AUTOMATED FIBER PLACEMENT OF LIGHTNING PROTECTION SURFACER FOR CARBON FIBER REINFORCED PLASTIC

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1. ABSTRACT

Carbon fiber reinforced plastic (CFRP) aircraft skins having complex curvature are often fabricated using a process called automated fiber placement (AFP) to consolidate the CRFP prepreg. This process uses specialized robotic application equipment to apply very narrow strips of CFRP prepreg edge-to-edge in layers across the surfaces of the layup. Each strip can be oriented to tailor the physical properties of the final part as desired. Application of expanded foil-based lightning strike protection films have been attempted through AFP equipment; however, protection performance is difficult to obtain with the narrow format of the material and the material does not resist the dynamic forces encountered in the robot. A conductive lightning strike protection prepreg has been developed for application through AFP machines at widths down to 6.35 mm (0.25 inch) wide. This narrow conductive prepreg has been created to be robust enough to survive the dynamic forces introduced by the AFP robot during the application process. Layup of this conductive prepreg can be applied by the AFP robot, in a tailored fashion, on a part to balance weight against strike protection levels for elevated efficiency and speed. This paper reviews the design, construction, application and test results achieved with this Lightning Strike Protection prepreg.

2. ACRONYMS AND SYMBOLS

AFP = automated fiber placement
ATL = Automated tape layup
CRFP = carbon fiber reinforced plastic
EM = electromagnetic
FRP = fiber reinforced plastic
gsm = grams per square meter
LSP = lightning strike protection
LSP Ribbon = LSP surfacer in a format for AFP machines
Ω = Ohm
mΩ = milli-Ohm
□ = square, unitless
µm = micro-meter

3. BACKGROUND

Fiber reinforced resin matrix composite materials are used in airplanes, wind generators, automobiles and other applications where stiff, light-weight materials, or parts consolidation are beneficial. The fibers are often made of carbon, glass, ceramic or aramid, and the resin matrix is an organic thermosetting or thermoplastic material. These composites are generally semi-conductive or insulating to electric current. To protect against lightning damage, a manufacturer often provides a low resistance pathway within the external skins to conduct the electrical current from one strike location to the other. Metallized materials have been used on the exterior surfaces of composite parts to provide the necessary electrically conductive region. Typical metalized materials include metal woven fabric, random non-woven mat, solid foil, and foraminous metallized sheet.

LSP material on the exterior of an aircraft is expected to:

- provide to the underlying composite structure a necessary measure of protection from strike induced damage,
- enhance the electrical conductivity of the underlying composite structure as required to support the enclosed systems,
- impact the weight of the aircraft minimally,
- conform to the contoured exterior surfaces,
- provide smooth, pin-hole free, paintable surfaces,
- resist corrosion and damaging effects from a suite of fluids and environments,
- integrate into the fabrication processes of the underlying composite structure, and
- be repairable.

Several of these objectives are exclusively or substantially controlled by the resin in the system. The resin-controlled objectives are not examined in this paper.

Wide area foraminous conductor foils for exterior aircraft use, are typically applied as large sheets cut from rolls of material that are about 1 meter wide. To adhere to the tools, the LSP surfacer must have two characteristics of import. It must be sufficiently flexible to conform wrinkle-free over surfaces having curvature in more than one axis and be sufficiently tacky to adhere to the surface well enough to retain the conformed wrinkle-free shape.

To fabricate aircraft skins, many layers of fiber reinforced plastic prepreg must be applied to a preform. To manage the quality, accuracy, labor, and cycle time of the fabrication processes, automated ply layup equipment is most often used for skin fabrication. AFP and ATL equipment are used ubiquitously to deposit prepreg ribbons in these applications. It was considered beneficial to be able to deposit LSP with the same equipment used to layup the FRP preform. AFP machines deposit the narrowest fiber, and therefor were considered the most challenging application of a LSP surfacer and are the subject of this study.

AFP machines are optimized to apply FRP prepreg. The stiffness and tack characteristics of FRP prepreg are markedly different than the stiffness and tack characteristics of the LSP surfacers intended for wide area application. In an AFP machine, the fibers are pulled from the creel to the head and pushed through the head for deposition at the tool surface for consolidation. To survive this, the ribbon (sometimes called the tow) must have adequate tensile strength to prevent breakage between the spool and the head, and adequate rigidity to prevent buckling between the head and the tool surface. These strength and stiffness properties are diametrically opposed to the qualities of a wide area LSP surfacer needed to conform wrinkle-free over complex curved surfaces. For this reason, LSP surfacers used for wide area application do not function well in AFP machines.

4. INTRODUCTION

AFP machines deposit FRP prepreg in ribbons 6.35 mm, 12.7 mm, or slightly wider. To create a LSP Ribbon, the objectives were as follows.

