Chapter 2

Lightning strike protection systems

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Abstract

This chapter presents state of the art numerical and experimental testing procedures to investigate the efficiency of *lightning strike protection* (LSP) systems. Thus, a coupled thermal-electrical *finite element analysis* (FEA) procedure is proposed to enable the investigation of the design variables that control lightning strike damage in Graphite/Epoxy composites. The major contribution of this chapter is the formulation and verification of temperature dependent material properties, a key attribute not considered within previous literature. The proposed procedure is applied to a test specimen and the results are verified against published experimental data, illustrating the accuracy and computational cost of lightning strike simulation and the requirement for temperature dependent material properties. The procedure is then applied to a number of practical LSP systems and the simulation results are used to further understand and quantify the physical behavior that minimizes material damage. Further, this chapter investigates using multiphysics (magnetic, electric, heat transfer, and computational fluid dynamics) to model the free burning electric arc (plasma) between the cathode and the anode during lightning strike of a composite, providing an estimate of the damage caused by resistive heating and overpressure.

2.1 Introduction

A lightning strike is a thermal plasma channel, made up of high temperature and fast moving electrons (30,000 C, 5,000 m/sec), conducting significant energy within micro-seconds (40-200 kJoule/Ohm)[1]. Striking a metallic *lightning strike protection*

[1]Refers to energy per unit resistance. See Equation (2.2).

(LSP) layer with such energy leads to a series of coupled physical processes. The metallic surface heats up, melts, vaporizes and once the surface temperature reaches the critical temperature, explosive boiling occurs, which results in an ejection of a mixture of vapor and liquid droplets.

Damage from lightning strike is a major challenge when using composites for the construction of aircraft structures. The physical consequences of a lightning strike on an aircraft can be summarized as: (a) Resistive heating at the lightning arc contact point, which decomposes the polymer resin, (b) An overpressure due to the explosion of the lightning channel, which leads to the propagation of a strong shock wave in a radial direction away from the arc. The explosion is due to the fast increase in the arc temperature in the conducting channel, up to 30,000 K within a time interval of a few microseconds, (c) A magnetic force due to fast conduction in any metallic component, including for example a metallic element used as part of a LSP system.

Experimental testing of lightning strike on aircraft materials and structures is expensive. Moreover, the large number of design parameters of the composite, plus those associated with an embedded LSP system result in a vast design space, for which purely empirical design and development is very time consuming. Thus, LSP systems are typically restricted to the most feasible design of a few considered, or are limited to a known, previously used design space. Unfortunately, this can result in non-optimum designs being selected, which can in turn cause problems at a later design stage.

Reviews of LSP systems for metallic and composite aircraft are available in [1, 2]. They describe the problem, guidelines [3], lightning damage to composite, current protection solutions, and alternatives. The objectives of LSP are to minimize structural damage, prevent hazardous electrical shocks to occupants, and to prevent ignition at fuel tanks. For nonmetallic components, compliance may be achieved by designing LSP to minimize the effect of a strike or to divert the resulting electrical current so as not to endanger the aircraft. A partial list of LSP guidelines and standards developed by government, military, and industry is shown in Table 2.1. The *US Federal Aviation Administration* (FAA) guidelines are non-specific, and allow manufacturers to implement different designs and certification strategies. The *Society for Automotive Engineers* (SAE) provides *aerospace recommended practices* (ARP) that can be utilized to demonstrate compliance.

SAE ARP 5414 [4], divides the surface of an aircraft into a set of six regions called lightning strike zones that represent areas likely to sustain lightning currents (Figure 2.1) [2]. Lightning zoning is a functional step in showing that the aircraft is sufficiently protected from both direct (the focus of this chapter) and indirect effects of lightning (addressed in Chapter 1). Zone 1 will have initial lightning strikes attaching themselves to the structure, these strike locations are called attachment points, and first return strokes, with Zone 1A having low expectation of hang on, Zone 1B having a high expectation of hang on, and Zone 1C having the first return stroke of reduced amplitude and a low expectation of hang on. Zone 2 will have subsequent swept strokes or re-strikes, with Zone 2A having low expectation of hang on and Zone 2B having a high expectation of hang on. Swept strokes occur as the

