Lightning Direct Effects Handbook

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REVISIONS

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Section	Description
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6.10	Added New Section on Spliced Lightning Strike Protection

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Section	Description
All	Updated header, figure and table references. Formatting was made uniform through the document without changing content.
6.4.5	Removed the word “huge”
6.11	Added New Section on Novel Lightning Strike Protection Methods

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6.0 Aircraft Skin Protection Effectiveness

The designer will find the following compilation of data useful for selection of candidates for lightning protection of the aircraft skins. This chapter provides further discussion of protection effectiveness based on previous test data. This chapter primarily addresses composite materials, since most aluminum skins are inherently self-protecting; however, protection of aluminum integral fuel tank skins from melt-through is also addressed. This section includes discussions pertaining to the following topics:

- **Aluminum Skin Melt-through**
- **CFC Skin Protection**
- **Non-Conductive Skins Protection**

Protection Methods Examined: Several protection effectiveness data for methods of protection for aircraft skins are presented in this chapter. The most common method for protection of composite skins involves the application of a “protection ply” comprised of a metallized coating on the outer surface of the composite laminate. This process is referred to as “metalizing.” These coatings provide varied amounts of protection, and direct comparisons can, and should, be made by lightning tests of skin specimens of similar construction and different protection systems. Many of the skin protection methods discussed in Chapter 5 of this handbook have been included.

The effectiveness of composite skin protection methods discussed in this chapter have been evaluated on various laminates including conductive carbon layups, non-conductive fiberglass and aramid fiber laminates. The success of the protection material may be influenced by the total thickness of the laminate and any core materials. Other conditions such as the thickness of paint and surface finishes can also influence protection effectiveness. Comparisons of relative damage for the different variables are shown in Figure 6-33 through Figure 6-36.

The most effective way to successfully protect an aircraft from direct effects is to apply one or more of the protective layers described in Chapter 5 to the exterior surfaces of the aircraft. By so doing, the majority of the lightning currents will flow on the outside of the aircraft. Keeping the lightning currents on the outside of the aircraft will significantly minimize effects to systems and personnel.

Dielectric coatings cannot protect the entire aircraft from a lightning attachment. On the contrary, the dielectric may actually increase damage at locations where the attachment occurs. Dielectrics should only be used to provide protection for small regions or components of the aircraft.

6.1 Aluminum Skins

Aluminum skins provide a high degree of conductivity, but may experience melt- through and physical deformation. Melt-through is predominately a concern for integral fuel tank design, but other, light-weight metal components such as control surfaces may experience deformation.

This section provides test data which will help to define the type of damage that may be expected when lightning attaches to painted aluminum skins of various thicknesses. The data will evaluate several thicknesses of skins and illustrate the effects of the various current components of lightning.

Melt-through: Studies have shown that the volume of metal melted away at a lightning attachment point is closely related to the charge carried into the point by the lightning arc, at specific current amplitudes. A nearly linear relationship exists between the amount of charge delivered to an arc attachment spot and the amount of metal melted from it. In determining the minimum amount of charge and current required to melt aluminum skins, the effects depend on current amplitude as well as charge, as shown in Figure 6-1.

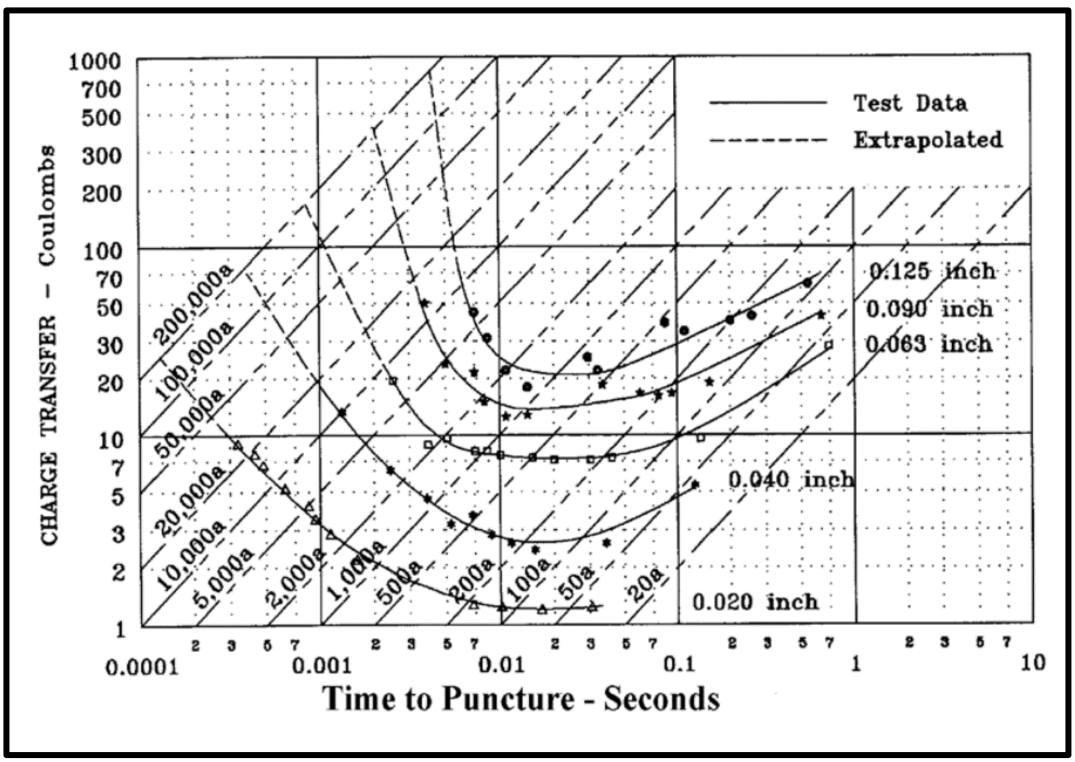


Figure 6-1: Time to melt-through on aluminum skins

Figure 6-1 provides guidance on the amount of coulombs and time required to melt through an aluminum skin, which may be considered to be the time at which fuel vapor ignition may occur as the hot lightning arc may then be presumed to be in contact with fuel vapor.

The data also explores the average current amplitude versus time. It has been shown that over 22 C, when delivered by a current of 200 A was enough to melt completely through a skin of 0.080 inch thickness. As little as 2 C, when delivered by about 130 A, melted a hole completely through a skin sample of 0.040 inch thick aluminum.

The 100,000 A stroke currents do not typically melt-though aluminum skins as their time duration and charge transfers are too low. Intermediate (component B) and continuing currents (component C) remain attached to a spot long enough to melt-through.

Whether melt-through occurs or not depends on the time that a lightning arc remains attached to a single spot. This is called the “dwell time”. Dwell times on painted skins have been determined to be less than 20 milliseconds, whereas dwell times on unpainted aluminum skins are less than 5 milliseconds. Skins in zones 1A or 2A must tolerate current Component B and, if the dwell time exceeds 5 milliseconds, also a portion of continuing currents, Component C. Component B by itself delivers 10 coulombs of charge, but Component B (5 milliseconds) plus Component C for a additional 15 milliseconds delivers 6 additional coulombs (at a rate of 400 A) for a total of 16 coulombs. Figure 6-1 shows that 10 coulombs melts through 0.040 in. of aluminum in 5 ms, but 16 coulombs melts through 0.080 in. thick skins. Flight experience has shown that 0.080 in. thick skins have resisted in melt-through, whereas thinner skins have been melted through; corroborating the data of Figure 6-1.

A study was conducted to determine the minimum skin thickness required to prevent melt-through in direct attachment Zones 1A, 1C, 2A, and 3 for both solid aluminum and bonded aluminum skins. The effect of the Component C* charge transfer was also assessed by testing each configuration with 18 and 6 C charge transfer. Solid aluminum skins ranging from 0.032 inches thick to 0.071 inches thick, and metal bonded aluminum panels ranging from dual 0.008 inches to dual 0.032 inches were included in the study. Metal bond panels had smaller melt-through areas than their equivalent solid counterparts. This is likely due to the dielectric properties of the adhesive layer in between the panels. The results of this study can be found in Table 6-1 and Table 6-2 below for the solid and metal bond panels respectively. In *Lighting Protection of Aircraft*[6.6], there is an equation used to model the theoretical melt-through size for a given charge transfer. Figure 6-2 below shows the expected theoretical melt-through size compared with the measured melt-through seen in this study. It is important to note that this equation only applies to solid skins.

Table 6-1: Melt-Through Skin Thickness Thresholds for Solid Panels

Zone	18 C Charge Transfer	6 C Charge Transfer
1A	None	None
1C	0.071”	0.050”
2A	None	0.050”
3	0.071”	0.050”

Table 6-2: Melt-Through Skin Thickness Thresholds for Metal Bonded Panels

Zone	18 C Charge Transfer	6 C Charge Transfer
1A	0.025”+0.025”	0.025”+0.025”
1C	0.012”+0.012”	0.012”+0.012”
2A	0.012”+0.012”	0.012”+0.012”
3	0.008”+0.008”	0.008”+0.008”

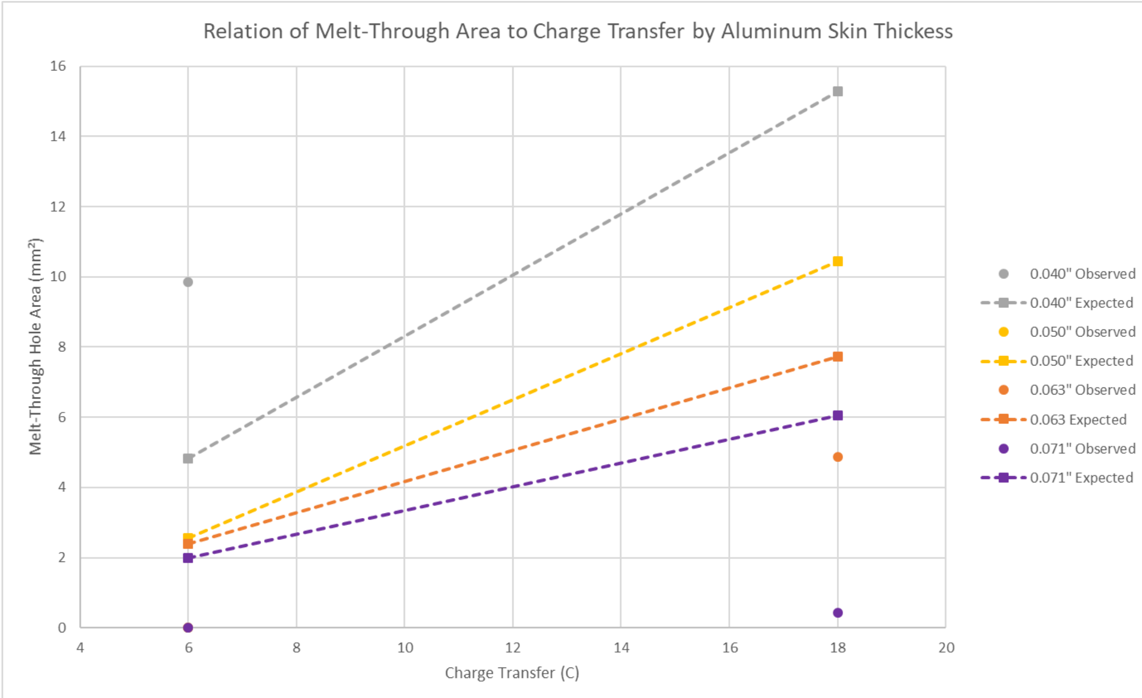


Figure 6-2 Graph of Melt-Through Area vs. Charge Transfer of Various Aluminum Skin Thicknesses

Few small airplanes can tolerate the weight of 0.080 in. skins on integral fuel tanks, nor require skins this thick for structural purposes. Therefore, other approaches need to be considered for lightning protection of small airplane skins.

Unpainted aluminum skins 0.040 in. survived and greater have resisted melt-through under the *Zone 1A* or *2A* lightning environment. The unpainted surface allows the lightning channel to attach to a subsequent point sooner than when a dielectric paint covers the aluminum, keeping dwell times less than 5 ms. This shorter “dwell time” results in less coulomb transfer, therefore less chance of skin melt-through.

Protection from Melt-Through for Metal Skins: The protection of thin aluminum skins (0.020-0.060) have utilized a variety of methods for improving resistance to melt-through. Typically four methods have been implemented in designs;

a. Increased metal skin thickness: This method is the least desirable because of the additional weight that may not be needed for structural reasons and is only there for melt-through protection. Whereas an aluminum unpainted skin of 0.060" may be adequate to prevent melt-through, a painted skin may need to be greater the 0.080" thick as shown in Figure 6-3(a).
b. Add a dielectric barrier to the inner surface: In regions of a limited area, adhesives or polysulfide-type fuel tank sealants have been added to create a barrier between the metal skin which may melt the fuel cell vapors. This method does necessitate controlling the thickness of the sealant over protected areas. Other approaches that provide similar results for fuel cells are bladder installations and internal thin-walled plastic fuel tank enclosures that are becoming increasingly popular with small aircraft

designs.

c. Addition of conductive particles within the exterior surface paint: The function of these particles is to reduce arc dwell time and improve the arc root dispersion, which allows multiple conduction paths through the painted surface. The technical reasoning behind this concept is sound, however verification testing is difficult unless the facility has the ability to test in a moving air stream or with the test article moving to verify decreased dwell times. Figure 6-3(b) illustrates the concept of improved arc root dispersion.

d. Laminated aluminum skins: The key to the success of this technique is to insure that a thermal barrier exists between the aluminum skin and the inner layer. Adhesive films have provided a sufficient barrier to prevent arc attachment to the inner aluminum skin. The arc remains attached to the edges of the hole melted in the exterior layer instead. A condition of an 0.020 in. (external) and a 0.030 in. (internal) aluminum ply, of total aluminum thickness 0.050 in. has successfully withstood the painted surface (i.e. 16 coulombs) zone 1A or 2A lightning environment. Figure 6-3(c) illustrates this protection concept.

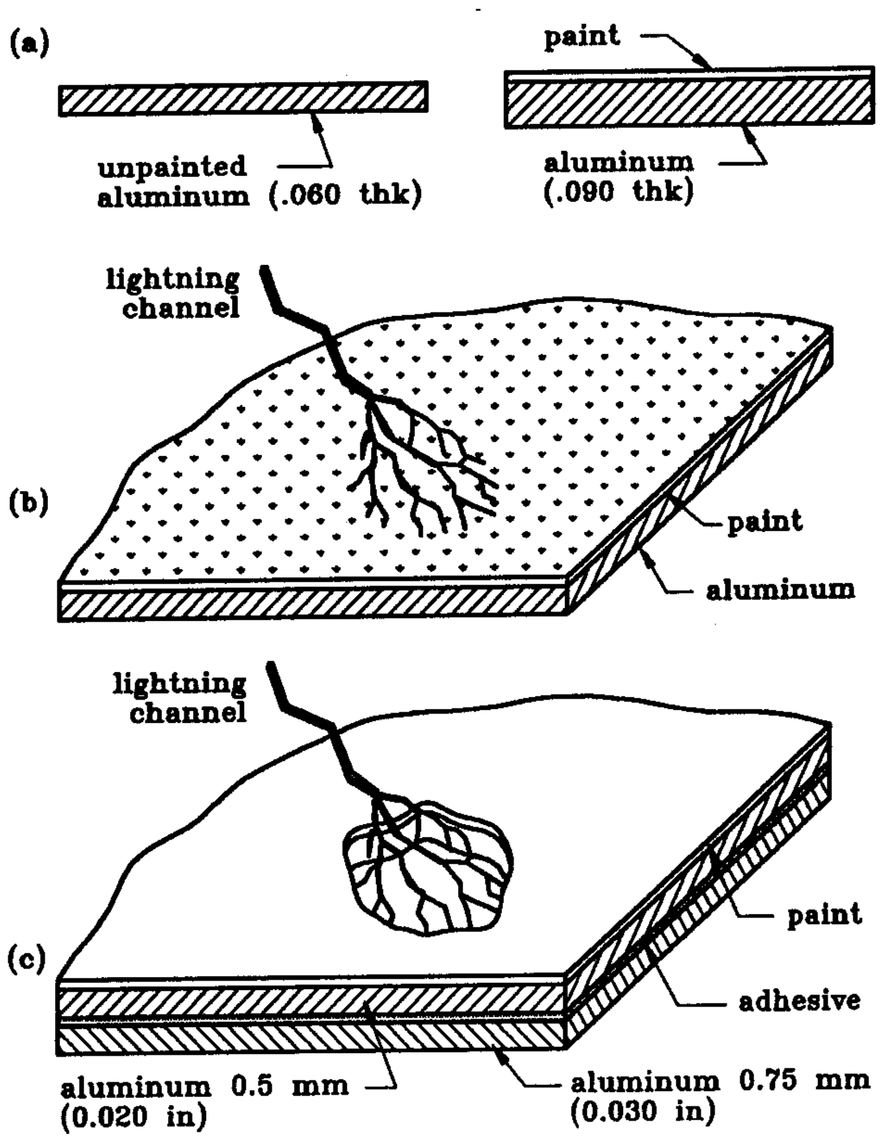


Figure 6-3: Methods for protecting against melt-through

a) Increasing skin thickness
b) Arc root dispersion / Decreasing dwell time
c) Laminated skins

Aluminum Skin Test Data: Lightning testing of aluminum skin panels has demonstrated the shock wave effects of stroke currents and the relationship of *Component B and C* charge transfer and melt-through. Panel thicknesses of 0.032, 0.040 and 0.080 were evaluated for lightning melt-through tolerance.

Table 6-3 lists typical test results. A *Zone 2A* strike of 5 ms dwell time (Components D and B only) will generally melt through a panel less than 0.080 inches thick. Even the 0.080 panels may show resolidified metal on the interior surface. Figure 6-4 through Figure 6-6 show typical damage to aluminum skins caused by Zone 1A and 1B test currents.

