANSYS, COMSOL, and ABAQUS with material properties, geometry, and current of lightning strikes as input. As of now, these solvers are not capable of considering heat loss due to the pyrolysis of the polymer matrix. Special arrangements like subroutines or user programs are required to incorporate the pyrolysis of the polymer matrix [17,19]. The temperature-dependent material properties of carbon fiber reinforced plastics are not readily available in the open literature. Those which are available need further experiments to increase confidence in data [20].

When FRPs are exposed to the high energy of lightning strikes, the phase transition of material takes place which results in thermal ablation. Thermal ablation damage is more due to component C than components A or D (see Figure 1) [21]. Ablation of this type is complex and needs better understanding. Resin decomposition and fiber vaporization is reported for GFRP [18]. For CFRP, oxidation, nitridation, and sublimation reactions along with resin decomposition takes place. Internal joule heating inside the composite structure also leads to additional mass loss [13,22,23]. Thermal ablation modeling can be done in FE software like ABAQUS and COMSOL. Ablation modeling can be achieved by analyzing temperature fields or by progressively removing elements at pre-decided ablation temperature [16,17,19]. Further experimental validations are required for these numerical simulations. One such study was carried out by the authors of this article and results are given in Figure 4 [69].

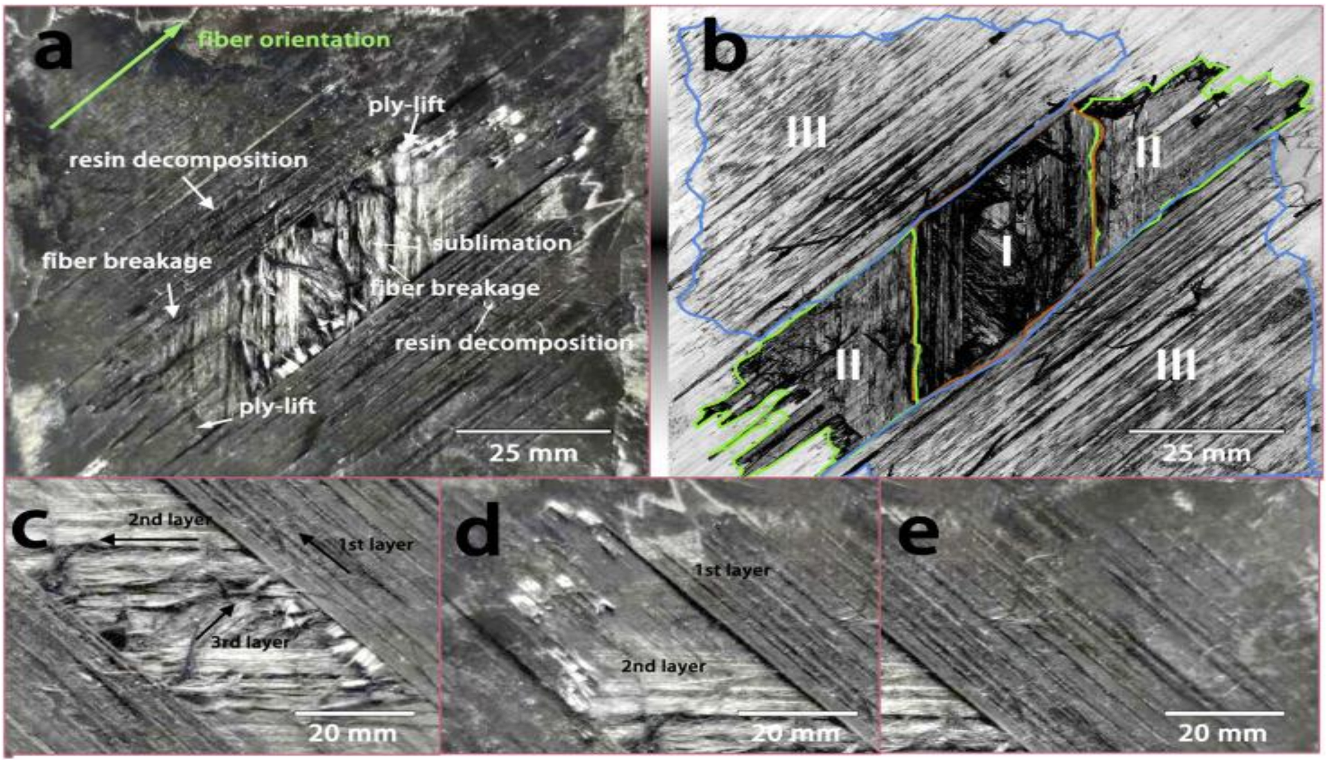

Figure 3. Damage morphology of CFRP sample after lightning strike [68].

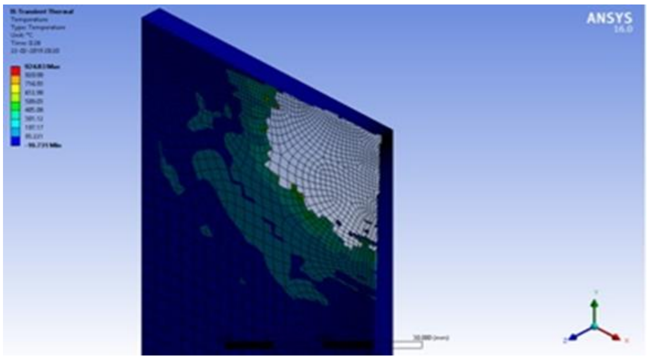

Figure 4. Thermal ablation damage of quarter plate of CFRP [69].

Inter-laminar damage or delamination is widely reported as important damage in experimental research [2,9,10,11,24]. Wang *et al.* [11] have experimentally obtained axial compression strength of lightning damaged CFRP. The typical modes of failure include fiber fracture, matrix cracking, and delamination. They have numerically predicted final residual strength with different damage models like the maximum stress criterion, Hashin criterion, and TSERPES. Electrical conductivity along with thermal decomposition temperature, inter-laminar fracture toughness & char yield is supposed to be related to delamination damage [25]. Ogasawara *et al.