LIGHTNING STRIKES ON METAL AND COMPOSITE AIRCRAFT AND THEIR MITIGATION

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Abstract

In this paper, the history of aircraft accidents due to lightning strikes and the statistics of lightning strikes on commercial aircraft are briefly mentioned. The mechanism of interaction between lightning and aircraft is described. Lightning can be simulated in the laboratory. Lightning testing is based on identifying and reproducing the key elements of a typical lightning current waveform; and also on classifying the various parts of an aircraft into different lightning zones. The evolution of aircraft structural materials from wood to metal to composites is traced; some of the newer hybrid materials ('fibre-metal laminates') that combine the advantages of metals and composites are mentioned. The lightning mitigation measures implemented by the world's two major aircraft manufacturers, Airbus and Boeing, are briefly described. Some of the nanomaterials proposed for enhancing the surface electrical conductivity of structural composites are reviewed.

Introduction

On the average, every commercial aircraft is struck by lightning at least once a year [1, 2]. Aircraft with metallic exterior surfaces are relatively safe because they act as a Faraday cage, protecting the contents; catastrophic accidents are still possible due to fuel vapor ignition, failure of critical electrical or hydraulic systems, etc. Due to the escalating jet fuel prices, aircraft manufacturers are using composites in ever increasing amounts. As these composites are not as good as metals in their electrical conductivity, special steps have to be taken to improve their electrical properties.

In this paper, a comprehensive view of the subject is presented by considering the following topics:

- History of aircraft accidents due to lightning
- Statistics of lightning strikes on aircraft
- Mechanism of lightning-aircraft interaction
- Lightning strikes on metal aircraft
- Lightning effects testing
- Aircraft structural materials: metals
- Aircraft structural materials: composites
- Hybrid materials for aircraft structures
- Mitigation measures taken by Airbus and Boeing
- Methods of enhancing the lightning strike protection of composites
- Case Study : Radome Protection

History of Aircraft Accidents Due to Lightning

Considering the fact that every commercial aircraft is struck by lightning at least once a year and the fact that the vast majority of these lightning strikes do not cause significant damage or harm, it is clear that the current lightning strike mitigation measures are quite effective. Of course, the serious consequences of the lightning strikes in some cases, however few, have motivated a thorough study of the various aspects of the problem.

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Lightning strikes on aircraft can be of two types [2]:

1. Lightning triggered by the intrusion of an aircraft in a region with an intense electrostatic field, and
2. Interception of a branch of lightning already in progress by an aircraft.

In the 1980s, it was convincingly demonstrated that the vast majority of lightning strikes on aircraft are initiated by the aircraft [3]. The National Transportation Safety Board (NTSB) of USA database confirms 40 lightning-related accidents in the USA alone between 1963 and 1989.

In 1963, a PAN AM Boeing 707 plane, at a height of 5000 feet in Maryland during a thunderstorm, was struck by lightning. Three fuel tanks exploded and the plane burst into flames. A 4 cm diameter hole (Fig.1) had burned through the top of a wing and lightning-induced currents through the fuel filler caps produced sparks inside the fuel tanks, igniting the fuel vapors.

In 1976, an Iranian Air Force Boeing 747 plane, at a height of 6000 feet near Madrid, Spain, was struck by lightning. A spark at a motor-driven valve was suspected to have caused the fuel tank explosion.

In addition to fuel tank explosion, major electrical system failure can also cause a catastrophic accident. This was the case with a Fairchild Metro III plane. This turbo-prop commuter plane was on its way from Hanover to Dusseldorf in Germany in 1988, when it was struck by lightning. The plane was at a height of 3000 feet, ready to land, when lightning caused the failure of a critical relay and disconnected all batteries and generators from the aircraft's electrical system. The pilots lost control of the plane and the plane went into a spiral dive and crashed.

Lightning can cause the failure of hydraulic systems also. In 1998, a US Airways Fokker F28 MK 0100 plane was on a domestic flight in USA when it was struck by lightning that caused the failure of the hydraulic systems. The pilots managed to land the plane safely. Hydraulic fluid was noticed on the vertical stabilizer. Lightning current, flowing in the bonding strap between the vertical and horizontal stabilizers, side-flashed to the hydraulic lines, burning through them and releasing the hydraulic fluid.

A clear case of aircraft-initiated lightning strike was evident in 1965 when a Convair aircraft, about to take off from the Salt Lake City airport, was struck by lightning. There was light rain, but no lightning. Three large holes were found on the runway, matching the exact dimensions of the two main landing gear systems and the nose wheel.

Other major and minor incidents of lightning strikes are mentioned in references [4]. A noteworthy very recent accident involved Air France Airbus A330, carrying 228 persons from Rio de Janeiro, Brazil, to Paris in 2009. Lightning strike is suspected to have caused [5] catastrophic electrical failure and sudden loss of cabin pressure while flying through an area of severe thunderstorms.

Statistics on Lightning Strikes on Aircraft

While there have been many investigations of lightning strikes on aircraft, the most noteworthy studies, from which much of the information we now possess is derived, are four air-borne studies involving instrumented aircraft [1-3].

- F-100F was a single-engine jet that penetrated thunderstorms for the 'Rough Rider' project from 1964 to 1966. It measured turbulence and obtained lightning data in the form of photographs, shockwave data, and electrical current records. Data for 49 lightning discharges were recorded.
- F-106B was a NASA (National Aeronautics and Space Administration) delta-wing, single-engine jet that flew 1500 times through thunderstorms at altitudes from 5000 to 40,000 feet between 1980 and 1986. It was struck by lightning 714 times, with high altitude strikes outnumbering low altitude strikes by 10 to 1, the dividing line being 6 km.
- CV-580 was a USAF/FAA two-engine turbo-prop plane flown in 1984 and 1985. It was instrumented with sensors to measure the time derivative of the surface electric field intensity, surface magnetic field intensity, current, etc.
- C-160 was a two-engine French plane flown during 1984 and 1988. It had video cameras and many sensors.