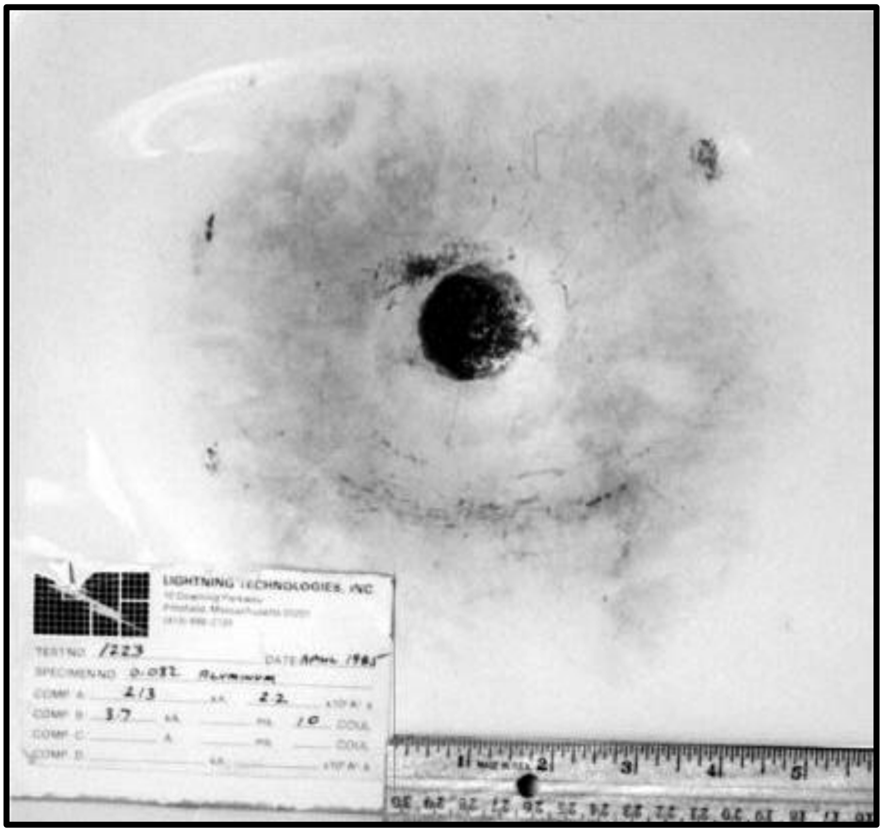


Figure 6-4: Aluminum Panel (0.032" thick)
Darkened area is a 2" in diameter dent to a depth of 1", no melt-through

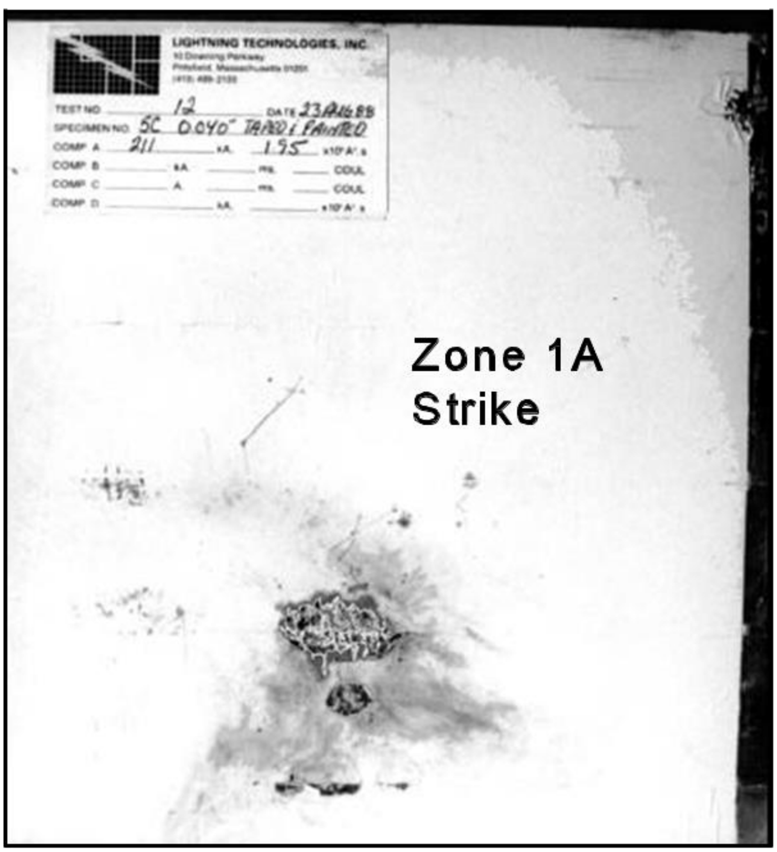


Figure 6-5: 0.040” painted aluminum panel with aluminum tape
Melted hole 0.2" through panel, foil loss 1" dia. minor indentation

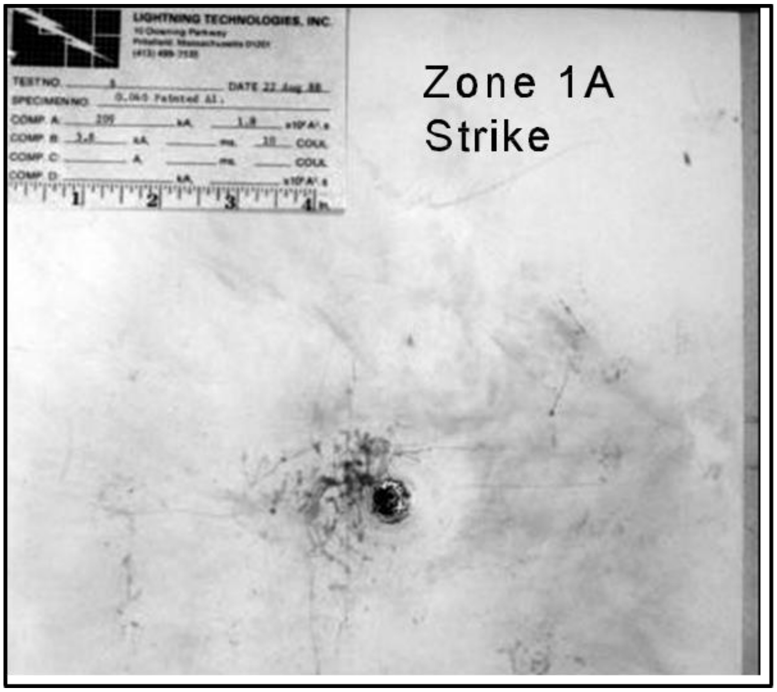


Figure 6-6: 0.040" painted aluminum panel
Dent, small hole aluminum panel with Zone 1A Strike

Table 6-3: Typical Aluminum Skin Test Data

Panel No.	Panel Thickness	Coating	Comp. A (kA)	Comp. B (C)	Comp. C (C)	Zone	hole	dent	repair	notes	Figure
1	0.032”	none	213	10	none	1A	none	2”	3”	pitting >2”	Figure 6-4
2	0.040”	primer	215	3.5	none	1	none	none	1”	primer burned, surface melting, metal splatter, no hole	
3	0.040”	paint	209	10	none	1A	0.1”	0.5”	1”	pitting	Figure 6-6
4	0.040”	paint & Al tape	211	none	none	(a)	0.2”	1”	2”	Tape evaporated, scorching and pitting beneath, small dent	Figure 6-5
17	0.040”	Al tape	none	3.80	none	(a)	0.1”	none	1”	0.25” pitting and burn	
18	0.080”	none	none	10.2	none	(a)	none	none	1”	slight cosmetic damage, no melt-through	
19	0.080”	none	none	10.0	26	(a)	none	none	1”	slight cosmetic damage, no melt-through	
20	0.080”	paint	none	10.2	none	(a)	none	none	1”	slight cosmetic damage, no melt-through	

(a) No zone definition is possible, current components were applied as specified in the table for evaluation purposes.

6.2 Carbon Fiber Composite (CFC)

The designer must decide what composite structures will require additional protection, since lightning damage to some aircraft surfaces may be safety tolerated surfaces and these may not require additional protection. The test data in this section illustrates damage that can be expected of both unprotected and protected, CFC laminates typical of small aircraft skin applications.

6.2.1 Unprotected CFC

The three examples selected for this section were fabricated of a 0.040 in. thick CFC laminate comprised of four, 0.010 in. fabric plies with no core or lightning strike protection on the exterior surface. The panels were tested to Zone 1A and 2A lightning environments.

Zone 1A - Unpainted: Figure 6-7 shows that the 0.040 in. thick unpainted CFC panel has very good tolerance to a lightning strike when surface treatments, such as paint, are eliminated. The laminate was undamaged except for minor, cosmetic loss of surface resin. There was no delamination and no puncture.

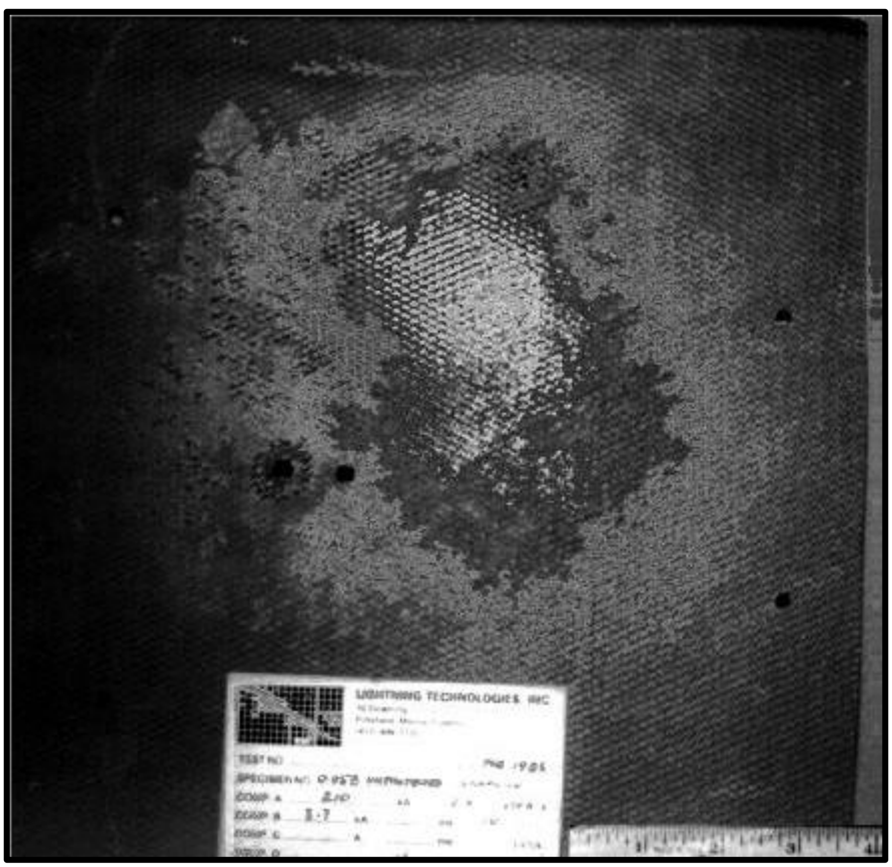


Figure 6-7: Unprotected and unpainted CFC panel subjected to a Zone 1A strike

The unpainted panel in

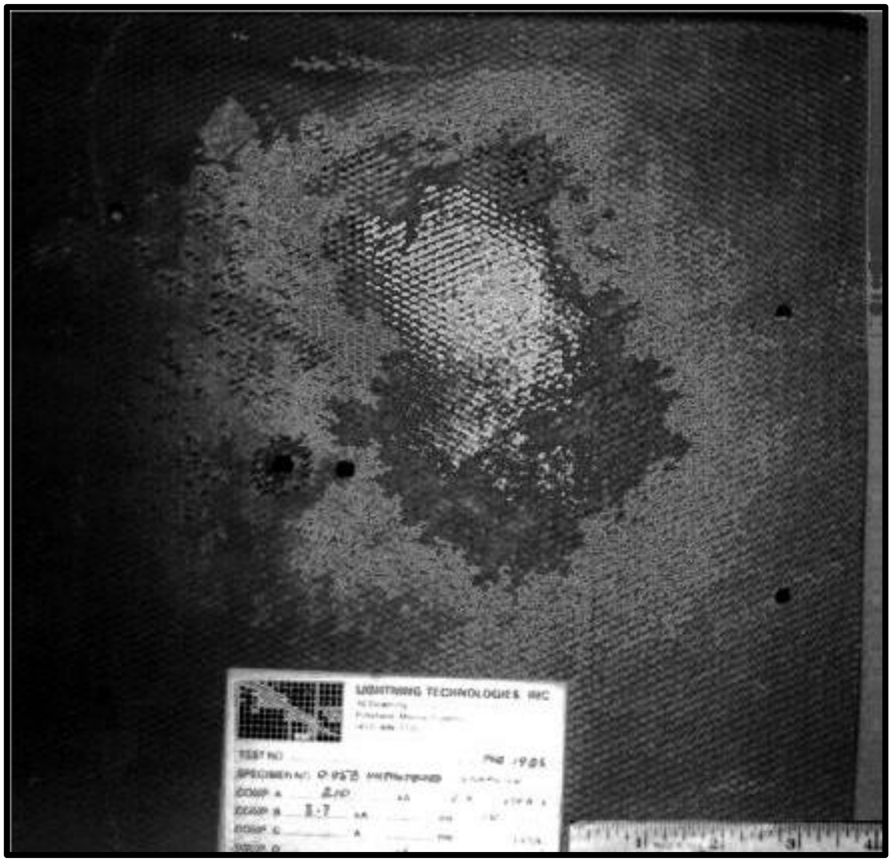


Figure 6-7: Unprotected and unpainted CFC panel subjected to a Zone 1A strike

illustrates the effects of non-conductive surface treatments on the CFC laminate. This is a typical illustration of the importance of allowing the arc root of the lightning channel an opportunity to spread out over a larger region. Although an unpainted carbon structure is not realistic, the importance of keeping surface treatments to a minimum thickness, even on protected composites, are important in minimizing damage.

<u>Zone 1A - Painted</u>: Figure 6-8 shows the results of a Zone 1A lightning strike to a 0.040 in. thick painted CFC panel. The laminate was damaged over a region of 30 to 40 square inches of the laminate. The laminate was also punctured on the back side of the panel.

Figure 6-8: Zone 1A strike to a painted exterior surface unprotected 4 ply 0.052 in. CFC laminate of woven cloth plies

Zone 2A - Painted: Figure 6-9 shows the results of a Zone 2A lightning attachment to an unprotected 0.040" thick painted CFC panel. The laminate was damaged over a region of 3 square inches. The inner ply laminate was also fractured over the approximate same area as the exterior surface, although the resin was not pyrolized on this ply.

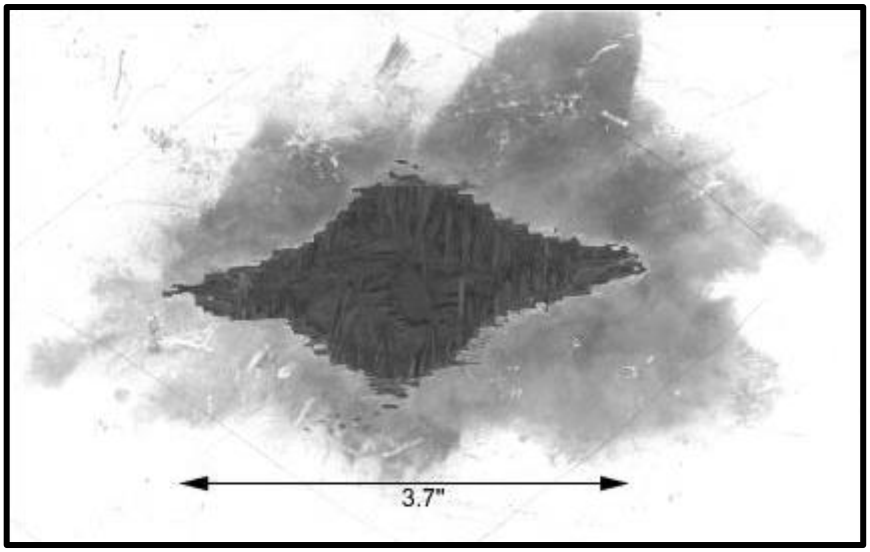


Figure 6-9: Zone 2A strike to exterior surface
unprotected 4 ply 0.052 in. thick laminate of woven cloth plies

6.2.2 Protected CFC Panels

Table 6-4 and Table 6-5 provide additional data of protected CFC panels test data. The tables are accompanied by photographs of the post-test condition of the panel.

Table 6-4: Carbon Fiber Composites: with foam core

Panel No.	Panel Thickness		Core	Thick	LSP	Paint	Zone	I (kA)	I Comps	delam	hole		repair area	Figure/Ref
	inner	outer								inner	inner	outer	outer	
21	0.008”	0.016”	foam	3/8”	NCC	5 mils	2A	100	D,B	4”	1”	3”	3.5”	Figure 6-10/b
5	0.008”	0.016”	foam	3/8”	NCC	5 mils	1A	200	A,B	6”	3”	6”	7”	Figure 6-13/b
6	0.016”	0.032”	foam	½”	EAF	5 mils	1B	200	A,B	2”	none	3”	8”	Figure 6-11/a
7	0.016”	0.032”	foam	½”	EAF	5 mils	1A	200	A,B	1”	none	none	3.5”	Figure 6-14/a
8	0.008”	0.016”	foam	3/8”	ECF	5 mils	1A	200	A,B	6”	none	none	9”	Figure 6-12/b
22	0.008”	0.016”	foam	3/8”	ECF	5 mils	2A	100	D,B	1”	none	none	6”	Figure 6-15/b

Abbreviations: NCC = Nickel Coated Carbon Fiber, EAF = Expanded Aluminum Foil, ECF = Expanded Copper Foil

References:

a) Lightning Technologies, Glasair III Lightning Protection System Development Report, LT-92-782, 1992.
b) Lightning Technologies, Lightning Tests on the Model LC40 Aircraft Components, LT-97-1398, 1997.
c) Lightning Technologies, Lightning Strike Tests on Cycom MCG Fiber Protected Panels, LT-83-145, 1983.

Analysis: Expanded copper foil demonstrated the best protection for both zones, being marginally better than expanded aluminum foil. Nickel coated carbon fiber permitted puncture in both zones.

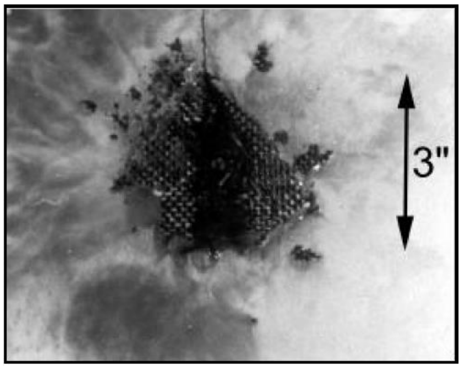


Figure 6-10: Ni CFC Panel Zone 2A Reference b, Test No. 4

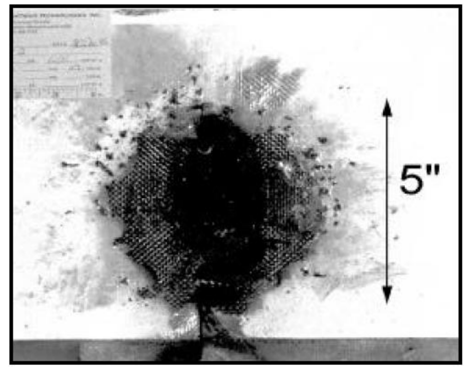


Figure 6-13: Ni CFC Panel Zone 1A Reference b, Test No. 12

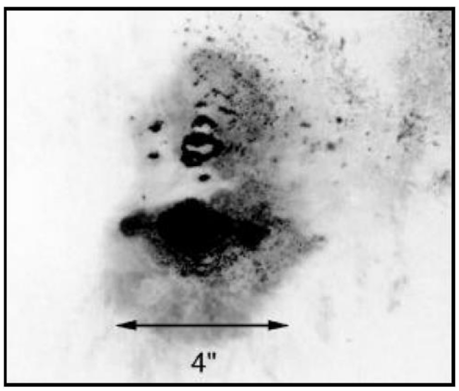


Figure 6-11:EAF/CFC Panel Zone 1B Reference a, Test No. 5

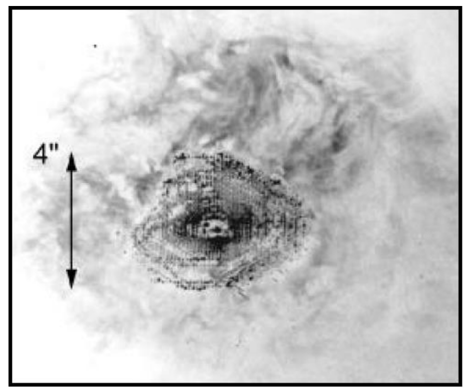


Figure 6-14: Al CFC Panel Zone 1A Reference a, Test No. 40

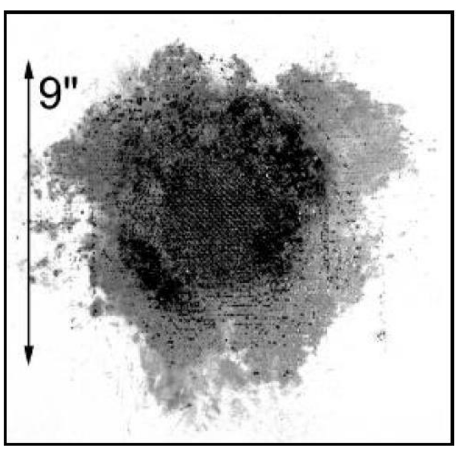


Figure 6-12: Cu CFC Panel Zone 1A, Test No. 10

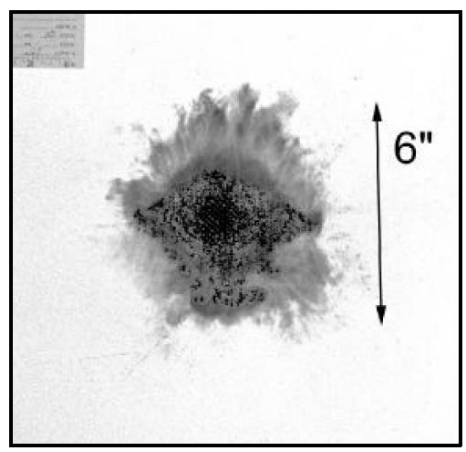
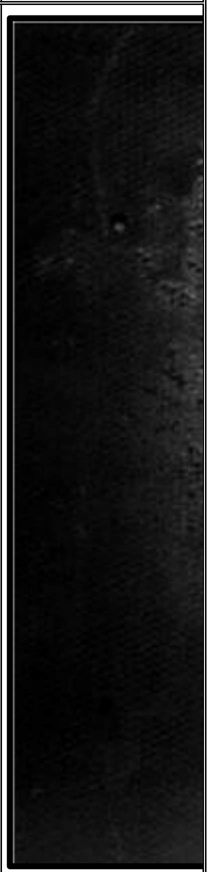


Figure 6-15: Cu CFC Panel Zone 2A Test No. 7

Table 6-5: Carbon Fiber Composites: no core

Panel No.	Panel Thickness		Core	Thick	LSP	Paint	Zone	I (kA)	I Comps	hole		delam	repair area	Figure/Ref
	inner	outer								inner	outer	outer		
9	N/A	0.040”	none	N/A	none	none	1A	200	A,B	none	none	none	5”	 Figure 6-7: Unprotected and unpainted CFC panel subjected to a Zone 1A strike /

10	N/A	0.040”	none	N/A	none	5 mils	1A	200	A,B	3”	3”	7”x9”	7”x9”	Figure 6-8/
23	N/A	0.040”	none	N/A	none	5 mils	2A	100	D,B	1.5”x3”	1.5”x3”	3”x4”	4”x5”	Figure 6-9/
11	N/A	0.024”	none	N/A	ECF	5 mils	1A	200	A,B,C*	none	none	none	9”	Figure 6-16/b
24	N/A	0.024”	none	N/A	ECF	5 mils	2A	100	D,B,C*	none	none	none	5”	Figure 6-19/b
12	N/A	0.032	none	N/A	IAW	5 mils	1A	200	A,B	none	none	3”	8”	Figure 6-17/d
25	N/A	0.032	none	N/A	IAW	5 mils	2A	100	D,B	none	none	2”	6”	Figure 6-20/d
26	N/A	0.032	none	N/A	WWM	5 mils	2A	100	D,B	none	none	1”	3”	Figure 6-18/d

Abbreviations: ECF = Expanded Copper Foil 0.029, IAW = Interwoven Aluminum Wires 1 ply, WWM = Woven Wire Mesh 200x200

References:

b) Lightning Technologies, Inc. Report: Lightning Tests on the Model LC40 Aircraft Components, LT-97-1398, 1997.

d) Lightning Technologies, Inc. Report: Learfan Development Tests, no released report

Analysis: ECF exhibited best protection both zones. Interwoven aluminum wire in the outer ply of carbon resulted in a localized region of delamination of the outer ply.