* [13] tried to predict delamination in CFRP with FEA numerical simulation. In a cohesive zone approach, the composites are modeled at the ply level and interface elements of zero thickness as cohesive elements. Damage initiation and propagation criterion can also be incorporated. ABAQUS platform was used by Dec *et al.* [26] with a suitable subroutine. Figure 3 exhibits uneven damages of the CFRP sample after lightning strike. Region-I, II and III are damages of the attachment region, the region along fiber orientation and the region normal to the fiber direction, respectively. Most severe damage is observed in Region-I. Moreover, fiber and resin sublimation and pyrolysis are depicted in Region-I, ply-lift and fiber breakage is observed in Region-II, and Region-III demonstrates resin decomposition and cracking [68].

Recently, Chen *et al.* [27] have used ANSYS, MATLAB, and FLUENT platform to simulate coupled field formulation of complex lighting strike phenomenon. Since lightning strike on the composite structure is also a fluid-structure interaction problem, they have used conventional serial staggered (CSS) method to solve lightning channel and composite structure modules independently.

The effect of the hygrothermal environment on lightning strike damage of CFRP with a fiberglass layer is studied by Li *et al.* [28]. It is found that hygrothermal aging significantly increases lighting strike damage with complete detachment of the fiberglass layer and causes substantial internal delamination

3.2 Effect of magnetic and acoustic pressure

From electromagnetism, the magnetic pressure distribution is [15,29]:

$$P = \begin{cases} \frac{\mu_0 I^2(t)}{4\pi^2 r^2}, & r < R \\ \frac{\mu_0 I^2(t)}{4\pi^2 R^2}, & r \geq R \end{cases} \tag{3}$$

Where P is magnetic pressure, R is arc channel radius, μ_0 is the vacuum permeability, I is the instantaneous lightning current in Amperes.