Standard	Title
ASTM D4935-10	Standard test method for measuring the electromagnetic shielding effectiveness of planar materials
IEEE STD 299	Standard for measuring the effectiveness for electromagnetic shielding enclosures
MIL-STD 285	Method of attenuation measurements for enclosures, electromagnetic shielding, for electronic test purposes
MIL-STD-1757A	Lightning qualification test techniques for aerospace vehicles and hardware
RTCA/DO-160G	Environment conditions and test procedures for airborne equipment
SAE AC20-53A	Documents to support aircraft lightning protection certification
SAE AC20-155	Protection of aircraft fuel systems against fuel vapor ignition caused by lightning
SAE ARP1870A	Aerospace systems electrical bonding and grounding for electromagnetic compatibility and safety
SAE ARP 5412B	Aircraft lightning environment and related test waveform
SAE ARP 5414A	Aircraft lightning zoning
SAE ARP 5415A	User's manual for certification of aircraft electrical/electronic systems for the indirect effects of lightning
SAE ARP 5416	Aircraft lightning test methods
SAE ARP 5577	Aircraft lightning direct effects certification

Table 2.1: Partial list of guidelines and standards. The user should check for latest revision of these documents.

aircraft flies into the lightning channel, making the lightning strike *sweep* across the surface. Zone 3 would support large lightning currents between areas of direct or swept stroke attachment points. The boundaries between zones are determined by laboratory tests of lightning strikes. A hang on is defined as a lightning strike plasma channel attached to the aircraft 0.1 ms or longer.

SAE ARP 5412 [5], defines four current components (A–D) representing the lightning flash current waveforms recommended for evaluating direct effects, as shown in Figure 1.2 (p. 13). Component A represents the first return stroke. Components B and C represent the lightning environment that might be caused by intermediate and long duration currents following return strokes or re-strikes. Current component D represents a subsequent stroke. It can be seen in Figure 1.2 (not to scale), that components B and C have much lower peak amplitudes than components A and D, but a very high charge transfer. Components B and C can be interpreted as currents that bridge the initial stroke A to the subsequent stroke D. Current waveform A is applied to Zone 1 regions only. Charge transfer is defined as the electrical charge [coulomb] that is transferred from the lightning strike plasma channel to the aircraft. It is higher for a hang-on because of the longer attachment time of the hang-on to the aircraft skin.