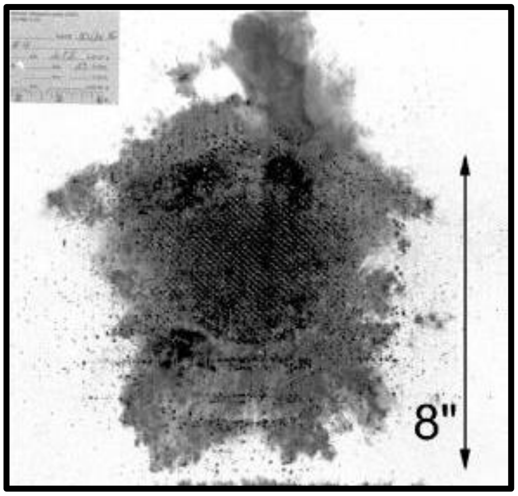


Figure 6-16: Cu CFC Panel, no core
Zone 1A, Test No. 9

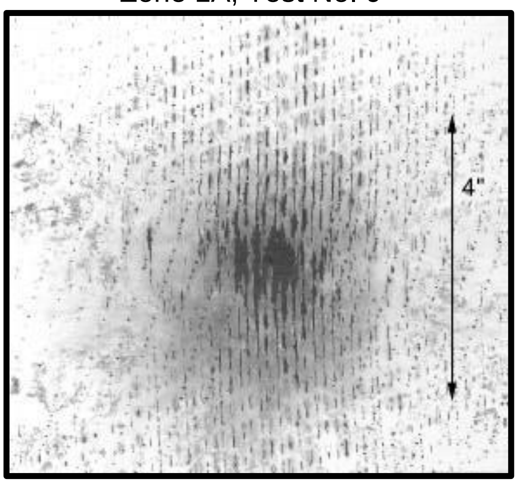


Figure 6-17: IAW CFC Panel, no core
Zone 1A

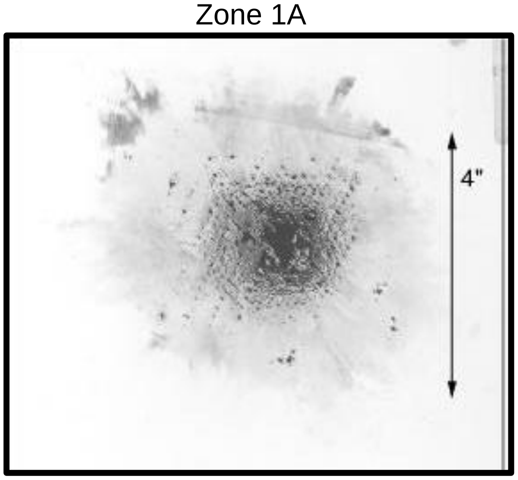


Figure 6-18: WS CFC Panel, no core

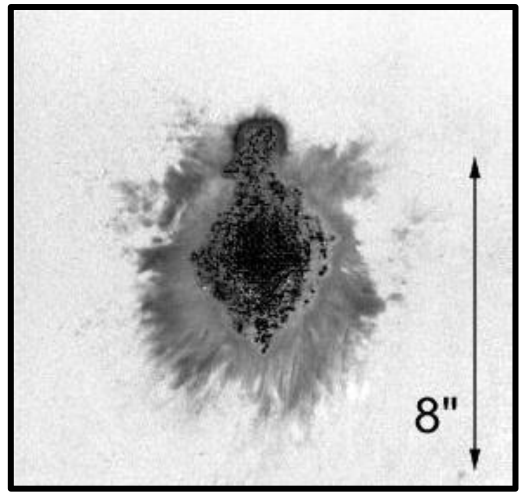


Figure 6-19: Cu CFC Panel, no core
Zone 2A, Test No. 6

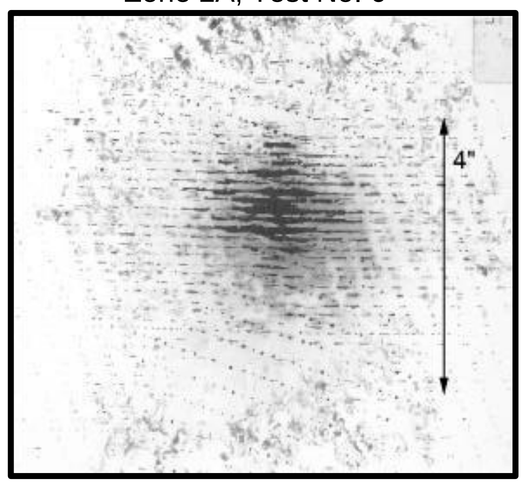


Figure 6-20: IAW CFC Panel, no core
Zone 2A

6.2.3 Carbon Fiber Composite (graphite) Panels

The following test panels were done for the US Air Force (Quinlivan, J. T., Kuo, C. J., Brick, R. O., *Coatings for Lightning* (sic) *Protection of Structural Reinforced Plastics, AFML-TR-70-303 Pt.1*, 1971). The tests were a Zone 2 strike, however due to the old nature of the test procedures the action integral is not known. The language used to describe the damage is that of the original document. Dimensions are 6" by 12", and foils are unperforated and unexpanded.

Table 6-6: AFML Test Data for CFC (no core)

Panel No.	**Panel Thickness**		**Core**	**Thick**	**LSP**	**Paint**	**Zone**	**I (kA)**	**I Comps**	**hole**		**delam**	**repair area**	**Figure/ Test No**
	inner	**outer**								**inner**	**outer**	**outer**		
27	N/A	0.040”	none	N/A	AF 1mil	5 mils	2	94	D,B	none	none	none	6”	Figure 6-21/019
28	N/A	0.040”	none	N/A	AF 3mil	5 mils	2	94	D,B	none	none	1.5”	2”	Figure 6-22/021
29	N/A	0.040”	none	N/A	AF 3mil	5 mils	2	94	D,B	none	none	1.5”	2”	Figure 6-23/023
30	N/A	0.040”	none	N/A	AF 6mil	5 mils	2	95	D,B	none	none	0.75”	1”	Figure 6-24/044
31	N/A	0.040”	none	N/A	Cu paint	5 mils	2	110	D,B	0.5”	1”	1”	4”	Figure 6-25/61
32	N/A	0.040”	none	N/A	Al plasma	5 mils	2	94	D,B	none	none	2”	6”	Figure 6-26/68

Abbreviations: AF = Solid Aluminum Foil

Figure 6-21: AF 1 mil, Test No. 019

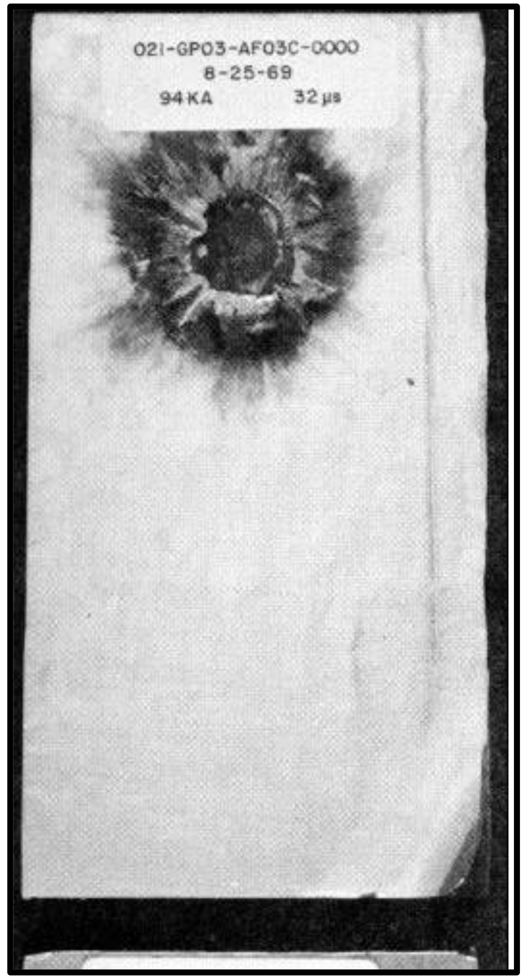


Figure 6-22: AF 3 mil, Test No 021

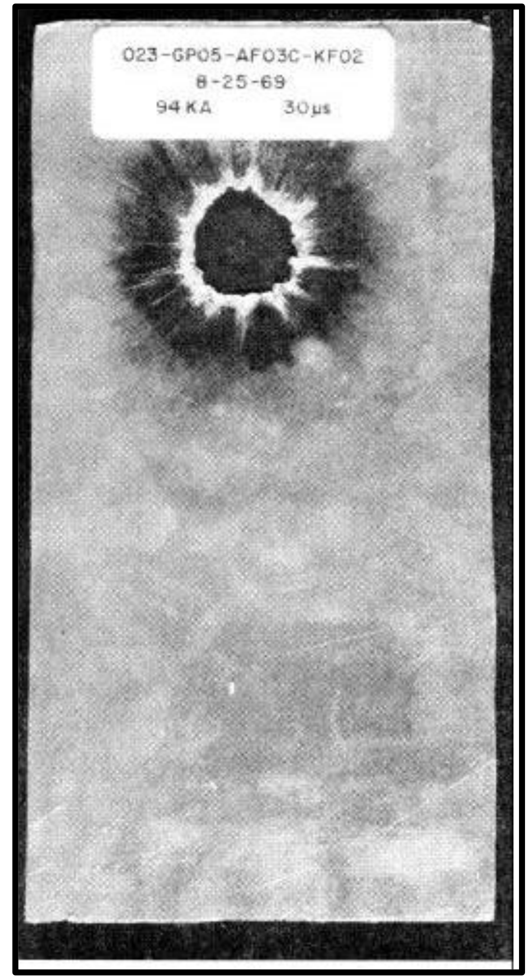


Figure 6-23: AF 3 mil, Test No. 023

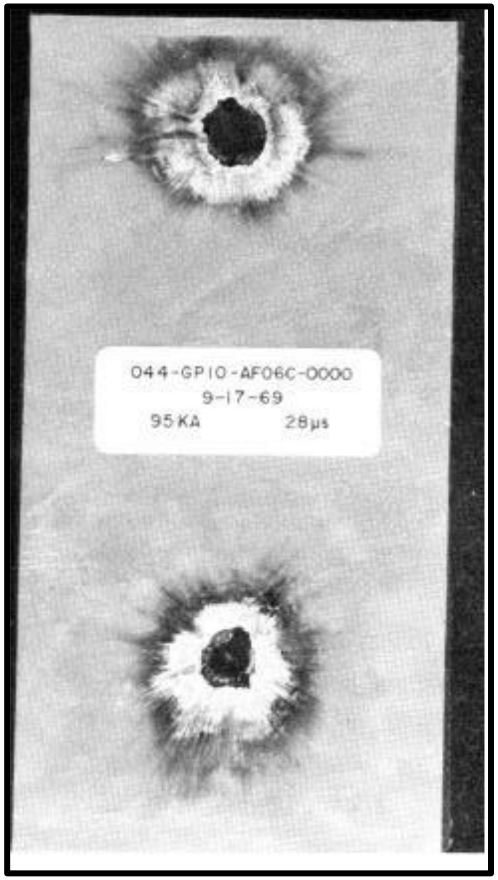


Figure 6-24:AF 6 mil, Test No. 044

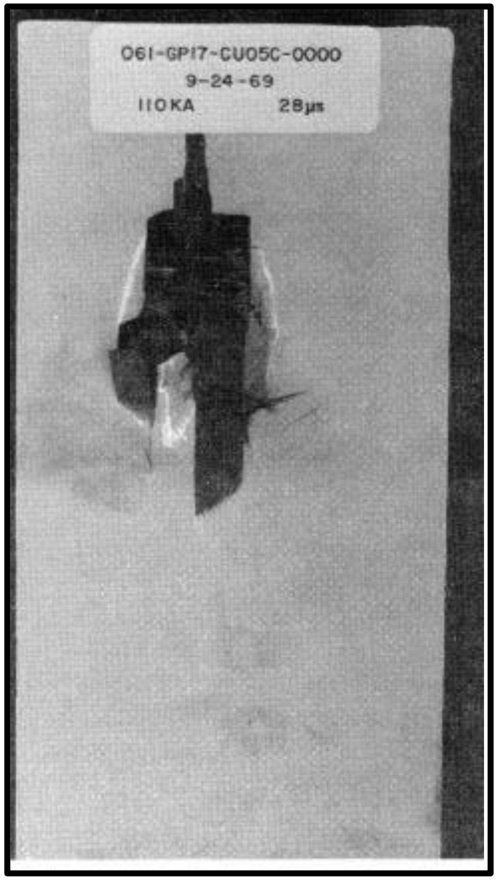


Figure 6-25: Cu Paint, Test No. 6

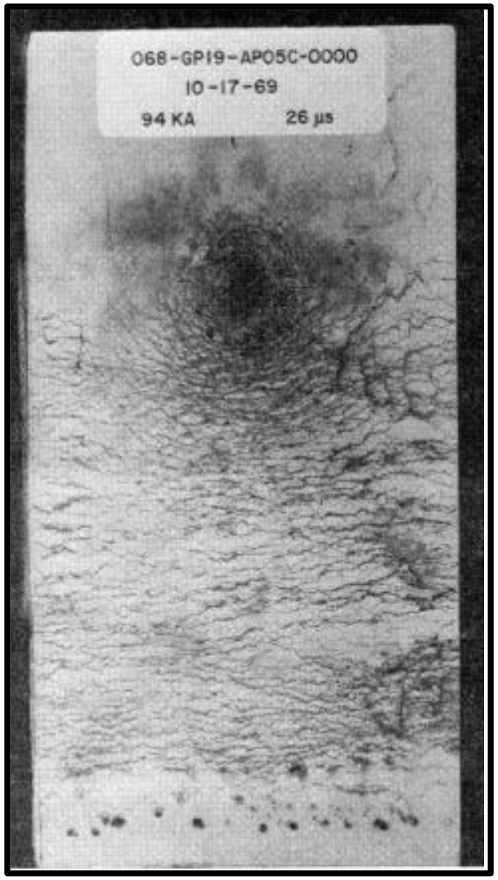


Figure 6-26: Al Plasma Spray, Test No 68

Analysis of CFC panel test data:

1) Conductive paints do little to protect against a severe strike with a conductive composite beneath.

2) Unperforated (solid) foils work well in aluminum, copper or the more resistive nickel. Application and maintenance problems persist however. Most designers will prefer the perforated and expanded variety.

3) Typically, protection from less conductive materials (such as nickel or stainless steel) will not perform as well as more conductive materials. There is likely to be little difference in maintenance, apart from galvanic concerns. There is also likely to be little difference in application.

4) A layer of significant dielectric strength placed over a conductive layer (such as carbon-based composites like graphite) will typically increase damage to the conductive layer when attachment occurs.

6.3 Non-Conductive Composites

The following examples show typical protection methods for non-conductive composites and define the magnitude of damage that can be expected for Zone 1 and 2 lightning attachments.

Table 6-7: Non-Conductive Composite with Fiberglass and Core

Panel No.	Panel Thickness		Core	Thick	LSP	Paint	Zone	I (kA)	I Comps	delamination	hole		repair area	Figure/Ref
	inner	outer								inner	inner	outer	outer	
13	0.016”	0.016”	foam	½”	Thor	5 mils	1A	200	A,B	7”	none	none	8”	Figure 6-27/a
14	0.024”	0.024”	foam	½”	LDS	5 mils	1A	200	A,B	4”	none	none	8”	Figure 6-29/a
15	0.024”	0.024”	foam	½”	EAF	5 mils	1A	200	A,B	1”	none	none	5”	Figure 6-30/a
16	0.016”	0.016”	foam	3/8”	ECF	5 mils	1A	200	A,B	1”	none	none	10”	Figure 6-31/b
33	0.024”	0.024”	foam	½”	WWM	5 mils	2A	100	D,B	1.5”	none	1”	2”	Figure 6-28/a
34	0.016”	0.016”	foam	3/8”	ECF	5 mils	2A	100	D,B	none	none	none	4”	Figure 6-32/b

Abbreviations: Thor = Thorstrand Aluminized Fiberglass, LDS = LDS 50-212 Aluminum Foil Perforated, EAF = Expanded Aluminum Foil 0.028, ECF = Expanded Copper Foil 0.029, WWM = Woven Wire Mesh 120x120

References:

a) Lightning Technologies, Glasair III Lightning Protection System Development Report, LT-92-782, 1992.

b) Lightning Technologies, Lightning Tests on the Model LC40 Aircraft Components, LT-97-1398, 1997.

Analysis: None of the fiberglass non-conductive panels showed puncture when protected by expanded foils of either copper or aluminum.

Figure 6-27: Thorstrand Fiberglass Panel

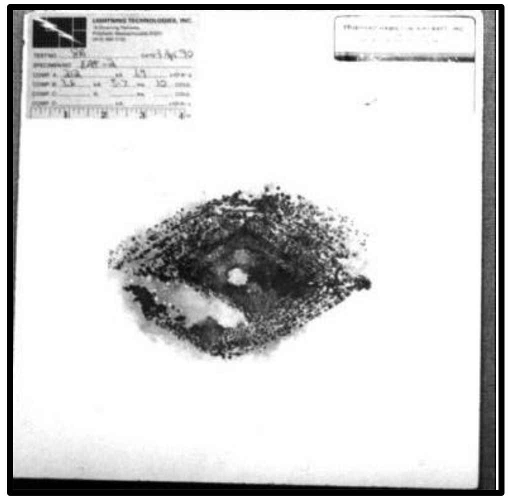


Figure 6-30: EAF Fiberglass Panel

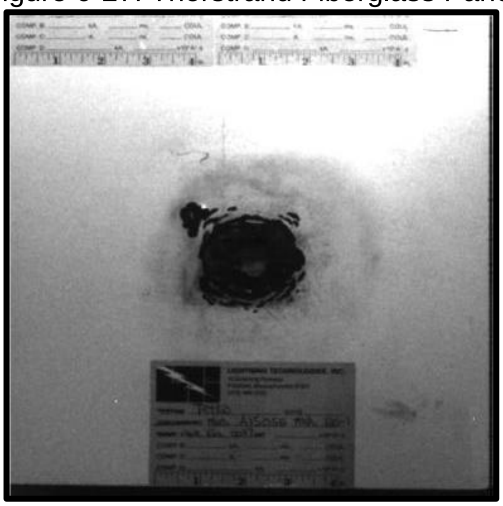


Figure 6-28: 120 x 120 Woven Wire Mesh protected Fiberglass Panel

Figure 6-31: 0.029 ECF protected Panel, Zone 1A

Figure 6-29: LDS 50-120 AF protected Fiberglass Panel

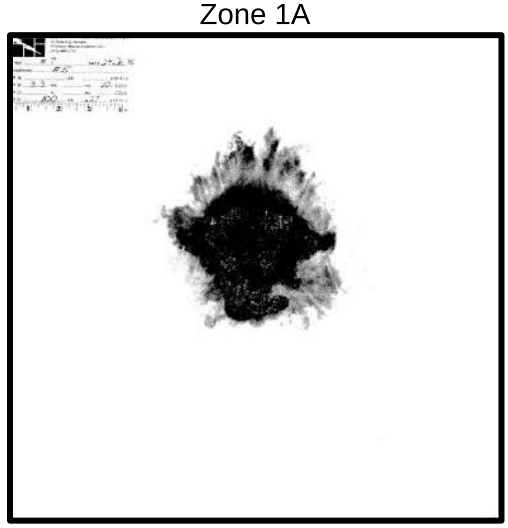


Figure 6-32: 0.029 ECF protected Panel, Zone 2A

6.4 Damage Codes

Pass/Fail assessment is currently used to determine the success of lightning strike test lay-ups. This is fine for certification of a specific lay-up but is very limiting for future design and for comparisons. Assigning an objective and consistent numerical measurement of the lightning damage is a way to determine the influential variables and to quantify their effects. A numerical measurement of lightning damage is also a way to use relative damage to compare panel results.