As of now, experimental values of acoustic pressure for lightning strikes are not known. In numerical simulations, researchers have assumed a uniform value of 10 MPa over the lightning arc attached area [15]. This assumption does not appear to be logical since acoustic pressure should be dependent on lightning current value. Recently Foster *et al.* [30] have tried to simulate the response of composite samples subjected to pressure loading. This is achieved through a simulation study using an established modeling approach for composite damage prediction. Although, authors are not very confident with the acoustic pressure loads which they have taken from published literature yet they managed to simulate damage due to acoustic pressure loading. It is concluded in their study that although acoustic pressure causes damage, it does not affect the overall scale of damage.

3.3 Effect of lightning electric and magnetic field

Pinholes and puncture damages are reported for composite wind turbine blades and aircraft fuse lags [31]. When lightning strikes, dielectric breakdown occurs, and insulators become instantly conductive. The high value of current conduction produces very high heat in the solid and leads to extensive damage. If the dielectric breakdown occurs, the material may experience instant puncture damage. The breakdown strength of GFRP laminated composite panels of thicknesses (2-10 mm) is between 15 and 30 $MV \cdot m^{-1}$ [32]. The breakdown strength is dependent on the thickness of the material, pressure, temperature, and environmental conditions. Efforts have been carried out to predict the electric field induced by the lightning around the composite structures (e.g., aircraft and wind turbines). These electric and magnetic fields can be obtained by solving Maxwell's equations. Numerical simulations (COMSOL Multiphysics) have been carried out to predict these fields [33]. The breakdown strength of composite structure should be sufficient enough to bear these electric and magnetic fields otherwise it can cause punctures or pinholes [34,35].

3.4 Decomposition of the polymer matrix

In addition to the thermo-electric coupling, the damage response of composites is also affected by the chemical decomposition of the polymer. Decomposition of the polymer matrix is typically expressed using an Arrhenius equation:

$$\frac{\partial \rho}{\partial t} = -A\, exp\left(-\frac{E_a}{RT}\right)\rho_v\left(\frac{\rho-\rho_c}{\rho_v}\right)^n \tag{4}$$

Where A, E_a, R, and n are the coefficient of the decomposing rate, the activation energy, universal gas constant, and the reaction order, respectively; ρ, ρ_v and ρ_c are the density, density at the virgin state, and density at the charred state, respectively. A, E_a, R, and n of the above equation Decomposition of the polymer matrix can be found from the thermogravimetric analysis [13,36].

The energy balance equation (2) can be modified to add this heat loss term:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla .(k\nabla t) + Q_J + \left(h_g - \bar{h}\right)\frac{\partial \rho}{\partial t}\,|_{x,y,z} \qquad (5)$$

$$+\dot{m}_{gx}\frac{\partial h_g}{\partial x} + \dot{m}_{gy}\frac{\partial h_g}{\partial y} + \dot{m}_{gz}\frac{\partial h_g}{\partial z}$$

Where h_g is the enthalpy of pyrolysis gas, $\bar{h}$ is the mass-weighted average of the enthalpy of the overall composite material. Both h_g and $\bar{h}$ are temperature-dependent. In addition, $\dot{m}_{gx}$,$\dot{m}_{gy}$, $\dot{m}_{gz}$ are the mass fluxes in three directions [18,26,37].

During the decomposition of the polymer matrix, material properties of composites exhibit high variations. Without accurate material properties, numerical simulations will give errors. These types of material properties (during decomposition) are not readily available in the literature. Further, these material properties keep on changing when temperatures are high [18,26,37].

Dong *et al.* [38] introduced a pyrolysis degree to describe the pyrolysis behavior of resin damage. In their work, they deduced that component D controlled the in-plane damage area, while component C induced in-depth damage. It is also shown in this work that the thermal damage contributes to a part of lightning in-plane damage, but approximately total lightning in-depth damage.

