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Review: Factors affecting composite laminates against lightning strikes

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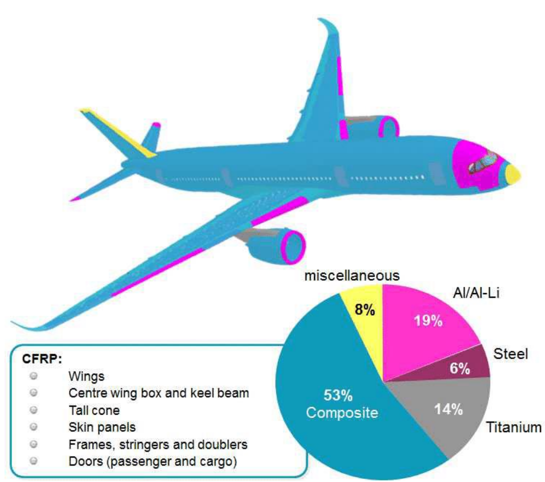
Abstract

Lightning strike protection (LSP) have recently been a newly developing field particularly with the emergence of graphene thin film integration into carbon fiber composite structures. This technology has a widespread application in airplanes, wind turbines, and other instruments which are susceptible to frequent lightning strikes. Electrical discharge of the instrument in a safe manner is vital for the safety of the passengers (in the case of flights) as well as the integrity of the aircraft structures because of their specific mechanical and structural properties, which are essential for their functioning. The purpose of the study is to fabricate graphene thin film coated carbon fiber composite structures for assessment with simulated lightning strikes. This study will look at different methods for incorporating GTF (graphene thin film) into Carbon Fiber Reinforced Plastic and assess the electrical conductivity through methods such as compressive molding, Resin Transfer molding fabrication to achieve highly conductive functionalized nanosized GTFs, integrated with carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs). The method developed must reduce the resistivity of the CFRP and provide a safe discharge outlet for the lightning strikes. In the current study we will develop GTF using GNP impregnated polymers. Electrospinning process will be one of the processes implemented to develop the GTF. The purpose would be develop viable methods for the fabrication of graphene thin film material, and simulated testing of lightning strikes.

Introduction

Lightning strike damage accounts for around 25% of the damage to wind turbines according to the 2012 US wind energy insurance claim report. The repair of the damage to wind turbines can be expensive, and often leads to significant periods of intermissions and let-ups during their maintenance. Lightning damage could occur blades, generators, control cables, and other control systems, with average cost exceeding $250,000, majorly due to the vulnerability of the blades, which are fairly susceptible, and difficult to repair. This is a major factor in discouraging users to switch from non-renewable energy to alternate energy forms. With increased dependance over the past two decades on polymeric composites, corresponding increased usage can be seen in the structural elements of wind blade structures, and aircraft structures. Both projects require high mechanical strength, relatively light weight, lower thermal expansion, corrosion resistance, fatigue resistance, and moreover lightning strike protection.



Modern structures are giving increased traction to using composite lightning strike protection (LSP) technologies as opposed to existing metal based protective films and foil technology. This is included in the fields of manufacturing, aerospace, and marine projects. In fact within aerospace industry, the latest flagship line of aircrafts developed by both Boeing (Boeing 787 Dreamliner) and Airbus (A350 XWB) use composite material components in the wings, stabilizers, and turbine housing. In fact composites account for 50% weight of the Boeing 787 Dreamliner, and 53% of the weight of the Airbus A350 AWB. The complete percentages of materials can be found in the image below. Unfortunately, the lightweight alternatives that carbon fiber reinforced plastic composites (CFRP) are, come with their own share of downsides. They bring limitations in manufacturing costs, maintenance issues, and significant maintenance costs. However, the advantages they provide in their scope for weight reduction, general workability, adjustable mechanical properties has had these materials generate interest.

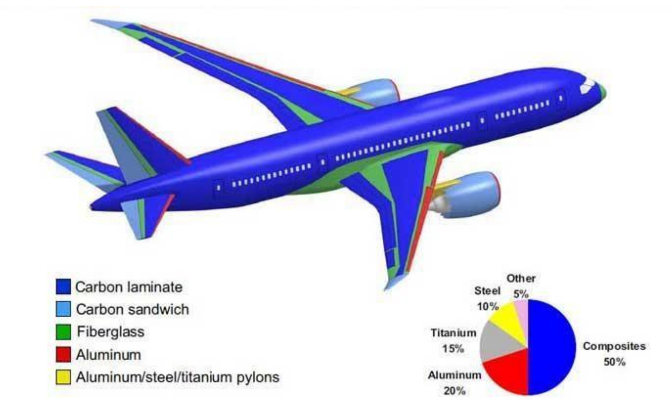


Fig 1. The image on the left shows the materials used in the body of Boeing 787 Dreamliner, and the image on the right shows the materials for the Airbus A350 XWB.

The issue of aircrafts acting as conductive "beacons" of electricity is one such issue which have been developed almost entirely through the development of CFRP/GFRPS (Carbon/Glass Fiber reinforced plastic composites) . Traditional aircraft frames were made of metals allowing high electrical conductivity, allowing the easy dissipation of lightning striking currents. However, the switch to composite fibers have brought direct issues in their low electrical conductivity, as well as issues in their anisotropic scattered current distribution on in-flight electrical navigational systems, and risk of igniting the fuel tank. Hence conventional systems use metallic foil/mesh systems to coat the planes while retailing the internal structure made of composite materials. This has been studied at length by Gagne et al. (2013), and the major results have been summarized below in Table 1. However, this is an inelegant solution, and significant research has been conducted to create commercially viable low maintenance composites with reduced resistivity.

Table 1: Commercially available modern LSP products

Type of LSP	Options	Characteristics	Commercial Products
Metallic Mesh or Foil	- Mesh materials(copper, alumium, broze, nickel) - Resin materials (epoxy, vinyl ester, modified epoxy) - Prereg materials or lay-up - Foil; perforated, printed or woven	- High conductivity og metals - Heavy surface material - Problem with porosity - Tendency to rust - High density	- Astrostrike - MicroGrid - SynskinHysol - Surfacemaster 905C
Metals ormetalized fibers bonded with resin	- Fiber materials: carbon, graphite, glass, polyester,synthetic fibers - Coatings (nickel,copper,silver,platinum) - PVD - SPS - Electroless - Thermal	- Lightweight - Less efficient thanmesh - Flexibleprocess(multicoatingand multilayerispossible) - Generally, more workable	- Metal fibers - Metal coated non-metallic fibers - Metal coated fibers
Advanced solutions : polymer-based film or conductive adhesives	- Enhanced polymer with additives - CNTs - Graphene sheets - Mix of CNTs and GS	- Lightweight - Smooth finish - Must be replaced if struck - Usually expensive to maintain	N/A