All the data from such research flights have been analyzed and published [6-8]. Some of the major conclusions are the following:

- The majority of lightning strikes occur when a plane is within a cloud.

- The majority of lightning strikes is associated with turbulence and precipitation: 70% with rain and 12% with a mixture of rain, snow, sleet, hail, etc.
- For piston, turbo-prop and turbo-jet research aircraft, flown in (former) USSR, UK, Europe and USA, almost all of the lightning strikes occurred at altitudes in the range of ground level to about 20,000 feet. Strikes above 20,000 feet are rare because the pilots can avoid thunderstorms at those altitudes.
- Forty per cent of lightning discharges involving aircraft occurred in areas where no thunderstorms were reported.
- For piston, turbo-prop and turbo-jet aircraft, on the average, one lightning strike was experienced during 3,000 hours of flight.

Mechanism of the Interaction between Lightning and Aircraft

Thunderstorm clouds (known as 'cumulonimbus clouds') are puffy and can extend from ground level to 50,000 feet and above. The temperature within such clouds decreases with increasing altitude, typically varying from 0°C at the lower levels to -40°C at the higher levels. The electric charge in the cloud is negative at the lower levels and positive at the upper levels; however, a thin layer of positive charge can exist at the bottom of the cloud.

Lightning flashes usually originate from charge centres in a cloud, particularly the cumulonimbus cloud [9]. The charges in the clouds are produced by complex processes as water droplets, hail and ice crystals collide with each other. The electric charges within the clouds produce electric fields. When these electric fields become sufficiently intense, they ionize the air and produce electric sparks which can develop into lightning flashes. These lightning flashes can be of three types:

1. Intra-cloud discharges are lightning flashes between regions of opposite polarity within a cloud.
2. Inter-cloud discharges are lightning flashes between regions of opposite polarity in adjacent clouds.
3. Cloud-to-ground discharges are flashes that may originate from the cloud and propagate to the ground or originate from tall objects on the ground and propagate to a cloud.

An aircraft can counter any of the above three types of discharges, depending on its position in relation to the clouds. A lightning discharge, whether it strikes an object or not, is termed a 'lightning flash'. A lightning discharge that involves an object (on ground or in the atmosphere) is called a 'lightning strike'. There is evidence that cloud-to-ground discharges produce more intense currents than the other two types of discharges.

Depending on the polarity of the cloud charge involved and the direction of its transport, there can be four types of cloud-to-ground lightning (Fig.2).

1. Downward negative lightning (90% of cloud-to-ground lightning)
2. Upward negative lightning (from tall objects on the ground)
3. Downward positive lightning
4. Upward positive lightning (from tall objects on the ground)

When the electric field due to the accumulated electrical charge in a cloud becomes sufficiently intense, a discharge toward the ground or an aircraft in the vicinity takes place. Any self-propagating electrical discharge creating a column of ionized air is called a 'leader'. 'Streamers' start from the leader and propagate towards the ground or a plane. A leader with branches is termed a 'stepped leader'. A leader can trigger one of two events:

1. If an aircraft is in the vicinity, a (stepped) leader can approach the aircraft, attach itself, traverse the length of the aircraft and then leave the plane and propagate further through streamers emanating from the aircraft. If one of these streamers from the aircraft reaches the ground (or another charge centre), the aircraft becomes a part of the conducting path between charge centres and the aircraft has suffered a 'lightning strike'.
2. If on the other hand, a different branch of the original leader from the cloud reaches the ground (or another charge centre) first, the streamers from the aircraft will die out. These two events are shown in Fig.3.

Lightning Current Waveshape [9]

The generalized wave-shape of the current flowing to the ground (or an aircraft in the conducting path) from a typical negative cloud-to-ground lightning flash has five major features, as shown in Fig.4.

The leader : This is the beginning discharge from a cloud, advancing at a speed of 0.03 to 0.06% of the speed of light (1 to 2 x 10^5 m/s). The average current in the leader is 20 to 200 A. The arc discharge has a diameter on the order of a few mm. The leader can be 4 km long.

The initial return stroke : As the negatively charged stepped leader approaches the ground, positive charge accumulates on the ground below it- or, more accurately, negative charge is repelled away from the area under the leader. When the electric field strength on the ground becomes sufficiently high, a streamer starts at the ground and works its way upward towards the approaching leader from the cloud.

Intermediate current : As the return stroke reaches into the cloud, it encounters a much more heavily branched leader, tapping the charge dispersed in the cloud. During this time, the 'intermediate current' is developed.

Continuing current : As the discharge continues to spread through the cloud, currents on the order of a few hundred amperes continue to flow in the lightning flash. These are called 'continuing currents'.

Restrike : Usually, the developing discharge within a cloud reaches into a different charge centre. Then a 're-strike' occurs, lowering additional electric charge from the cloud.

Bidirectional Leader Theory

The mechanism of lightning initiation by a conducting object that is not attached to the earth (such as an aircraft in flight) is often called the 'bidirectional leader' theory. According to this theory, when an electric discharge from a negatively charged cloud approaches a plane, the plane launches a positive leader from one aircraft extremity and, a few milliseconds later, a negative leader in the opposite direction from another extremity, as shown in Fig.5.

Swept Stroke

A lightning flash initially attaches to or enters an aircraft at one spot and exits from another. Usually the entry and exit points are extremities of the aircraft where the electric field intensity is amplified. Since the aircraft is in flight, the motion of the aircraft through the relatively stationary flash channel causes the attachment (entry and exit) points to move along the surface of the aircraft. This is known as the swept-stroke. As the sweeping action occurs, the type of surface can cause the lightning channel to attach and dwell at various surface locations for different periods of time. If part of the surface, such as the radome, is nonmetallic, the flash may continue to dwell at the last metallic attachment until another exposed metallic surface (the fuselage) is available. Or the flash channel may puncture the nonmetallic surface and reattach to a metallic object beneath it (the radar dish).