4. Characterization of lightning strike damage

The flexural strength, flexural stiffness, and inter-laminar shear strength (ILSS) after the lightning damage can be examined by standard engineering methods. Hirano *et al.* examined the residual strength of lightning damaged samples by 4-point flexural testing. Table 2 shows mechanical properties before and after lightning damage of CFRP composite [39]. The low-velocity impact can cause barely visible damage to the internal structure of a laminated composite. These impacts might cause delamination in composite materials. If this damaged material is further exposed to lighting strike, then the damage might be severe. More experimental and numerical studies are required to understand the effect of low-velocity impact and lightning strikes on composite structures.

Different damages occurred on lightning stroked wind turbines and aircraft structures which include punctures, pinholes, matrix cracks, fiber-matrix interface debonding, delamination, matrix carbonization, and fiber breakage. The definition of damage is not standardized. Researchers have measured damage using a range of techniques with different fidelity [40].

Table 2. Mechanical properties after lightning damage of CFRP composites.

Property	Applied current (kA)	Mechanical property (MPa/GPa)
Flexural strength		610 MPa
Flexural stiffness		52.5 GPa
ILSS		66.9 MPa
Flexural strength after lightning	40	147 MPa
	100	N/A

4.1 Visual inspection

This method is quite simple and involves visual inspection with naked eyes or simple magnifying glass. The lightning strike damaged polymers generally have a central hot spot zone with degraded fibers and a surrounding zone with vaporized or degraded polymer. Damage is generally visible, but the use of UV light and dye penetrant makes it clearer. Visual inspections show fiber breakage along several layers, fiber dissipation, and resin vaporization around the discharge point. Change in any cross-section can also be identified [41].

4.2 Ultrasonic scanning

Ultrasonic testing is a non-destructive testing technique based on the propagation of ultrasonic waves into the material. It monitors the precise location of delamination between specific plies. The fundamental shape of the damage area is evaluated using ultrasonic scanning, advanced optical microscopy. The damage models fiber damage, resin deterioration, and internal delamination of graphite/ epoxy composite can be evaluated using ultrasonic testing for different peak currents [2,9]. Pulse-echo ultrasonic testing uses a transducer operating in the range of 0.5 to 20 MHz. Kovach *et al.* [21] recommended that it should be carried out on both sides of the specimen. Szatkowski *et al.* [42] carried out a non-destructive damage assessment by “Through Transmission Ultrasound (TTU) damaged area measurements” method. The ultrasonic air-coupled C-Scan technique is a good alternative to the traditional ultrasonic immersion C-Scan technique, when the detection of small defects is not demanded moreover; it captures the damage with reasonable accuracy [41].

4.3 X-ray inspection

X-ray diffraction also known as XRD is also a non-destructive test to analyze all kinds of matter ranging from fluids to powders and crystals. X-ray Computed Tomography (CT) has one X-ray source, a series of detectors, and a rotational geometry for the test specimen. These configurations of these components can be modified according to the specimen/object of various sizes and compositions. The gray levels in a CT image reflect whether X-rays are scattered or absorbed as they pass through. X-ray energy and material density and composition decide the level of X-ray attenuation [43]. To assess, internal damage in lightning damaged CFRP specimen Wang *et al.* [44] used a micro-focus X-ray system.

5. Lightning strike protection materials

Since lightning strikes carry large electrical currents, aircraft and wind turbine blades protection requires materials with high electrical conductivity to avoid catastrophic structural damage. The surface resistivity of composites used in aerospace/wind turbine applications is considered electrically insulating. Wind turbine blades are designed with interconnected receptors and conductors. Conductor wires connect the blade tip to the root. The incoming lightning charge is expected to be grounded via the receptor, to the conductor [46]. The effectiveness of lightning strike protection (LSP) solutions lies in the specific electrical conductivity of the material. The specific electrical conductivity of the material is a ratio of electrical conductivity to the density of the material. Materials that pose high specific electrical conductivity are best suited for LSP solutions.