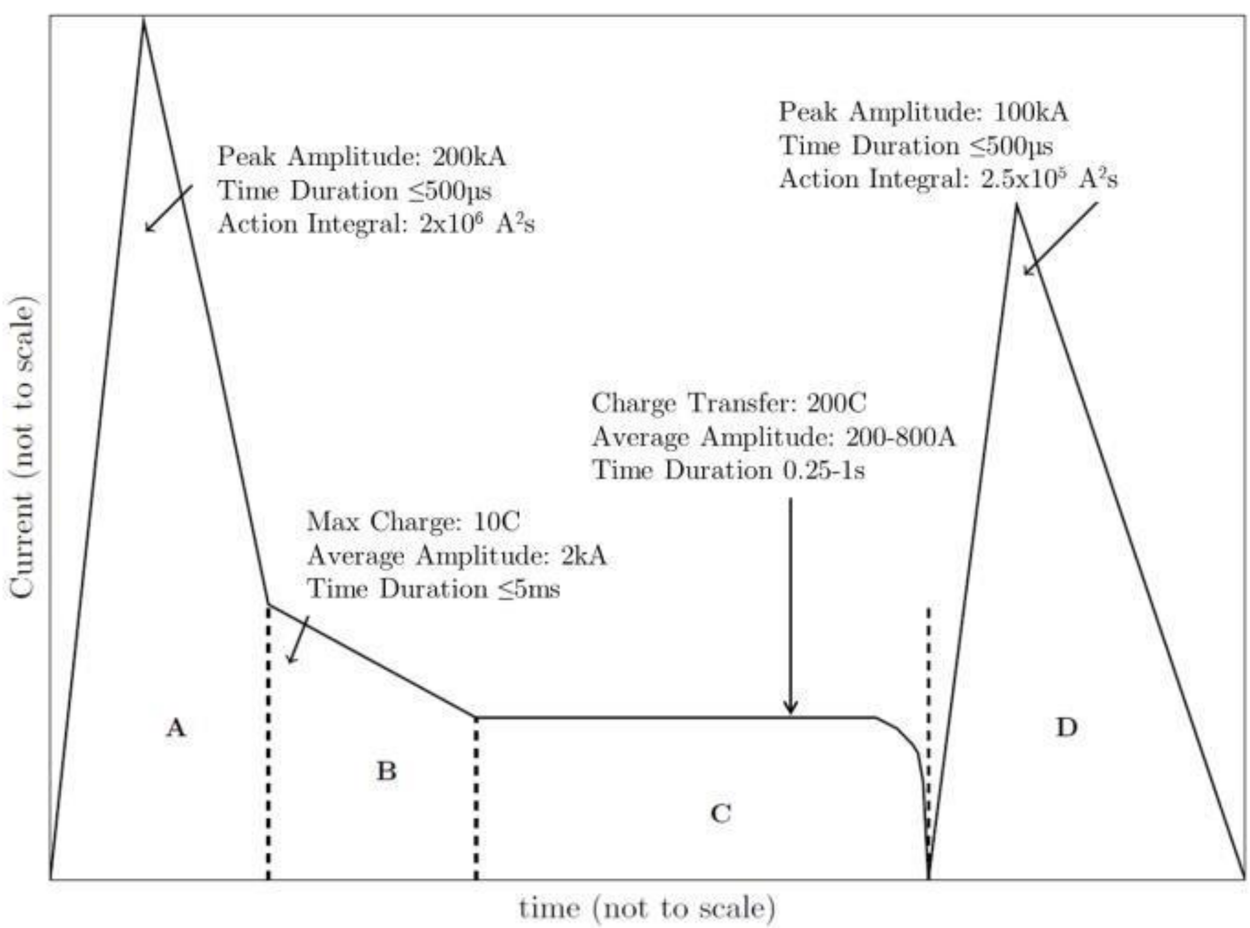
A major challenge is developing scientific testing technology for understanding the direct effects of a lightning strike. We would need to design testing parameters for complex multi-transient loads such as magnetic, electric, thermal, inertial, mechanical fatigue and others. The purpose of this review paper is focus on the existing latest material development and simulation-testing of composite LSP systems using literature based on actual experimental results. Simulations would require complex modelling systems with heavy underlying assumptions to get an idea of the very complex phenomena that lightning strikes are. This is a fairly underdeveloped aspect, and only a cursory overview will be provided on the modelling aspect. Essentially, the focus would be on the scope of testing parameters, and their limitations.

Another aspect to consider alongside the testing is the idea of damage control for the simulated testing. Most literature has been focused on aspects such as area damaged by the simulated lightning strike, and volume damaged into the material. Both aspects fall within the purview of the direct damage applied, but there is also indirect damage to be considered. This occurs mainly due to the anisotropic electrical conductivity property of composites. Factoring transient loads, and conductive pathways in modelling simulation of lightning strikes is often past the scope of most available literature. Likewise electrical conductive fatigue, is another aspect to be considered, particularly for aircrafts, and their frequent tendency to be struck by lightning (as discussed earlier) will be another aspect to be minimally considered within this paper.

Background

1. Lightning waveform by SAEARP 5412

Lightning is largely a probabilistic feature, with waveforms and current distribution varying substantially from strike to strike. However, some basic test results are summarized by the SAE ARRP 5412B standard in the below figure.



The lightning waveform standard is made of multiple strikes of different intensities and dispersion time. As can be seen, the return stroke for the first segment (Section A) is of high intensity. This is measured by the discharge caused by the negative charged “leader” electron across the surface to the positive (or neutrally charged) ground state. The important aspect is that the first strike in segment A leaves conductive pathways for the remaining charge for a smoother, less resistant discharge. Following this, a transitional component folows the first stroke of the lightning strike.

The results of Component C are more interesting. The waveform is part of the “suspension phenomenom” of aircraft due to motion of the aircraft relative to the earth. As the aircraft moves forward, the inertia of the charge causes a plateau region. The European Union Aviation Safety Agency (EASA) recommends a suspension (dwell time) of 20ms, with the minimal requirement being 50ms. Component D is considered to be the re-strike element, or the “aftershock”. Commonly, the significant brunt of damage occurs in component A and D, due to the transient loads.

2. Understanding the electrical governing equations.

Wang et Hu views the electric field through the idea that the lightning striking distance is determining the relative spatial position between the “leader” electron, and the instrument geometry. The electric field is given with the assumption of a virtually charged leader electron.

$$\nabla \times \mathbf{E} = 0,$$

$$\nabla \cdot \mathbf{E} = \rho_v / \varepsilon_0,$$

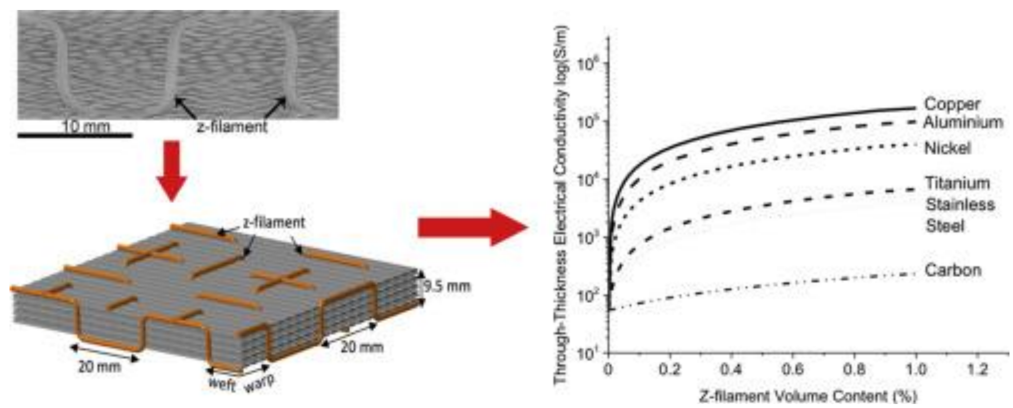
$$\mathbf{E} = -\nabla \phi$$

Here E denotes the electric field tensor, Pv is the source of the electrical charge, r is the radius of the vertical cylindrical lightning stepped leader channel, λ is the line charge density, ε0 is the permittivity of the free space, and ϕ is the electric potential.

3. Materials to improve electrical conductivity of CFRPs/GFRPs

(A.) Low resistivity Z- Filaments by S.Abbasi et al.

This strategy looks at using woven metal z- filaments made of materials with high electrical conductivity (e.g copper, etc) to improve the electrical conductivity of the entire material. A very low volume percentage (1-3% vol) is used to increase the electrical conductivity by over three orders of magnitude.



The structure was woven manually in an orthogonal pattern using long arrays of stainless steel. This was then warped to the carbon fabric in a cross-ply pattern in a 0/90 configuration before being impregnated with the liquid epoxy, as a binding agent. Vacuum bagging was used in the processing.

(B.) Multifunctional graphene/POSS epoxy resin by M. Raimondo et al.

