



Lightning Protection of Carbon Fibre Reinforced Plastics – An Overview –

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Abstract—With the growing interest to construct more efficient aircraft, more components are designed out of light-weight CFRP structures. CFRP however, are poorer electrical and thermal conductors than aluminum alloys that have been used in aircraft and aerospace construction as the principle material. Without additional design features CFRP structures are susceptible to sever damage in the event of a lightning strike. Moreover, electromagnetic fields can penetrate through less electrical conducting CFRP regions into the airplane. Thus, there is a need for lightning protection and EM shielding measures. This study provides an overview of the lightning strike phenomenon, the lightning damage to CFRP structures and the current lightning protection solutions. Advanced materials like polymer-based nano-composites or graphene-reinforced composites are promising candidates for lightweight, multifunctional protection measures, but still with limited stage of maturation.

Lightning Strike Protection, Direct Effects, CFRP Structures

I. INTRODUCTION

Lightning to an aircraft is a rare event, but it does occur sufficiently often that it should be regarded as something that sooner or later is almost certain to occur. It is generally assumed that each transport aircraft is struck by lightning at least once every year. During the lightning strike there is a direct contact between the aircraft surface and the lightning arc.

This study provides a short overview of the lightning strike phenomenon, the lightning damage to carbon fiber reinforced structures and the current lightning protection solutions. Nowadays CFRP structures are employed extensively in aircraft design in order to decrease the overall weight and to increase specific mechanical properties of airframe parts. Thus, the main emphasis is given here to lightning protection measures applicable to CFRP airframe parts (including primary and secondary structures).

II. LIGHTNING AIRCRAFT INTERACTION

The electric breakdown of air at normal conditions occurs at electrical field strength of 3000 kV/m. This value depends on density of air and is only half the standard value at around 6000 m. The ambient electric fields in thunderclouds are generally much less than these values and such high values only tend to occur at lightning stepped leader tips. An

uncharged aircraft located in a thundercloud electrical field or near an approaching leader will become polarized and local field values at the aircraft surface will become large where the surface curvature is high enough such as wing tips, pitot tubes, nose tips, rimes of nacelles etc., see Fig. 1.

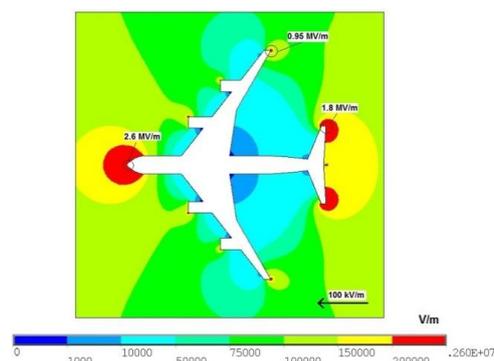


Figure 1. 2D electrostatic field of an aircraft in a 100 kV/m ambient field. The values in the figure are indicative only, since the curvature in the 3rd dimension will enhance these values.

Numerical 3D simulations indicate E-field enhancements over the ambient value of up to a hundred can occur for specific field directions [1], [2], [3]. Hence, in these particular directions electric fields as low as 30 to 300 kV/m might be sufficient to cause corona breakdown at aircraft extremities. This corona breakdown can result in the development of bi-directional leaders extending from these aircraft extremities. While the enhanced E-field strengths fall off rapidly away from the extremities, it is known that positive leader can propagate even for quite low E-field strengths of approximately 60 to 700 kV/m [4]. Triboelectric frictional charging can give an aircraft a net charge. Depending on polarity this net charge can augment or inhibit streamer formation.

A. Lightning current waveforms

The environment and test current waveforms defined in ARP5412 account for the best lightning data and analysis currently available [5], [6]. Several current waveforms which represent idealized environments are defined for aircraft analysis and testing. The lightning current is comprised of current components A, Ah, B, C, D, and H, and the Multiple Stroke (MS) and Multiple Burst (MB) Waveform sets [5], [7].

The lightning flash used for evaluating direct effects is composed of the individual components, see Fig. 2.

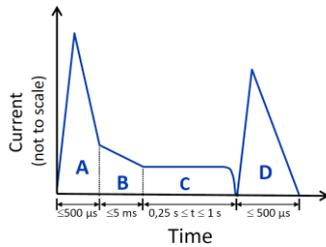


Figure 2. Scheme of the waveform for return current.