Lightning Strikes on Metallic Aircraft

The effects of lightning on aircraft can be divided into 'direct' and 'indirect' effects. Direct effects occur at the entry and exit points and can include holes in metal skins, puncturing or splintering of nonmetallic structures such as radomes, damage to antennas and fuel ignition. The indirect effects are produced by the high voltages and currents induced within the aircraft by the lightning electric and magnetic fields. The indirect effects include damage to any of the many electronic systems.

Aluminum alloys were once exclusively used for the major aircraft structural parts, such as the fuselage and wings. A metallic aircraft can easily handle static charge buildup as well as lightning strikes. When a plane is in flight, the aerodynamic friction not only causes drag, it also creates static electricity. As water, snow or ice particles hit the aircraft, they frequently transfer a charge to it. Hence the name 'P-static' or 'precipitation-static'. The fuselage, wing and tail planes of the (metallic) aircraft provide a conductive path from the point of impact of the particles to points at which electrons can leave the aircraft.

If there is a break in the conductive path, the electrons (from static charge buildup) will accumulate until there is enough voltage to cause a spark across the break. 'Static wicks' are attached to the trailing edges of control surfaces and are designed to help dissipate this charge to the surrounding air. Without the static wicks, the static charge on the aircraft surface would try to 'jump' the nonconductive control hinges to the rest of the aircraft. The 'jump' or arc could cause damage to the aircraft surface if the static charge builds up sufficiently. To keep the static buildup to a minimum, and to provide a safe passage for lightning currents, conductive bonding strips are attached. It should be noted that static wicks are not 'lightning arresters'!

In the design of metallic skins (for the fuselage, wings, etc.,) and sub-structures, the goal is to minimize the lightning effects in terms of melting at lightning attachment points, resistive temperature rise, magnetic force effects, arcing across bonds, hinges and joints and ignition of vapors within the fuel tanks.

Melting at Lightning Attachment Points [10]

When lightning strikes an aluminum plane, usually burn marks are observed from the entry to the exit points, sometimes at more than a hundred locations. The aluminum skin should have enough residual fatigue/fracture strength in the presence of these stress concentrations to successfully complete the flight. When the melt through occurs on a panel enclosing the fuel, there is a danger of the fuel vapors igniting, causing an explosion; a hole melted through the wall of a pressurized enclosure can also lead to serious consequences.

The quantity of metal melted at a lightning attachment point depends on the charge carried, the type of metal and the thickness of metal. While the quantity of melted metal increases with the lightning flash charge, it decreases as the metal thickness increases and as the melting point of the metal increases.

The ignition thresholds for clean (unpainted) metal skins have been studied. The amounts of electric charge and current required to melt through aluminum and titanium skins of various thicknesses and to cause fuel ignition have been measured. For aluminum skins, for a given current, as the skin thickness increases the charge and time required for fuel ignition increase. For titanium skins, the melting point (1668°C) is higher than the fuel ignition temperature. So it is not necessary for a hole to be melted completely through the skin for fuel ignition to occur. For ignition, only a hot spot needs to be formed on the inside surface of a titanium skin. The lower thermal conductivity of titanium prevents rapid heat transfer away from the arc attachment point and accounts for the generally lower charge ignition thresholds compared to aluminum.

Protection Measures for Metal Skins

Some of the measures that can be taken to improve the resistance to melt-through are:

- Increased metal thickness. This is the most obvious, but the least desirable, method as this would increase the weight.
- Addition of a dielectric barrier to the inner surface. Polymer fuel tank sealants have been added to create a barrier between the metal skin and the fuel vapors.
- Addition of conductive particles (such as aluminum powder) in the exterior surface paint. These particles reduce lightning arc dwell time and enhance the arc root dispersion, allowing multiple conduction paths through the painted surface.
- Laminating the aluminum skins. Adhesive films between layers of aluminum skins provide a thermal barrier that prevents arc attachment to the inner aluminum skin, in addition to serving as crack arresters.

Lightning Effects Testing

Lightning can be simulated in the laboratory. Laboratory tests are based on two important steps: (a) Idealization of voltage/current waveforms derived from actual measurements of lightning parameters, and (b) Division of an aircraft surface into lightning strike zones. These steps are briefly described below.

Idealized Voltage/Current Waveforms

The generalized Waveshape of current in a negative cloud-to ground lightning discharge was shown in Fig.4. A series of idealized voltage and current waveforms, with which aircraft are to be tested for the effects of lightning, have been given [11] based on Fig.4. These waveforms, of which the major ones are shown in Fig.6, are:

A. First return stroke

B. Intermediate current

C. Continuing current

D. Subsequent return stroke (100 kA amplitude pulse)

D/2. Multiple stroke (MS) flashes following D: 13 pulses of 50 kA amplitude following D, with gaps of 10 to 200 milliseconds

H. Multiple bursts (MB) of 10 kA amplitude: 20 bursts each composed of 20 pulses.

Lightning is a complex and variable phenomenon. Extreme values of voltage (up to 10^8 V), current (up to 200 kA), current rate (up to 10^{12} A/s) and voltage rate (up to 10^{14} volts/s) can be manifested during a lightning strike. The peak current is only one factor in causing physical damage; equally important is the energy dissipated, represented by the 'action integral', defined as $\int i^2\, dt$.

Natural lightning packs both high voltage and high current together. Laboratory simulations involving both high voltage and high current are only possible with specialized equipment available in only a few labs. More readily available are laboratory equipment that can handle either high voltage technology or high current technology.

Lightning Strike Zones on an Aircraft

The surface of an aircraft has been divided [12] into a set of regions called 'lightning strike zones'. These zones represent the areas likely to experience the various types of lightning currents. There are three major zones:

- Zone 1: Regions likely to experience initial lightning attachment and first return strokes.
- Zone 2: Regions likely to experience first return strokes but also likely to experience subsequent return strokes because the aircraft is in motion. This is the swept-stroke zone.
- Zone 3: Regions which are unlikely to experience any arc attachment but which will have to conduct large lightning currents between attachment points.

These zones depend upon the type of aircraft and are shown in Fig.7 for a large passenger aircraft. Zone-1 includes the radome and the wing tips. Zone-2 includes the areas on the fuselage and the wings. Zone-3 includes large areas on the wings. Zone-1 is further subdivided into three subzones while Zone-2 is subdivided into two subzones.