This study looks at using carboxylated partially exfoliated graphite (CpEG) and glycidal polyhedral oligomeric silsesquioxane (GPOSS) nanoparticles to improve the electrical conductivity of the polymers. Essentially, the technique uses POSS's advantage of having covalently bonding reactive functionalties for creating longer chains. This is fairly intuitive since the chemical composition is intermediate between that of Silica and Silicone. The properties allows the POSS to have controlled motion of its chains while retaining general mechanical workability and processability of the base resin, due to it's polymer dimensions. The processing used pristine grapheme as an intercalcated graphene (IG). This was further used to create thin graphene sheets (GTFs) to create a total of 29 mono-layer sheets before being binded using an epoxy tetraglycidyl methylene dianiline (TGMDA). Particular use of GPOSS   allows full epoxidized with glycidyl groups making compatible the POSS molecule with epoxy precursors and reactive diluents. This allows gives the advantage of allowing the reaction and inclusion into the T20BD network formation during the curing cycle over conventional POSS.

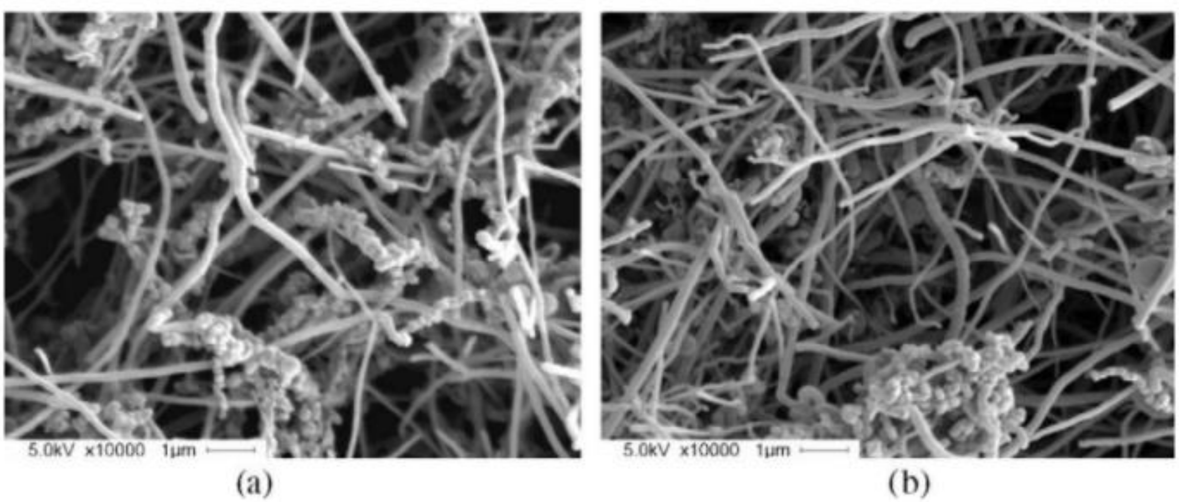
(C.) Carbon nano-fiber paper by J. Gou et al.

The electrical conductive of CFRP's are enhanced in this paper by using a combination of carbon fiber mat and Pyrograf Carbon nano-fiber to create carbon fiber paper. While carbon fiber is by itself a poor conductor of electricity, carbon fiber impregnation allowed the electrical conductivity to increase. Gou uses a base sheet of pure carbon nanofibers, and a top layer containing a mixture of nanofibers and nickel nanostrands to create the carbon nano-fiber paper. The mats were oriented at of 0, -45, 90, +45, 0, 45, 90 degrees using resin transfer moulding (RTM) to create the nano-fiber mat. Multiple methods were attempted using both

Carbon nano-fiber paper monolayer, and bi-layer. An interesting development pursued by the paper is the usage of nickel nano-strands. This is summarized in the below table.

CNFP Identification	Nickel nanostrands (g)	CNFP Structure
CNFP-1	9.75	Mono-layer paper with latex binder
CNFP-2	19.95	Bi-layer paper with latex binder
CNFP-3	19.95	Mono-layer without latex binder

In order to meet the requirements of lightning strike protection, the electrical pathway of the CNFP was modified with nickel nano-strands within the network structures of carbon nano-fiber paper, in which nickel nano-strands could efficiently bridge individual CNFs. The usage of nickel nano-strands is interesting development, since the nano-strands would allow significantly increased conductive pathways.



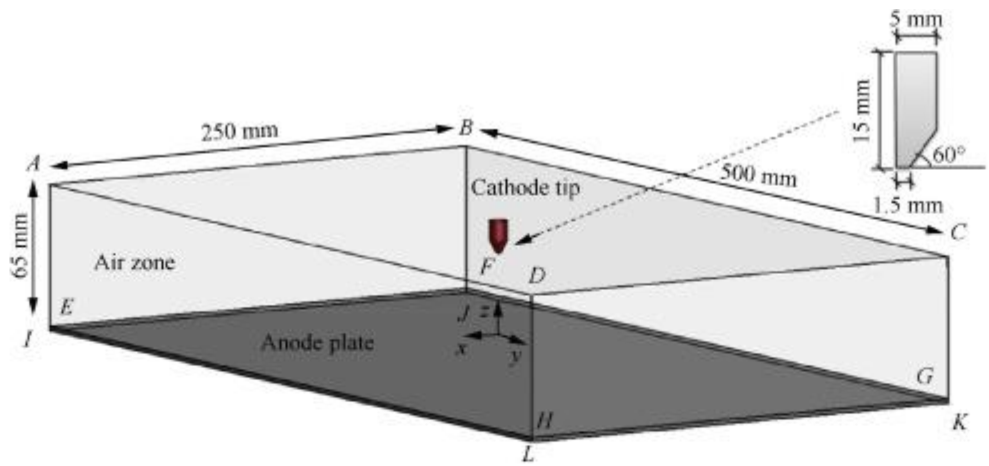
An interesting material used in this study is nano-clay, as a binding agent. The layers of dispersed clay tend to self-assemble into stacks with regular Van der Waals gaps. Thus, the CNFP could behave like a filter, preventing the silicate layers from entering the pores of the CNFP. The other side of the CNFP could retain it's open network structure this way.

Understanding the impact of lightning strikes on a thermal level

It is vital to understand the impact that lightning According the American Aviation authority, an aircraft statistically expects a lightning strike around every 10,000 flight hours. Lightning strikes delivers close to 200,000 A in a time period between 5 ms to 50ms.

A lightning strike provides an impact on magnetic, electric, thermal and inertial aspect of the object. Karch et al. studied the idea of thermal radiation by the plasma on the plane. His study determined that a minimal level of damaged was caused on the inside of the laminate, with microscopic damage only detected by tomography. He has proved a non-negligible effect on the damage to the internal micro-structures.

On a more advanced level, Xianteng et Al. performed a damage analysis of aircraft composite laminate suffered from lightning swept stroke and arc propagation. He uses a three-dimensional model of lightning with the calculation region being composed of cathode, anode plate and air zone as shown in the below figure.



The results are summarized (abridged):

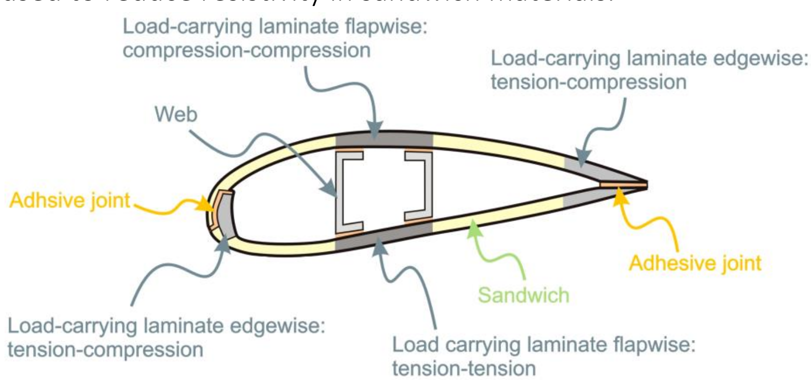
"The major conclusion was that the thermal energy rises periodically, lightning plasma leader develops rapidly from cathode tip to anode plate with the air electrical conductivity increasing Thermal plasma impingement and stagnation on anode plate surface makes arc root expand after initial attachment. At the same time, overpressure occurs in attachment region. Furthermore, the lightning discharge channel obviously distorts and expands in sweeping process. Driving by airflow, reattachment in arc root causes the whole arc plasma channel displaced from initial attachment position. Temperature in arc plasma channel decreases over time. This is however for values higher that 10000 K"

Method

1. Method for fabrication of the composite laminate

As described early, the conventional material used in aircrafts and wind turbines is Carbon Fibre. Therefore the base material throughout almost all literature is carbon fibre. A higher percentage od carbon would be desirable for a wide range of reasons. It would indicate lower weight; a compelling argument in the aviation industry, since a higher weight would require more fuel, and ergo, be more expensive. Furthermore carbon fiber allows for fairly high level of workability, variable hardness (by varying the configuration angles of carbon fibre sheets), and impressive weight bearing capability. Within the realm of this experimentation, the only aspect that we would need to change is the conductivity of carbon fibre, or in other words, find a way to massively reduce the resistivity of the material.

