Non-Destructive Evaluation and Performance Metrics of Lightning Strike Protection System

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ABSTRACT

The increasing use of composite materials in aircraft structures has led to higher risk of damage from lightning strikes. New approaches have been developed to protect composite skin aircraft that are more vulnerable to damage from lightning strikes than aluminum skin ones. Those lightning strike protection (LSP) systems typically include increasing the electrical conductivity of the outer layer of the composite skin with conductive foils, meshes, or other approaches. During the development of LSP systems, an objective performance characterization method is needed to compare them. This is typically performed by measuring the maximum depth, average damage depth and damaged area using non-destructive ultrasonic testing (UT). This paper investigates the use of other metrics that might be more appropriate to characterize lightning strike damage. Damage area detected by pulsed thermography and ultrasonic measurements are compared. Several metrics, such as flaw size, maximum damage depth, and total volume damage are used to rank the performance of LSP systems. It is shown that for a similar maximum material damage depth, the area and volume can change significantly. In addition, ranking using the deepest or average depth flaw does not always correlate with ranking using volumetric data.

KEYWORDS: non-destructive evaluation, thermography, ultrasound, composite, lightning strike protection

1 INTRODUCTION

Aircraft are commonly struck by lightning. Commercial and military aircraft can expect to be struck by lightning once every 1,000-10,000 hours of flight time (SAE Aerospace, 2013a)(Black, 2013). While this is seldom an issue for aluminum constructed aircraft, where even the worst-case lightning (200 kA) can be quickly conducted away, it is problematic for less conductive composite aircraft. Therefore, lightning strike protection (LSP) is crucial for composite aircraft.

LSP provide a continuous conductive path of low resistance over the entire aircraft exterior. Typically a fine, lightweight metallic mesh is embedded in a surfacing film, or within the outer laminate ply. It is placed in contact with metal bonding strips or other structures that connect the outer conductive surface to a metallic ground plane, such as an engine or other metal conduit in the fuselage.

LSP testing involves evaluating both direct and indirect effects of lightning strikes. The SAE ARP 5416 (SAE Aerospace, 2013b) provides recommended practice to simulate lightning tests for the evaluation of indirect effects, direct effects, and fuel systems tests. There are many parameters to consider before conducting lighting testing such as the target lightning zone, the type and configuration of test specimens, waveform intensity, success criteria, and more.

Different areas of an aircraft are susceptible to different rates of lightning attachment and current conduction between entry and exit points. Lightning zone designations SAE ARP 5414A (SAE Aerospace, 2012) categorize these areas and layout the specific requirements for proper LSP. There are three possible regions of aircraft that can be split into six different zones. Briefly, these are: regions susceptible to first return strokes (Zone 1), regions susceptible to swept strokes (Zone 2), and areas where lightning is unlikely to attach (Zone 3). These regions can be split into a total of six zones that are distinguished by whether or not hang on occur. Zoning definitions are presented in Table 1, and the typical Zone locations on a commercial aircraft is presented in Figure 1. Areas such as the fuselage are classified as Zone 2A because they are not likely areas of first strokes but are susceptible to less intense subsequent return strokes due to the swept stroke effect. Wings, except the wing tips, are generally considered Zone 3 since they are not susceptible to strikes. They do, however need to safely conduct current to lightning discharge points.

Table 1 Lightning Zone Definitions for Commercial Aircraft (Sweers et al., 2012)

Zone Designation	Description	Definition
1A	First return stroke zone	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	First return stroke zone with a 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.
1C	Transition zone for first return stroke	All areas of the airplane surfaces where a first return stroke of reduced amplitude is likely during lightning channel attachment 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.
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	Strike locations other than Zone 1 and Zone 2	Those surfaces not in Zone 1A, 1B, 1C, 2A, or 2B, where any attachment of the lightning channel is unlikely, and those portions of the airplane that lie beneath or between the other zones and/or conduct a substantial amount of electrical current between direct or swept stroke attachment points.