For conducting lightning simulation tests in the laboratory, the various lightning current waveforms shown in Fig.6 are associated with different lightning strike zones as shown in Table-1 [12]. This matching of current waveforms with different parts of the aircraft is based on lightning incidence data and experimental observations.

Table-1 : Current Waveforms for Different Lightning Zones

Aircraft Zone	Current Components
1A	A, B, C, MS, MB
1B	A, B, C, D, MS, MB
1C	A, B, C, MS, MB
2A	B, C, D, MS, MB
2B	B, C, D, MS, MB
3	A, B, C, D, MS, MB

Types of Laboratory Tests [13,14]

Laboratory tests can be subdivided into (a) tests for direct effects and (b) tests for indirect effects. Depending on the type of objects that are tested, the tests can also be subdivided into (c) specimen tests (d) model tests (e) component or sub-assembly tests and (f) full-scale tests.

Tests for Direct Effects: Specimens or components are subjected to the appropriate current waveforms mainly to assess the drastic melt-through (metal) or perforation (composite) effects.

Tests for Indirect Effects: These tests assess how well electrical and electronic equipment withstand the indirect effects of lightning. Such tests can be 'proof tests' and 'transient analysis tests' on complete aircraft or tests on individual pieces of electronic equipment.

Specimen Tests: Specimens, usually in the form of panels, fabricated from materials used for different parts of the aircraft, are subjected to the electrical inputs appropriate for the particular zone in which the aircraft part is situated. Specimens are inspected before and after the tests, ultrasonically if they are composites; test specimens may be cut further from the test panels to measure the residual tensile, compressive and fatigue strengths [15].

Model Tests: Models of aircraft are subjected to high voltages or high currents in the laboratory to simulate lightning strikes.

Component or Sub-assembly Tests: Actual components or sub-assemblies are tested under conditions appropriate for the zones in which they are located in an aircraft. For example, the transcowl sample, which is part of the covering for the aircraft engine, is subjected to the current intensities and waveforms required for zone 1C [15].

Full-Scale Tests: These are mainly intended to identify system incompatibility problems- systems which may operate properly by themselves but which may fail when the complete vehicle is subjected to lightning currents. For example, redundant systems may provide no redundancy when they are simultaneously affected by the same induced voltages.

While laboratory tests are very important in lightning simulation, finite element analysis can play an important role in modeling complex assembled airframes and simulating lightning strikes [16, 17] ; the results can be obtained much faster and cheaper.

Aircraft Structural Materials: Metals

The choice of aircraft structural materials depends on the type of aircraft (military or commercial), the design life of aircraft and the flight envelope (distance, time between flights, etc). The choice of materials is based on durability, damage tolerance and costs (operational costs and maintenance costs). Damage tolerance requires resistance to impact damage (due to hail, bird strike, engine debris, etc), environmental damage (due to corrosion, erosion, lightning strike, etc) and fatigue damage.

From the first flight attributed to the Wright brothers in 1903, up to 1927, all major aircraft were made mostly of wood; the record-breaking flight in 1927 up to 40,000 feet, which identified the jet stream, was made in a 'Vega' plane. By 1932, however, every major new aircraft was built mostly of metal. The change from wood to metal was not merely a materials revolution, it was also a cultural revolution.

Aluminum, which was used for the cylinder block of the engine for the Wright brothers' 1903 plane (strengthened by precipitation hardening even before the phenomenon was understood), displaced wood as the main aircraft structural material for fuselage, wing skins, etc. Aluminum (mainly alloyed with copper) has advantages such as low density, high conductivity, good bonding characteristics, etc. It also has some problems such as difficulty in welding, need for shaping first and then heat-treatment, low modulus and poor shear strength.

Aluminum-lithium alloys are increasingly being used due to the lower density and superior properties [18-20]. Their use in Airbus A380 has resulted in a 350 kg saving in the freight version and a 200 kg saving in the passenger version. First and second generation of Al-Li alloys had disadvantages of reduced ductility, fracture toughness and thermal stability. The third generation alloys, such as Weldalite 049, have overcome these problems; improved fabrication methods such as laser beam welding and friction stir welding are also available. The use of these alloys in the nose section of Airbus A350 XWB has resulted in a 600 kg reduction. Airbus A380, which is one of the world's largest commercial aircraft, weighs close to a million pounds, can seat 555 people, and had its first test flight in 2005. Its structure is made of 61% aluminum alloys, 22% composites, 10% Ti (aero-engine parts and air-frame fasteners) and steel (exhaust components, brake rotors, etc) and 3% GLARE (a 'fibre-metal laminate', which is described later). Seven years were needed to develop, qualify and produce a full set of new aluminum alloys for wing and fuselage structures.

As mentioned earlier, aluminum alloys generally provide a safe passage for the lightning currents due to their good electrical conductivity; but localized heating, which can result in melt-through, has resulted in fuel tank explosions.

Aircraft Structural Materials: Composites

While the change from wood to metal was cultural, the change from metal to composites in recent years has been due to economic necessity- the rapid escalation of jet fuel prices. The aircraft manufacturers have been responding to the needs of airlines to reduce the structural weight of aircraft.

While the extensive use of composites in aircraft is very recent, the trend started many years back. In the 1950s, glass fibres were first used (2%) in Boeing 707. In the 1960s, boron-epoxy and carbon-epoxy composites were tried for aircraft control surfaces like ailerons. The first significant use of composites in commercial aircraft was by Airbus in 1983 for the rudder of A300 and A310, and then in 1985 for the vertical tail-fin. In the latter case, the 2000 + parts (excluding fasteners) of the metal fin were reduced to fewer than 100 parts for the composite fin, lowering its weight and manufacturing costs.

Composites offer many advantages such as high specific strength and high specific stiffness. Their electronic transparency allows antennas to be hidden inside for streamlining without loss of reception. There are also disadvantages such as variability in properties from part to part, problems due to moisture absorption, difficulty in damage detection, brittleness, ultraviolet degradation of polymeric matrices and decrease in lightning strike protection due to the reduced electrical conductivity.