- It is desirable that a direct lightning strike does not cause damage worse than what is expected with wide area conductors.
- The electrical sheet resistance of the resulting application is expected to be comparable to wide area LSP applications.
- The installed weight is expected to be comparable to wide area LSP applications.
- Application should be made with an industry-standard AFP machine.
    - The ribbons must feed through the AFP machine without jamming.
    - The application must be in a sustained operation without resin accumulation on the machine, or breakage of the ribbon.
    - The ribbon must exhibit sufficient tack to remain in the intended position on surfaces having typical compound curvatures.

Design of Lightweight Perforated Copper Foil for Lightning Protection of Fiber Reinforced Plastic [1] describes foraminous conductors designed for wide-area application. These conductors were designed for application as large sheets, although the principals can be applied to design conductors for deposition by AFP. This work describes the design, application and testing of a unique LSP surfacer solution applied by AFP. The work described and conducted in the publication was a screening effort to confirm feasibility of the approach.

5. APPROACH

To obtain the strength of the LSP Ribbon needed to feed through the AFP machine without breaking, it was deemed necessary to create a new lightweight LSP conductor with tensile strength sufficient to survive the web path of an AFP machine. The principals described in Engineered Lightning Protection Conductor [2] were applied to design a foraminous foil of similar geometry to the geometry described in Unitary Expanded Metal Mesh Having Linear Down-Roll Strands [3]. The conductor was perforated to create a pattern of continuous down-web strands connected by infrequent cross-web stabilizing strands as shown in Figure 1.

To provide tack sufficient to hold the applied ribbon to the tool surface, the foraminous conductor was impregnated with a tacky epoxy surfacing film such that the epoxy resin was used on both faces of the ribbon. See Figure 2.

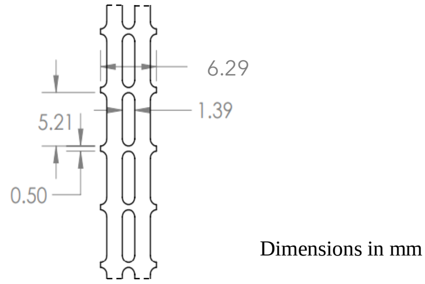


Figure 1 Perforated Conductor

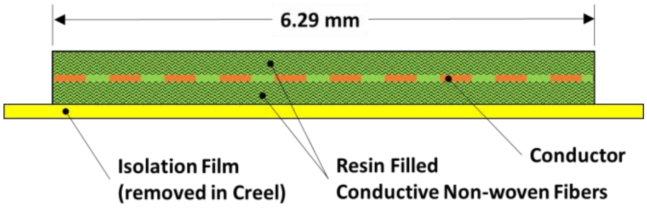


Figure 2 LSP Ribbon Cross Section Illustration

To provide necessary sheet resistance to manage the damage at and near the strike site, and to manage the installed weight of the LSP surfacer system, electrical conductivity was provided by managing the layup of the LSP Ribbons and by embedding conductive non-woven fibers into the epoxy resin on each face of the LSP Ribbon as described in Protection Film [4]. The LSP Ribbons were oriented in the layup to bias the conductivity as needed to minimize the weight impact of the LSP. The conductive non-woven fibers provide conductivity between overlapping LSP conductors. (See Figure 3) This reduced the electrical potential gradient between overlapping LSP conductors to reduce damage from arching at and near strikes.

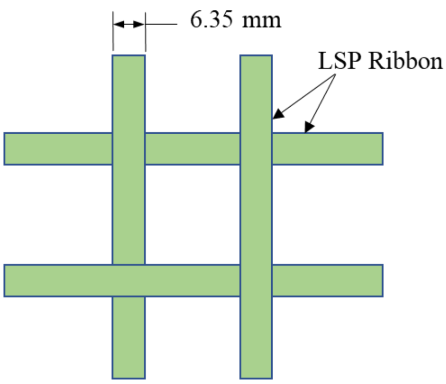


Figure 3 Overlapping LSP Ribbons

To provide stiffness to the LSP Ribbon needed to feed it through the AFP machine without jamming, the embedded conductive non-woven fibers on each face of the ribbon (see Figure 2) were made with carbon fibers.

6. CONFIGURATION

Each ribbon was nominally 6.29 mm wide. Figure 2 is a cross sectional illustration of the LSP Ribbon created for this evaluation. The impregnated construction weighed 236 gsm at 0.173 mm thick, without liners. The LSP Ribbon was symmetrical about the conductor and was delivered to the AFP machine level-wound on a spool with a polyethylene separating film on one face on the ribbon. Each component of the construction is further described below.

6.1 Conductor

The conductor was 18um thick copper foil perforated with the pattern shown in Figure 1. It exhibited 1.84 mΩ/□ sheet resistance in the long direction of the ribbon.