In the swept stroke zone the attachment time is relatively short so that only a fraction of the component C charge is transferred into a particular attachment area. A crucial parameter is the dwell time, which is a function of the aircraft's speed and the type and thickness of the dielectric coating on the airframe structure. According to ED-84 [7] the dwell time of 20 ms should be sufficient (US approach). Typically dwell times of between 20 and 50 ms are assumed. In Europe the dwell time of 50 ms is widely used as the default, leading to a total charge of 10 C (contribution of the current component B) + 45 ms x 400 A = 28 C. This parameter is of the most importance for melting and puncture of metallic structures.

The current waveforms can be applied individually or as a composite of two or more components together in one test:

- Component A corresponds to the so-called "First Return Stroke Current"
- Component B represents the "Intermediate Current"
- Component C describes the "Continuing Current"
- Component D represents the so-called "Re-strike Current"

A tabulated summary of the characteristics of the individual current waveforms used for evaluating direct effects can be found elsewhere, see for example [8].

B. Zoning Concept

When an aircraft is struck by lightning, currents flow through the aircraft. Therefore a pair of entry/exit point can be defined. At these points the lightning channel is in direct contact with the airframe structure for a certain period of time. These points are defined as the initial attachment points.

When an aircraft has been struck, lightning currents in the channel flow through the aircraft. During this period the aircraft moves significantly relative to the stationary lightning channel. An attachment point to an airframe surface therefore moves relatively to the lightning channel, causing a local stretching of the channel as shown in Fig. 3. The electrical potential across the arc AC distance grows as the length AC increases, until the gap between the aircraft surface and the arc breaks down and a new attachment point is formed. This process continues, so that the arc sweeps back in a discontinuing manner. The dielectric coating on the surface, the local geometry and the current waveform affect the dwell time considerably. The sweeping process generates a series of discrete attachment points [9]-[12]. The purpose of lightning zoning is to determine the surfaces of the aircraft which are likely to experience lightning attachment. According to

EUROCAE ED-91 reference [13] aircraft surfaces are subdivided into different zones as follows

- Zone 1** Surfaces of the aircraft for which there is a high probability of initial lightning arc attachment (entry and exit areas)
- Zone 2** Surfaces of the aircraft for which there is a high probability of lightning flash being swept from Zone 1 point of initial arc attachment
- Zone 3** This zone includes all of the remaining airplane areas not covered by Zones 1 and 2. In this zone there is a low probability of an attachment of the lightning arc. However, Zone 3 areas may carry substantial lightning currents by direct conduction between the attachment (entry and exit) points.

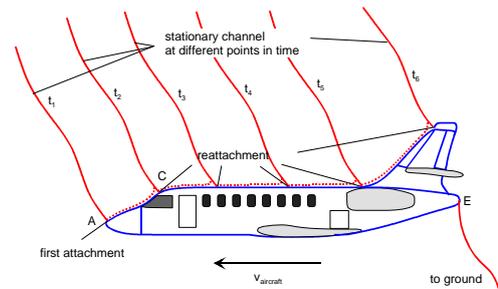


Figure 3. Principle of sweeping process on an aircraft in flight.

Zones 1 and 2 are further subdivided into **A** and **B** regions, depending whether the lightning arc will hang on for a protracted period of time. An **A** region is one in which there is a low probability that the lightning arc will remain attached and a **B** region is one which there is a high probability that the lightning arc will remain attached. Finally an additional zone, **Zone 1C** is defined, "in which by virtue of the change in current parameters along a lightning channel and the time taken for sweeping of the attachment point across the surface of the aircraft, the threat to the aircraft is reduced" [13], [14].

The locations of the lightning strikes zones on any aircraft are dependent on the geometry of the aircraft and operational factors. The standard rules are given in the EUROCAE document ED-91. An excellent overview about the aircraft zoning concept and numerical procedures for determination of aircraft zoning areas can be found in references [15], [16]. The lightning current waveforms which are applied for an assessment of structural damage in a laboratory experiment depends upon the location of the considered airframe part (on the aircraft zoning area)

- Zone 1A** $A+B+C^*$ (C^* is a reduced C component)
- Zone 1B** $A+B+C+D$
- Zone 1C** A_h+B+C^* . The impulse A_h corresponds to a « lower » impulse A.
- Zone 2A** $D+B+C^*$
- Zone 2B** $D+B+C$
- Zone 3** $A+C$. The lightning current is applied by conduction.