The easiest way to develop this is by using a low resistivity material in the polymer matrix of carbon fibre. This is the method attempted by S. Abbasi (2020) from the School of Engineering, RMIT University, Melbourne. Essentially, small sections of highly conductive thin rods were embedded into the composition material along the z-direction (along the through-thickness). This would create multiple “routes” of conductive pathways. Essentially “doping” is not a particularly new idea, but while conventional doping materials are embedded into the matrix in powder form (like carbon nano-fibres, carbon nano-tubes, graphene, metal particles (e.g. copper), polyaniline [6] or milled carbon particles) , this approach uses thin rods. The improvements in electrical conductivity can be controlled using variable volumes of the z-pins (metal rods). The improvements in the through-thickness conductivity can be controlled up to approximately 10^6 factors. An interesting advantage of this method is that z-pins can also be used to reduce resistivity in sandwich materials.

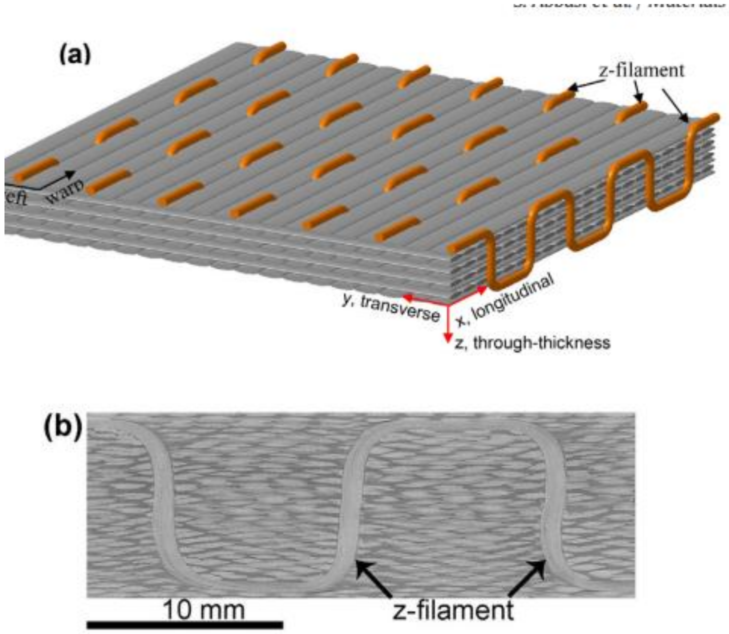


This is of particular interesting within the case of wind turbines, and allows for more aerodynamically designed lighter turbine blades, which will dramatically improve the efficiency of the system . The major limitation of the conventional rods based system is that that they do not increase the in-plane electrical conductivity because the z-pins are discrete and not connected. However, what Abassi et Al. have is a potential solution is to incorporate electrically conductive continuous filaments into composites to increase both the in-plane and through-thickness electrical conductivity.

Table 2
Volume fraction of in-plane fibres for the 2D laminate and 3D woven composites.

Z-filament	Fibre volume fraction
None	0.39
Carbon	
0.70 vol%	0.38
1.30 vol%	0.34
Copper	
0.65 vol%	0.36
1.13 vol%	0.35
Stainless steel	
0.65 vol%	0.35
1.13 vol%	0.33

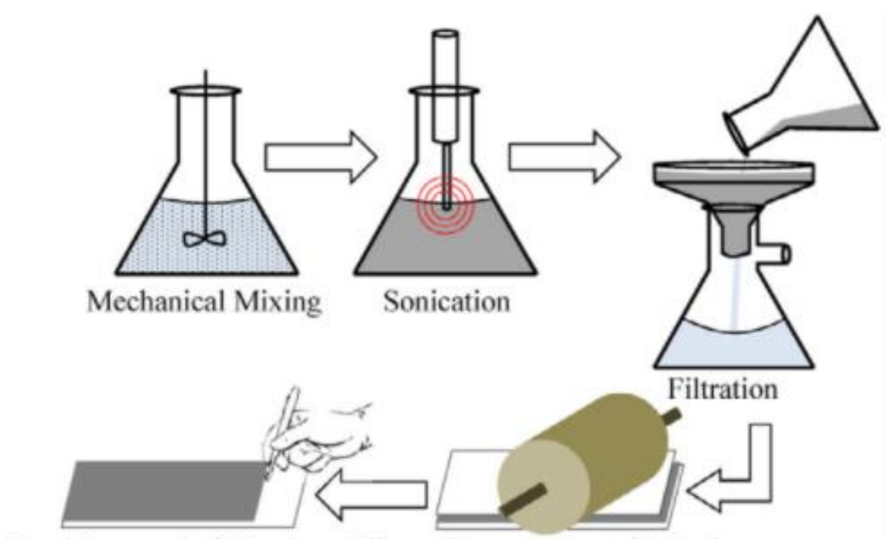
Instead what Abassi attempts to do is using 3 dimensional woven z-filaments to increase the electrical conductivity of the material. His studies have revealed that the "improvement made to the electrical properties is substantial (several orders of magnitude), and that it can be tailored via the judicious design of the z-filaments. This is demonstrated by an evaluation of the electrical properties of carbon-epoxy laminates containing orthogonally woven filaments made of thin metal wires (e.g. copper, stainless steel) or carbon tows. The volume fraction of the z-filaments is kept very low (under 1.5 vol %) to minimize any adverse impact on the mechanical properties of the composite materials"



The more conventional method for developing the polymer is either using thin sheets of a different material, or using nano-tubes (usually carbon fiber, or other such nano-composites) and impregnating them directly into the polymer matrix.

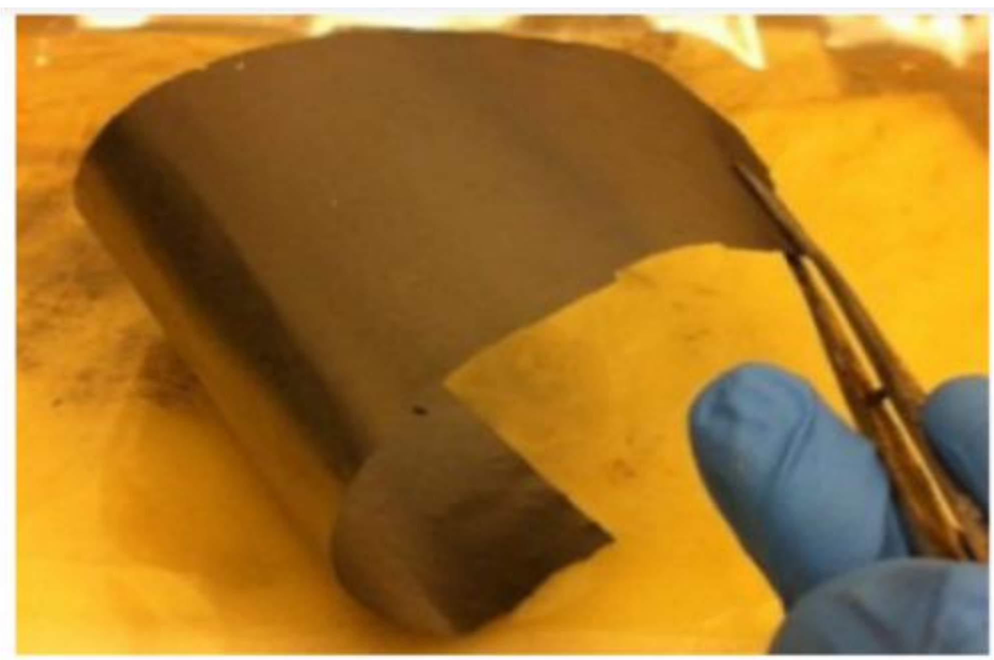
B Zhang et Al. Has attempted the idea of using thin sheets of graphene to reduce the resistivity. The concept is based on zero-overlap semimetal with electron and holes as charge carriers. Each carbon atoms has six electrons, and the four outermost electrons are available for chemical bonding, but in the 2-D plane, each atom is connected to three other carbon atoms, and one electron is freely available for electronic conduction in the 3-D space.