6.2 Resin

The resin (see Figure 2) was a B-staged epoxy. It encapsulated the conductor with equal thickness covering each face of the conductor.

6.3 Conductive Non-Woven Fibers

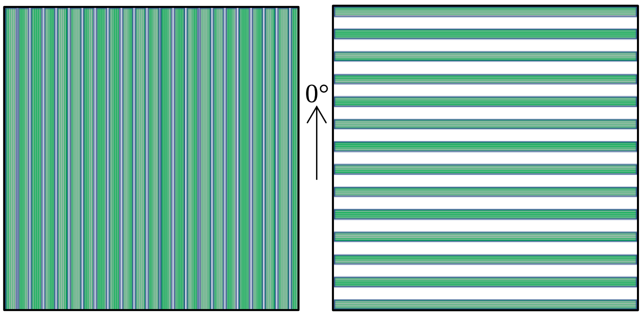
Conductive non-woven fibers (see Figure 2) filled the resin on each face of the conductor. The fibers were made of carbon and coated with copper for enhanced conductivity, and with nickel for enhanced corrosion resistance properties.

7. LAYUP PATTERNS

By using the AFP robot, any combination of the lanes can be used to apply the ribbons, thus creating any pattern of ribbons desired. For this evaluation, four layup patterns designated “AXS1, “AXS2”, “C”, and “C45” were chosen to assess the ability to apply the LSP Ribbons to achieve useful conductivity and protection.

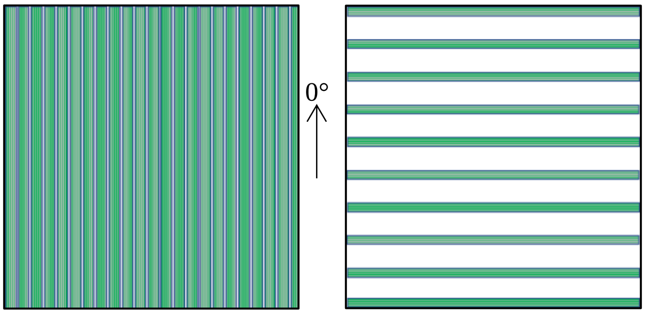
For layup pattern “AXS1”, the first ply onto the tool was applied using all lanes in the 8-tow head to deposit the LSP Ribbons immediately adjacent to each other for the entire length of each ribbon. Overlaps up to ½ the width of a ribbon were allowed where necessary to accommodate the complexity of the surface. The first ply was oriented with the ribbons applied along an imaginary 0° orientation of the tool. The second ply was consolidated against the first ply, but oriented orthogonally to the first ply using every other lane in the 8-tow head to deposit the LSP Ribbons with gaps equal to the width of one ribbon. See Figure 4 for an illustration of this pattern.

For layup pattern “AXS2”, the first ply onto the tool was applied using all lanes in the 8-tow head to deposit the LSP Ribbons immediately adjacent to each other for the entire length of each ribbon for complete coverage of the tool surface. Overlaps up to ½ the width of a ribbon were allowed where necessary to accommodate the complexity of the surface. The first ply was oriented with the ribbons applied along an imaginary 0° orientation of the tool. The second ply was consolidated against the first ply, but oriented orthogonally to the first ply using every third lane in the 8-tow head to deposit the LSP Ribbons with gaps equal to twice the width of one ribbon. See Figure 5 for an illustration of this pattern.



Ply 1: All Lanes　　Ply 2: One lane out of two

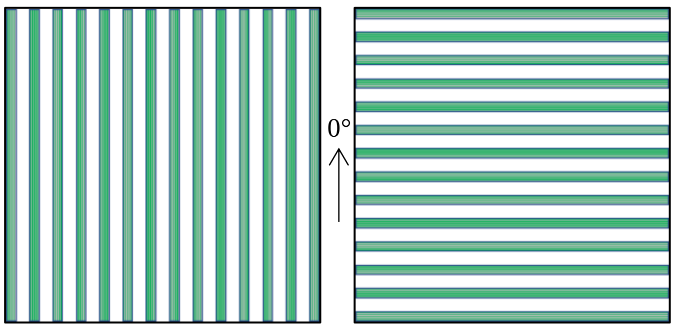
Figure 4　　Ply layup pattern “AXS1”



Ply 1: All Lanes　　Ply 2: One lane out of three

Figure 5　　Ply layup pattern “AXS2”

For layup pattern “C”, the first ply onto the tool was applied using every other lane in the 8-tow head to deposit the LSP Ribbons with gaps equal to the width of one ribbon. The first ply was oriented with the ribbons applied along an imaginary 0° orientation of the tool. The second ply was consolidated against the first ply, but oriented orthogonally to the first ply using every other lane in the 8-tow head to deposit the LSP Ribbons with gaps equal to the width of one ribbon. See Figure 6 for an illustration of this pattern.