When metallic airframe skins are replaced by composite / CFRP panels, the question raises, whether the reduction of

conductivity of the airframe parts might influence the zoning procedure of the aircraft. The computational zoning procedures are based on electrostatic field calculations and do not take the finite conductivity of the materials into account until now [16].

Experimental work on assessing the behaviour of graphite epoxy composites to lightning attachment has been already carried out in the late 70ties [17]. The results of all lightning tests conducting showed that there is “*no measureable difference in attachment point behaviour between metal and graphite epoxy composite*”. In order to model the impact of finite conductivity, a new method was implemented by solving full Maxwell equations [18]. The results of the simulations showed, that no significant impairment of charge redistribution on the composite airframe skin is found. These results indicate that that first attachment areas of composite aircraft need not to be altered compared to metallic aircraft.

C. Damage Mechanisms

Lightning strike causes damage to airframe structures by several different physical mechanisms:

- Thermal Effects
 - Resistive volume Joule heating due to current flow in the electrically conducting structures [1]
 - Direct heat input from the hot plasma channel [19]
 - Thermal radiation from the hot plasma channel. Recent experimental investigations show that contribution of thermal radiation is negligible, see [20], [21].
- Transient Mechanical Force Effects
 - Shock waves from the supersonic expansion of the hot plasma channel [22].
 - Magnetic volume forces [23]
 - Shock waves caused by exploding materials [24]-[26]

Some of the effects can be well quantified [22], [23], [25], [26], [27], [28]; some still cannot because they depend on a complex transient interaction at the interface between the plasma channel root and composite structure involving the hot plasma, the impressed electric current and the thermal, mechanic and dynamic behaviour of the composite structure.

In a recent publication [29] Schlieren photography was used to visualize shock waves generated by lightning discharge on unprotected CFRP laminates. The shock waves propagated radially from the insulating diverter sphere. Moreover, “*multiple shock waves generated from points on the CFRP's surface other than the lightning spot*” were observed [29]. This indicates strongly that the vaporization of epoxy resin generates shock waves. In tests using an Al sample shock waves propagating outward from the single lightning spot were observed only. The obtained results support the assumption that shock waves during transient current components contribute to the mechanical damage of CFRP laminates.

It is generally accepted now that

- the severe mechanical damage at and around the lightning attachment area of CFRP parts occurs during

the transient current components and the shock waves generated by exploding vaporized materials at the arc attachment area are the main reason for it [24], [25], [26], [28], [29]. However, the contributions from the shock waves caused by the supersonic expansion of the hot plasma channel and the magnetic volume forces caused by the impressed current flow cannot be neglected completely [28], [30]. Even the contribution of the magnetic forces should be taken also into account.

- the thickness and the mechanical properties of the dielectric coating above the metallic lightning protection layer affects adversely the thermo-mechanical damage of the CFRP airframe structures [24], [25].
- the extent of damage of the CFRP structure can be reduced by increasing the surface weight of the expanded copper foil and the increases of the strength of the CFRP structures [26].
- GFRP separation plies do not generally prevent the flow of electric current into the CFRP structure. If the lightning currents can penetrate the insulation layer, the magnitude of the thermo-mechanical damage of the CFRP laminate can be even magnified [31].
- and finally the extent of mechanical damage of CFRP does not saturate at high values of the paint surface weight as it was occasionally assumed in the past.

D. Resistive Joule Heating

When lightning currents flow in aircraft structures energy is dissipated by the current in the form of heat. The so-called action integral AI is an important lightning current parameter for determining – in first order approximation – the degree of Joule heating (when neglecting any temperature dependence of the material properties and any potential material phase transitions and material anisotropy) and the temperature increase of the structure [1]. Because of their high current amplitudes, the transient current components A and D have the highest action integrals and will produce more volume heat and therefore higher material temperatures, when flowing through (low-)conducting airframe parts.

It is important to note that CFRP cannot be considered as homogenous isotropic material. The electrical and thermal conductivities and the thermal expansion coefficient of the carbon fibres are anisotropic, so that the number and the direction of the singly plies as well as the volume fractions of the carbon fibres and epoxy resin affect the material properties of the CFRP laminates, causing them to be temperature and even time dependent as well as anisotropic. Thus, the effective properties of different CFRP parts can vary widely and any comments to CFRP are of general nature. However, there are principle differences between CFRP and aluminium alloys:

- 1) The electrical conductivity of the CFRP is at least 3 order magnitudes lower than that of aluminium alloys.
- 2) The high surface resistivity of CFRP is the reason for the difficulty to achieve good electrical contact at CFRP/CFRP or CFRP/metallic interfaces.
- 3) The strong anisotropy of the laminate can be slightly reduced by placing single plies at different angles.