Essentially, the fabrication uses an extensive process involving mechanical mixing, sonication, filtration, compression with roller, and manual removal of film from surface to create thin sheets of graphene, more commonly known as Graphene Thin Film (GTF). Since the manual processing can make the results product with very different properties, the average density of each sample was calibrated to be as close to 2 g/cm^3. To ensure consistency with the carbon-fiber however, 8 sheets of carbon fiber were lay on top of one another, at pre-set angles of (0,90) degrees to ensure maximum strength. Rather the lack of consistency would only be stemmed from the GTF samples. The material was cured to ensure moisture to gain strength. Furthermore sonication was done for rapid dissolution, by breaking the intermolecular forces. This is mainly crucial since it impractical to stir the mixture.To bind the pristine graphene layer with the carbon-fiber, an epoxy based binder was used. This will be explained much later in the paper.



Correspondingly to ensure the results could be compared, several parallel (control) samples were also prepared. Firstly, a sample without applying the graphene thin film was fabricated called the pre-reg control panel. Furthermore samples were made were several layers of graphene thin films were embedded throughout the sample.

A significant advantage of the usage of the fabricated graphene thin film (GTF) is the workability, and flexibility. These are vital properties with significant use for the aviation industry. With wing designs and aircraft models evolving, particularly in terms of combat aviation, having flexible sheets of graphene thin films can significantly aid developers. Another major advantage is just how thin graphene films can be designed. A significantly lighter design would massively reduce costs. The major advantage of using graphene is the relative lightness of the material, particularly when compared to other metals, (like the metal rod system used by Abassi mentioned earlier). The major disadvantage that arises is the lack of consistency for the procedure in terms of sheet designed. Not having a consistent size, or density , or even thicknesses can massively reduce interest within the commercial aviation industry. This major downside is further augmented by the level of manual processing required. The sample required a lot of finesse in every stage of processing, and this would be both labour intensive, and time-consuming. It would be highly impractical for this process to be hand made, rather than processed in an assembly line. The intensive processing (particularly the curing) would like almost 4-5 days to develop a single sheet. For the processing to be more viable, massive strides need to be made in the processing of the fabrication.



Graphene, as is well known, goes against most conventional norms of electrical conductivity. It is one of the only non-metallic conductors of electricity, making it an unconventional choice. It would be interesting to see how graphene compares, however, to traditional metallic sheets. P. S. M Rajesh et al. has conducted intensive research on the Damage response of composites coated with conducting materials subjected to emulated lightning strikes. The team, from the Department of Mechanical Engineering, Ecole Polytechnique de Montreal used eight different coating materials to study the effect of metallic coating sheets.

The results are summarized in an abridged fashion below.

Table 1
Some conductive coatings/materials reported in the literature for lightning strike protection.

Material or coating	Electrical conductivity	Lightning strike tested?
Nickel-coated single walled nanotubes	Sheet resistance: 2–4 × 10^2 Ω □$^{-1}$ with 4 wt% nickel-coated nanotubes	Yes; reduced damage compared to unprotected specimen
Carbon nanofiber paper	34,100 S m^{-1} for panel with paper composed of 6.94 g nanofibers and 19.55 g nickel nanostrands	Yes; only 1% area of paper damaged in a zone 2A test with peak amplitude of 100 kA
Indium tin oxide (ITO) coated carbon fiber	(NA)	Yes; composites prepared with 40% ITO in colloidal suspension were better protected than composites with lower or no ITO
ITO nanoscale inclusions/epoxy	136,600 S m^{-1} at 40% ITO loading	No
Graphene nanoflakes/epoxy	5222 S m^{-1} at 8% graphene loading	No
High aspect-ratio carbon nanotubes (CNTs)/epoxy	>1 S m^{-1} between 0.4 and 1% CNT loading	No
Silver nanoparticles in colloid	63,000 S m^{-1} with 10% silver nanoparticle loading	No
CNTs + short carbon fiber/epoxy	~1 S m^{-1} with nanotubes and fibers, each loaded to 2% of epoxy	No
Polyaniline/epoxy	761 ± 135 S m^{-1} for camphorsulfonic acid doped polyaniline blended for 10 min.	No (but high voltage tests performed on the material)

2. Resin system

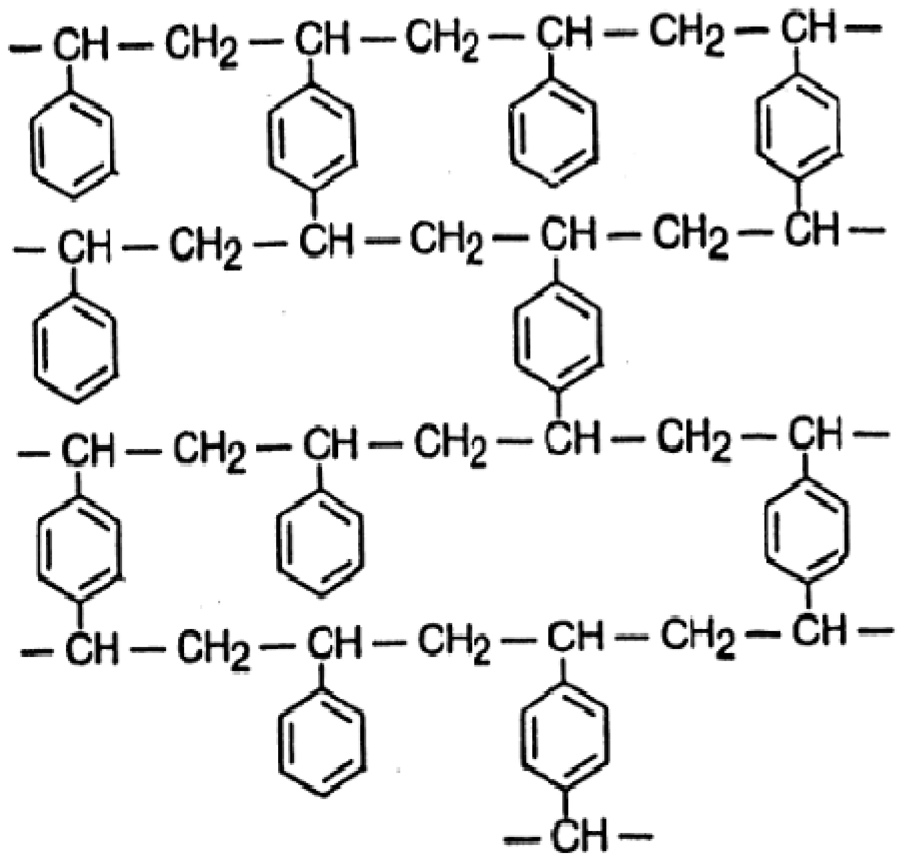
P.S.M Rajesh uses f Cycom 5276-1 resin, a toughened epoxy resin system, which falls under the category of thermoset composite. The material can be cleaned using the autoclaving process, making it a vital advantage in the aviation industry. The method uses the idea that the boiling point of water (or steam) **increases when it is under high pressure**, therefore saving time and expense. CYCOM 5276-1 resin is fairly used as a binding agent for most kinds of aircrafts, so the material has been tested for a long period of time. This means that further testing is not needed for factors like adhesion fatigue.