6.4.1 Damage Code Measurements

It was determined by comparing many test panels that four individual damage measurements need to be combined to represent the overall damage to the test panel. Definitions of the four individual damage measurements to be incorporated into the overall damage code are listed below.

1. **Outer delamination:**
    a. Outer delamination is determined by tap test from the outside of the laminate. This also encompasses resin loss.
2. **Outer hole:**
    a. <u>Solid laminate</u> – an outer hole is fiber breakage or fiber loss on at least one lamina, measured by the longest direction of fiber breakage and its orthogonal where there is also no resin to carry the load between fibers.
    b. <u>Sandwich panel</u> - An outer hole is an opening in the laminate which passes through the laminate to the core. Size is measured by the longest opening dimension and its orthogonal.
3. **Inner damage:**
    a. <u>Solid laminate</u> - Measured from the inside of the laminate, inner damage has two levels; delamination and damage. The size of delamination is measured by the long direction and its orthogonal. If there is additional damage including resin loss or fiber damage, this supersedes the delamination measurement in the damage code. Note: it is unlikely that one will see fiber damage or resin loss on the inside of the panel which, in most cases, will be preceded by delamination.
    b. <u>Sandwich panel</u> - same criteria as for the solid laminate on the inside composite laminate.
4. **Inner hole:**
    a. <u>Solid laminate</u> – an inner hole is an actual opening in the laminate which passes all the way through the inside composite laminate.
    b. <u>Sandwich panel</u> - An actual opening in the laminate which passes all the way through the inside composite laminate.

Repair area is defined by the largest dimensions of damage to the composite or LSP, whichever is greater, that need to be replaced after a lightning strike event. The repair area is an important metric for consideration but it does not contribute to the damage code value.

The individual damage codes are combined in a specific order to give more importance to certain of the individual codes. A hole on the inside of a test panel is the most important measurement. It is the definitive measure of failure because it means a possible attachment to the equipment underneath the panel. Damage on the inside of a panel is next in importance followed by a hole on the outside and then damage on the outside.

6.4.2 Damage Code Levels

Table 6-8 lists the definitions used to assign the levels for each of the damage measurements. This definition is crucial to the amount of distinction between the damage levels of the panels. More distinction was desired for the damage on the inside of the panels so there are more levels with smaller windows for Codes 3 and 4.

Table 6-8: Damage Code Levels

Code 1 outer delamination (in.)	**Code 2 outer hole (in.)**	**Code 3 inner damage (in.)**	**Code 4 inner hole (in.)**
L: x ≤ 4 delamination	L: x ≤ 1 hole	L1: x ≤ 4 delamination	N: no hole
M: 4 < x ≤ 8 delamination	M: 1 < x ≤ 2 hole	L2: 4 < x ≤ 8 delamination	L: x ≤ ½ hole
H: x > 8 delamination	H: x > 2 hole	L3: x > 8 delamination	M: ½ < x ≤ 1 hole
		M1: x ≤ 1 damage	H: 1 < x ≤ 1½ hole
		M2: 1 < x ≤ 2 damage	V: x > 1½ hole
		H: 2 < x ≤ 5 damage	
		V: x > 5 damage	

6.4.3 Damage Code Combination Numerical Assignments

After a damage code is determined for each of the four damage measurements, the codes are combined. Table 6-9 lists every combination for all the levels of the four damage codes.

	Code 1	Code 2	Code 3	Code 4
315 combinations =	3 levels x	3 levels x	7 levels x	5 levels

The damage code combinations are listed in order from least damage to most damage so numbers are assigned sequentially. To use Table 6-9, find a particular four code combination and use the numerical value to the left of it.

There are five sections to Table 6-9 because there are five levels to Code 4 (N, L, M, H, V). Code 4 is the most important damage measurement and determines the Pass/Fail status of the panel. Only the codes in the first section have no inside holes (N). These panels correspond to the numerical values of 1 through 63. Anything above 63 is considered a Fail.

Each of the damage code combinations is weighted equally in Table 6-9 but the combinations are not truly weighted equally because of the way that the levels are set up in Table 6-8. The information is skewed towards more information on the failed panels.

Table 6-9: Damage Code Numerical Assignments

	outer delam	outer hole	inner dmg	inner hole		outer delam	outer hole	inner dmg	inner hole		outer delam	outer hole	inner dmg	inner hole		outer delam	outer hole	inner dmg	inner hole		outer delam	outer hole	inner dmg	inner hole
	Code 1	Code 2	Code 3	Code 4		Code 1	Code 2	Code 3	Code 4		Code 1	Code 2	Code 3	Code 4		Code 1	Code 2	Code 3	Code 4		Code 1	Code 2	Code 3	Code 4
1	L	L	L1	N	64	L	L	L1	L	127	L	L	L1	M	190	L	L	L1	H	253	L	L	L1	V
2	M	L	L1	N	65	M	L	L1	L	128	M	L	L1	M	191	M	L	L1	H	254	M	L	L1	V
3	H	L	L1	N	66	H	L	L1	L	129	H	L	L1	M	192	H	L	L1	H	255	H	L	L1	V
4	L	M	L1	N	67	L	M	L1	L	130	L	M	L1	M	193	L	M	L1	H	256	L	M	L1	V
5	M	M	L1	N	68	M	M	L1	L	131	M	M	L1	M	194	M	M	L1	H	257	M	M	L1	V
6	H	M	L1	N	69	H	M	L1	L	132	H	M	L1	M	195	H	M	L1	H	258	H	M	L1	V
7	L	H	L1	N	70	L	H	L1	L	133	L	H	L1	M	196	L	H	L1	H	259	L	H	L1	V
8	M	H	L1	N	71	M	H	L1	L	134	M	H	L1	M	197	M	H	L1	H	260	M	H	L1	V
9	H	H	L1	N	72	H	H	L1	L	135	H	H	L1	M	198	H	H	L1	H	261	H	H	L1	V
10	L	L	L2	N	73	L	L	L2	L	136	L	L	L2	M	199	L	L	L2	H	262	L	L	L2	V
11	M	L	L2	N	74	M	L	L2	L	137	M	L	L2	M	200	M	L	L2	H	263	M	L	L2	V
12	H	L	L2	N	75	H	L	L2	L	138	H	L	L2	M	201	H	L	L2	H	264	H	L	L2	V
13	L	M	L2	N	76	L	M	L2	L	139	L	M	L2	M	202	L	M	L2	H	265	L	M	L2	V
14	M	M	L2	N	77	M	M	L2	L	140	M	M	L2	M	203	M	M	L2	H	266	M	M	L2	V
15	H	M	L2	N	78	H	M	L2	L	141	H	M	L2	M	204	H	M	L2	H	267	H	M	L2	V
16	L	H	L2	N	79	L	H	L2	L	142	L	H	L2	M	205	L	H	L2	H	268	L	H	L2	V
17	M	H	L2	N	80	M	H	L2	L	143	M	H	L2	M	206	M	H	L2	H	269	M	H	L2	V
18	H	H	L2	N	81	H	H	L2	L	144	H	H	L2	M	207	H	H	L2	H	270	H	H	L2	V
19	L	L	L3	N	82	L	L	L3	L	145	L	L	L3	M	208	L	L	L3	H	271	L	L	L3	V
20	M	L	L3	N	83	M	L	L3	L	146	M	L	L3	M	209	M	L	L3	H	272	M	L	L3	V
21	H	L	L3	N	84	H	L	L3	L	147	H	L	L3	M	210	H	L	L3	H	273	H	L	L3	V
22	L	M	L3	N	85	L	M	L3	L	148	L	M	L3	M	211	L	M	L3	H	274	L	M	L3	V
23	M	M	L3	N	86	M	M	L3	L	149	M	M	L3	M	212	M	M	L3	H	275	M	M	L3	V
24	H	M	L3	N	87	H	M	L3	L	150	H	M	L3	M	213	H	M	L3	H	276	H	M	L3	V
25	L	H	L3	N	88	L	H	L3	L	151	L	H	L3	M	214	L	H	L3	H	277	L	H	L3	V
26	M	H	L3	N	89	M	H	L3	L	152	M	H	L3	M	215	M	H	L3	H	278	M	H	L3	V
27	H	H	L3	N	90	H	H	L3	L	153	H	H	L3	M	216	H	H	L3	H	279	H	H	L3	V
28	L	L	M1	N	91	L	L	M1	L	154	L	L	M1	M	217	L	L	M1	H	280	L	L	M1	V
29	M	L	M1	N	92	M	L	M1	L	155	M	L	M1	M	218	M	L	M1	H	281	M	L	M1	V
30	H	L	M1	N	93	H	L	M1	L	156	H	L	M1	M	219	H	L	M1	H	282	H	L	M1	V
31	L	M	M1	N	94	L	M	M1	L	157	L	M	M1	M	220	L	M	M1	H	283	L	M	M1	V
32	M	M	M1	N	95	M	M	M1	L	158	M	M	M1	M	221	M	M	M1	H	284	M	M	M1	V
33	H	M	M1	N	96	H	M	M1	L	159	H	M	M1	M	222	H	M	M1	H	285	H	M	M1	V
34	L	H	M1	N	97	L	H	M1	L	160	L	H	M1	M	223	L	H	M1	H	286	L	H	M1	V
35	M	H	M1	N	98	M	H	M1	L	161	M	H	M1	M	224	M	H	M1	H	287	M	H	M1	V
36	H	H	M1	N	99	H	H	M1	L	162	H	H	M1	M	225	H	H	M1	H	288	H	H	M1	V
37	L	L	M2	N	100	L	L	M2	L	163	L	L	M2	M	226	L	L	M2	H	289	L	L	M2	V
38	M	L	M2	N	101	M	L	M2	L	164	M	L	M2	M	227	M	L	M2	H	290	M	L	M2	V
39	H	L	M2	N	102	H	L	M2	L	165	H	L	M2	M	228	H	L	M2	H	291	H	L	M2	V
40	L	M	M2	N	103	L	M	M2	L	166	L	M	M2	M	229	L	M	M2	H	292	L	M	M2	V
41	M	M	M2	N	104	M	M	M2	L	167	M	M	M2	M	230	M	M	M2	H	293	M	M	M2	V
42	H	M	M2	N	105	H	M	M2	L	168	H	M	M2	M	231	H	M	M2	H	294	H	M	M2	V
43	L	H	M2	N	106	L	H	M2	L	169	L	H	M2	M	232	L	H	M2	H	295	L	H	M2	V
44	M	H	M2	N	107	M	H	M2	L	170	M	H	M2	M	233	M	H	M2	H	296	M	H	M2	V
45	H	H	M2	N	108	H	H	M2	L	171	H	H	M2	M	234	H	H	M2	H	297	H	H	M2	V
46	L	L	H	N	109	L	L	H	L	172	L	L	H	M	235	L	L	H	H	298	L	L	H	V
47	M	L	H	N	110	M	L	H	L	173	M	L	H	M	236	M	L	H	H	299	M	L	H	V
48	H	L	H	N	111	H	L	H	L	174	H	L	H	M	237	H	L	H	H	300	H	L	H	V
49	L	M	H	N	112	L	M	H	L	175	L	M	H	M	238	L	M	H	H	301	L	M	H	V
50	M	M	H	N	113	M	M	H	L	176	M	M	H	M	239	M	M	H	H	302	M	M	H	V
51	H	M	H	N	114	H	M	H	L	177	H	M	H	M	240	H	M	H	H	303	H	M	H	V
52	L	H	H	N	115	L	H	H	L	178	L	H	H	M	241	L	H	H	H	304	L	H	H	V
53	M	H	H	N	116	M	H	H	L	179	M	H	H	M	242	M	H	H	H	305	M	H	H	V
54	H	H	H	N	117	H	H	H	L	180	H	H	H	M	243	H	H	H	H	306	H	H	H	V
55	L	L	V	N	118	L	L	V	L	181	L	L	V	M	244	L	L	V	H	307	L	L	V	V
56	M	L	V	N	119	M	L	V	L	182	M	L	V	M	245	M	L	V	H	308	M	L	V	V
57	H	L	V	N	120	H	L	V	L	183	H	L	V	M	246	H	L	V	H	309	H	L	V	V
58	L	M	V	N	121	L	M	V	L	184	L	M	V	M	247	L	M	V	H	310	L	M	V	V
59	M	M	V	N	122	M	M	V	L	185	M	M	V	M	248	M	M	V	H	311	M	M	V	V
60	H	M	V	N	123	H	M	V	L	186	H	M	V	M	249	H	M	V	H	312	H	M	V	V
61	L	H	V	N	124	L	H	V	L	187	L	H	V	M	250	L	H	V	H	313	L	H	V	V
62	M	H	V	N	125	M	H	V	L	188	M	H	V	M	251	M	H	V	H	314	M	H	V	V
63	H	H	V	N	126	H	H	V	L	189	H	H	V	M	252	H	H	V	H	315	H	H	V	V

6.4.4 Damage Codes for AGATE Data

There are 8 metal examples and 26 composite examples in the AGATE handbook for a total of 34 pieces of data. A damage code was assigned to each of the test panels from the AGATE handbook using the process described in Section 6.4. The results are shown in Table 6-10 through Table 6-15.

Table 6-10: Damage Codes for AGATE Data - Metal

Panel No.	Panel Thickness	Coating	Zone	hole	dent	repair area	Damage Code	Figure
1	0.032”	none	1A	none	2”	3”	37	Figure 6-4
2	0.040”	primer	1	none	none	1”	1	
3	0.040”	paint	1A	0.1”	0.5”	1”	64	Figure 6-6
4	0.040”	paint & Al tape	(a)	0.2”	1”	2”	100	**Error! Reference source not found.**
17	0.040”	Al tape	(a)	0.1”	none	1”	64	
18	0.080”	none	(a)	none	none	1”	1	
19	0.080”	none	(a)	none	none	1”	1	
20	0.080”	paint	(a)	none	none	1”	1	

(a) No zone definition is possible, current components were applied as specified in the table for evaluation purposes.

Table 6-11: Damage Codes for AGATE Data – CFC foam core

Panel No.	Panel Thickness		Core	Thick	LSP	Paint	Zone	delam	hole		repair area	Damage Code	Figure
	inner	outer						inner	inner	outer	outer		
21	0.008”	0.016”	foam	3/8”	NCC	5 mils	2A	4”	1”	3”	3.5”	196	Figure 6-10
5	0.008”	0.016”	foam	3/8”	NCC	5 mils	1A	6”	3”	6”	7”	269	Figure 6-13
6	0.016”	0.032”	foam	½”	EAF	5 mils	1B	2”	none	3”	8”	8	Figure 6-11
7	0.016”	0.032”	foam	½”	EAF	5 mils	1A	1”	none	none	3.5”	1	Figure 6-14
8	0.008”	0.016”	foam	3/8”	ECF	5 mils	1A	6”	none	none	9”	12	Figure 6-12
22	0.008”	0.016”	foam	3/8”	ECF	5 mils	2A	1”	none	none	6”	2	Figure 6-15

Table 6-12: Damage Codes for AGATE Data - CFC no core

Panel No.	Panel Thickness		LSP	Paint	Zone	hole		delam	repair area	Damage Code	Figure
	inner	outer				inner	outer	outer	outer		
9	N/A	0.040”	none	none	1A	none	none	none	5”	2	Figure 6-7
10	N/A	0.040”	none	5 mils	1A	3”	3”	7”x9”	7”x9”	306	Figure 6-8
23	N/A	0.040”	none	5 mils	2A	1.5”x3”	1.5”x3”	3”x4”	4”x5”	296	Figure 6-9
11	N/A	0.024”	ECF	5 mils	1A	none	none	none	9”	3	Figure 6-16
24	N/A	0.024”	ECF	5 mils	2A	none	none	none	5”	2	Figure 6-18
12	N/A	0.032”	IAW	5 mils	1A	none	none	3”	8”	2	Figure 6-17
25	N/A	0.032”	IAW	5 mils	2A	none	none	2”	6”	2	Figure 6-20
26	N/A	0.032”	WWM	5 mils	2A	none	none	1”	3”	1	Figure 6-18

Table 6-13: Damage Codes for AGATE Data - AFML CFC no core

Panel No.	Panel Thickness		LSP	Paint	Zone	hole		delam	repair area	Damage Code	Figure
	inner	outer				inner	outer	outer			
27	N/A	0.040”	AF 1mil	5 mils	2	none	none	none	6”	2	Figure 6-21
28	N/A	0.040”	AF 3mil	5 mils	2	none	none	1.5”	2”	1	Figure 6-22
29	N/A	0.040”	AF 3mil	5 mils	2	none	none	1.5”	2”	1	Figure 6-23
30	N/A	0.040”	AF 6mil	5 mils	2	none	none	0.75”	1”	1	Figure 6-24
31	N/A	0.040”	Cu paint	5 mils	2	0.5”	1”	1”	4”	166	Figure 6-25
32	N/A	0.040”	Al plasma	5 mils	2	none	none	2”	6”	2	Figure 6-26

Table 6-14: Damage Codes for AGATE Data - Fiberglass foam core

Panel No.	Panel Thickness		Core	Thick	LSP	Paint	Zone	delam	hole		repair area	Damage Code	Figure
	inner	outer						inner	inner	outer	outer		
13	0.016”	0.016”	foam	½”	Thor	5 mils	1A	7”	none	none	8”	11	Figure 6-27
14	0.024”	0.024”	foam	½”	LDS	5 mils	1A	4”	none	none	8”	2	Figure 6-29
15	0.024”	0.024”	foam	½”	EAF	5 mils	1A	1”	none	none	5”	2	Figure 6-30
16	0.016”	0.016”	foam	3/8”	ECF	5 mils	1A	1”	none	none	10”	3	Figure 6-31
33	0.024”	0.024”	foam	½”	WWM	5 mils	2A	1.5”	none	1”	2”	4	Figure 6-28
34	0.016”	0.016”	foam	3/8”	ECF	5 mils	2A	none	none	none	4”	1	Figure 6-32

Table 6-15: Damage Codes for AGATE Data - All

Panel No.	Test Article ID	Damage code
1	**M-.032,no paint**	37
2	**M-.04,primer**	1
3	**M-.04,paint**	64
4	**M-.04,paint,tape**	100
5	**C-core,NCC**	269
6	**C-core,EAF,1B**	8
7	**C-core,EAF,1A**	1
8	**C-core,ECF**	12
9	**C-.04,no paint**	2
10	**C-.04,paint**	306
11	**C-.024,ECF**	3
12	**C-.032,IAW**	2
13	**F-core,Thor**	11
14	**F-core,LDS**	2
15	**F-core,EAF**	2
16	**F-core,ECF**	3
17	M-.04,tape,paint,B	64
18	M-.08,no paint,B	1
19	M-.08,no paint,BC	1
20	M-.08,paint,B	1
21	**C-core,NCC**	196
22	**C-core,ECF**	2
23	**C-.04,paint**	296
24	**C-.024,ECF**	2
25	**C-.032,IAW**	2
26	**C-.032,200WM**	1
27	**C-.04,AF-1**	2
28	**C-.04,AF-3**	1
29	**C-.04,AF-3**	1
30	**C-.04,AF-6**	1
31	**C-.04,Cu paint**	166
32	**C-.04,Al plasma**	2
33	**F-core,120WM**	4
34	**F-core,ECF**	1

Zone 1A
Zone 2A
Refer to note for Table 6-10

M = Metal
C = Carbon Fiber
F = Fiberglass

NCC = Nickel Coated Carbon Fiber, outer ply only
EAF = Expanded Aluminum Foil – perforated and stretched solid metal foil
ECF = Expanded Copper Foil – perforated and stretched solid metal foil
IAW = Interwoven Aluminum Wires, 8-10 wires per inch

WWM = Woven Wire Mesh – Aluminum wires at 0.0004” diameter
AF = Solid Aluminum Foil

6.4.5 AGATE Data Damage Code Graphs

Shown below in Figure 6-33 is all the data from the AGATE Handbook plotted using the damage codes assigned from the method described in section Damage Codes.