Ply 1: One lane out of two　　Ply 2: One lane out of two

Figure 6　　Ply layup pattern “C”

To demonstrate the ability of the AFP system to achieve electrical properties at any chosen orientation, a variant of layup pattern “C” was applied by rotating the pattern 45° on the tool. The new pattern was designated “C45”. This pattern biased the sheet resistance at a 45° angle to the tool.

8. APPLICATION

To assess application characteristics of the LSP Ribbons, Coriolis Composites Technologies SAS in Quéven, France made layup through their C1 AFP Machine. See Figure 7. This machine had an 8-tow head and creel (cabinet holding the ribbon material) which allowed layup of 8 fibers/ribbons at a time, to speeds up to 0.8 m/s. Two layup patterns were applied to flat panels for lighting testing and 3 layup patterns were applied to a contoured tool surface to demonstrate layup on a representative aircraft surface.

Figure 7 Coriolis C1 AFP Machine

8.1 Contoured Surface Application Demonstration

A tool approximately 2 m wide x 2 m long x 0.5 m deep was used to represent very complex aircraft surfaces. The tool surface presented to the machine both tight and relaxed positive and negative complex curvature. See Figure 8.

Figure 8 Contoured Application Tool

These demonstrations were performed with up to 8 strands at a maximum speed of 0.24 m/s. A contourable vacuum film was placed on the mould as a separator ply for easy removal of the LSP plies after layup. During operation, the LSP material was held at 18°C in the creel, 12°C in the transfer tubes, and 10°C in the head. Application was made with 500 N pressure and 55°C to 60°C at the compactor with a heating lamp.

Three layup patterns were performed:

“ASX1” – See Figure 9
“C” – See Figure 10
“C45” – See Figure 11

Figure 9 Layup Pattern “AXS1” on Contoured Tool

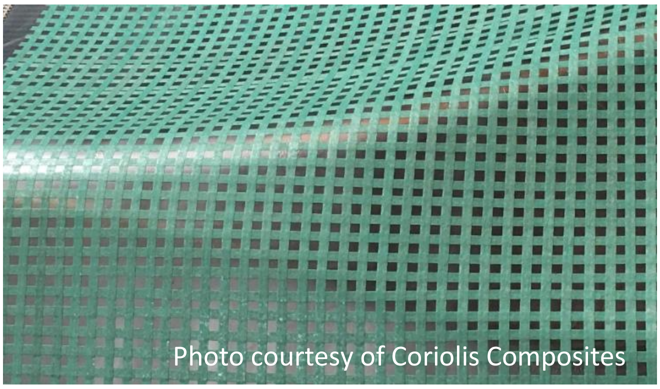


Figure 10 Layup Pattern “C” on Contoured Tool

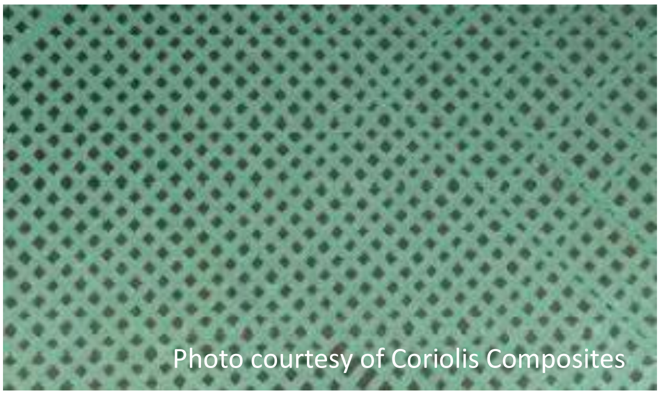


Figure 11 Layup Pattern “C45” on Contoured Tool

8.2 Flat Panel Application for Test Panels

Using the same machine conditions used for the Contoured Surface Application Demonstration, two layup patterns were applied to flat invar tool panels[i] for lighting testing:

“ASX2” – See Figure 12
“C” – See Figure 13

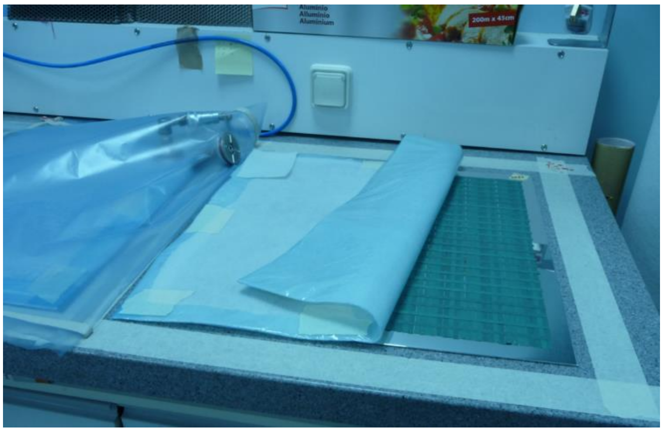


Figure 12 Layup Pattern “AXS2” on a Flat Tool

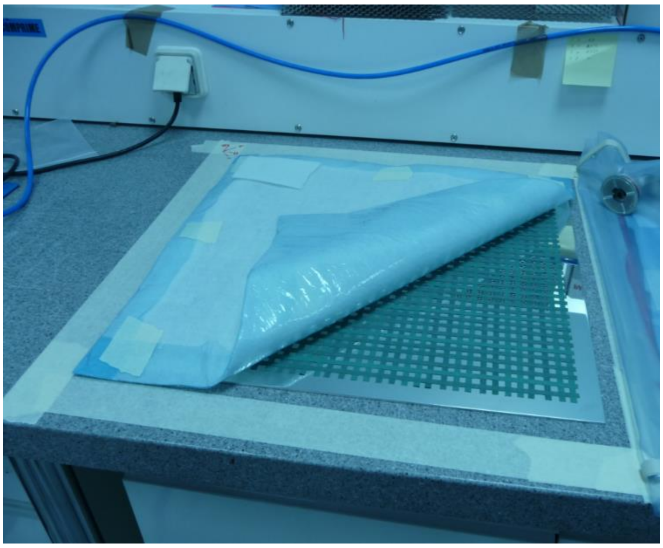


Figure 13 Layup Pattern “C” on a Flat Tool

9. LIGHTNING ATTACHMENT TESTING

Industry accepted simulated strikes as described in ARP5412 and ED-84 [5] were chosen to represent regions of the aircraft as described in ARP5414 and ED-91 [6]. Two test waveforms were chosen to represent the largest surface area of the airframe. For transport aircraft, Zone 2A and Zone 3 [6] cover the greatest amount of surface area. See Figure 15.

9.1 Lightning Strike Test Panels

The test panels were constructed of unidirectional carbon fiber epoxy prepreg. The LSP Ribbons were consolidated to the flat tool plates by AFP machine. See Table 1 for the AFP Ribbon application patterns and characteristics of each test panel. Plies of M21/34%/UD194T800S unidirectional carbon fiber prepreg, from Hexcel Corporation, were vacuum laminated to form consolidated LSP layups 460 mm square. Plies were arranged [45, 0, 135, 90, 0, 90]s[ii] to be 2.29 mm thick after curing.

The tool and panel were then placed in a vacuum bag under a vacuum of approximately 28 inches mercury (94.8 kPa) and the bag was placed in an autoclave at 60 psi (414 kPa). The panels were cured at 350°F (177°C) for 120 minutes.

After curing, the panels were separated from their tools and machined to 430 mm square. 12 holes 8.992 - 8.687 mm diameter were drilled equidistant apart on a 370 mm diameter circle to align with holes in the test fixture as illustrated in Figure 14.

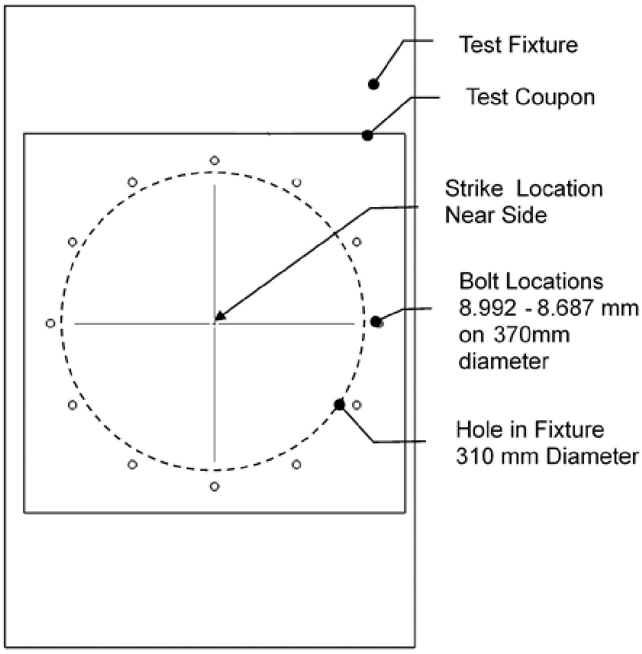


Figure 14 Test Specimen in Fixture

The face of each panel was washed clean with soap and water to remove any machining fluids and other contaminates. The surface was scuffed with 3M™ Scotch-Brite™ Ultra Fine Pad 7448 on an orbital sander with deionized water until the surface exhibited a dull appearance. All abrading residual, debris, and/or cleaner residue was removed with isopropyl alcohol and a clean lint-free towel. A mask was applied to the face of the panel around each drilled hole to create a paint-free region around each hole. To each panel, three box coats of epoxy primer[iii] were applied to a dry-film thickness of approximately 20 µm followed by heavy box coats of paint[iv],