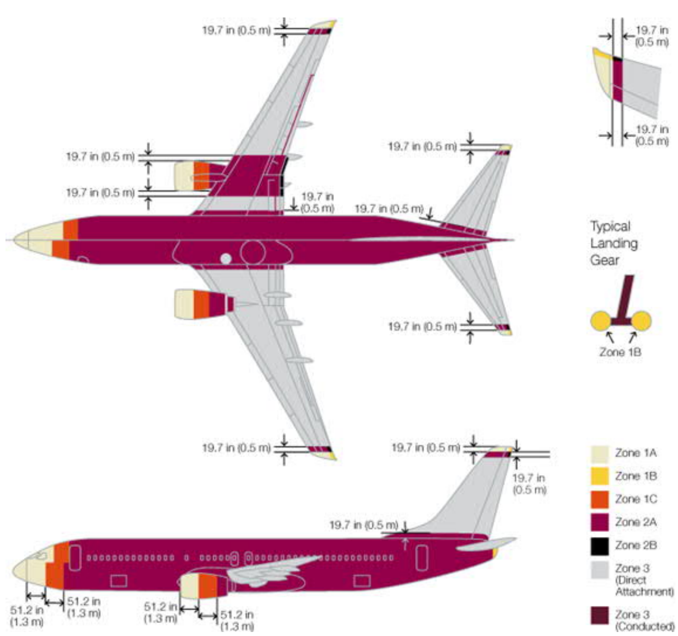


Figure 1: Depiction of lightning zones on a commercial aircraft (SAE Aerospace, 2012)

Lightning strike damage depends on the type of aircraft skin material and finish, dwell time, and lightning currents at the attachment points. For carbon fibre composites, thermal effects are more pronounced than for aluminium. Because of the thermal conductance and low electrical conductivity, resin often melts, vapourizes, or delaminates fibre plies. Composite materials may experience embrittlement or vapourization of the resin, delamination or burn through, and fibre breakage. Bonding between resin and fibres tends to breakdown resulting from temperature rises. Gases from vapourization may be trapped inside the structure and may release explosively.

Fibre damage is often caused by peak current, while electrical charge causes resin damage, and delamination is caused by action integral. As a general rule, mechanical effects from current peaks lead to breaking, delamination, and puncture while continuing current leads to thermal effects such as to melting or puncture. CFRP materials are at greater risk of shatter since they are not as ductile as aluminum. This often increases damaged area in relation to physical depth.

In contrast, aluminium skins will be at greater risk of melting but their ductility means they will suffer less from acoustic shock than composite structures (Rupke, 2012). For metal structures, high currents form at points in the airframe and may cause damage. Additionally, lack of electrical bonds between structural parts may lead to arcing. Care must be taken to avoid these arcs, especially if in the vicinity of a fuel tank.

Post-test evaluation depends on what the tester has decided criteria will be. A combination of destructive and nondestructive evaluation techniques may be employed. It is recommended to use visual inspection and ultrasound to assess the damage area, while X-radiography technique is optional (Kovach, 2013). More specifically, for the ultrasound inspection, it is recommended to perform pulse-echo from both side of the panel, and measurement should focus on the damage area and maximum damage depth.

Although, LSP is relatively thin and light, it can still add significant weight to the aircraft due to their widespread use over composite fuselage and wings. For example, based on its fuselage size and typical LSP areal weight, it is estimated that the B787 uses over 2 tons of metal mesh just for lightning strike protection. Thus, research and development in LSP are focused at developing new, less weight-intensive and more efficiently processed options. In this paper, ultrasound measurements are compared with pulsed thermography measurements in terms or damage areas, maximum damage width and height. In addition, an estimated overall volume damage is performed on the ultrasonic data to identify several LSP schemes, some of which novel being currently developed at the National Research Council of Canada.

2 EXPERIMENTAL SETUP

2.1 Material

Fifteen 12 x 12 inches carbon fibre composite panels were used in this work. Three baseline panels, without LSP protection (LSP A), were only primed and painted. Other panels were covered with various LSP schemes, then primed and painted similar to a typical white aircraft-grade paint. Due to sensitive nature of the data the schemes are not detailed further in this paper, and are referred to as letter B to G.