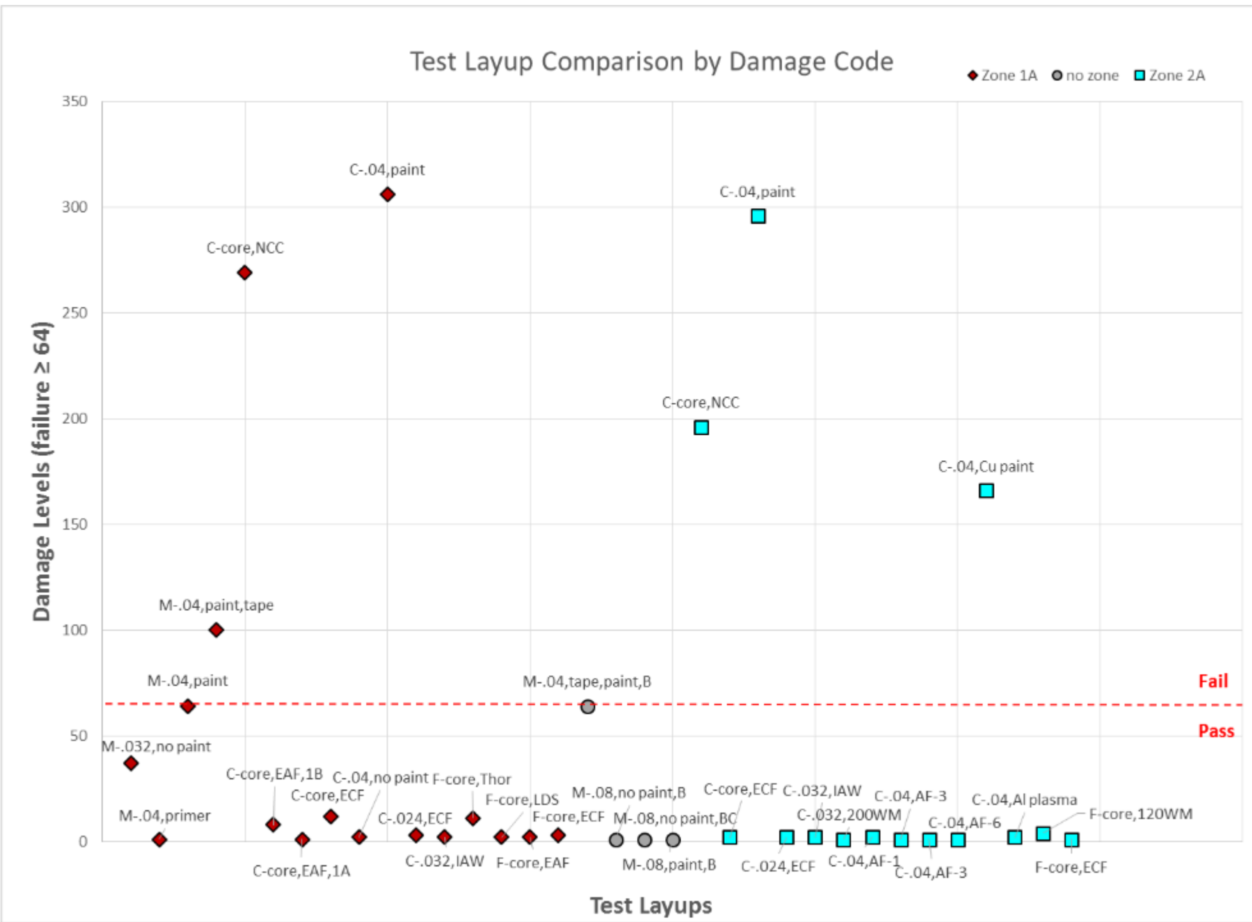


Figure 6-33: AGATE Data Graph with Damage Codes

Partial data is shown in the following graphs to emphasize the effect of different variables (i.e. - adding paint, lightning strike protection, and panel material).

No conclusions could be made about the effectiveness of various laminate thicknesses or whether using a core versus using a solid laminate was better because there was not enough data.

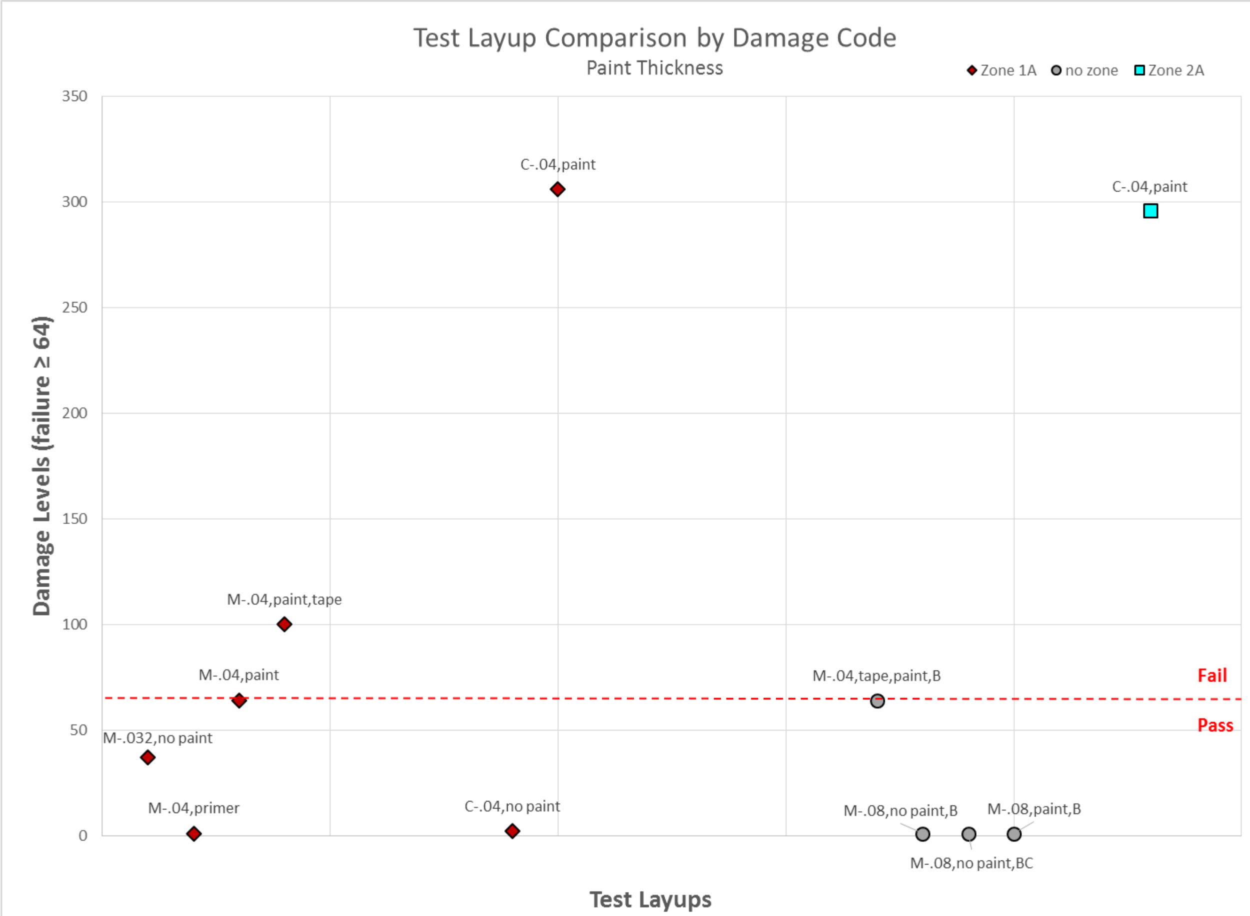


Figure 6-34: AGATE Data Graph by Paint Thickness

Analysis: adding paint is a detriment.

- 0.04” thick carbon fiber panel with no paint passes but with paint fails definitively in both zones.
- The results for primer on the zone 1A metal panels were very different than the results for paint. The 0.04” metal panel with primer had very little damage but the 0.04” panels with paint and/or tape failed.
- Even though the 0.032” metal panel has no paint, it still sustains more damage than the 0.04” metal panel with primer because it is thinner.
- For the no zone metal panels, the 0.08” thick panels are basically not affected.
- The no zone metal panel that is 0.04” thick fails with a hole even with just Component B (10 coulombs of charge transfer, 2 kA amplitude, and ≤5 milliseconds of time duration).

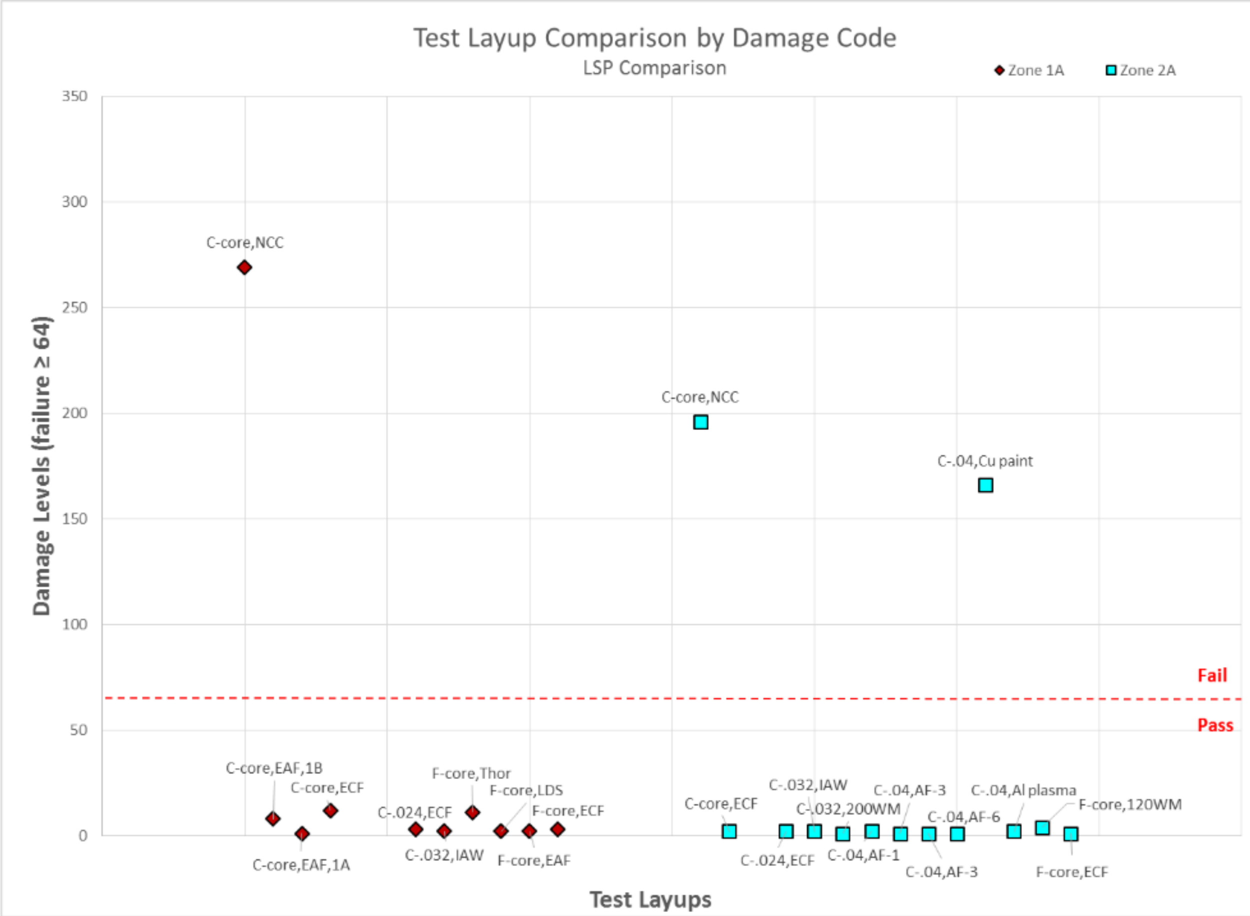


Figure 6-35: AGATE Data Graph by Lightning Strike Protection

Analysis: The Nickel Coated carbon fiber and the copper paint failed as effective lightning strike protection materials. All the other lightning strike protection materials appear to be equally good because they all passed at almost the same levels. The expanded copper foil may have an advantage because it passed on a much thinner panel (0.024”).

- The panels with Nickel Coated carbon fiber as the lightning protection failed in both zones.
- The copper paint failed on 0.04” thick carbon fiber in zone 2A but the aluminum plasma and three thicknesses of aluminum foil passed on 0.04” thick carbon fiber.

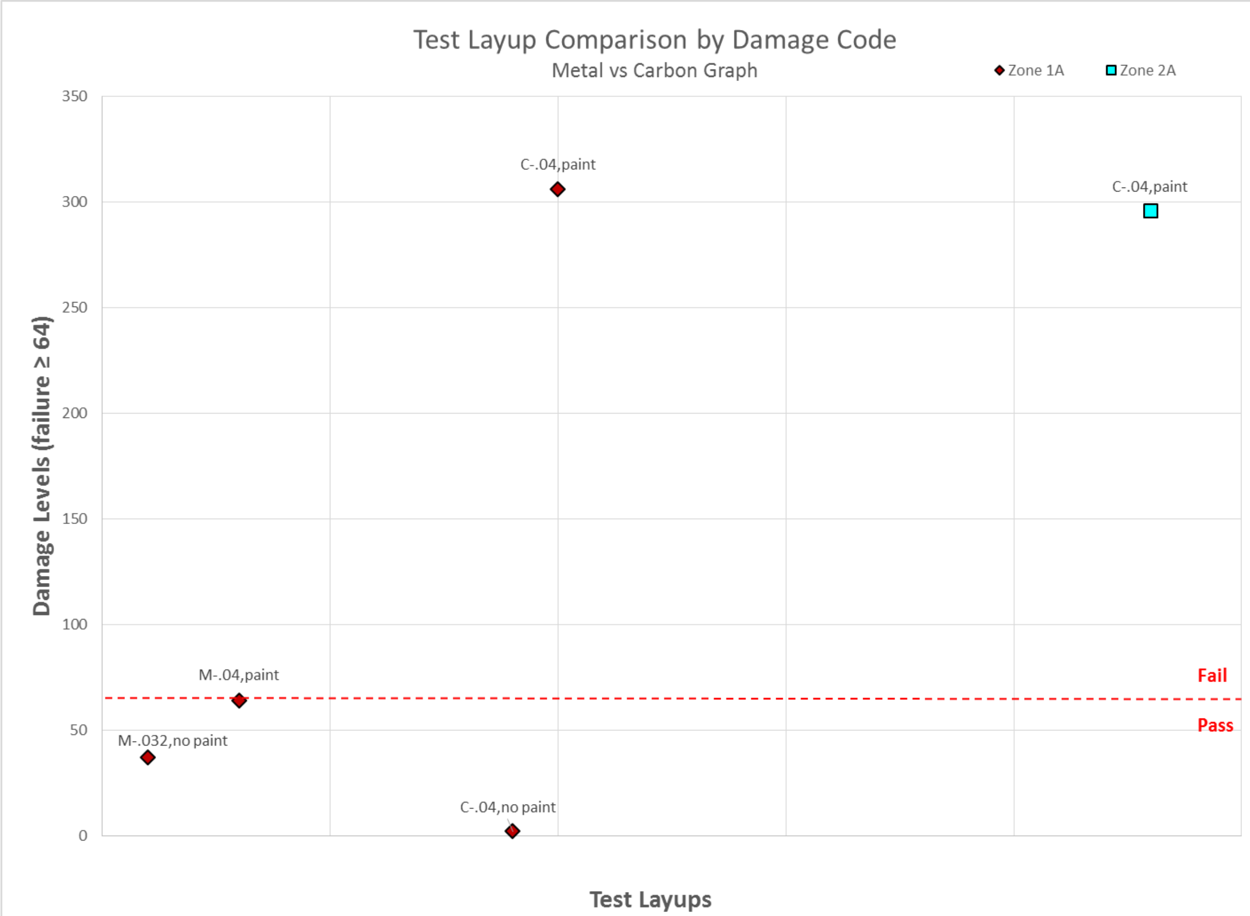


Figure 6-36: AGATE Data Graph by Panel Material

Analysis: Metal panels with paint withstand lightning strike much better than carbon fiber panels with paint.

- A 0.04” thick metal panel with paint just failed but a 0.04” thick carbon fiber panel with paint failed much worse in both zones.
- The 0.032” metal panel with no paint and the 0.04” carbon fiber panel with no paint had much more similar outcomes than the test panels with paint.

6.5 Updated Materials – Round Robin Test Results

Materials and processes for construction of composites, particularly lightning strike protection, have evolved since the previous testing detailed in this document occurred over 20 years ago. The aircraft manufacturers comprising the Kansas Aviation Research and Technology Growth Initiative group (KART) funded a project entitled “Standardization of Lightning Strike Protection for Advanced Composites” to study lightning testing with current materials and compare the results with previous tests to see if the new materials performed differently in regards to lightning protection.

6.5.1 Updated Materials

Listed below are general descriptions of the updated materials used in the test panels for this project:

- An epoxy composite surfacing film with lightweight expanded copper foil (ECF) for lightning protection.
- An epoxy composite surfacing film with lightweight expanded copper foil (ECF) for lightning protection, including a light scrim for improved material handling during layup.
- 263 g/m^2 plain weave Phosphor Bronze Lightning Strike (PBLS) which consists of 193 g/m^2 PW carbon fibers with 70 g/m^2 phosphor bronze interwoven wires.
- Hybrid combination of plain weave and unitape carbon fiber reinforced epoxy resin system with unitape on the inside and plain weave on the outside surfaces.
- 3/8” core material made of aramid fiber paper with hexangular cell shape coated with a heat resistant phenolic resin to increase strength and thermal properties (Nomex core).
- 140 g/m^2 of a conductive epoxy film used to protect aircraft from a direct lightning strike.

6.5.2 New Materials Test Results

Table 6-16: New Materials – Carbon Fiber Composites – no core

Panel No.	Panel Thickness	LSP	Paint (mils)	Zone	I (kA)	I Comps	delam	hole		damage area	dmg code	Figure
							inner	inner	outer	outer		
4-6	0.04”	ECF2	12.8	1A	200	A,B,C*	1”x1.5”	none	0.25”	3.5”x4”	1	Figure 6-37
4-7	0.04”	ECF2	13.7	2A	100	A,B,C*	1”x1.5”	none	none	2.5”x3”	1	Figure 6-40
4-19	0.04”	PBLS	11.5	1A	200	A,B,C*	3”x7”	3”x7”	1.5”	10”x10”	312	Figure 6-38, Figure 6-41
4-20	0.04”	PBLS	10.6	2A	100	A,B,C*	1”x3”	0.5”x2”	0.5”x1”	4.5”x5”	302	Figure 6-39, Figure 6-42
2-31	0.04”	film	10	1A	200	A,B,C*	5”x1.5”	0.3”x0.3”	2”x5”	9.5”x10”	114	Figure 6-43, Figure 6-46
2-32	0.04”	film	11	2A	100	A,B,C*	1.8”x12”	0.3”x0.3”	2.5”x3”	7”x8”	125	Figure 6-44, Figure 6-47
2-37	0.04”	film	6	1A	200	A,B,C*	2.5”x1.5”	none	0.3”x0.3”	6”x9”	2	Figure 6-45
2-38	0.04”	film	7	2A	100	A,B,C*	2”x3.5”	none	1”x2”	4”x4.5”	5	Figure 6-48

Abbreviations: ECF2 = Expanded Copper Foil 0.029 lbs/ft^2 (142gsm), PBLS = Phosphor Bronze Lightning Strike interwoven wires, film = conductive epoxy film

Analysis:

- Expanded copper foil demonstrated the best protection for both zones at ~12 mils of paint.
- Expanded copper foil at ~12 mils of paint provided less damage than the conductive film at ~6 mils of paint.
- Conductive film permitted puncture in both zones with ~12 mils of paint but had no puncture in either zone with ~6 mils of paint