Composite materials for aircraft structures consist of a continuous fibre reinforcement (such as carbon and Kevlar) in a polymeric matrix (such as epoxy, a thermoset, or PEEK, a thermoplastic). Unidirectionally reinforced plies from a 'pre-preg' are cut, stacked together at required orientations and consolidated into laminated parts. Composite sandwich panels, with a core material such as honeycomb, sandwiched between two thin composite laminates, are used where resistance to bending and buckling is required along with reduced weight.

Two-dimensional composites (composites with reinforcing fibres in one plane) have poor mechanical properties in the thickness direction. They are typically prone to delamination. To overcome this problem, three-dimensional composites, with reinforcements introduced by 'stitching' or 'tufting' in the thickness direction, have been developed. While the mechanical properties in the thickness direction are improved in these composites, the in-plane properties are impaired due to the damage to the in-plane reinforcements.

This problem has been overcome by 'nanostitching' [21-23], a process in which carbon nanotubes are introduced in the thickness direction. One of the methods for doing this is by growing carbon 'nano-forests' on the carbon fibres comprising the reinforcing fabric in the plies of the laminate, as shown in Fig.8. These fabrics are then stacked together, a polymer matrix is infiltrated and the composite is laminated. Another advantage of nanostitching is that along with the improvement in mechanical properties, the electrical conductivity in the thickness direction is also enhanced- thus improving the lightning strike protection.

Hybrid Materials for Aircraft Structures

The combination of metals with fibre reinforced polymers into aircraft structural materials is denoted as 'hybrid materials'. These materials are also known as 'Fibre Metal Laminates' or FML [24-27]. This development was the result of searching for ways to improve the fatigue crack growth resistance of aluminum alloys; the concept has its origin in the addition of reinforcing fibres into the bondline of thin laminated aluminum sheets.

The FML technology combines the advantages of metals and of fibre reinforced composite materials. Metals are isotropic, have a high bearing strength, have a high impact resistance and are easy to repair. Composites have high specific stiffness, specific strength and excellent fatigue resistance. The combination overcomes the fatigue and corrosion problems of metals and the low bearing strength, low impact resistance and poor repairability of composites.

Examples of Fibre Metal Laminates

ARALL (ARamid ALuminum Laminate), GLARE (GLAss REinforced Fibre Metal Laminate), CARALL (CARbon Fibre ALuminum Laminate), TiGr (Titanium Graphite Laminate) and CentrAL (Central Reinforced Aluminum) are examples of FMLs. The constituents of some of these hybrid materials are given in Table-2. The concept and various types of FML were developed at the Delft University in Netherlands.

ARALL, the first FML, was developed in the 1970s and was made by combining layers of high strength aluminum sheets and unidirectional aramid fibres impregnated with a resin. While all four grades of ARALL that were developed exhibited many advantages including resistance to lightning strike damage, they proved unsuitable for fuselage structures due to the poor compression properties of the aramid fibres.

GLARE [28-31] is a second generation FML, developed in 1987, for use in fuselages. Glass fibres replaced the Kevlar fibres. GLARE laminate was selected for the upper fuselage skin structures of Airbus A380. This was the first structural application of GLARE in a commercial airline. Each A380 plane has about 380 m^2 of GLARE, saving 794 kg (compared to aluminum alloy). Six grades

Table-2 : Some FML Types and Constituents

FML Type	Metal Constituent	Fibre/Polymer Constituent
ARALL	Aluminum 7075-T6	Aramid/BSL-312-UL Aramid/AF 163-2
GLARE	Aluminum 2024-T3 Aluminum 7475-T761	S2-Glass/FM 94 S2-Glass/FM 906
CARALL	Aluminum 2024-T3	T 300-Carbon/Epoxy
TiGr	B Titanium Ti-15-3	IM 7-Carbon/Polymide

of GLARE have been developed, with unidirectional and cross- ply glass reinforcements.

GLARE panels have been subjected to 'direct hit' as well as 'current flow' tests to assess their resistance to lightning strikes. In GLARE, the glass fibre layers are non-conducting. Therefore, the lightning current must find its way through the aluminum layers. As these layers are not electrically connected, the current can only be transmitted through the thin outer aluminum layer. When lightning strikes the surface, a lot of heat is created in the FML. The outer aluminum layer melts and vaporizes locally. The underlying fibre layer carbonizes and the fibre layer will be partially damaged. In very severe hits, the second pre-preg layer may also be damaged, but the rest of the material will be intact. GLARE also shows excellent fire resistance when exposed to open flames in fire wall tests.

'TiGr' consists of thin foils of Ti alternating with graphite-polymer layers [32] . The concept of TiGr builds upon previously developed FML materials. Compared to aluminum alloys and other FMLs, TiGr offers higher specific stiffness and strength, higher bearing strength and impact resistance and improvement in lightning strike protection. But it is more expensive.

Current Lightning Strike Protection Measures

Airbus and Boeing are the current leading aircraft manufacturers. Competition and rising fuel costs have driven both to increase the use of composites. Starting from modest beginnings, the weight percentage of the carbon fibre reinforced polymer matrix composites (CFC) in the aircraft structures in the Boeing Dreamliner 787 and the Airbus A350 has exceeded 50 per cent. It should be noted that the structural framework for the fuselage and the wings is still made of metal (mostly aluminum alloys) in order to provide electrical continuity for lightning strike protection and only the covering panels fabricated from CFC. One of the major differences between Airbus and Boeing is in their response to the question: Should pilots or computers have the ultimate control over the aircraft as it approaches its design limits in an emergency? Airbus gives the ultimate control to the computers while Boeing gives the pilots the ability to override the computers.