2.2 Lightning test

Lightning direct effects tests were performed on 15 carbon fibre composite panels, including 7 different LSP, and 1 baseline. Tests were conducted in order to determine the ability of the applied protection schemes to minimize lightning strike damage. Testing was conducted in accordance with the general guidelines of SAE ARP5416, for strike zone 1A, 2A and 3.

2.3 Ultrasound testing

Ultrasonic inspections were carried out in pulse-echo mode from the back side of the panels. The inspections were carried out using 3-axis gantry system with a 0.040 inch point step and increment spacing and a 5 MHz contact probe, coupled with water. C-scan images of the damage areas were generated. For each data point, the full waveform was recorded and damage depth was estimated based on the reflection. Maximum damage width, height, depth and area were determined. In addition, the overall damage volume was obtained by integrating the depth over the damage area.

2.4 Pulsed thermography

Pulsed thermography (PT) is an NDE method that uses thermal stimulation to detect defects through the generation of thermal contrast. It consists of heating the specimen and monitoring the surface temperature evolution over time. After the excitation, the surface temperature increases (in the case of warm excitation) and decreases due losses associated with thermal diffusivity and convection from the environment. The thermal diffusion is affected by the presence of discontinuities in the structure or changes in material properties. These discontinuities change the propagation of the thermal wave and cause a temperature difference between sound and defective areas. The PT experiments were carried out using commercial system that employed 4,800 J Xenon flashes and equipment with a longwave (8–12 μm) infrared camera to monitor the surface temperature.

3 RESULTS AND DISCUSSIONS

Photos representing the visual damage in panel with LSP scheme A, B and G are presented in Figure 2. Ultrasonic and thermography results are presented in Figures 3 and 4, and Tables 2 and 3. Qualitatively, they all appear to be similar and provide a good idea of the shape and area of the damage. The ultrasonic and thermography results have the advantage of the photos, that they can be used to identify subsurface damage. While the ultrasonic allows for depths measurements and volumetric damage estimate, the inspection required access to the back surface, while the pulsed thermography provided similar damage areas, but not allowing for depth and damage volume estimation.