5.1 Metallic materials

Aluminum and copper are currently used due to their high specific conductivity and low cost compared to silver which has high specific conductivity but high cost. When metals like calcium, lithium, potassium, and sodium react with water, the reaction is exothermic with the release of water. If metal is fragile, it can ignite the hydrogen. Water is abundant in the atmosphere. To avoid galvanic corrosion, the LSP material should have comparable electric potential with carbon [47]. The electrical and thermal conductivities of prospective LSP Metallic materials and carbon materials are produced in Table 3.

For composite structures, LSP is provided by applying a metal film over the surface. This screen could be a foil, (i.e., a flat and thin piece of metal) or a woven or non- woven mesh. Foils are not preferred because they may cause delamination and affects resin bonding. If the material under the foil vaporizes, the pressure might build up, which would further cause even more damage [51]. Metal meshes can be of two types: a woven mesh and a non-woven mesh. A woven mesh is manufactured by machine weaving. While a non-woven mesh is manufactured by perforating a foil. Interwoven wires are also being used for LSP, (e.g. Boeing787 [52]). A non-woven mesh can be produced from nearly pure metals for maximum electrical conductivity. Vaporization of LSP material is desired for protection of the underlying structure, and the LSP function as a sacrificial layer [53]. If metallic meshes have enough mass and electrical conductivity, they can handle current up to 200 kA.

A possible way is to use coatings with a thickness to provide enough conductivity. Metals can be coated on glass or carbon structures. This coating can be carried out by Physical Vapor Deposition (PVD), Spark Plasma Sintering (SPS), or Flame Spray with aluminum. Another way is to increase the electrical conductivity of polymer with a suitable linked network inside the composite, also referred as a nanocomposite [54]. A nanowire is a wire with its diameter measured in nanometers. Nanowires have properties well suited for better electrical conductivity, magnetic susceptibility, and stiffness. They can also reduce damage to the epoxy by creating a conductive path and reduce arcing [55].

Nickel coated carbon fiber nonwoven veils (Ni-CFNVs) is introduced by Guo *et al.* for a better LSP solution. The high electrical conductivity of Ni-coating and ablation resistance of carbon fiber makes Ni-CFNVs a better solution to conventional copper mesh [56]. Furthermore, interconnected and nickel coated carbon fibers produced by Hollingsworth & Vose Company under brand name AFN is a lightning protection fabric. No interfacing is required in this solution so, problem of galvanic corrosion and delamination is reduced. Test results showed near zero structural damage response [71].

Extended foils of copper or aluminum on CFRP surface is also an excellent option with their laying directions are optimally designed according to aircraft lightning zoning standards [75].

5.2 Carbon materials

Carbon materials such as carbon fiber, CNT, graphene, graphite, improve electrical, mechanical, and thermal properties of composites [55,57,58]. Carbon fibers and graphite can be used as fillers for their high electrical properties but carbon black, carbon nanofibers have shown even better electrical conductivity [59,60]. Recently, Kumar *et al.* [61] has used a multi-wall carbon nanotube buckypaper (BP) — a paper-like sheet — interleaved between CFRP laminates for possible lightning strike protection by improving through-thickness electrical conductivity. Lombetti *et al.* [70] proposed to use stainless steel and copper tufting to improve through-thickness mechanical and electrical properties of epoxy/carbon composites. They reported that damage due to lightning strikes is suppressed significantly, compared to unprotected laminates. The case of the copper and stainless steel tufted composite panel is shown in Figure 5. A very small amount of damage is observed in the composite panel with a few spots of resin burn. This is because the current is dissipated successfully through the metal wire tufts. The authors had also highlighted that there is no additional internal damage apart from that appeared directly on the surface of the sample. A novel silver modified buckypaper-carbon fiber/phenol-formaldehyde (SMBP-CF/PF) composite for lightning strike protection (LSP) is proposed by Xia *et al.* [73]. Lightning strike protection, thermal dissipation with nearly unaffected residual strength is found in their study.