However certain binding agents might require significant processing. Raimondo et al. used tetraglycidyl methylene dianiline (TGMDA) with with an epoxy reactive diluent 1–4 Butanediol diglycidyl ether (BDE). This required curing with epoxy followed by Hielscher model ultrasonication, and magnetic stirring. This kind of extensive processing can be intensive but it allowed for a high level of dissolution into the initial liquid epoxy mixture, and furthermore the resin had impoved in it's flame retardancy. This is a crucial factor since even small flames occuring the fuel tank can be fatal.

While synthetic resins are fairly commonplace within conventional aircraft structurals, Gou et al. has attempted a very different type of material- nanoclay. Essentially, through sufficient treatment (which is summarized below), the clay particles are just the right size to block the pores of the CFNP, and create an impermeable sheet. The layers of the nano- clay are allowed to self-assemble into columns with divisions in regular van der Waals gaps.

Nano-filler based resin systems is a completely different type of resin, apart from epoxy resins according to Divya et al. The study used a coating of Single-walled carbon nanotubes (***SWCNT***) with nickel and **Thermosetting bismaleimide** (BMI) resin. The lightning strike damage bearing was measured against the MIL STD 1757 standard 20 (Zone 2A lightning strike), and the results showed slight improvements over conventional epoxy resin. A significant amount of data was not available though there is serious scope for research and development in this type of blends.

Another type of thermosetting resin system was developed by Yokozeki et al. The study uses divinylbenzene and has created new thermosetting resin systems. Divinylbenzene is commonly known as a cross-linking agent with low viscosity that improves the quality and performance of sheet molding composites. Yokozeki et al. emulsified this sample of PANI-DBSA. Very limited processing was required, apart from the use of a doping agent. The results were particularly staggering. The PANI-based resin (CF/PANI) had 5.92 and 27.4 times better electrical conductivity in in-plane 12 and through-thickness directions, respectively, compared with traditional epoxy-based CFRPs . This has easily the most promising of results, and even though testing was limited, there is significant amount of data, and research backing to make this a highly prospective and appealing endeavor. One of the major reasons for this the use of protonic acid, and its impact on electrical conductivity will need to be studied in significantly more detail.



Kamiyama et al. has prepared an intensive study in CFRP's by using carbon fibers but varying different kinds of resins as binding materials. Testing has been completed for epoxy (the control), bismaleimide (BMI), and polyetheretherketone (PEEK). The results were quite interesting. Fundamentally, PEEK and BMI outperformed the epoxy in terms of the simulated lightning strike, though all three samples have similar levels of insulative properties. This certainly suggests much need of development in the fabrication and research of these materials as superior alternatives to the epoxy resin based blends. Kamiyama's study has further indicated that lightning strike damage is dependant on both the electrical conductivity of the CFRP, and the usage of resin. The resin in fact plays a major role in terms of thermal degradation onset temperature and char yield of resin. This means that more intensive means of testing would need to be done on these grounds to see their performance against a wider range of metrics.

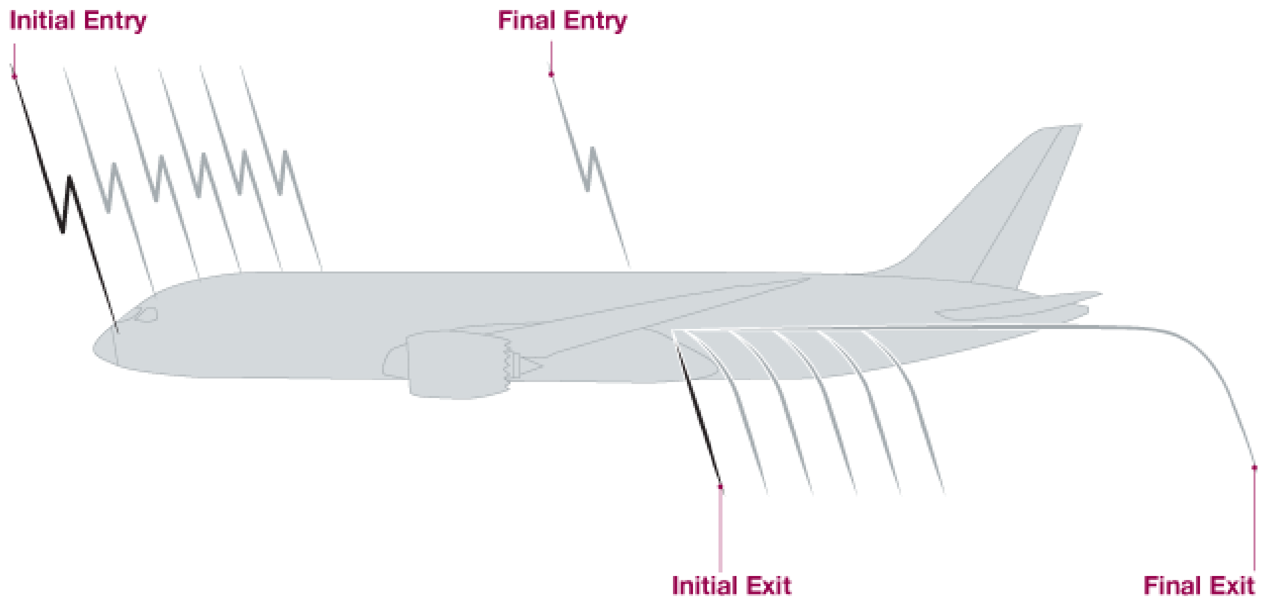
Furthermore, a superior impulse handling behaviour (impact/dynamic inertia) of thermoplastics when compared to thermosets are also studied at depth. Thermoplastics are compounds like PEEK, while thermosets are brittle compounds like epoxy. This is crucial since there is often a substantial mechanical load exerted on the aircraft during lightning strikes.

A major limitation of this very innovative approach by Kamiyama is the different volume fractions used in each of the three panels. For a more direct comparison between the resin types, a more detailed study needs to be done with the electrical conductivity, and particularly the damage attrition of the carbon fiber blends.

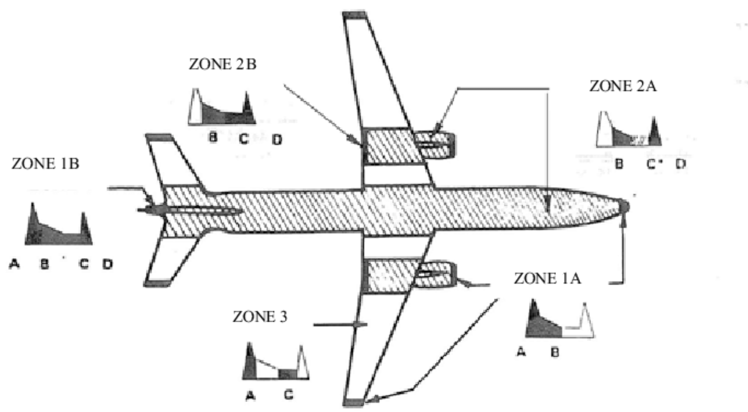
3. INSERT FLOWCHART
4. Could add finishings (refer to paint, glass coating ;Kumar)

Testing Processes

Commonly, lightning usually strikes at certain faces of the aircraft, such as the nose, or the wingtip. The aircraft uses the principle of Faraday's cage to protect the passengers, and lets the current travel through special sections on the aircraft's conductive skin, and exits via the tail.



SAE Aerospace Recommended Practices (ARP) 5414 defines six aircraft lightning strike zones, with some more prone to the occurrence than others.