[i] *Each invar tool was treated on the surface with FreKote 700-NC™ release agent from Henkel Corporation.*

[ii] *Refer to Composites Materials Handbook MIL-HDBK-17 Volume 2, Section 1.6 Material Orientation Codes*

[iii] *Aviox CF Primer 37124 system from AkzoNobel*

[iv] *Aviox Finish 77702 urethane paint system from AkzoNobel*

each averaging approximately 25 µm per box coat until the final thickness of paint was achieved. See Table 1 for the thickness of paint measured on each test panel.

Table 1 Lightning Strike Test Specimen

		Effective		Resistance		
Specimen	Layup Pattern	Foil Weight[v] (gsm)	LSP Weight[v] (gsm)	Direction Ply 1[v] (mΩ/□)	Direction Ply 2[v] (mΩ/□)	Paint (µm)
-12	AXS2	117	288	2.1	6.3	418
-13	C	88	216	4.2	4.2	418
-14	C	88	216	4.2	4.2	412

The mask was removed from each drilled hole, and the epoxy surface was abraded to expose the copper conductor in a region around each drilled hole to a diameter large enough to form a mating surface with the attachment fasteners.

To understand how these patterns compare to large area conductor applications, Table 2 was assembled from industry product information for comparative large area conductive surfacer products[vi].

Table 2 Comparative Large Area LSP

		Resistance	
ECF Weight (gsm)	Impregnated Weight (gsm)	LWD (mΩ/□)	SWD (mΩ/□)
73	220 - 240	3.1	12
142	288 - 310	1.6	4.8

9.2 Lightning Attachment Testing

The test panels were loaded to aluminum test fixtures as shown in Figure 14 and attached with protruding head fasteners. The fastener heads were covered with tape to prevent unintended arc attachment. All simulated strikes were conducted by Lightning Technologies, NTS Pittsfield in Pittsfield, Massachusetts, USA.

To maximize the possible benefit of using AFP to apply LSP surfacer, Zone 2A and Zone 3 as defined in SAE ARP5414 [6] were used to define lightning strike threat levels because these environments represent the largest surface area on transport aircraft. See Figure 15.

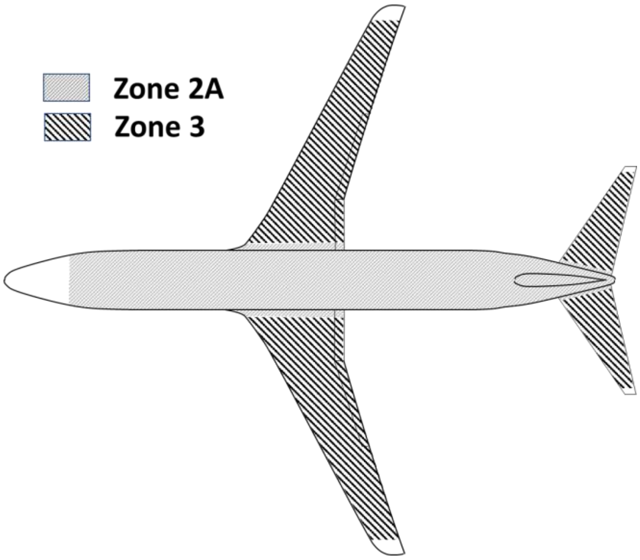


Figure 15 Transport Aircraft Zoning Illustration

The tests were accomplished per SAE ARP5416 [7] section 5.2 High Current Physical Damage Tests using waveform as prescribed in SAE ARP5412 [5]. A jet diverting test electrode was used to inject the current. Waveform characteristics were recorded for each discharge, including Charge Voltage, Action Integral, Charge Transfer, Peak Current, Average Current and Pulse Width as appropriate to the current component.

To assess the damage inflicted by the simulated strike, each panel was fully immersed in water, and scanned on a Mistras ultrasonic scanning gantry with UTWin software. The transducer operated with a 19 mm focal length and scanned uni-directionally. Pulser settings were: 400 V, 820 pf, 2000 ohms, 15 MHz, in pulse-echo mode. Receiver settings were: 100 MHz sampling, 0.1 microsecond envelope, 4.2 microsecond delay, 20.977 microsecond width. Scans were made from the back side of the panel. Post-scan replay gating was used to locate the deepest detectable damage. Damage area was determined by measurement of a circumscribed region containing the visible damage. Results of the direct attachment tests and the subsequent ultrasound microscopy are described in Table 3. See Figure 16 through Figure 21 for post-test images and scans.