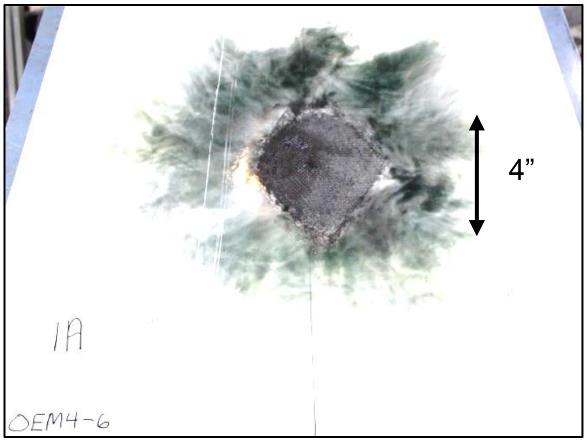


Figure 6-37: 0.029 ECF, Zone 1A, outer

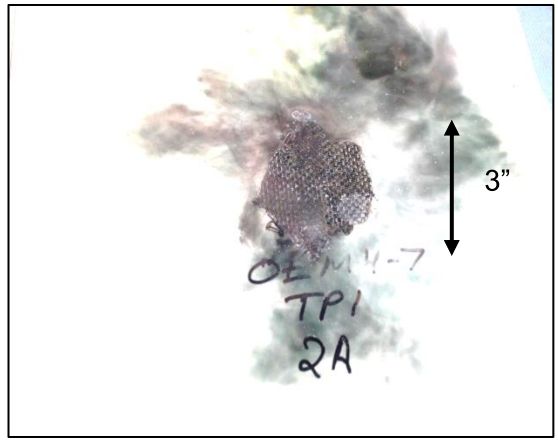


Figure 6-40: 0.029 ECF, Zone 2A, outer

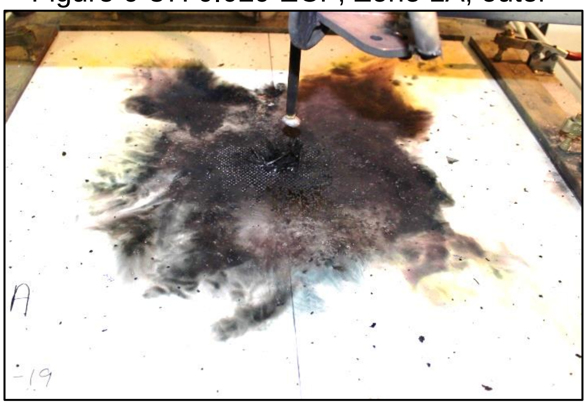


Figure 6-38: PBLS, Zone 1A, outer

Figure 6-41: PBLS, Zone 1A, inner

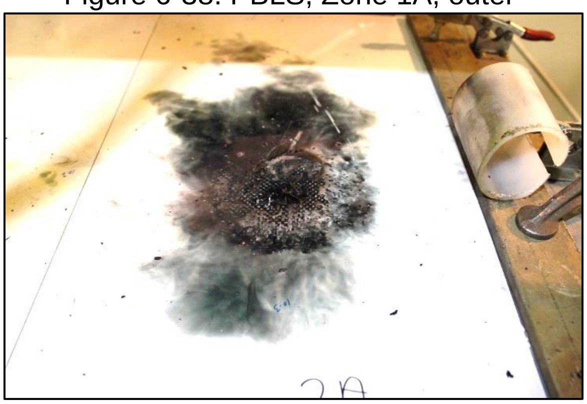


Figure 6-39: PBLSE, Zone 2A, outer

Figure 6-42: PBLSE, Zone 2A, inner

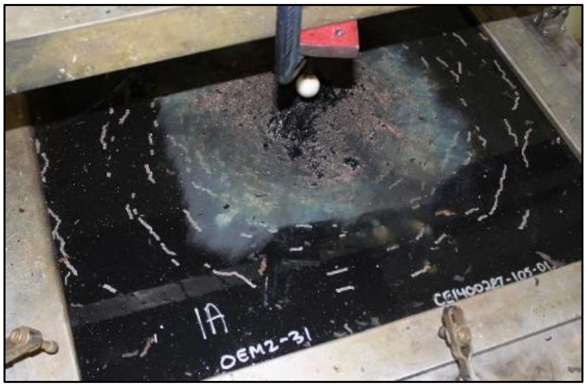


Figure 6-43: Film, Zone 1A, outer, 12 mils of paint

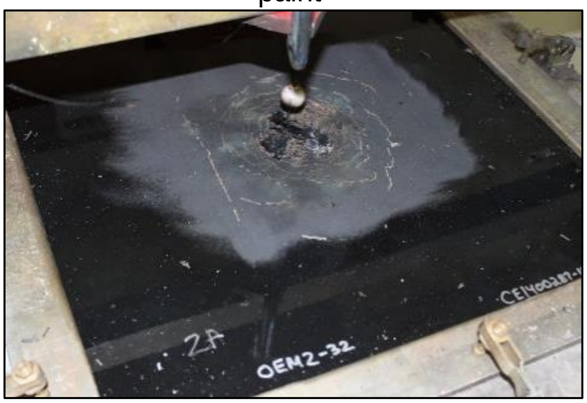


Figure 6-44: Film Zone 2A, outer, 12 mils of paint

Figure 6-45: Film, Zone 1A, 6 mils of paint, no hole

Figure 6-46: Film, Zone 1A, inner, 12 mils of paint

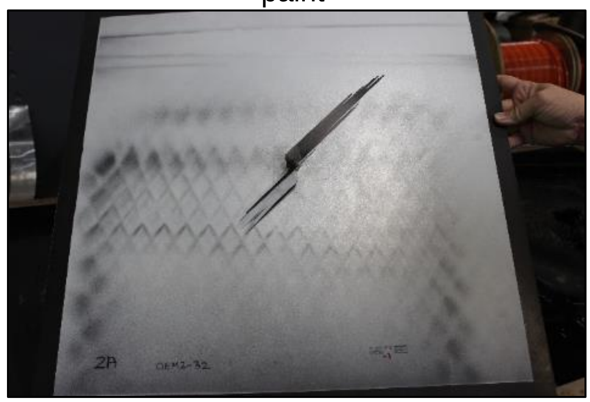


Figure 6-47: Film, Zone 2A, outer, 12 mils of paint

Figure 6-48: Film, Zone 2A, 6 mils of paint, no hole

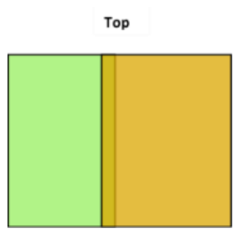
6.6 Lightning Protection Splice Configurations

6.6.1 Splice Theory

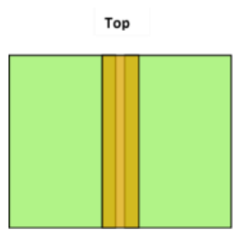
Lightning strike protection materials may occasionally need to be spliced together for various reasons. LSP materials are manufactured in rolls of limited width, and may not be wide enough to completely cover a large component. Sections of material must be spliced together to provide continuity of current in case of a lightning strike. When an external aircraft component is damaged, the area is often repaired by removing the damaged section and replacing it with new material. The lightning strike protection is normally added as a patch, or splice, which overlaps the original lightning strike protection material from the surrounding undamaged section.

Two splice types are evaluated here. The diagrams below provide a visual description of the splices for clarification:

1. Single Overlap – the right edge of one LSP film is overlapped by the left edge of another LSP sheet by approximately one inch.



2. Butt and Splice – The right edge of one LSP sheet is butted against the left edge of another LSP sheet, resulting in a ply with a vertical seam. A second LSP ply, approximately two inches wide, is centered over the seam of the first ply, running vertically over the entire length of the seam.



Materials and Testing Level

Spliced panels were tested with two different LSP materials; expanded copper mesh and a conductive film which utilizes silver micro-particles as the conductive material. Spliced panels tested were either thick plain weave or thick unitape, carbon/epoxy plies. All spliced panels were tested at Zone 2A test level.

6.6.2 Splice Comparison

Single Overlap vs Butt and Splice

The following examples are a representative set for comparison between Single Overlap vs Butt and Splice configurations of expanded copper foil. All composite panels were either plain weave or unitape. All splice panels were tested at lightning strike level for Zone 2A.

Table 6-17: Single Overlap vs Butt and Splice Comparison

Panel No.	Splice Type	LSP	Ply type	Paint	hole	delam		damage area	Damage Code	Figure
						inner	outer	outer		
2-7	Single	ECF	uni	12 mils	none	1.5"x2"	3.5"x4"	5.5”x6"	7	Figure 6-49
2-16	Single	ECF	woven	12 mils	none	none	3"x4"	3”x7.5”	1	Figure 6-50
2-23	Single	ECF	uni	12 mils	none	none	3.5"x6"	6”x7.5”	2	
2-29	Single	ECF	uni	12 mils	none	none	1.25"x3"	4.5”x5"	4	
2-5	Butt Splice	ECF	uni	12mils	none	none	3"x3.5"	4”x4.5”	1	Figure 6-51
2-13	Butt Splice	ECF	uni	12 mils	none	1"x4.75"	3"x4.5"	3”x4.5”	14	Figure 6-52
2-21	Butt Splice	ECF	uni	12 mils	none	1"x4"	2"x3"	4"x14"	4	
2-27	Butt Splice	ECF	uni	12 mils	none	1"x2"	3.5"x4"	4”x4”	7	

Abbreviations: ECF = Expanded Copper Foil 0.015 lbs/ft^2 (73gsm**),** Single = Single Overlap splice

Analysis:

- Similar damage in terms of repair area size and outer delamination area were seen on both Single Overlap and Butt and Splice panels.
- No hole was permitted on any spliced panels at Zone 2A.
- On average, slightly less inner delamination was recorded on Single Overlap panels, but with limited dataset no trend could be determined from the results.
- At 2A lightning strike level, damage codes for all ECF, Single Overlap and Butt and Splice panels averaged 3.5 and 6.5, respectively.
- At 2A lightning strike level, there is little difference in the behavior of Single Overlap and Butt and Splice panels with ECF. Splice panels were not tested at Zone 1A lightning strike level.

Figure 6-49: Single, Unitape, ECF
12 mils of paint

Figure 6-50: Single, Woven, ECF
12 mils of paint

Figure 6-51: Butt Splice, Unitape, ECF
12 mils of paint

Figure 6-52: Butt Splice, Unitape, ECF
12 mils of paint

Spliced panels vs Full panels (no splices)

The following examples are a representative set for comparison between Spliced panels vs Full panels (without splices) tested at Zone 2A lightning strike level. All carbon/epoxy composite panels tested were either plain weave or unitape. Lightning strike protection included expanded copper foil with 12 mils of paint, or conductive film averaging 8 mils of paint. All splice panels were tested for Zone 2A.

Table 6-18: Spliced Panels vs Full Panels Comparison

Panel No.	Splice Type	LSP	Ply type	Paint	hole	delam		repair area	Damage Code	Figure
						inner	outer	outer		
2-23	Single	ECF	uni	12 mils	none	none	3.5"x6"	6”x7.5”	2	
2-26	Full	ECF	uni	12 mils	none	none	3.75"x4"	4"x4.5"	7	Figure 6-53
2-27	Butt Splice	ECF	uni	12 mils	none	1"x2"	3.5"x4"	4”x4”	7	Figure 6-54
2-16	Single	ECF	woven	12 mils	none	none	3"x4"	3”x7.5”	1	Figure 6-55
2-12	Full	ECF	woven	12 mils	none	none	3"x3.5"	3.5"x3.5"	4	Figure 6-56
2-35	Single	film	uni	10mils	none	none	5"x7"	9”x9.5"	8	
2-33	Full	film	uni	6 mils	none	3"x4"	3.5"x5.5"	4"x5.5"	8	
2-41	Single	film	woven	5 mils	none	none	5"x6"	8.5”x9"	8	Figure 6-57
2-40	Full	film	woven	7 mils	none	none	4"x4.5"	7"x10"	8	Figure 6-58

Abbreviations: ECF = Expanded Copper Foil 0.015 lbs/ft^2 (73gsm**)**, Film = conductive film, Single = Single Overlap splice, Full = full LSP sheet with no splices

Analysis:

- Inner delamination was not seen on the ECF, Uni panels without splices, while ECF, Uni panels with either Butt Splice or Single Overlap splice incurred delamination on four out of seven panels tested.
- Overall damage in terms of outside fiber damage and outer delamination area was similar across all ECF, Uni panels between Full, Butt Splice and Single Overlap.
- Panels with conductive film LSP in both Woven and Uni showed similar outer damage, and delamination damage as ECF, although outer repair area was generally larger than ECF.
- All damage codes for Zone 2A Spliced vs Full panels tested with ECF or conductive film were between 1 and 14, indicating minimal damage levels.
- It can be concluded that spliced panels are an acceptable method of grafting two sections of lightning strike protection where necessary for Aircraft Zone 2A. No inference can be made concerning higher lightning strike levels.
-

Figure 6-53: Full, Uni, ECF,
12 mils of paint

Figure 6-54: Butt Splice, Uni, ECF
12 mils of paint

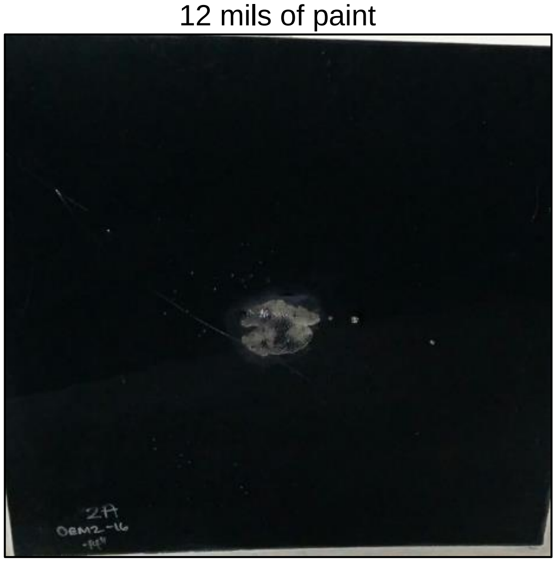


Figure 6-55: Single, Woven, ECF
12 mils of paint

Figure 6-56: Full, Woven, ECF
12 mils of paint

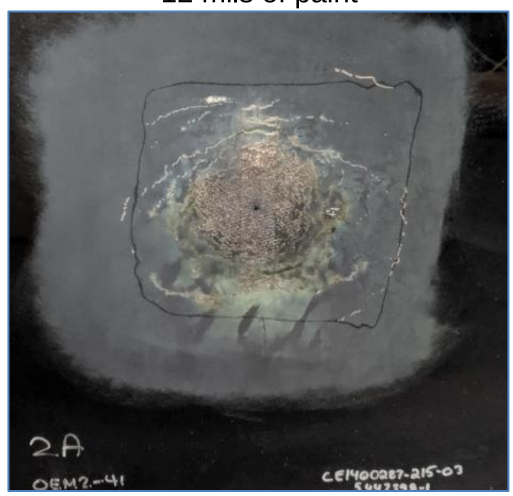


Figure 6-57: Single, Woven, Film
5 mils of paint

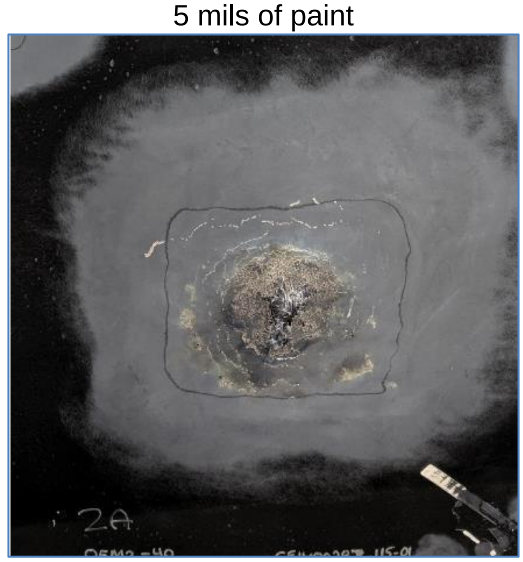


Figure 6-58: Full, Woven, Film
7 mils of paint

Character of Splice Panel Surface Damage

Spliced panels often display damage along the lightning protection seam lines where there is a discontinuity of the current path and higher contact resistance, as seen in Figure 6-59. Visual inspection suggests that this may result in a redistribution of damage rather than an increase in overall damage. Testing at higher, Zone 1A lightning strike level would be necessary to determine whether this phenomenon would result in greater damage in comparison to full panels without splices.

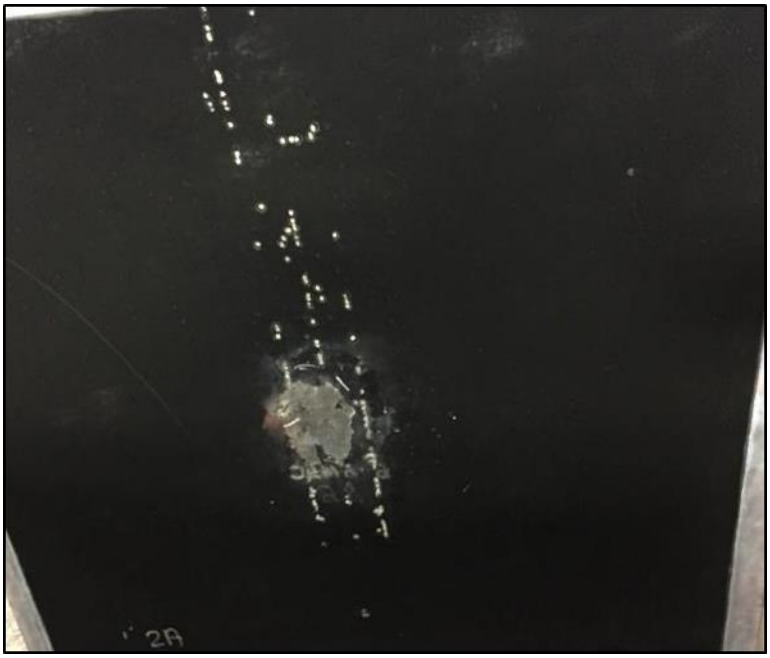


Figure 6-59: Butt and Splice Panel with Seam Damage

6.6.3 New vs Old Materials Comparison

It is important to note that there is a substantial amount of time which has passed between different rounds of testing. This has allowed for new processes and new materials to develop and these factors are present in the updated materials testing. However, the fundamental fiber and matrix content is relatively unchanged, and testing parameters are consistent. Lightning strike protection materials, where comparable, have produced similar results despite the nearly twenty year time span. Overall this is a good indicator that the results of the previous testing remain valid for thermoset composite materials moving into the future. Splices in the lightning strike protection materials on thermoplastic composite panels are studied further and discussed at length in section 6.10.

6.7 Thermoplastic Composites

6.7.1 Background

Recently the aerospace industry has shown increased interest in pursuing thermoplastic composites (TPCs) as an alternative to the commonly used epoxy resin based thermoset composites (TSCs) that have dominated the composites industry in previous decades. In preparation for widespread commercial application, KART has funded a project entitled “Update of AGATE Handbook – New Materials” to assess the response of thermoplastic composites to lightning strike.

Some potential advantages of TPCs include faster processing times, less material waste in production, and their ability to be welded. Welding of TPCs would allow for overall weight reduction by eliminating a portion of the many fasteners currently required to build an aircraft. The material properties of thermoplastics for high performance composites such as low melt polyaryletherketone (LM PAEK)/carbon and polyphenylene sulfide (PPS)/carbon are largely equivalent to those of high performance thermoset composites (TSCs) such as epoxy/carbon. The basic difference between TPCs and TSCs lies in the matrix. Thermoset resins are cured by addition of a curing agent in a chemical reaction, which results in a cross-linked polymer. The reaction is irreversible, in that it cannot be transformed into a liquid with addition of heat energy and will simply decompose above its service temperature. On the other hand, thermoplastics are linear, semi-crystalline polymer chains whose secondary bonds between linear chains can be broken with addition of sufficient thermal energy. As a result, thermoplastics can be melt processed out of autoclave without permanent degradation of the polymer chains.

Since TPCs have only recently been considered as structural aircraft components, their response to lightning strike is not well documented. This section will provide a dataset, which details the behavior of LM PAEK/carbon fiber TPCs.

6.7.2 Materials

Panel configurations included two fiber arrangements, two panel thicknesses, four lightning protection schemes, and two paint thicknesses.

1. Unitape: Toray TC1225 unidirectional tape, T700-12K T1E 145gsm FAW 34%RC
2. Fabric: TC1225 5HS T300J 3K 277 gsm

The unidirectional tape carbon fiber panels consisted of 8 plies (0.04 inches) and 16 plies (0.08) for thin and thick panels, in a quasi-isotropic, symmetrical/balanced layup schedule. The layup sequence for the five-harness satin carbon fiber fabric (5HS) was orthotropic and consisted of 4 plies (0.048 inches) and 8 plies (0.096 inches) for the thin and thick panels respectively.

Four different protection schemes were utilized in testing. The three lightning strike protection (LSP) conductive materials tested on the TPCs are listed below. The fourth protection scheme, no lightning strike protection, is a bare TPC panel, which is then painted according to the prescribed paint scheme.

1. ECF 1: 3CU7-125FA (141.6 gsm) – (CU1)

2. ECF 2: 3CU7-100FA (195.3 gsm) – (CU2)
3. Conductive Spray Coating (SU)
4. No Protection (NP)

All panels were painted with aircraft industry standard paint over the LSP. For the NP panel, the paint was directly applied to the top composite ply. The details of the coating are:

1. PPG CA-7501 epoxy primer
2. PPG F565-4010 epoxy intermediate coat
3. PPG CA8000 polyurethane topcoat

Three panels of each configuration were painted and tested as follows:

1. One Zone 1A panel was designated to be painted with 10-12 mils of paint and struck once,
2. One Zone 2A panel was designated to be painted with 10-12 mils of paint and struck twice,
3. One Zone 2A panel was designated to be painted with 5 mils of paint and struck twice.

The nomenclature for the panel ID's is specified in Table 6-19 below.

Table 6-19: Panel ID Nomenclature

Naming Pattern: ABBCC-#	
A	5- 5HS; U- unitape
BB	TK- Thick panel; TH- Thin Panel
CC	CU1- 142 gsm ECF; CU2- 195 gsm ECF; SU- conductive spray; NP- no protection
#	1- 1A (10-12 mils); 2- 2A (10-12 mils); 3- 2A (5 mils)

6.7.3 Analysis

The following sections examine the data with respect to the individual test variables, both in terms of damage codes (see Section6.4.1), and with respect to the size and extent of damage to resin, fiber, and delamination. See Section 6.7.4 for full measurement details.