- 4) The voltage across the arc root is greater for CFRP than for aluminium alloys resulting in greater energy input at the arc attachment area.

It is interesting to compare the order of magnitude of the heat transferred from the arc at the contact between the arc and the sample surface and the Joule heat resulting from the current flow generated within the sample volume under the arc root. The heat transferred from the arc can be approximately estimated using the charge transferred from the arc [19], [21], [32], [33]. The generated Joule heat under the arc root can be approximately estimated, if we assume that the current density within the conducting layers is uniform [8], [23]. Such estimation does not give the exact values but the correct order of magnitude. However, the results indicate that

- The Joule heat generated the transient current components is much larger for the CFRP ply than for lightning protection made from expanded copper foil.
- For the CFRP ply the Joule heat generated by the transient current components is significantly larger than the energy deposited directly by the arc.
- For the intermediate B and the continuing C components the energy deposited by the arc is comparable to the generated Joule heat for the CFRP lamina.

Since it is generally accepted now that the severe mechanical damage of the CFRP parts originates mainly from the generated Joule heat the existing lightning protection measures “try” to reduce the electrical resistance of the CFRP airframe parts by incorporating high conducting metallic layers on the surface or by adding conducting metallic particles to the dielectric coating or resin matrix of the CFRP airframe parts.

In order to assess the possible enhancement of the electrical conductivity of CFRP by addition of high conducting particles the simple mixture rule can be used, which gives the upper bound values. The volume fractions of the individual particles should be above the percolation limit. Using the Reuss mixture rule the following upper values for the composite with aluminium, silver, and CNT particles of about 6.1×10^5 , 1.21×10^6 , and 2.01×10^6 S/m can be estimated (assuming that the conductivity of UD CFRP lamina is 10^4 S/m and that volume content of conducting particles is above the percolation limit, but not larger than 5 %, since larger admixture adversely affect the mechanical properties of the epoxy resin and therefore of the composite). This is in fact a substantial theoretical increase of the electrical conductivity in the fibre direction of the CFRP lamina. In practice, however, these values cannot be achieved, because of the electrical contact resistance at the interfaces of different conducting particles. Generally, the contribution of the conducting particles is significantly reduced at least by one order of magnitude; the real conductivities of the composites can be increased but are still of the order of 10^4 to 10^5 S/m and are absolutely not sufficient for lightning protection purposes. Nevertheless, the addition of the conducting particles increases the electrical (and thermal) conductivity of the CFRP lamina perpendicular to the fibre direction; this change can help to reduce glow edge phenomena and reduce thermal damage caused by thermal loads that occur on CFRP airframe parts.

III. LIGHTNING PROTECTION MEASURES FOR COMPOSITE MATERIALS

The objective of the lightning protection is to reduce the extent of thermo-mechanical damage of composite structures to an acceptable level, where the specific definition of the acceptable level may depend on the design, use and location of the airframe composite structure. The critical airframe areas are

- the lightning arc attachment areas (Zone 1 and 2) and
- the assembly areas.

There are a lot of technical and commercial issues which have to be considered for choosing the most appropriate lightning protection measure, among other things

- the general lightning protection effectiveness,
- the electro-chemical compatibility with composites materials,
- the adhesiveness with the composite structure and the ability for dielectric / paint coating,
- the additional weight of the total lightning protection system (mass per unit area),
- the resistance of the lightning protection materials to external environmental threats,
- the cost of lightning protection materials or systems,
- the complexity and cost of manufacturing processes and
- the complexity and the cost of repair and maintenance.

In following sections a short overview of the frequently proposed / used lightning protection measures is given.

A. Metallic expanded foils

Metallic expanded foils are used as the current standard lightning protection measure of outer composite airframe parts. They are typically 50 to 100 μm thick. Their mass per unit area depends on their thickness and on the geometry of openings and strand widths. Because of the topology of the expanded foils their material properties not isotropic but orthotropic [35]. The expanded metallic foils are placed on the top of the composite laminate but underneath protective dielectric coatings, e.g. a paint layer. The specific design of lightning protection layer helps to dissipate the lightning strike energy over the surface of the airframe component and sometimes to prevent but in the most cases to reduce the thermal and the mechanical damage of electrical non-conductive or low-conductive composite structures. Since the electrical resistivity of expanded copper foils is generally 2 orders of magnitude smaller than that of CFRP laminate the lightning current flows almost completely within the lightning protection layer not affecting directly the CFRP structure [26], [37].