Essentially, our types of electrical components are studied for direct effects. They are A,B, C snf D. Furthermore, the indirect effect is studied for aspects such as impulse, and mechanical fatigue using Component E, but that is beyond the scope of this paper. Each of these components represents a different type of lightning strike components. Either individually, or a combination of multiple components can be tested.

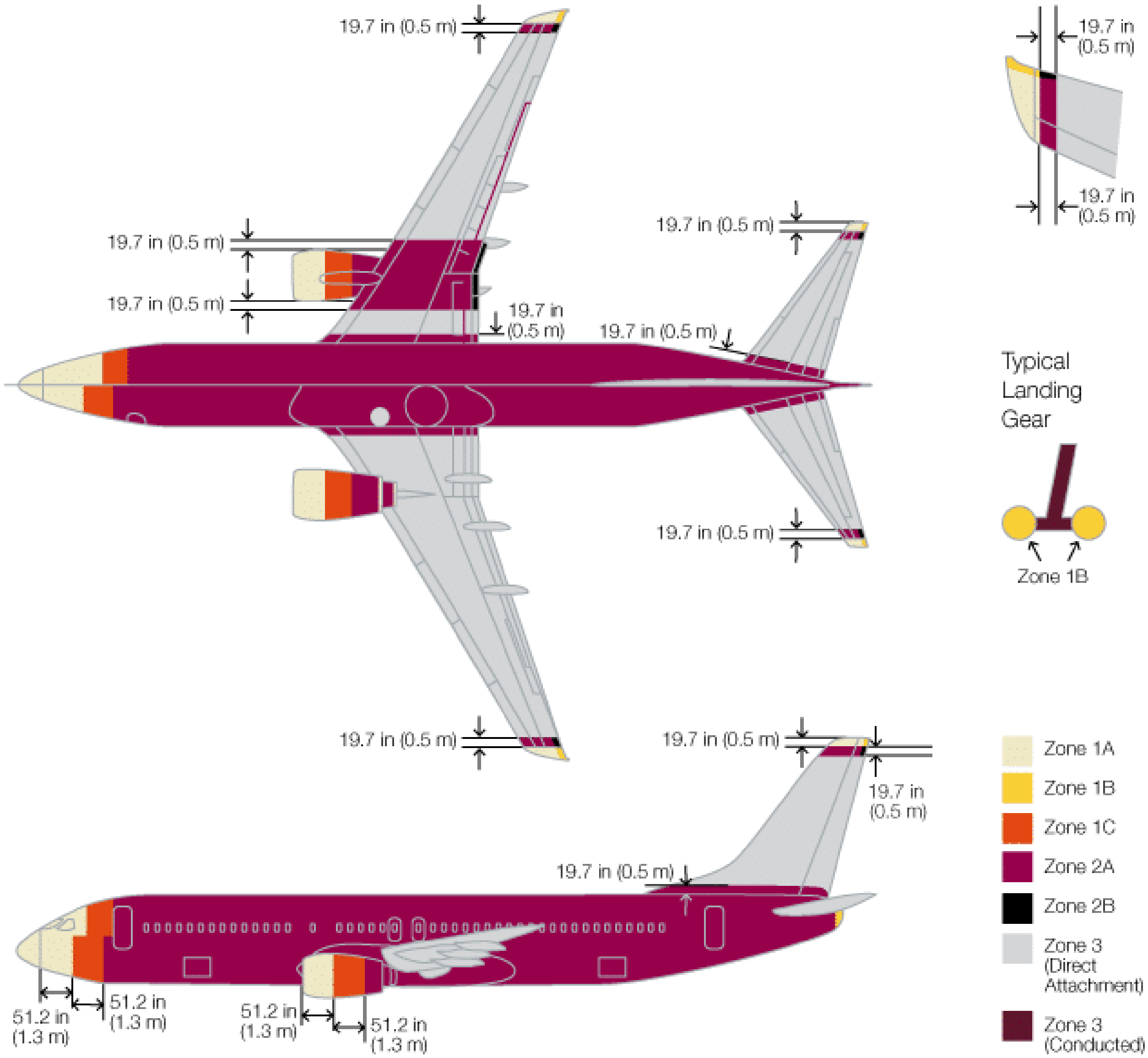
Here is the abridged version of SAE Aerospace Recommended Practices (ARP) 5414 designated zones, and style of lightning strike.

Zonal Strikes

Zone cross sections	Type of strike	Simulated strike	Impact testing

	simulated	impact	
1A	First return stroke zone	All areas of the aircraft surfaces where a first return stroke is likely to occur during lightning channel attachment with a low expectancy of flash hang on	Component A represents the initial high peak current. It has a peak amplitude of 200kA (10 percent) and an action integral (2 i dt ∫) of (20 percent) with a total time duration not exceeding 500 nano seconds
1B	First return stroke zone with long hang on	All areas of the airplane surfaces where a first return is likely during lightning channel attachment with a low expectation of flash hang on.	
1B	Transition zone for first strike	All areas of the airplane surfaces where a first return stroke of reduced amplitude is likely during lightning channel attached with a low expectation of flash hang on.	
2A	Swept stroke zone	All areas of the airplane surfaces where a first return of reduced amplitude is likely during lightning channel attachment with a low expectation of flash hang on.	Component B represents the intermediate current. It has an average amplitude of 2kA (10 percent) flowing for a maximum duration of 5ms.
2B	Swept stroke zone with long hang on	All areas of the airplane surfaces into which a lightning channel carry subsequent return stroke is likely to be swept with a high expectation of flash hang on.	
3	Other strike zones	Those surfaces not in	

	(exclusding Zone 1 and 2)	Zone 1A, 1B, 1C, 2A, or 2B, where any attachment of the lightning channel is unlikely , and those portions of the airplane that lie benath or between the other zones and/or conduct a substancial amount of electrical current between direct or sweot stroke attachment points.	
E	Indirect strike impact	All areas of the aircraft where a primary strike, or a combination of primary strikes have been struck. The indirect strike measures for factors such as friction, mechanical load, impulse, fatigue and other factors. This is much more harder to measure, and very little literature is available to be commented upon.	

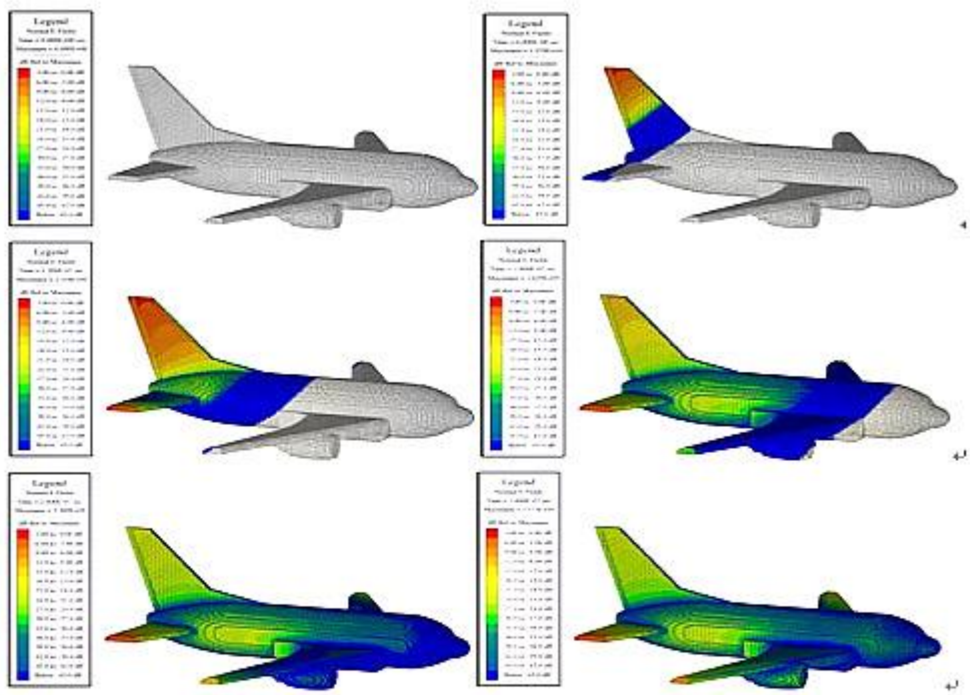


Primarily, there are two ways of developing testing standards for lightning striking protection. The first method would be to develop physical recreations using high impulse current transmission in very small periods of time. The alternate method would be recreate this in a simulation using a combination of an MCAD software alongside a certain models of civil aircraft.