CNTs can be added to the composite matrix to increase the mechanical, electrical, thermal properties. Ma *et al.* [62] has theoretically proved that the addition of CNTs into the epoxy matrix will increase through-thickness electrical conductivity. The axial electrical conductivity of carbon nanotubes is reported to be 2107 $S{\cdot}m^{-1}$ [63]. Graphene has significant prospects to be used as LSP material. It's specific electrical conductivity, and thermal conductivity is highest among common LSP materials (refer Table 3). However, the stacking of Multi-graphene platelets (MGPs) is challenging because of large Vander Waals forces. If graphene and CNT are mixed, electrical conductivity is further increased [64].

Recently, Zhao *et al.* [72] proposed a non-metallic lightning strike protection film consisted of 2 functional layers, for better electrical conductivity and thermal insulation. Graphene and conductive polymer veil is used to improve electrical conductivity and graphite is for thermal insulation. This film is claimed to have better dispersion of lightning current and capable of blocking heat propagation from lightning plasma.

Polymer polyaniline (PANI) nanocomposites are one of the recent interests in conducting polymers. PANI based composites show better dielectric properties and EMI shielding with an improvement in electrical conductivity, which makes them even more suitable for LSP solutions [43,65].

Thus we can observe that there are number of LSP solutions available, but their automation, low cost, industrialization potential and application are also key factors. Keeping this in context Juan *et al.* [74] studied prospect of using electroless copper coated CFRP laminates for LSP materials. These electroless copper coatings serve as a sacrificial layer during lightning strike and protect CFRP laminates.

Table 3. Electrical and thermal conductivity, density of metallic and carbon materials.

Materials	**Density (g·cm^{-3})**	**Electrical conductivity (S·m^{-1})∗10^{6}**	**Specific electrical conductivity (S·m^{-1}-cm^{-3})**	**Thermal conductivity (W·m^{-1}-K^{-1})**
Metals [48]				
Lithium	0.53	10.7	20.0	85
Aluminum	2.69	38.2	14.2	237
Beryllium	1.80	25.0	13.5	218
Copper	8.93	59.8	6.6	386
Silver	10.49	68.0	6.4	407
Iron	7.87	10.3	1.3	73
Carbon materials [49,50]				
Graphene	0.3	100	333.3	3000
CNT	1.4	1	0.7	100-200
Graphite	2.25	0.0727	0.03	