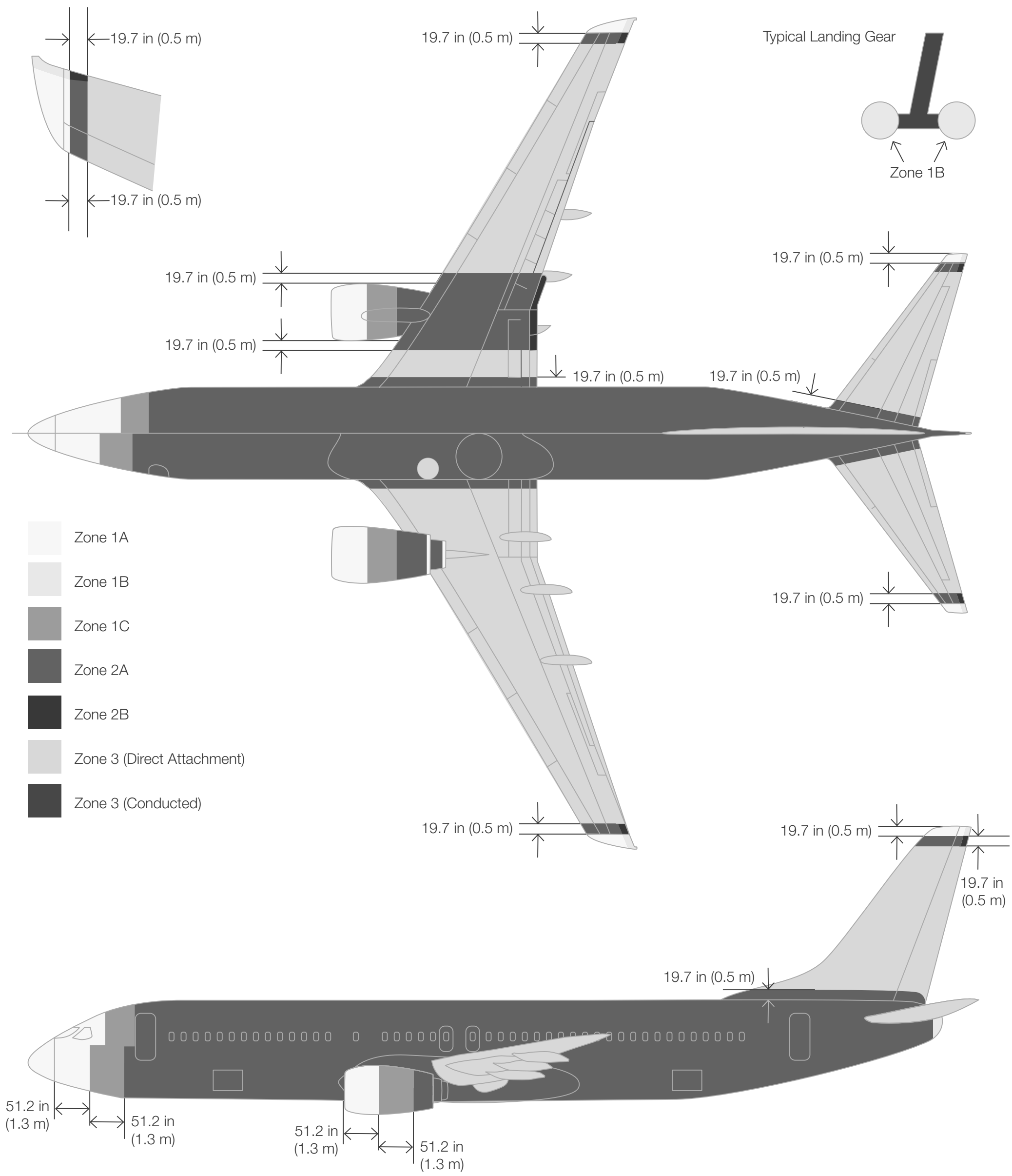

Figure 2.1: Lightning strike zones. Copyright, Boeing (2012).

COMPONENT A (First return stroke)	
Peak amplitude	200kA (± 10%)
Action integral	2 x $10^6 A^2 s$(± 20%)
Time duration	500 μs

COMPONENT B (Intermediate current)	
Average amplitude	2kA (± 20%)
Max. charge transfer	10 Coulombs (± 10%)
Time duration	5 ms

COMPONENT C (Continuing current)	
Amplitude	200-800 A
Charge transfer	200 Coulombs (± 20%)
Time duration	0.25 to 1 s

COMPONENT D (Subsequent return stroke)	
Peak amplitude	100 kA (± 10%)
Action integral	0.25 x $10^6 A^2 S$(± 20%)
Time duration	500 μs

Table 2.2: Simulated lightning current waveforms per SAE 5412 [5]. See Figure 1.2 (p. 13).

The physical consequences of a lightning strike on an aircraft can be summarized as:

a. Dielectric puncture of skin covering electrically conducting elements, which produce holes that result in direct attachment of the lightning channel to the enclosed equipment.

b. Thermal convection from the plasma lightning channel and the aircraft surface.

c. Exploding conductors due to lack of sufficient cross section area to transfer the lightning current.

d. Resistive heating at the lightning arc contact point that decomposes the FRP resin.

e. Thermal sparking at interface joints between two parts with insufficient cross section area to transfer the lightning current.

f. Voltage sparks due to induced voltages in the aircraft structure or wiring.

g. An overpressure due to the explosion of the lightning channel, which leads to the propagation of a strong shock wave in radial direction away from the arc. The explosion is due to fast increase in the arc temperature in the conducting channel, up to 30,000 K within a time interval of a few microseconds.