For special applications solid flat strips can be integrated in the expanded foils, by partly not perforating the foil [38]. From thermo-physical point of view, the best metal is aluminum, because of its outstanding electrical conductivity to mass density ratio. Moreover, the ratio of thermal conductivity to mass density of aluminum is greater than that of copper. The same is true for the latent heat of melting and vaporization. However, aluminum alloys are extremely vulnerable to galvanic corrosion with carbon composite structures.

B. Woven wire fabrics

The principles of protection of woven wire fabrics are very similar to those of expanded metallic foils. The diameter of the mesh wires varies generally from about 50 to 250 μm . The surface weight varies between some tens of g/m^2 to 300 g/m^2 . The metallic meshes can be applied to complex airframe shapes; however not as easily as expanded copper foils, this is particularly true of tightly woven fabrics. However, because of the electrical contact resistance at the crossing points their effective in-plane averaged electrical resistance is larger than the corresponding expanded metallic foils with the same mass per unit area. The lightning protection effectiveness of woven wire fabrics originates on one the hand from the improved electrical conductivity of the metal wires as compared with that of the composite. On the other hand the crossing points intensify the local electric fields that enable dielectric breakdown of primers and paints at a multiplicity of points in the vicinity of the lightning attachment. This may divide the lightning arc into many conductive filaments of low intensity, thereby dispersing the lightning energy over a wider area and reducing the thermo-mechanical damage. The metallic meshes generally offer a satisfactory protection level but their lightning protection effectiveness is generally smaller than that of expanded metallic foils with the same surface weight.

C. Woven wire fabrics

This method protects CFRP laminates by the addition of metallic wires woven into the outer ply of a CFRP laminate.. The metallic wires are typically woven bi-directionally. The periodic appearance of the wires within the CFRP ply intensifies the electric field at multiplicity of locations, supporting in dielectric breakdown and multiple lightning attachment points which results in a significant arc root dispersion [39]. Lightning tests have shown that interwoven wires provide a significant reduction in damage compared to unprotected samples. Simulated lightning strikes indicate that the stroke currents enter a wide area of the laminate surface and usually vaporize the exposed portion of wires. However, interwoven wire fabric tends to cause cracking of the laminate due to the differential coefficient of thermal expansion and/or due to explosion of the metallic wire caused by lightning current loads [1]. Although the damage may be limited to the outer CFRP plies this is considered as a severe drawback of the interwoven wires protection measure.

D. Metal coatings

Metals can be coated on different non-metallic substrates. There are various procedures for metal coating such as Physical Vapour Deposition, Thermal Spraying, Electro- and Auto-Catalytic Electroless Plating. These procedures can be applied on airframe structures with complex outer shapes.

Physical Vapour Deposition (PVD) describes a variety of vacuum assisted deposition methods that are used to deposit thin films by the condensation of a vaporized form of the desired material onto various substrate surfaces. Typically, PVD processes are used to deposit films with thicknesses in the range of a few nanometers to thousands of nanometers. coatings are sometimes harder and more corrosion resistant

than coatings applied by the electroplating process [40], [41]. PVD is more environmentally friendly than chemical coating processes. However, it requires cooling systems to dissipate large heat loads and to avoid thermal distortion of the substrate material.

Thermal Spraying (TS) “*comprises a group of coating processes in which finely divided metallic or non-metallic materials are deposited in a molten or semi-molten condition to form a coating. The coating material may be in the form of powder, ceramic rod, wire, or molten materials*” [42]. The cold spray process is strictly not conforming to this definition because the powders are neither molten nor semi-molten, but this process is anyway included as part of thermal spray technology [43]. The most sprayed metal for aerospace applications is aluminium. The sprayed metals solidify on the exterior surface of the composite, resulting in a hard, stiff, conductive layer. Metallic coatings sprayed on manufactured parts may have a somewhat rough finish and may require additional smoothing. TS coatings may contain layered splats, porosities, unmolten or partially melted particles, and oxides for metals and alloys [44]. These structural irregularities of the coating films are the reason that the effective electrical conductivity of the sprayed metallic layer is generally lower than that of bulk metals.