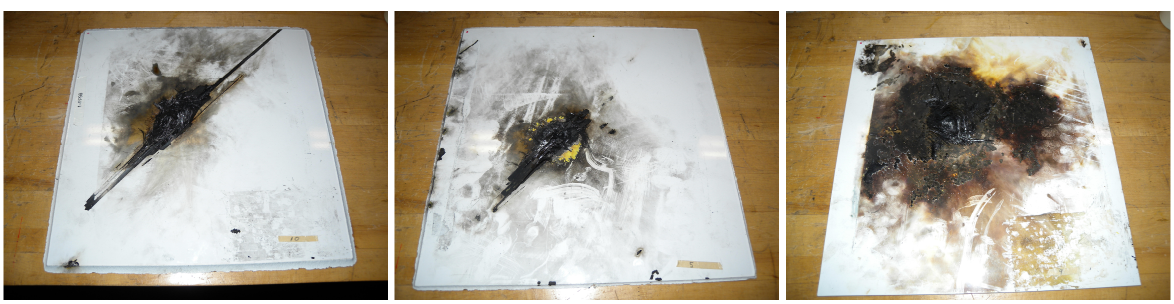


Figure 2: Photos of lightning damage in panels with LSP A, LSP B, and LSP G

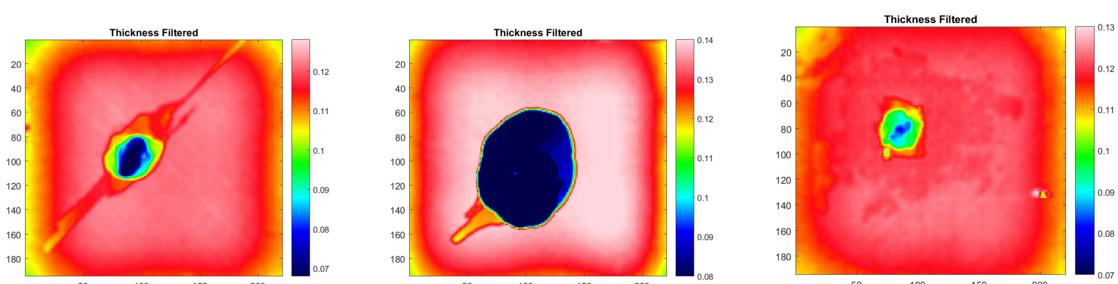
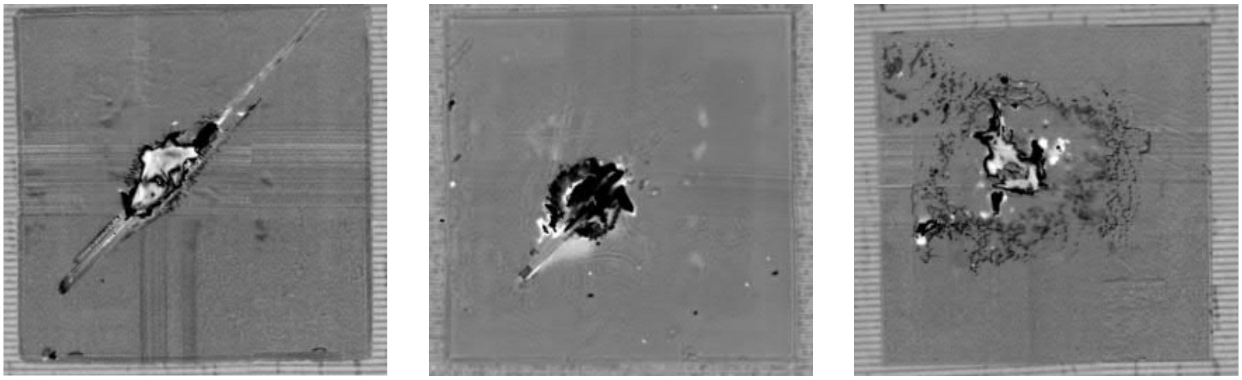


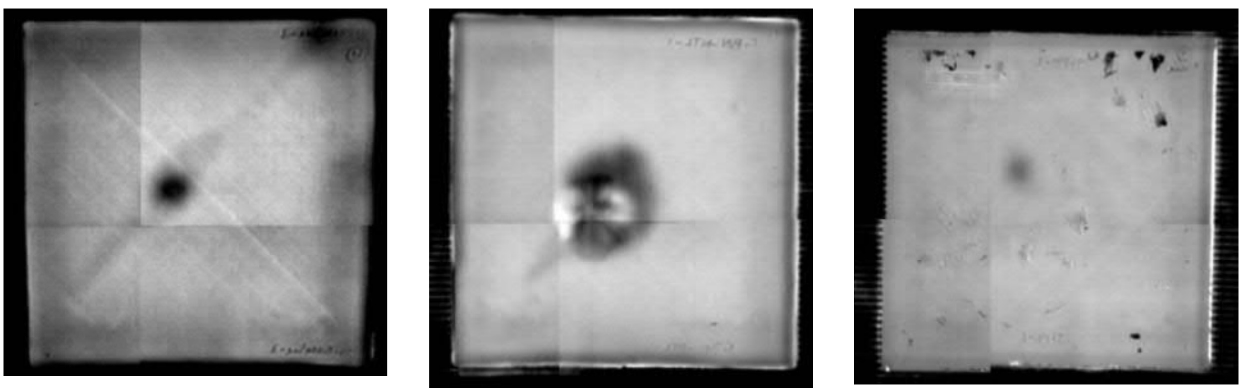
Figure 3: Damage depth in inches for LSP A, LSP B, and LSP G obtained by ultrasonic measurements

Summary of the ultrasonic damage sizing is provided in Table 2. It can be seen that if damage area, or maximum width, or maximum height are used as performance metrics, LSP G would appear to have a better LSP scheme. On the other hand if the selection is based on maximum depth, LSP D and H would be better. Furthermore if the estimated damage volume is used both, LSP G and H would be considered to have similar performance.