Carbon fibres are fairly good electrical conductors but the polymer matrix in CFC is an insulator. Several measures have been taken to ensure lightning strike protection in aircraft that utilize significant amounts of CFC. Expanded aluminum or copper 'Microgrid' [33] and 'Strikegrid' [34] materials are incorporated into the outer surface of the composite structures. The lightning strike energy is dissipated over the surface of the component, which prevents damage to the composite material. The grid materials, shown in Fig.9, are applied on the fuselage and wings, rudder and vertical stabilizers, spoilers, ailerons, vanes, flaps and engine nacelles. The grid material is very thin and is available in several widths in rolls. Lightning strike simulation tests have shown that they protect CFC panels from serious damage. In the case of fuel tanks, two layers of the expanded metal grid are applied for extra protection.

Since sparking inside the wings, which serve as the main fuel tanks, can ignite the fuel vapors in the tanks, several precautions are taken:

- As mentioned earlier, a thin metal mesh is embedded in the outer layers of the composite fuselage and wings; two layers of the mesh are used for the fuel tanks for extra protection.
- Since a gap between the fasteners and the holes can be a source of sparking causing the current to jump across the gap, each fastener is installed precisely and tightly.
- Inside the wings, any gap along the edges where the wing skin meets internal structural spars can cause a spraying of electrons in a lightning strike, called 'edge glow'. This can ignite the fuel vapor. To prevent this, the edges are sealed with non-conducting goop or glass fibre.
- In addition to the various measures to suppress ignition sources, Boeing has installed a nitrogen-generating system (NGS) that reduces flammable vapor in the wing tanks by filling the space above the fuel with nitrogen as the fuel level drops.

Methods of Enhancing the Lightning Strike Protection of Composites

As mentioned earlier, while carbon fibres have some electrical conductivity, the polymer matrix in CFC makes the composite a poor conductor. In order to seal CFC from moisture absorption, the composite structures are painted. The paint can be made conducting by adding particles of carbon, copper, aluminum, etc. But lightning protection from conducting paints is only marginal due to insufficient conductivity and due to erosion from intense rain or hail [37]. Several methods are being explored by Airbus and Boeing in order to increase the electrical conductivity of the outer layer of a CFC panel:

- Aluminum or copper mesh or screen incorporated in the outer layer (current technology). There can be potential problems with this approach. Aluminum forms a severe corrosion couple with the carbon fibre and several layers of glass fibre are usually placed on top of the carbon fibres; but this leads to a weight penalty. In the case of copper mesh, bonding with the polymer matrix composite is critical because the large difference in the coefficients of expansion can cause micro cracking of the epoxy matrix, leading to corrosion of copper.
- Carbon nano-tube bucky pre-preg (emerging technology)
- Carbon nano-graphene platelets (emerging technology)
- Carbon nano-tubes decorated with silver particles (emerging technology)
- Metal (Ni) coated carbon fibres
- Combination of materials, for example: Ni coated carbon fibre fabric + nano materials like Ni nano strand or bucky papers

The various lightning protection systems are compared based on:

- Degree of damage due to lightning strike
- Degree of damage protection
- Simplicity of repair

Many of the current non-nano composite approaches incorporate larger-scale conductors that add to the structural weight, complicate manufacturing and have repair problems due to phase discontinuities. Nano composites do not suffer from these problems because property enhancement is achieved with small additions of nano particles.

Some of the nano materials being considered for improving the electrical conductivity of CFC skins of aircraft are [38] :

- Carbon Nano-Tubes (CNT)
- Carbon Nano-Fibres (CNF)
- Nano Graphene Platelets (NGP)
- Carbon Nano Sphere Chains (CNSC)

Carbon Nano-Tubes : Discovered in 1991, carbon nanotubes are cylindrical tubes of nanoscale dimensions. CNTs can be single-walled (SWNT) or multi-walled (MWNT). Conceptually, a SWNT can be considered to be formed by rolling a single layer of graphite (called a graphene layer) into a seamless cylinder. A MWNT can be considered to be a co-axial assembly of cylinders of SWNTs, one within the other; the separation between the tubes is less than a nanometer. SWNT can be of the ‘zigzag’, ‘armchair’ or ‘chiral’ types, depending on how the graphene layer is rolled. Nano-tubes are characterized by molecular perfection, high electrical and thermal conductivity, and very high values of stiffness and strength. The strong van der Waals attraction leads to spontaneous roping of many nano-tubes.

CNTs have been expensive due to the difficulties in manufacturing them. They have also been difficult to process in traditional methods of fabricating discontinuous reinforcements and matrices, because of the problems in dispersing and aligning them in a polymer matrix. In order to overcome these difficulties, a ‘bucky paper’ has been developed. CNTs have also been incorporated in conductive coatings that can be applied to aircraft surfaces; the enhanced electrical conductivity due to these coatings elevates lightning strike protection and in addition, provides an easy method for preventing ice-buildup.

A carbon ‘bucky paper‘ is a macroscopic aggregate [39-42] of CNTs which are also called ‘bucky tubes’. The bucky paper provides a solution to the problem of dispersing CNTs in a matrix so that the unique properties of the CNTs can be realized in a bulk composite. Bucky paper is ten times lighter but potentially 500 times stronger than steel when sheets of bucky paper are stacked and pressed together to form a sheet. Unlike CFC, bucky paper is said to conduct electricity like copper and disperse heat like steel. Bucky paper, on the skin of CFC in aircraft, would be 15 per cent of the weight of copper mesh used currently for lightning strike protection. Bucky paper, researched since 2000, is available commercially in 12 inch width rolls of 100 feet length. Bucky papers have been produced by suspension-filtration, domino-pushing and hydro-entangling.

Carbon Nano-Fibres : CNF has a tubular structure [43, 44], with the side walls composed of angled graphite sheets. The nano fibres consist of graphite platelets arranged in various orientations with respect to the fibre axis, giving rise to assorted conformations and unique properties. They are commercially available and can be prepared as CNF paper. They have been applied to CFC by Resin Transfer Molding (RTM) to improve the electrical conductivity.