Paint Thickness

After testing, paint thicknesses were measured with calipers and it was found that the panels specified as 10-12 mils actually had 8-10 mils of paint, while the panels specified as 5 mils of paint had 5-7 mils. For this reason, four select panels were repainted to match the specifications and create a better delineation in the data. The range in paint thickness after repainting was 12-14 mils.

The paint did not adhere well to ECF and NP panels and could be peeled off with limited force. Since the epoxy-based primer does not chemically bond to the LM PAEK substrate, additional adhesion promotion may be necessary. SU panels did not have the same adhesion issues. It should be noted that in only two cases did the paint delaminate beyond the edge of the damage to the LSP. These were cases of extreme damage to the panels (see Figure 6-61 and Figure 6-62).

<u>Zone 1A:</u> Testing was not designed to determine the effect of paint thickness at 1A.

<u>Zone 2A:</u> When making direct comparisons, no clear trend can be determined as to the effect of paint thickness on damage, as seen in Figure 6-60 below. However, for panels painted with 5 mils of paint, the 5HS sustained less damage than the unitape on average. In contrast, with 8-10 and 12-14 mils, on average, the unitape panels sustained less damage than the 5HS.

In terms of damage codes:

- In 12 out of 32 instances, the panels with 5 mils and the panels with 8-10 mils performed the same.
- In 10 out of 32 instances, the 8-10 mils bore less damage than the panels with 5 mils of paint.
- In 10 out of 32 instances, the panels with 5 mils bore less damage than 8-10 mils panels.
- In 6 out of 7 instances, the panels with 12-14 mils, 8-10 mils, and 5 mils of paint all performed the same and received a damage score of 1.
- In 1 instance, the 12-14 mils scored higher than both the 8-10 and 5 mils.

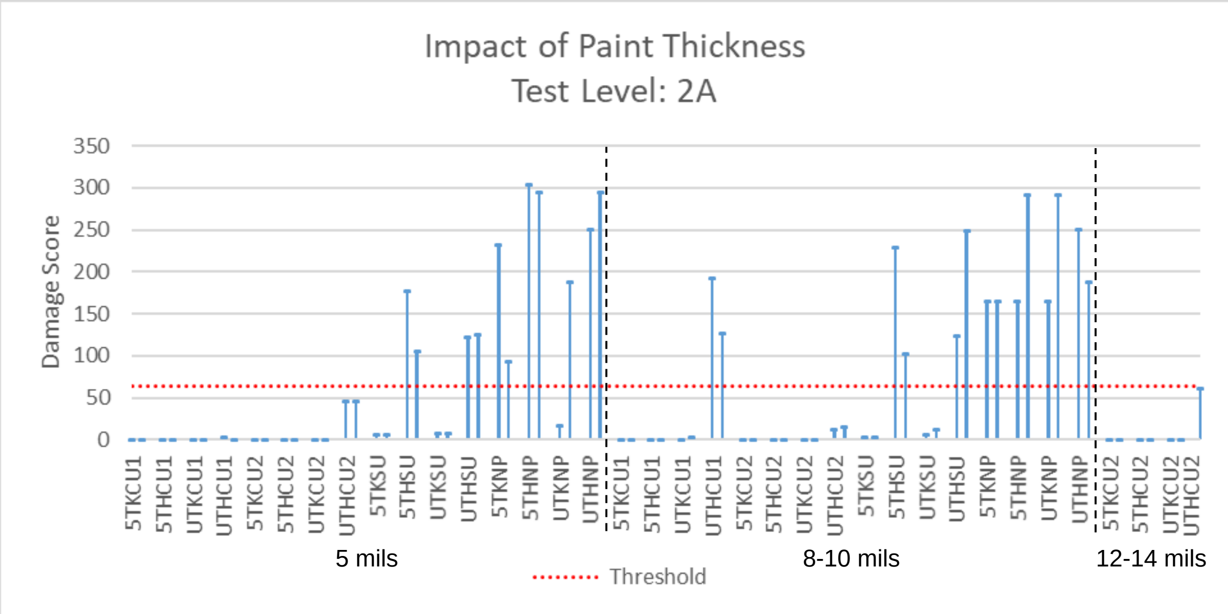


Figure 6-60: Direct Comparison of Paint Thickness Impact at 2A Test Level

Lightning Strike Protection

<u>Zone 1A:</u> Testing shows overall the two different weights of ECF performed nearly identically, except in the case of the thin unitape panels. Two out of four of the ECF thick panels had no fiber breakage and very little fiber damage or resin loss on the outside of the panel. The inside of three of the ECF thick panels had no delamination or damage while the fourth panel had an inside delamination area of 4.5 inches. The bulk of the repair area of the ECF thick panels comes from LSP loss rather than panel damage. Figure 6-65 below shows the typical damage areas by damage type for ECF panels. Boundaries of the respective damage types are outlined and color-coded.

Four unique panel configurations of ECF, thin, zone 1A panels were tested. The UTHCU1-1 panel with the lighter weight of ECF dramatically outperformed the UTHCU2-1 panel (see Figure 6-63 and Figure 6-64 below) so these panels were tested again. In total, there were six data points for the ECF, 5HS and unitape, on thin panels. Only two shots of six had no hole on the inside and they were both on a UTHCU1 panel. Four of the six test points had fiber damage on the inside in addition to inside delamination, though one of these four did not have an inside hole.

The 5THCU1 and 5THCU2 panels both split along the 0° and 90° directions, which can be seen in Figure 6-61 and Figure 6-62 below. The thin orthotropic layup seems not to have been able to withstand the acoustic shock; this is discussed more in the Fiber Arrangement section below. In the case of the thin unitape panels, the lighter weight of copper scored much lower based on the damage code. This could have been due to a split attachment point on the CU1 panel distributing the arc root energy. The lighter (142 gsm) ECF panel was tested again and, though there was a slight increase in damage on the retest, it was still significantly less than the panel with the heavier (195 gsm) ECF. This result is unexpected considering the additional mass of copper per unit area in CU2 should conduct current with less resistance, as well as requiring more energy to vaporize. This subject needs further investigation.

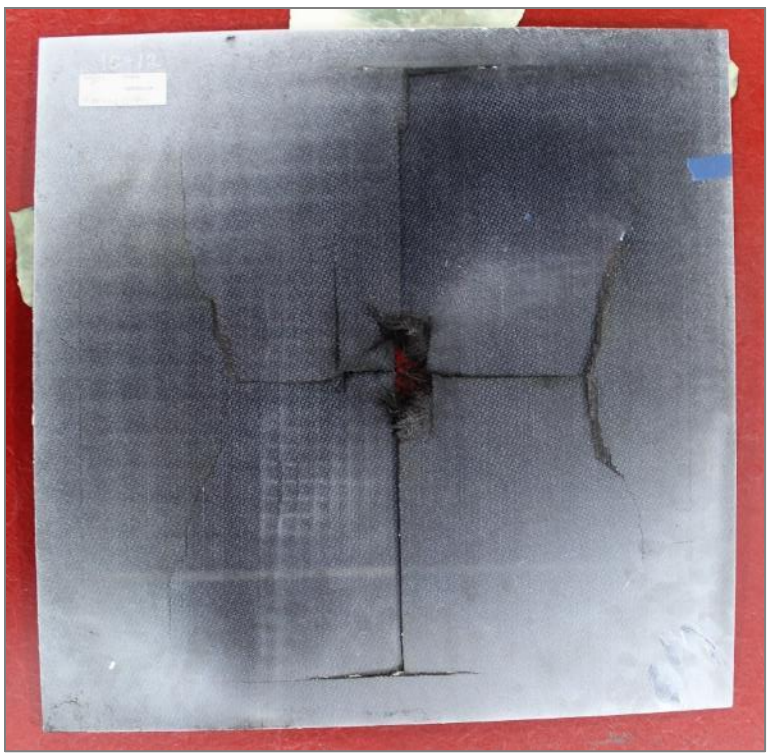


Figure 6-61: 5THCU1, Zone 1A

Figure 6-62: 5THCU2, Zone 1A

Figure 6-63: UTHCU2-1, Zone 1A

Figure 6-64: UTHCU1-1, Zone 1A

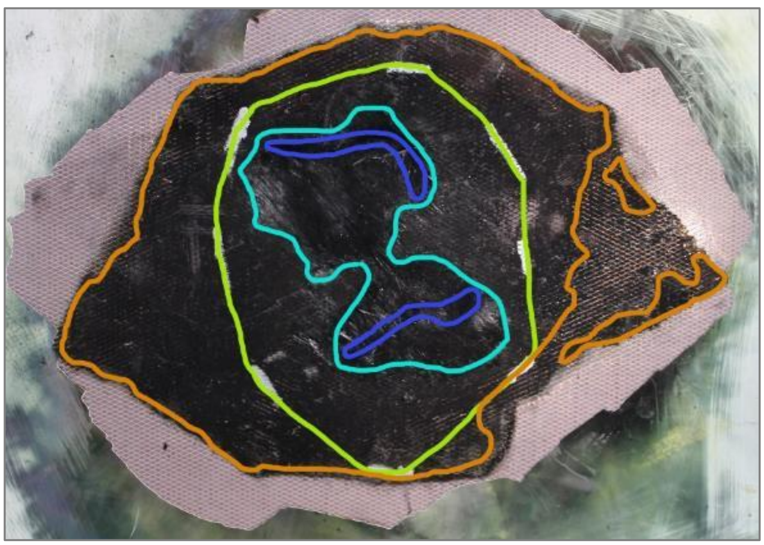


Figure 6-65: Composition of Damage and Repair Area, UTKCU2-1.
Orange: LSP loss, Green: Delamination, Turquoise: Resin loss, Blue: Fiber breakage.

Nearly all of the panels with the conductive spray coating received severe damage with holes on the insides of the panels ranging from 3 to 36 square inches and 7.59 to 36 square inches of inside delamination resulting in damage scores of over 300. This is not entirely surprising as the coating is rated for a Zone 2A strike. The top lamina not only had fiber breakage but a larger area of resin burnout and the LSP was vaporized all the way to the paint line. At the Zone 1A level, only the thin unitape panel protected with the conductive spray coating did not result in a hole on the inside of the panel. This anomaly may be attributed to a small diagonal seam gap defect between unitape sections, which may have allowed extra LSP spray to fill the gap (see Figure 6-66 below). This could increase the conductivity along the longitudinal direction, increasing current distribution on the top ply instead of penetrating through the laminate. The area of the outer delamination and the repair area for the SU panels were very similar, meaning that the damage to the LSP did not go much further than the delamination area. The area of fiber breakage was considerably smaller than the delamination area.

Figure 6-66: UTHSU-1 Panel Defect (left) and Resulting Damage (right)

The NP panels consistently scored near the maximum on damage codes with an average repair area of 53.8 square inches. There was extensive damage including large holes through every thick and thin panel with no protection.

A direct comparison of the three lightning strike protection schemes at Zone 1A indicated that only the ECF was consistently able to prevent severe damage, and only on the thick panels, where the damage was primarily limited to vaporization of the LSP. Excluding anomalies, the no protection and conductive spray coating LSP schemes did not protect the panel well and resulted in extensive damage to the composite. Panels with all protection schemes had varying nonzero areas of inside delamination, with the exception of three ECF panels which were free of inside delamination. Every panel without LSP sustained through holes receiving damage scores near the maximum value. The two different weights of ECF (CU1 and CU2) vastly outperformed the other LSP schemes and, between the two, CU1 consistently provided slightly better protection than CU2 despite CU1 being the lighter weight of ECF.

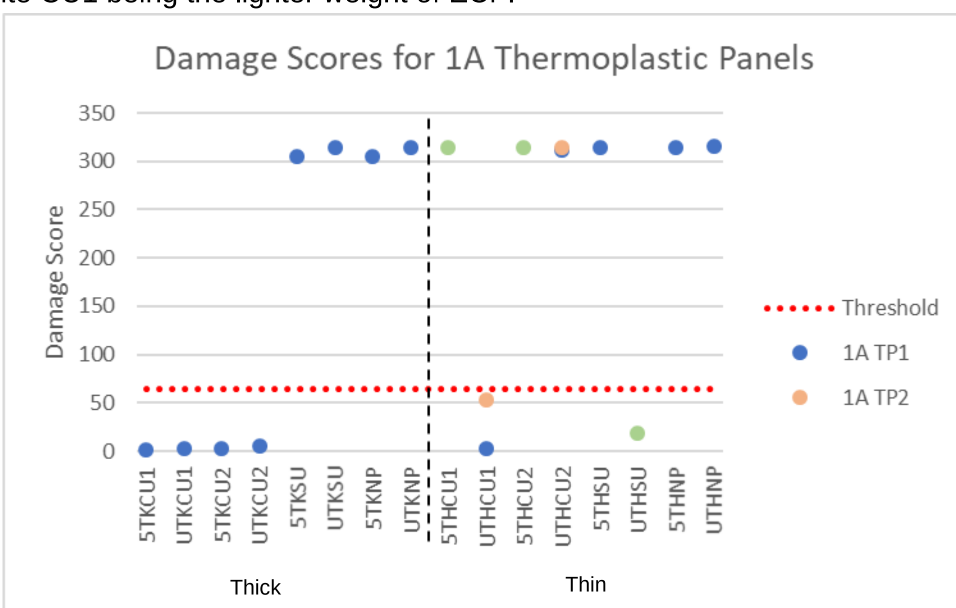


Figure 6-67: Damage Scores for 1A Thermoplastic Panels

*The green dots represent anomalous data: 5THCU1 and 5THCU2 were orthotropic layup, UTHSU panel contained a gap defect between unitape sections.

Zone 2A: None of the ECF thick panels experienced any inside delamination at the Zone 2A test level. All ECF panels sustained only minimal damage to the upper plies with the exception of the thin unitape CU1 (with 8-10 mils of paint), which received punctures through the panel on both test points. Barring this exception, there was little fiber breakage, though minor fraying of the fibers was quite common. After initial testing at 8-10 mils, all CU2 panels were repainted to 12-14 mils and tested again. The outcomes were similar to the result from the initial testing. Across all 2A ECF panels, the average outside delamination, fiber breakage, inside damage and inside hole areas were quite low; 3.3, 0.4, 2.7 and 0.1 square inches respectively. For comparison, the average repair area was 14.2 square inches. Like in the Zone 1A strikes, the majority of the repair area comes from LSP loss at the Zone 2A level.

Thick panels with conductive spray performed well at the Zone 2A test level. The 5HS panels had no inside delamination. However, three of the four unitape test points had inside delamination ranging from 6.0 to 8.3 square inches, with evidence of polymer melting on the back of the panel. All of the conductive spray thin panels sustained extensive damage, scoring well over 64 on the damage codes, indicating the presence of a hole through the panel. The main difference between the Zone 1A and 2A strikes was the damage severity into the depth of the panel, and the ratio of the delamination area to the repair area. In the Zone 2A strikes, the repair and outer delamination areas were very similar while at Zone 1A the repair area was usually much larger than the delamination area, indicating that there was more LSP damage beyond the delamination area. The same concentric LSP damage shown in Figure 6-43**Error! Reference source not found.** and Figure 6-45 of the conductive film TSC panels was seen on the TPC panels with the spray coating, but on a smaller scale (see Figure 6-68). This difference is likely due to the film versus spray-on nature of the LSP or the matrix material of the panel. More testing is required to determine the cause.

Figure 6-68: Concentric LSP damage of Conductive Spray

With only two exceptions out of 16 test points, the thick and thin panels with no protection sustained extensive damage, including holes through the panels. These exceptions were on test point 1 on UTKNP-2 and UTKNP-3; both of which were Zone 2A strikes on panels with 16 plies.

A direct comparison of lightning strike protection schemes at the Zone 2A level indicated that thick panels protected with either ECF or conductive spray were able to consistently minimize damage, although the ECF thick panels sustained less fiber damage, as well as resulting in a smaller repair area. Two out of eight thick panels without LSP also received minor damage with no through hole. Conductive spray was best able to protect the thin composite panels in this study. Two test points of the thin unitape with CU1 ECF received holes through the laminates, while all 17 remaining test points on the thin ECF panels sustained minor damage to surface plies along with only minor inside delamination, including four CU2 test points and one CU1 test point which did not incur delamination on the inside of the panels. In contrast to the Zone 1A results, the CU1 scheme did not consistently outperform the CU2. All thin conductive spray panels and all thin panels with no protection sustained through holes. These results suggest the thickness of the panel plays an important role in its durability when subject to a lightning strike.

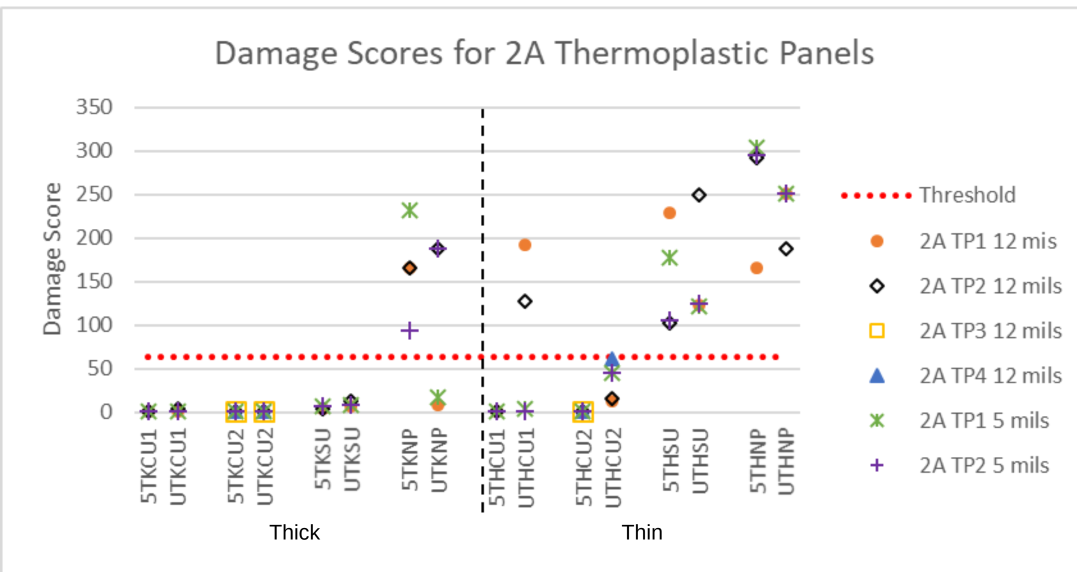


Figure 6-69: Damage Scores for 2A Thermoplastic Panels

Fiber Arrangement: Unitape vs. 5HS

Zone 1A: When tested at the Zone 1A level, the thin 5HS panels fractured along the central X and Y axes almost over the full area of the panel, likely because its thin, orthotropic layup could not withstand the acoustic shock. If these panels had included 45 degree plies it would likely have sustained less damage. Both unitape and 5HS thick, CU1 and CU2, panels displayed equivalent results with only minor surface damage. Thick, unitape and 5HS, conductive spray panels received extensive outside delamination, inside delamination, and holes. This result was similar for the unprotected, unitape and 5HS, thick panels. Both unitape and 5HS CU2 thin panels also scored near the maximum on the damage codes.

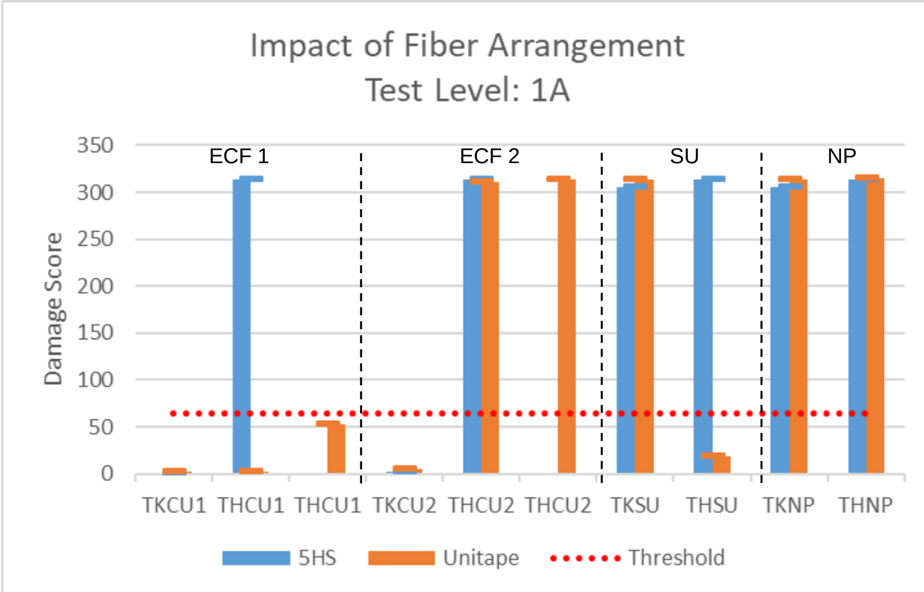


Figure 6-70: 5HS vs. Unitape Performance at 1A Test Level
*Note the data in the 2nd THCU1 and THCU2 column represent re-tested panels

Zone 2A: At the 2A test level, the thick 5HS panels typically scored less than or equal to the unitape panels in terms of damage codes; the exception being all four of the thick 5HS with no protection failed according to the damage codes, while two of the four unitape panels passed according to the damage codes. The thin 5HS panels typically scored less than or equal to the unitape panels; the exception being two out of four conductive spray and two out of four without LSP unitape panels scoring lower than their 5HS counterparts.