LSP A – Front LSP B – Front LSP G – Front

Figure 4 Damage area obtained by pulsed thermography from the strike surface



LSP A – Back LSP B – Back LSP G – Back

Figure 5 Damage area obtained by pulsed thermography from the back surface

The thermography measurements provided similar results in terms of maximum width and height, and based on those, LSP scheme G would be considered the better scheme closely followed by B, D and H. In addition, one can get an idea of the damage depth by observing the contrast in the thermographic images obtained from the back side. Stronger contrast over the damage area, as seen in Figure 5 LSP A and B shows deeper defect, while no to slight contrast such as in LSP G, indicate a shallower damage.

Table 2 Damage estimation by ultrasonic measurements

LSP ID	Thickness (inch)	Area ($inch^2$)	Maximum Depth (inch)	Volume (in^3)	Max Width (inch)	Max Height (inch)
LSP A	0.119	5.7	0.059	0.14	7.5	6.9
LSP A	0.118	7.9	0.063	0.13	8.7	8.8
LSP A	0.126	5.1	0.064	0.14	8.3	8.7
LSP B	0.130	17.6	0.108	1.20	5.4	5.7
LSP C	0.131	10.4	0.071	0.19	7.8	8.0
LSP D	0.120	9.7	0.024	0.10	3.9	4.0
LSP E	0.128	10.5	0.079	0.23	9.6	9.7
LSP E	0.130	11.8	0.069	0.22	7.9	8.2
LSP F	0.122	7.8	0.661	0.15	7.3	7.9
LSP F	0.125	6.2	0.073	0.13	4.0	4.8
LSP F	0.129	7.5	0.073	0.17	4.2	5.0
LSP G	0.110	2.2	0.045	0.05	1.6	1.9
LSP G	0.117	4.4	0.043	0.07	2.7	2.3
LSP G	0.120	4.1	0.040	0.06	2.1	2.5
LSP H	0.111	10.2	0.020	0.05	3.9	3.8

Table 3 Estimation of damage by thermography measurements

LSP ID	Max Width (inch) - Front	Max Height (inch) - Front	Max Width (inch) – Back	Max Height (inch) - Back
LSP A	7.7	7.2	5.4	5.0
LSP A	9.7	10.2	2.9	3.3
LSP A	8.6	8.5	8.4	8.4
LSP B	4.3	4.5	4.9	5.1
LSP C	7.6	7.9	7.6	7.4
LSP D	4.1	5.3	4.2	3.9
LSP E	10.6	11.3	9.9	9.9
LSP E	9.0	10.1	9.0	9.1
LSP F	7.4	8.1	7.1	7.8
LSP F	4.1	4.8	4.1	4.7
LSP F	4.6	6.3	4.0	4.7
LSP G	2.8	3.7	1.4	1.4
LSP G	3.4	3.5	1.2	1.1
LSP G	3.6	4.3	1.2	1.5
LSP H	4.1	4.8	4.4	4.1

Since there is no clear single LSP scheme outperforming all others based on the various metrics, there is a need to perform further tests. To identify the best LSP schemes based purely on the NDE results, it is recommended that destructive testing, such as compression after lighting strike impact, be carried out. Only once these results are available and can be correlated back to the NDE data can the proper metrics be selected. Nonetheless, the NDE measurements carried out here out are still useful as, even without correlation with residual panel strength, they can be used to rapidly discriminate the potential LSP candidates. In our case, LSP A, B, C, E and F clearly underperform the other schemes in all metrics; and thus reduces the LSP candidates from 8 to 3.

4 CONCLUSION

Pulse-echo ultrasonic testing and pulsed thermography were carried out on composite panels covered with different types of LSPs subjected to lightning strike to quantify the damage area/volume. Based on those non-destructive evaluation results it was possible to identify 3 lighting strike protection schemes that performed better than the others. However, among those three, there is no clear outperformer as it depends on the selection criteria, performance metrics, used to rank the LSP schemes. The NDE results need to be calibrated with the panel residual strength and subsequently identify the best LSP scheme and performance metrics, which is the subject of future studies.

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