E. Solid metal foils

Solid unperforated foils were used in the past as a lightning protection method with a limited applicability. Such metal foils can be adhesively bonded to low- or non-conducting surfaces to provide a conducting path for the lightning current. Metal foils provide protection of the composite structure that is about the same as that by the expanded metallic foils. Metal foils are better from the point of the view of the effective electrical conductivity than woven fabrics and metallic meshes. The solid foils do not encourage arc root dispersion as e.g. metallic meshes or expanded metallic foils. Thus, at least for the continuing current the beneficial effect that reduces the impressed energy density at the arc attachment area is not supported by solid metallic foils.

Manufacturing concerns have limited the application of solid metal foils. These foils do not drape smoothly over a 3D curved structures. Solid foils also have smooth, impervious surfaces, which makes them difficult to bond to the composite surface and difficult to paint as well. Because of these difficulties solid metal foils are nowadays less commonly employed as compared with other protection options.

F. Ionisable and conductive paints

Paints are inherently non-conducting with electrical conductivities generally less than 10^{-4} S/m. Conductive coatings are required for a variety of applications such as static charge dissipation (ESD) and electromagnetic shielding (EMI). The amount of DC conductivity required depends upon the specific application. It seems to be very attractive to use conductive paints for lightning protection purposes, since a paint coating is necessary for environmental protection of the composite structure and finally of esthetical reason.

Conceptually, there are three methods possible to design conductive coatings:

- to utilize conductive polymers as the continuous matrix
- to use conductive pigments with volume fractions above the percolation limit
- to combine both above methods

While there have been many recent advances in conductive polymer technology, the use of such conductive polymers is limited due to loss of electrical conductivity upon environmental exposure and poor processability and solubility. Hence, conductive carbon blacks, graphite, carbon nanotubes, and metal flakes are used for most of high conducting coatings.

There are two different paint lightning protection concepts

- **Conductive paints:** Conductive metallic particles or carbon allotropes are embedded in polymer matrix. The advantage of carbon allotropes is their high conductivity with low specific weight, enhancing relatively high loading without affecting the rheological properties and reducing mechanical properties.
- **Ionisable paints:** These paints are composed of classical polymer matrix charged with special pigments which have a low ionisation potential. Ionisable paints can be used just as classical aeronautic paints.

Paint lightning protection systems won't need costly and complex industrial investments and could be simply apply using the current manufacturing processes. Currently there are neither conductive nor ionisable paints that could provide a sufficient lightning protection level. Thus, they can be only associated with other protection measures, particularly to minimize the adverse effects of conventional paint systems.

G. Coated carbon fibres

The electrical conductivity of the C-fibres can be enhanced by metallic coatings. Metals can be deposited on fibres using e.g. the electroplating method or the colloid spray method. Nickel is the most used metal for fibre coating, since it is relative cheap, it is resistant to environmental corrosion, and it has a rather good electrical conductivity [45]. The C-fibres are coated with an approximate 0.2 to 0.4 μm thick nickel films. The additional surface weight caused by coating is between 20 and 200 g/m^2 . The mechanical properties of the composite plies made from coated nickel fibres tend to decrease slightly. The metallic coatings can increase the electrical conductivity of the fibres and thus increase the effective conductivity of CFRP plies [46], [47]. Generally only the upper ply of a CFRP laminate is made from coated fibres in order to decrease the overall additional weight. This upper ply should be able to withstand the lightning strike and to conduct the lightning strike current. However, the lightning protection level of the nickel coated fibres is lower than that of expanded metallic foils [48], [49]. Thus, the metallic coating of C-fibres can be only used for electromagnetic shielding purposes (EMI), rather than lightning protection of the outer airframe parts.

It should be noted that recently there is an increased research concern on coating or reinforcing of C-fibres with

conductive nano-fillers, see e.g. [50], [51], [52]. The results obtained are encouraging, but for lightning protection applications still not sufficient.

Thus, this procedure can be only used to support other lightning protection measures when there is a need to conduct lightning current in the upper ply of the CFRP laminate.

H. Epoxy resins with carbon allotropes

There is a recent growing focus on the potential effects of carbon allotropes, nanoparticle reinforcement of composite materials to augment their mechanical, electrical, and thermal properties. It is thought that the new nano-particle reinforced composites could be employed in a vast range of novel applications; such as erosion resistance, deicing, structural health monitoring and what is important here lightning strike protection purposes. Particularly in aerospace applications, the use of carbon nanotubes due to their superior properties for multifunctional applications seems to be very promising [53].