Very little literature is available for simulations, but Zou Tianchun et al has made substantial progress in this regard. The model developed by Zou uses CADfix as a pre/post processer and set the current component as a plane wave excitation. The peak amplitude of it is 200 KA and the duration is 500 nano-seconds. "The current component was applied along the y-axis onto the body, setting the electromagnetic environment for the aircraft.

The actual simulation itself was set on EMA3D electromagnetic simulation platform, from which the lightning attachment points on the aircraft at different times after the strike, and the peak induced electric field from lightning at the surface of aircraft during this time had calculated.

Here is the summary of the results.

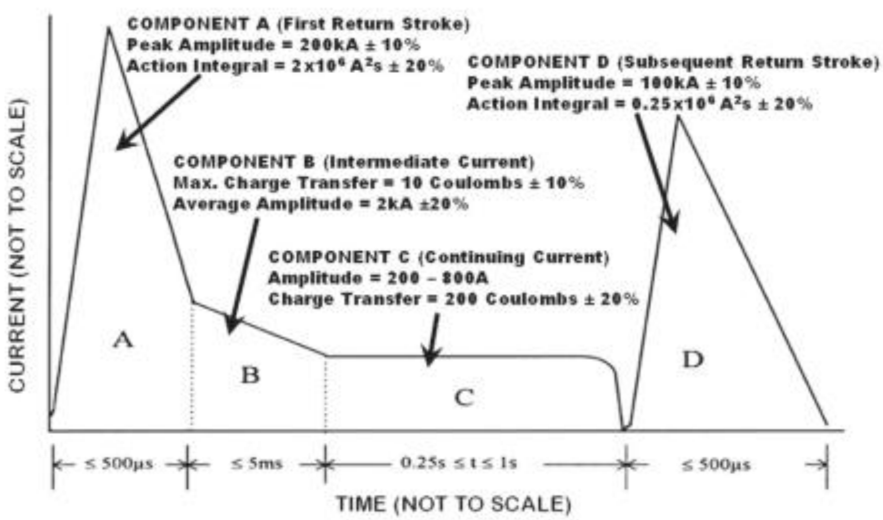


"This excitation source is the direction of the top rear of the aircraft, so the more serious lightning attachment area is the wing tip and the tail end. This is consistent with the theoretical basis for this article. According to the simulation results, not only the length of time in that lightning current spread for this composite aircraft, but also the largest induced electric field data on the aircraft during this period can be seen."

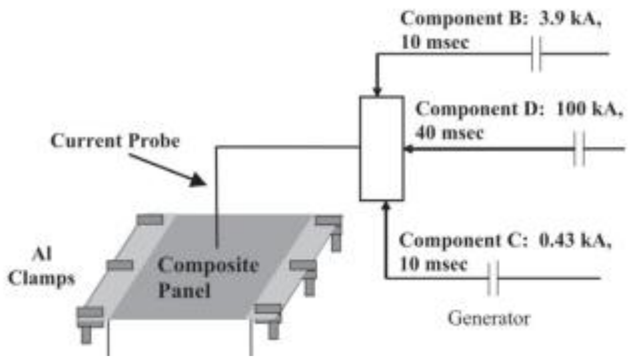
Physical testing

Physical testing is done using a standard experimental rig on most papers. Papers often differ in the actual aspect being tested (the zone), and correspondingly the exact configurations to ensure the impulse is limited across a short period of time. While most literature is focussed on a single zone testing, T. S. M Rajesh used a more structural rig to subject the sample to a standard lightning waveform, which is divided into structural sections to emulate each of the zones. The component testing is essentially segmented into 3 components A, B and C. Stroke B is taken as the transitionary zone between A and B. Furthermore, stroke D is also applied on the object, with stroke D being the second strike of a lower current when compared to A. Essentially, for measuring the impulse, the sample is clamped tightly in a metallic frame, and an arc is struck using a positive electrode (called the striker). The emulated component of the strike has a current of 40kA.The components are applied in a single smooth series, with each stroke meant to emulate a particular aspect of the strike as mentioned above. The impulse damage (as is often the case) is studied in terms of area and volume damaged, using an ultrasonic evaluation (ultrasonic non-destructive evaluation (NDE)). The area is studied for damage when compared to the ideal cuboid of perfect preset dimensions. The ultrasonic machine uses phased array pulse-echo technology to asses the damage in the composite panels. The damage is then mapped in 3D and viewed using softwares.

The setup by B Zhang is quite similar in most aspects except that it looks at 4 components strike, at A, B, C, D. The experimental current data is as follows: from component A-D: 0kA at A, 3.9 kA at component B, 0.424 kA at component C, and 100 kA at component D. The comparison is made between the side facing the current probe. The comparison is made between the graphene coated panel against the control panel to see how the current transmission varies.



The setup is quite similar with the clamp holding the panel, and current probes on either side delivering and recording the current flow. Managing the current flow in the specified time (partularly within the shortest time frame of 5ms) frame is fairly difficult, so a range has been used, to describe the zones. The time ranges can be seen in the above picture. To improve accuracy, the image actually represents the average of multiple strikes.



To account for isolation between the ends of the panel, the experimentation was done in a reverberation chamber. This chamber is capable og creating, and maintain isotropic, homogenous, sustained, uniformed, and randomly polarized fields throughout the experiment. The panel is exposed to a polarized field to account for a more varied scope of testing, and to be more realistic when measuring lightning strikes.

The reverberation chamber utilises a 3.4 m paddle wheel to create a electrical field with the frequency being regulated to as low as 100 MHz. This paddle wheel essentially sintered any flux and other electrical energy that passed through the test panels around the room until that energy was picked up at the Rx antenna. The reception regions and transmission compartment were kept separately with a buffer region being used, called the access panel by Zhang et al. This separation room would dramatically reduce the field leakage occurring and reduce any role of leakage where the receptors takes in readings. Finally, to improve the processing, the open hole measurements were taken to identify the current flow between the transmission room to the reception room. A standard input power of 50 W were applied and the energy measured on the reception side were compared to view the field leakage compared to the open hole measurements. The difference between the open-hole reference measurement and the test-panel measurement was considered to be the shielding effectiveness of the material. The open-hole reference and test-panel measurements both contained all chamber insertion losses, so when the difference between the measurements was calculated, the insertion loss was essentially cancelled out of the final SE value. “This led to an open-hole measurement of all energy that was transferred from the transmission room to the reception room. A test panel was then installed in the fixture. The same input power of 50 W was applied to the transmission compartment. The energy measured on the reception side with a test panel installed was compared to the open-hole measurement. The difference between the open-hole reference measurement and the test-panel measurement was considered to be the shielding effectiveness of the material. The open-hole reference and test-panel measurements both contained all chamber insertion losses, so when the difference between the measurements was calculated, the insertion loss was essentially cancelled out of the final SE value.

This processing attempted by Zhang et al. was found to be superior in terms of processing. It accounts for a wider scope through factors such as open hole measurement, while also having the procedure to account for ambient energy loss due to field leakage. Finally, the EMI shielding effectiveness was measure, making this a more robust testing procedure.

While Zhang et al. used open hole measurements, T. S M Rajesh et al. used Ultrasonic phased-array pulse-echo technique to identify the damage in the composite panels subjected to lightning impulse tests. Rather than using a buffer zone, this method uses water tank in an immersion technique for scanning. The rear surface was scanned with the ultrasonic test system with 64 elements and a 5MHz probe (LM-5 MHz, Zetec).