Table 3 Lightning Strike Test Results

		Effective			Damage		
ID	Layup Pattern	Foil Weight[v] (gsm)	LSP Weight[v] (gsm)	Strike Zone	Max Depth (mm)	Area[vii] (cm^2)	Back-Side Crack
-12	AXS2	117	288	3	0.19	38.7	No
-13	C	88	216	2A	1.96	129	No
-14	C	88	216	3	1.63	77.4	No

[v] Calculated from the ribbon property distributed over the applied pattern

[vi] Information extracted from product data sheets for 3M™ Scotch-Weld™ Structural Adhesive Film AF 555XS, 3M™ Scotch-Weld™ Structural Adhesive Film AF 191XS, and 3M™ Scotch-Weld™ Low Density Composite Surfacing Film AF 325LS

[vii] A circumscribed rectangle encompassing the visible damage.

Figure 16 -12 Post-test Image

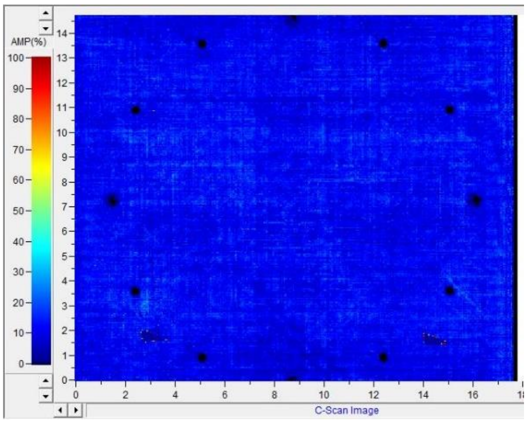


Figure 17 -12 Post-test Ultrasound

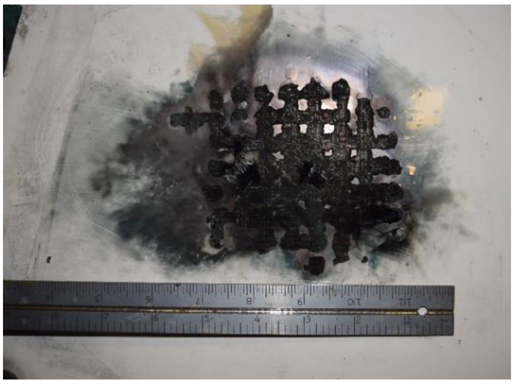


Figure 18 -13 Post-test Image

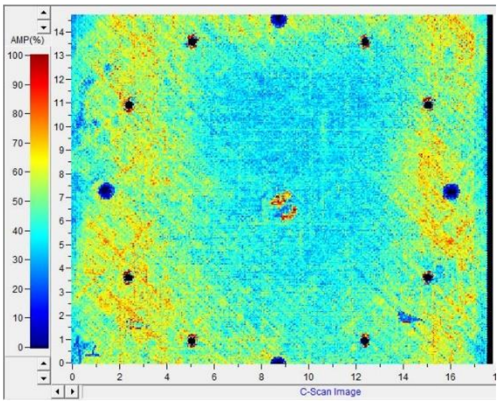


Figure 19 -13 Post-test Ultrasound

Figure 20 -14 Post-test Image

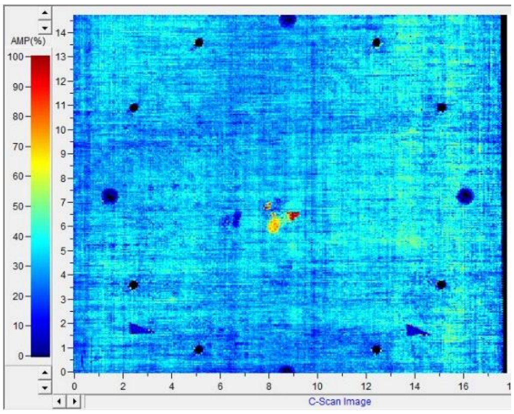


Figure 21 -14 Post-test Ultrasound

10. RIBBON-TO-RIBBON CONDUCTION

Ribbon-to-ribbon conduction is a unique aspect of this approach to achieve electromagnetic protection with AFP-applied LSP surfacer. A simple test was devised to estimate electrical resistance between two overlapping ribbons, after curing, to determine if there was electrical contact. Four LSP Ribbons 100 cm long were applied in a rectangular arrangement to a flat tool plate such that two of the ribbons were in contact with the other two ribbons. See Figure 22. Plies of unidirectional FRP prepreg were applied to cover the fibers and consolidated as described in Section 9.1. After curing, the epoxy resin was abraded from the extreme end of each ribbon to provide contact area for a resistance probe, and each ribbon was bisected to isolate each ribbon-to-ribbon overlap as shown in Figure 23. Point-to-point resistance measurements were made using a Fluke Corporation model 189 multimeter[viii] between adjacent measurement sites (See Figure 23) where the surface resin was abraded to the conductor to determine the ribbon-to-ribbon electrical resistance. See Table 6 for resistance measurements. The average ribbon-to-ribbon electrical resistance was 0.19 Ω. The area of contact between intersecting ribbon conductors was 40.3 mm^2. One may characterize the ribbon-to-ribbon resistance as 4.7 $m\Omega/mm^2$ distributed over the ribbon-to-ribbon contact area.