The usually used PAN-derived C-fibres offer a sufficient high electrical and a reasonable thermal conductivity, but the epoxy matrix is from electrical point of view an excellent electrical isolator. Thus, the general procedure is to improve the matrix properties, and possibly to network the carbon fibres both within and between the adjacent plies. Meanwhile various studies have shown that the incorporation of carbon nanotubes or short carbon fibres can significantly enhance the electrical conductivity of the resin matrix. Moreover, first results indicate that the damage of unprotected CFRP laminates can be significantly reduced by utilizing CNT's or SFC's [54], [55], [56]. However, the lightning protection level using modified epoxy resins is still insufficient for airframe CFRP laminates

Recently there is an enormous increase of research and development activities on graphene-reinforced polymers. It is known that the addition of small quantities of graphene materials can simultaneously provide significant improvements in strength, toughness, electrical and thermal conductivity, and chemical inertness to a number of polymers [51], [57], [58], [59], [60]. Graphene is a single layer graphite sheet that consists of sp^2 carbon atoms covalently bonded in honeycomb crystal lattice. The mechanism for the interaction in polymer graphene-nanocomposites – which in the ends determines the effective physical properties of the polymer graphene-nanocomposites – depends on the polarity, molecular weight, hydrophobicity, reactive groups, etc., present in the polymer, graphene/graphite and solvent [61], [62]. The graphene platelets have emerged as very promising nanofillers in multifunctional composites, even more promising than single or multiwall carbon nanotube structures. This has raised expectation levels for polymer composite applications, coatings and adhesives, where the excellent properties of graphene might be exploited in order to produce high performance, multifunctional composite structures. However it remains the case that currently there are no mature techniques suitable for industrial-scale production of graphene-reinforced polymers.

Meanwhile various studies have shown that the incorporation of graphene platelets can significantly enhance the mechanical, thermal, and electrical properties of polymers

and CFRP laminates, see e.g. [61], [63], [64], [65], [66], [67], [68], [69]. The results obtained are encouraging, but for lightning protection applications as a standalone system far from being sufficient.

Some studies have reported that simultaneous use of mixture of CNTs and graphene platelet shows a “*synergetic effect*” between graphene platelets and MWCNTs [70], [71]. This mixing procedure has improved the electrical as well as the mechanical properties of composites. Due to the presence of MWCNTs, the graphene platelets [71] were unable to stack, preventing aggregation by the long and tortuous MWCNTs. These MWCNTs bridged the gap between adjacent graphene platelets introducing additionally electrical contacts and increasing the effective electrical conductivity (but which is still not sufficient for an application as a standalone lightning protection measure).

IV. SUMMARY

The main goal of a lightning strike protection is to avoid or to reduce damage to an acceptable level. In fact all LSPs are based on the following basic protection principles

- **Increase of electrical surface conductivity**
LSP have to provide a continuous conductive path of low resistance over almost the entire aircraft surface. To create a conductive path typically an expanded foil embedded in a surfacing film is placed on the top of the upper composite ply. A conductive path reduces the amount of Joule resistive heating and prevents electrical current flow inside the composite material.
- **Arc root dispersion**
Enhancement of the local electric fields that enable dielectric breakdown or reduction of dielectric strength may promote the arc root to divide into many paths and not to be concentrated at just one location. This lightning energy dispersion over a wider area reduces the magnitude of the thermal and electrical flux and may reduce the thermo-mechanical damage.
- **Mechanical strength / fracture toughness increase**
The mechanical damage of composite laminates can be reduced by increase of the mechanical strength / fracture toughness, e.g. by increasing laminate thickness, increasing ply strength, enhancing interlaminar (shear) strength by nano-modification of the matrix or stitching, and finally by reinforcement with ductile metallic fibres.

At the begin of composite aircraft applications lightning strike problems weren't recognized initially, so the quick solution was simple to bring metallic structures back into the aircraft, which tends to negate the benefits that composites can bring. However, a “moderate” increase of the effective electrical conductivity does not provide a sufficient lightning protection level. Recently, there is an enormous increase of research activities to produce high performance, multifunctional nano-reinforced composite structures. The results obtained are encouraging, but for lightning protection applications as a stand-alone system far from being sufficient.

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