Nano Graphene Platelets : 'Graphene' is a single-atom thick sheet of graphite and it was discovered in 2004 that it can exist in a stable form. It can be visualized as a CNT unrolled. It is an outstanding electrical and thermal conductor. It has a very high stiffness and strength. NGP can easily be dispersed in many polymers at high loadings (up to 40 per cent by weight), unlike CNTs and CNFs [45, 46]. NGPs can be mixed with other nano materials such as CNTs, CNFs and nano clays to produce hybrid nano-composites. NGPs can reinforce thermosets, thermoplastics and elastomers. They are expected to be very effective for lightning strike protection.

Carbon Nano Sphere Chains : This material [47] is available in large quantities and is highly pure carbon and highly conductive. The electrical conductivity of this material makes it a candidate for lightning strike protection of aircraft; the conductivity coupled with its hydrophobic nature makes it attractive for preventing ice-buildup.

Combinations of the various types of nanomaterials are being explored for enhanced lightning strike protection.

Case Study: Radome Protection

Radome (radar + dome) is a dome-shaped housing for a radar antenna, transparent to radar waves. Radomes are mostly located at the nose of the aircraft but sometimes they can be located on the fuselage or tail also. If located at the front (directly below the cockpit), a radome is susceptible to bird strikes, erosion, precipitation static, water ingression (through punctures and burns) as well as lightning strikes. Electronic transparency for transmitting and receiving radio signals requires that the radome should be fabricated from non conducting materials such as polymers or glass fibre reinforced polymeric composites. Lightning strike protection of radomes is thus important and difficult.

Radomes are tested in the laboratory to improve their design. The currents applied during tests depend on the location of the radome on the aircraft. Typically, radomes are located in Zone 1A or Zone 1C (nose mounted), 2A (fuselage mounted) or 1B (tail mounted).

Solid bars, powdered metal strips, thin foils, segmented diverter strips and combinations of these materials have been used on radomes for lightning strike protection. The segmented diverters, placed outside the radome, create an ionized channel above the diverters and arc plumes are developed between the segments. Solid bars are either placed outside or inside the radome (Fig.10) in a radial pattern (typically 6 to 12 bars) on the nose of the aircraft (Fig.11). They afford lightning strike protection but do act as an impediment to RF (radio frequency) performance. The solid bars are fixed with fasteners to the A-sandwich (two composite laminates with a core) or C-sandwich (three composite laminates with two cores) radome structure and electrically connected to the metallic frame of the fuselage; this ensures the conduction of lightning currents away from the radome during a strike. In spite of all these design features, radomes get perforated and burnt locally due to static electricity and lightning strikes; they also get damaged due to hail, bird strike, etc. 'Erosion boots', made of polyurethane are used at the nose of the aircraft and they are sprayed with an anti-static coating. The radomes need to be replaced periodically.

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Fig.1 Hole Burned Through the Top of Wing in 1963 PAN AM Boeing 707 (Atmospheric Science University at Albany)

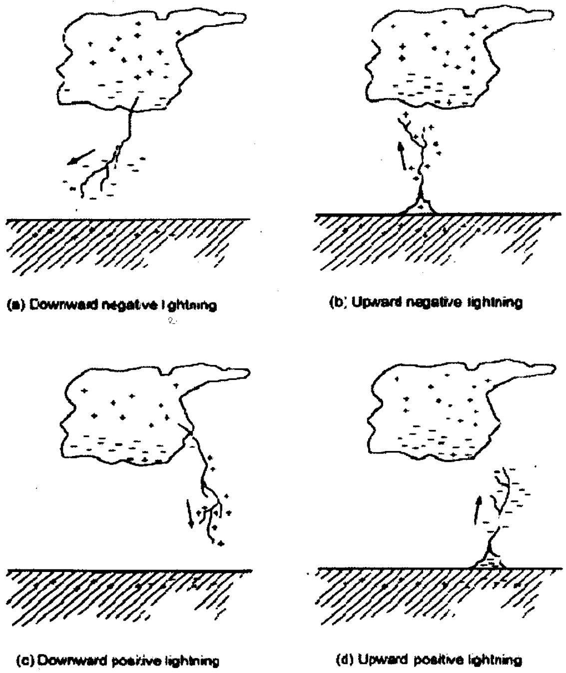

Fig.2 Four Types of Lightning Discharges [2]

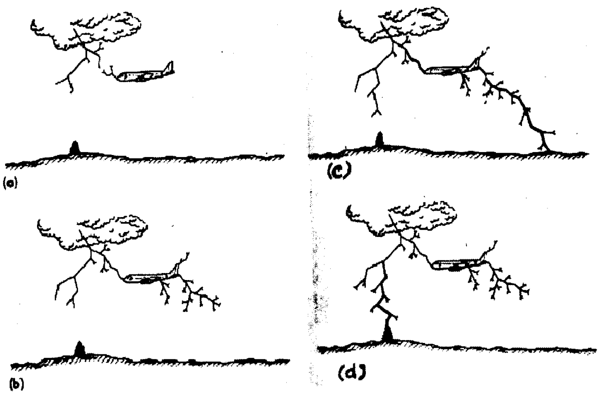

Fig.3 Lightning Discharge from a Cloud : (a) Streamers Start fromCloud Towards Plane and Towards Ground, (b) Streamers from Cloud Link with Streamers from Plane, (c) Streamers from Plane Reach the Ground ('Plane Struck by Lightning'), (d) Streamers from Cloud Reach the Ground {Ref. 2]

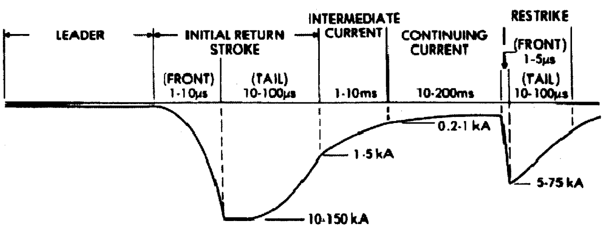

Fig.4 Generalized Waveshape of Current in a Negative Cloud-to-Ground Lightning Discharge [9]

Fig.5 Lightning Entering and Exiting from a Plane [10]