[viii] *Followed the equipment makers instructions for use.*

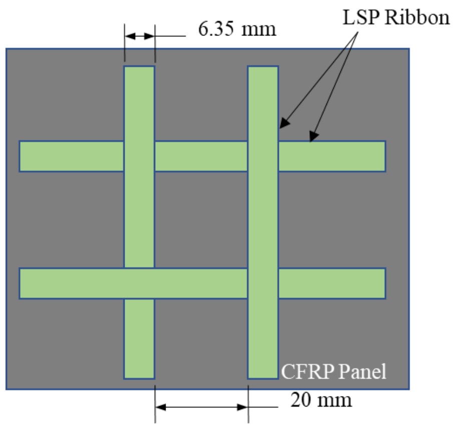


Figure 22 Ribbon-to-Ribbon Resistance Test Panel

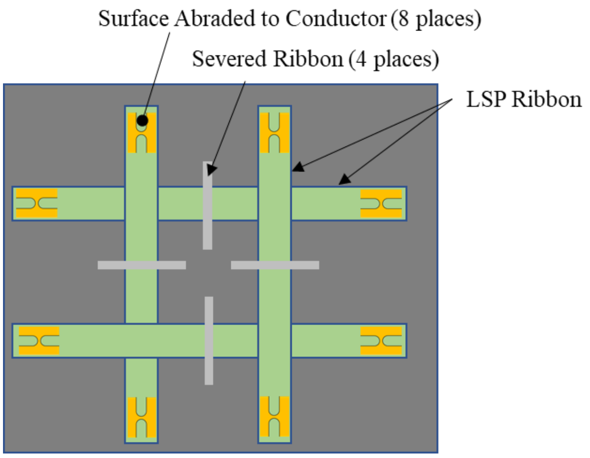


Figure 23 Ribbon-to-Ribbon Resistance Test Specimen

Table 6 Ribbon-to-Ribbon Electrical Resistance

	Point-to-Point Resistance (Ω)				
Specimen	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Average**
1	0.19	0.21	0.18	0.19	0.19
2	0.18	0.18	0.21	0.21	0.20
3	0.19	0.18	0.19	0.20	0.19
				Average	0.19

11. CONCLUSIONS

An LSP Ribbon can be applied via AFP machine. The LSP Ribbons can be applied in patterns that provide weight and conductivity in the range of wide area conductor applications. Light weight LSP Ribbons may be applied in patterns that can be adjusted to meet local weight and conductivity requirements. Light weight LSP Ribbons can be applied in patterns that protect skins from punch-through at Zone 2A strike sites and protect from significant damage at Zone 3 strike sites.

Strike Zone 2 and Strike Zone 3 environments were used for this evaluation. Many complex surfaces, that would be suitable candidates for AFP-applied LSP, are located in Zone 1 regions. It would be beneficial to understand the layup options that would provide protection from Zone 1 strike environments.

Conductivity of the LSP Ribbons was accumulated and biased through the layup and arrangement of ribbons. There may be intentional gaps between ribbons, in coverage across the surface, dependent upon the arrangement of ribbons. These gaps may impact the frequency dependent EM shielding qualities. It would be beneficial to understand EM shielding levels provided by layup and ribbon arrangement options.

Ribbon-to-ribbon resistance was measured to confirm electrical connection at intersecting/overlapping ribbons. It may be beneficial to characterize further the ribbon-to-ribbon conduction properties of this system, and limits to support strike protection of the structure and EM shielding quality.

On surfaces having complex contours, it is necessary to consider how the contour affects the placement of ribbons and their orientation. It is necessary to establish rules for the relative positioning of these ribbons to define acceptable gaps and overlaps between adjacent ribbons for proper electrical performance. For this trial, we defined rules to allow complete coverage of the complex surfaces and avoid unexpectedly large gaps. Standardization of this set of parameters governing the ribbon placement may be useful.

12. REFERENCES

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[6] ARP5414B Aircraft Lightning Zoning, SAE International, AE-2 Lightning Committee, December 2018 (Reference also: EUROCAE ED-91A, Lightning Zoning, European Organisation for Civil Aviation Equipment, January 2019)

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13. ACKNOWLEDGMENTS

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