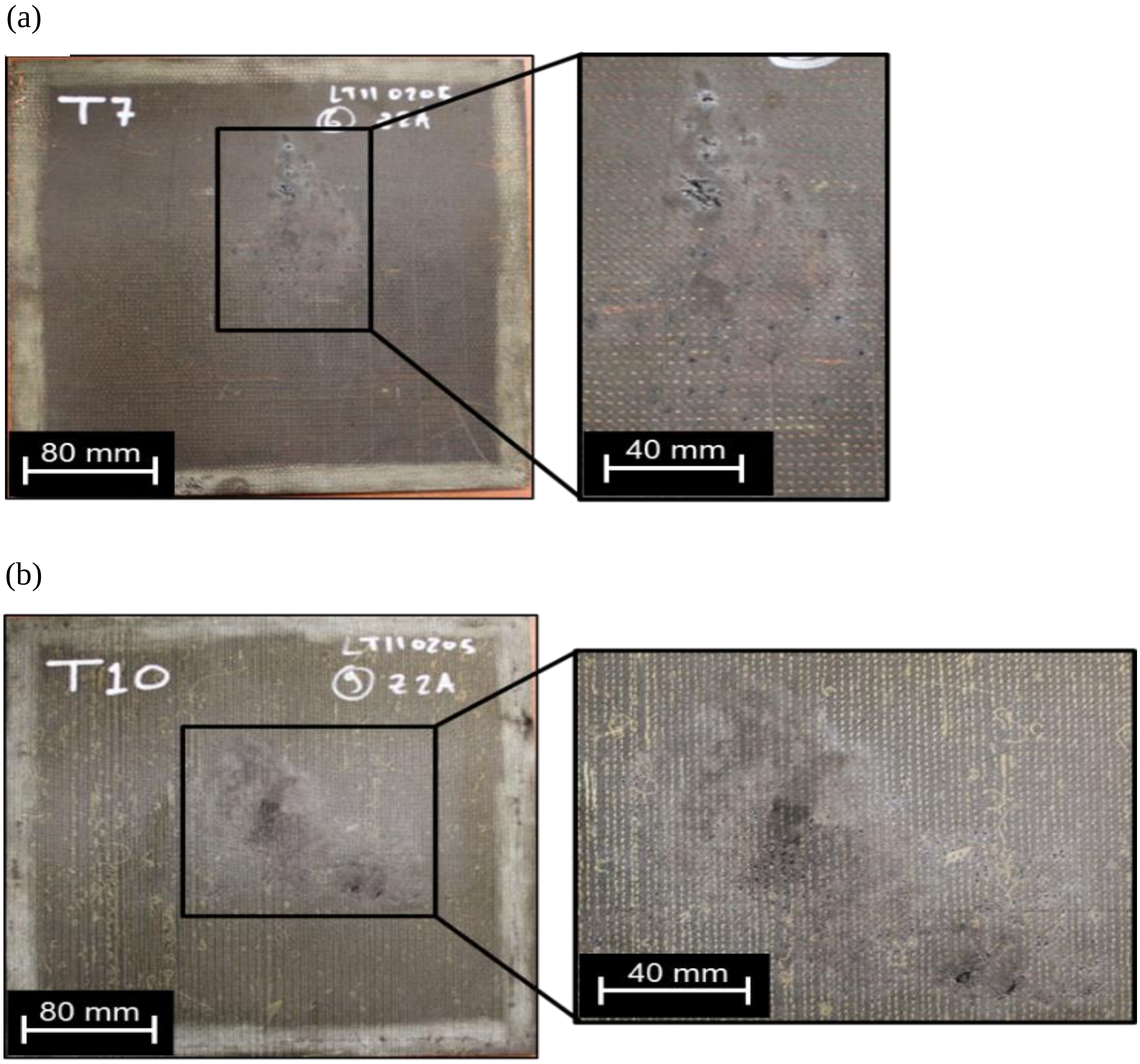

Figure 5. Composite laminates after lightning strike: (a) copper tufted and (b) stainless steel tufted [70].

6. Conclusions and future scope of work

Delamination damage, thermal ablation damage, dielectric breakdown and coupled thermo-electric modeling of CFRP composites have been developed but need further justification with experimental data. A fully coupled model that covers all the damage analysis simultaneously is highly pursued. These models require temperature-dependent material properties, which are not readily available. Moreover, these models need to incorporate the effect of resin decomposition and pyrolysis of gases. Composite structures are susceptible to low-velocity impact during fabrication or service life. This impacted structure may further get exposed to lightning strikes, which may be catastrophic for structural integrity. A study is required to understand the response of composites under lightning strikes and then low-velocity impact or vice versa.

Aluminum or copper meshes as LSP solutions are popular and perform well, but a further reduction in density is required. Metal fibers and metal coatings have shown improved electrical conductivity, but most of these have not yet been tested for lightning protection. Nanoparticles and CNTs have issues like dispersion which can be addressed by proper distribution methods. Metal nanowires have a relatively high electrical conductivity, but it has not been tested for LSP. The main potential lies in making the non-conductive polymer in to conductive by using nanowires or carbon materials. That solution will have broad applications like unmanned aerial vehicles, helicopters, wind turbine blades, and EMI protection for equipment & vehicles.

The primary challenge is to find a material with a higher conductivity/density ratio without some big disadvantage or a solution that avoid damage to aircraft and wind turbine by making use of lightning physics.

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