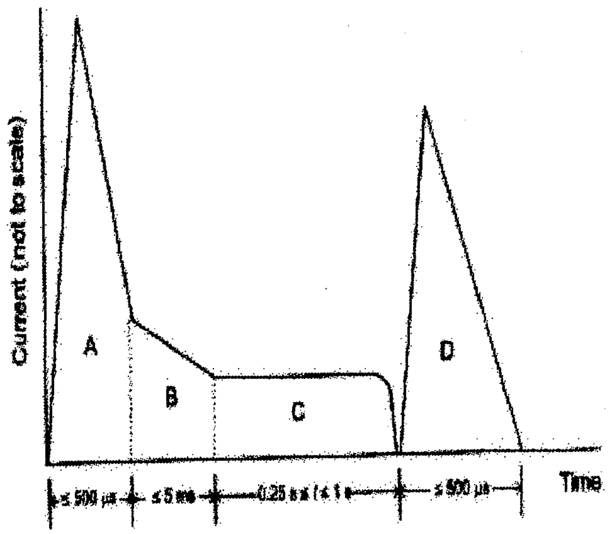

Fig.6 Major Components of the Lightning Current Waveforms used in Testing [11]

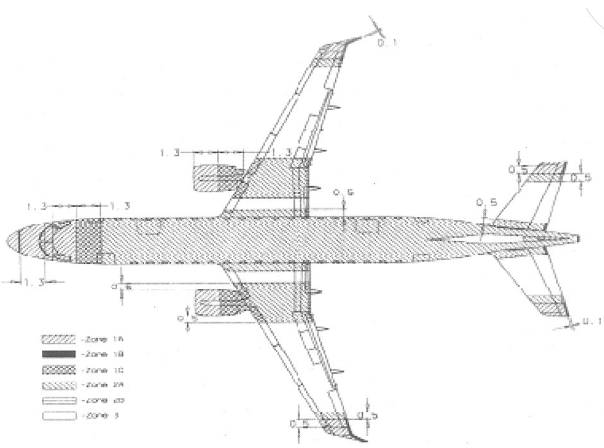

Fig.7 Lightning Strike Zones for a Large Passenger Aircraft [13]

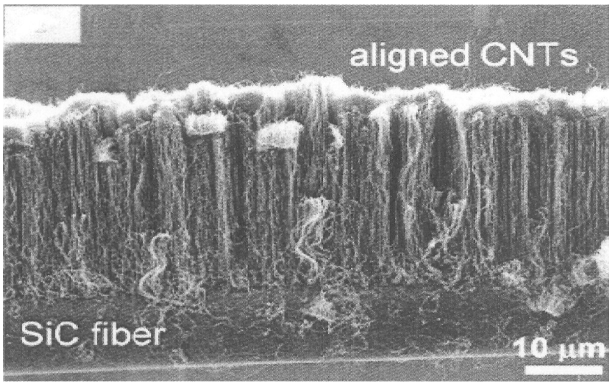

Fig.8 Carbon Nano Forest on a Single Fibre

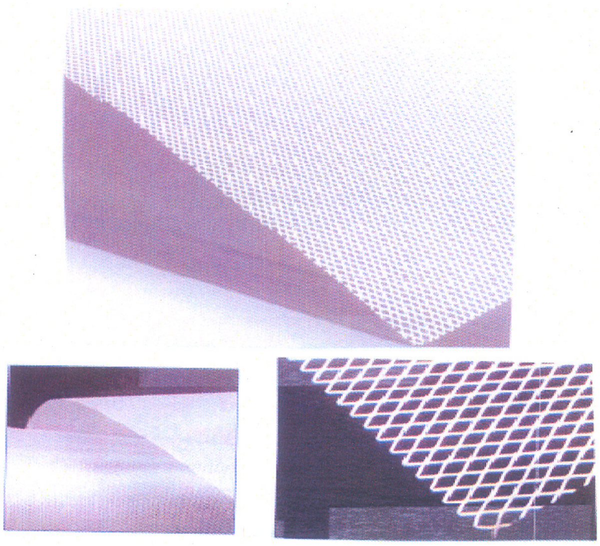

Fig.9 Expanded Metallic Grid for Lightning Strike Protection of Composites [34]

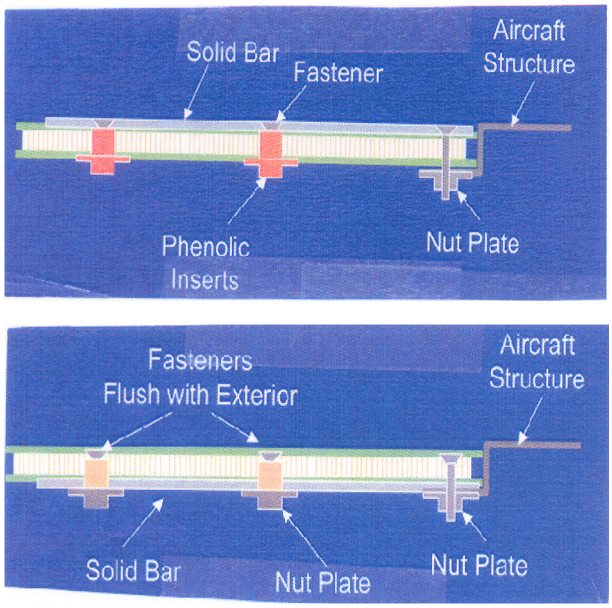

Fig.10 Solid Bar Lightning Diverters Mounted Outside (Top) and Inside (Bottom) of a Radome [48]

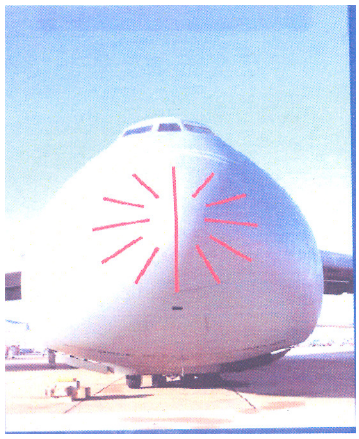

Fig.11 Lightning Diverter Bar Placement in a Radial Pattern on a Radome [48]