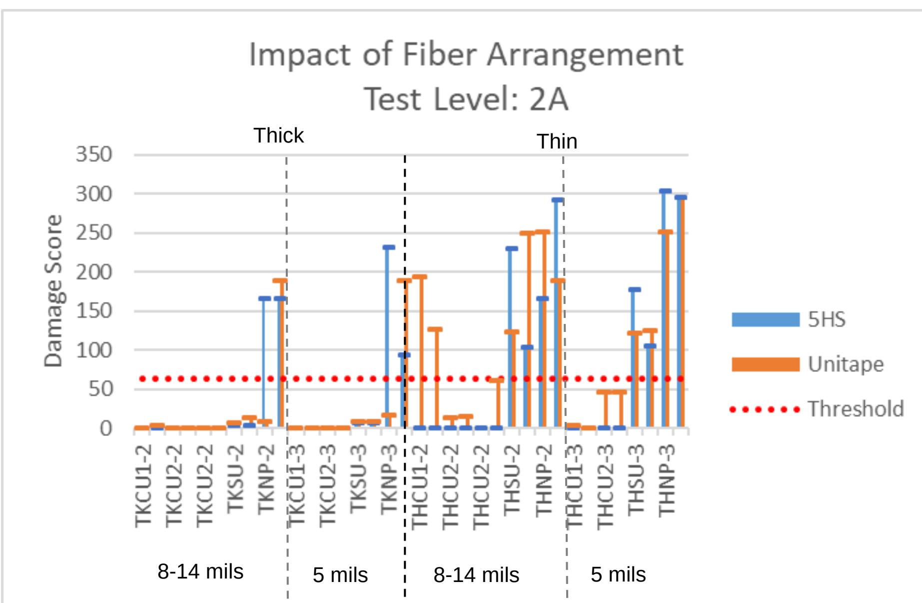


Figure 6-71: 5HS vs. Unitape at 2A Test Level

Damage Morphology

There is evidence that both fiber orientation and lightning strike protection play a role in the damage morphology. The influence of fiber orientation is most prominent in the test panels with no lightning strike protection. Shown on the left in Figure 6-72 is the unitape panel without LSP, with top layer fiber orientation of -45°. The damage is elongated along the length of the fibers. A perpendicular protrusion of minor surface damage can also be seen extending out near the middle of the length of the main damage area. The 5HS panel shown on the right of Figure 6-72 displays a more symmetrical damage morphology in both fiber/resin damage and delamination, extending out along both the 0° and 90° fiber directions.

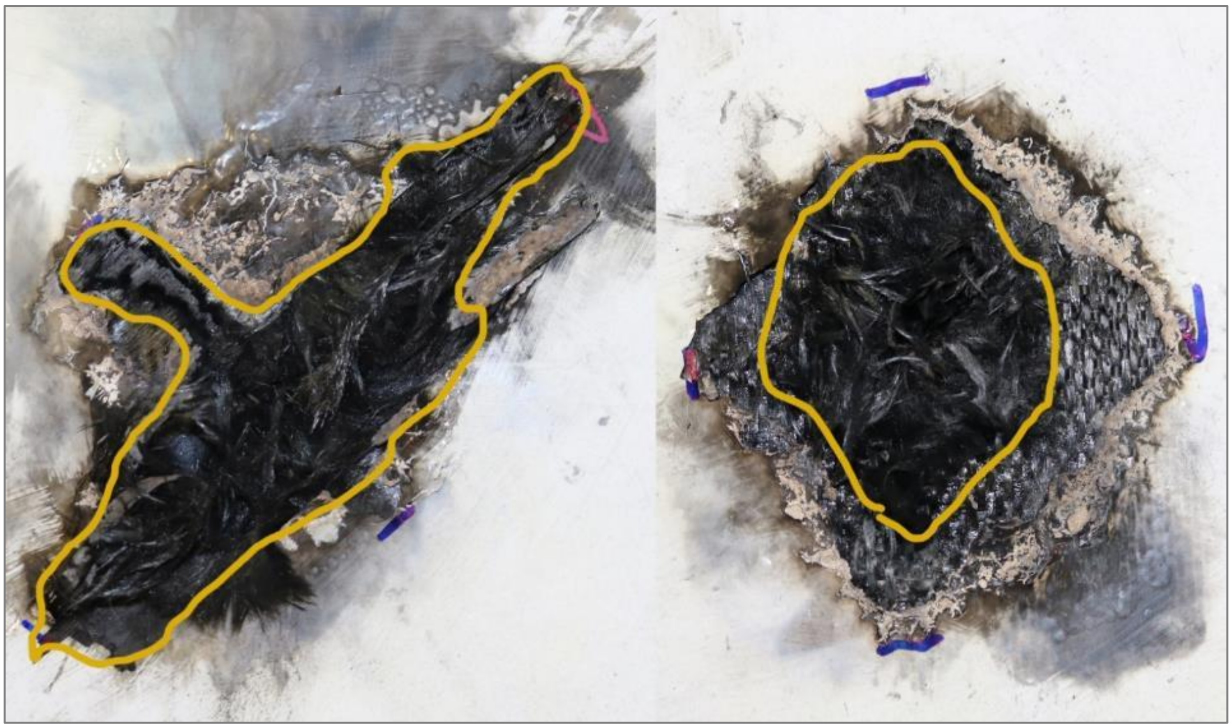


Figure 6-72: UTHNP (left) and 5THNP (right).
Orange outline represents fiber and resin damage area (outer hole).

The ECF protected panels are shown in Figure 6-73 with the unitape top layer at 45°, and 5HS woven with top ply orientation at 0° and 90°. In the ECF unitape, the influence of the conductivity of the copper layer reduces the elongation of the damage relative to the unprotected panels, yet the damage area is still longer along the length of the fibers. The second, smaller damage area in the unitape panel is likely a result of a split attachment point, which still displays a slight elongation along the fiber direction. The pattern of damage suggests that the more isotropic conductivity of the copper mesh distributes the energy over the surface of the laminate as intended, rather than conducting primarily through the fibers. The damage to the 5HS panel is oriented along the 0° and 90° directions. The delamination area is marked by a silver marker, and is only 15% greater in the 90° direction. The resin damage is almost completely symmetrical at the center of the delamination with minor surface resin damage to the immediate right, outside of the delamination boundary.

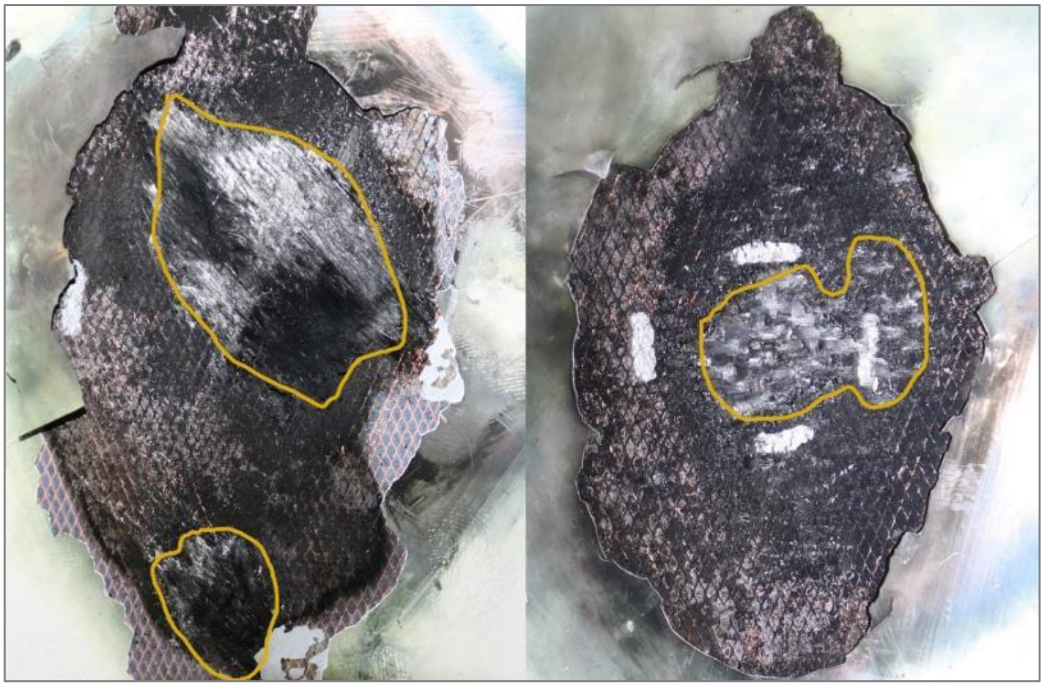


Figure 6-73: UTKCU1 (left) and 5TKCU1 (right).
Orange outline represents fiber and resin damage area (outer hole).

Figure 6-74 is another ECF protected panel with UTKCU2 and 5TKCU2. The unitape orange outlined resin damage area is again slightly elongated along the fiber direction, but not as severely as the unprotected panel. The orange outlined area of the 5HS panel is the damage to the resin and fiber which is again oriented along the 0° and 90° fiber directions and more symmetrical in proportion than its unitape counterpart. The outer hexagonal area is mainly LSP damage, illustrating the influence of the diamond shaped mesh on the distribution of the current energy.

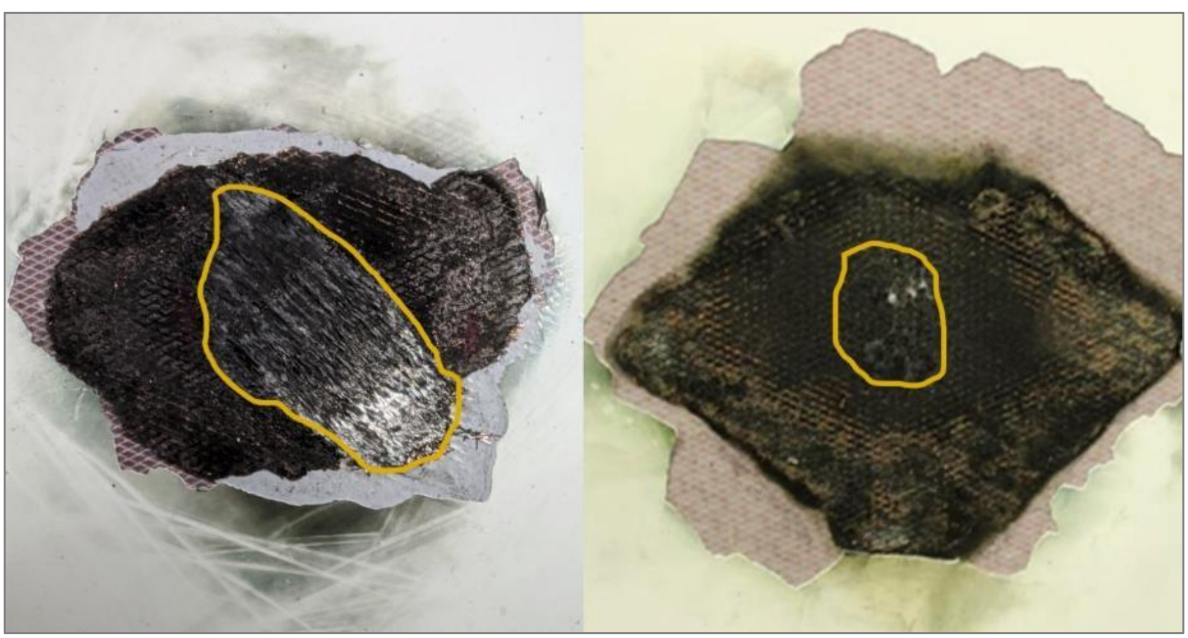


Figure 6-74: UTKCU2 (left) and 5TKCU2 (right).
Orange outline represents fiber and resin damage area (outer hole).

The UTHSU and 5THSU panels protected with conductive spray LSP are shown in Figure 6-75. The diagonal damage morphology can once again be seen on the unitape panel. The damage is less elongated than the unprotected panel yet more irregular in shape. The shape of the 5HS damage, while less elongated, is also more irregular in shape than either the copper LSP or no protection panels. This pattern of irregular shapes and multiple damage areas is not uncommon on conductive spray panels.

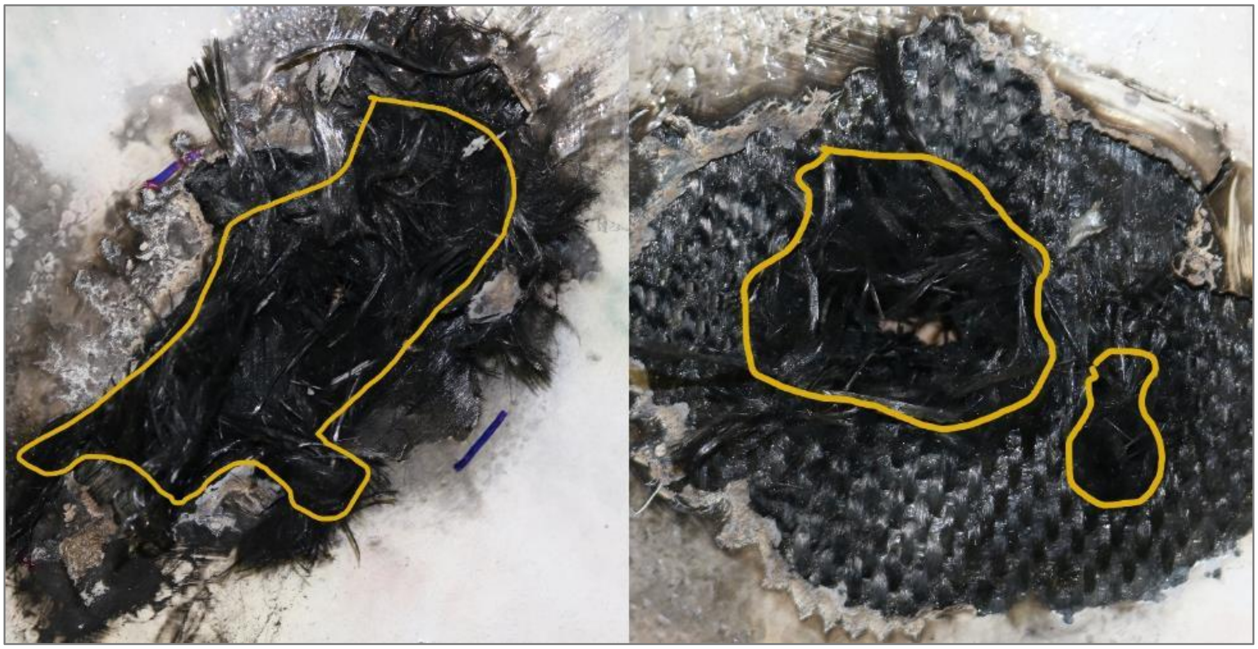


Figure 6-75: UTHSU (left) and 5THSU (right).
Orange outline represents fiber and resin damage area (outer hole).

TPC vs. TSC

Due to the many differences in testing parameters between these TPC panels and TSC panels from earlier testing (see Section 6.5), no definite trends or conclusions could be drawn. In general, the damage to the TPC panels was no worse than the damage to the TSC panels. One notable difference was that TPC panels displayed a visible melting signature on the inside of the panel whose boundaries coincided with delamination as seen in Figure 6-76: This phenomenon can be attributed to the fact that the TPC matrix absorbs energy from the strike through latent heat of fusion during phase change. This is a potential advantage over TSCs which pyrolize without first transitioning into a liquid. A post-test examination comparison of C-Scan imaging to photographic image of TPC panel 5TKCU2-2 reveals that the primary damage zone (PDZ) ends abruptly at the edge of the copper damage as seen in Figure 6-77. The PDZ is defined as the continuous area surrounding the arc root attachment, which contains the visible physical damage (often including LSP and paint loss), as well as thermal effects on the panel, which often coincide on the same region of the panel.

Figure 6-76: UTKSU-3 Test Point 2, Melting on Inside of Panel.
The melting border, indicated by the dotted line, coincides with the delamination border.

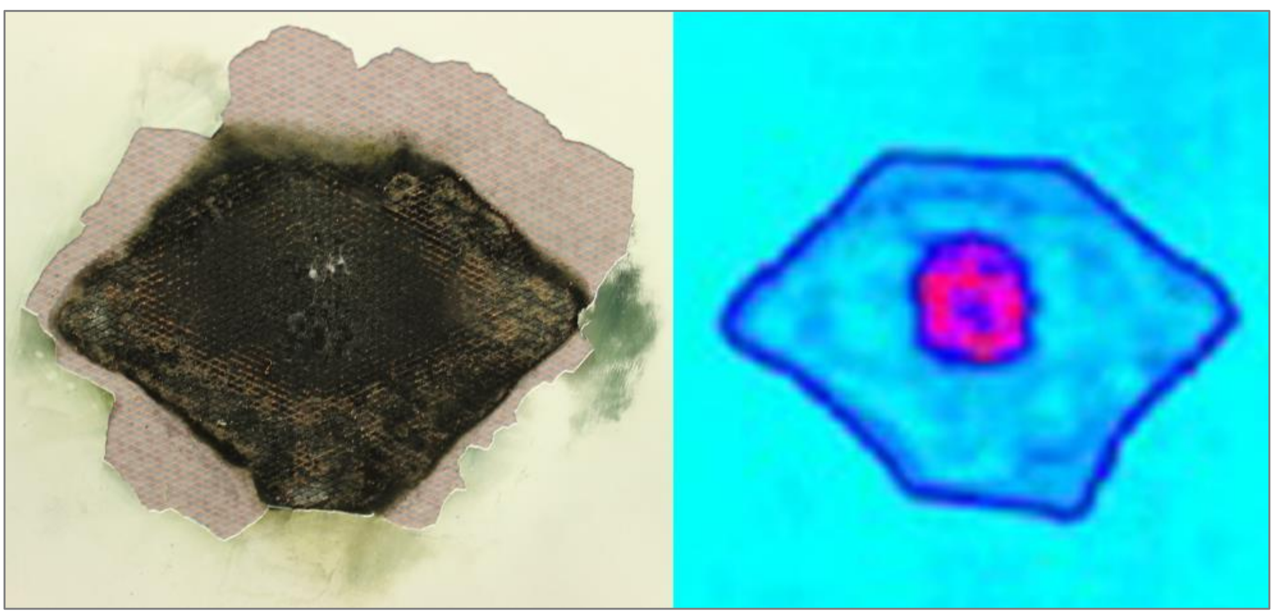


Figure 6-77: Damaged panel 5TKCU2-2 (left), pulse echo amplitude of PDZ (right)

6.7.4 Test Data

All damage measurements were taken to the nearest quarter inch, but measurements reported in the following tables have been rounded to the nearest 0.1 inch. Shown in Table 6-20 through Table 6-24 below are the results of Zone 1A and 2A strikes to thick and thin TPC panels while Figure 6-60 and Figure 6-67 above show the results of Zone 1A and 2A respectively. LSP loss or damage is only included in the repair area measurement, all other damage measurements only consider damage to the matrix and/or fibers.

Measurements of damage to the test panels are recorded in four categories: inside and outside panel damage, and inside and outside holes. Overall repair area was determined by extent of any damage including LSP loss or damage. Damage scores were determined based on the definition of damage codes located in Section 6.4.1 of this document. Damage scores are listed for reference and comparison to previous test materials.

Table 6-20: Damage to Panels with 10-12 mils of Paint after Zone 1A Strike

Panel ID	Damage		Hole		Repair Area (in)	Damage Score
	Outer (in)	Inner (in)	Outer (in)	Inner (in)		
5TKCU1-1	3.3x4	0	0	0	5.5x6	1
UTKCU1-1	5x4.5	0	0	0	6x6	2
5TKCU2-1	5x3.5	0	0.5x0.5	0	5x5	2
UTKCU2-1	4x3	1.5x3	1.8x0.5	0	4x4	5
5TKSU-1	4.8x5	2.3x3.3	3.5x3	2.3x3.3	4.8x5	305
UTKSU-1	6.3x4.5	10x3.3	5.5x3.3	2x1.5	10x3.3	314
5TKNP-1	4.5x5.5	3.5x4	3x4	3x3.5	5x6	260
5TKNP-1	7.5x5.5	17.3x5	3.5x4.5	2x2	17.3x5.5	278
5THCU1-1	4.5x4.5	12x18	12x18	14x14	18x14	314
UTHCU1-1	4.5x4.5	0.8x1	0	0	6x6.5	2
UTHCU1-2	5x4.3	3x0.8	3.3x2.5	0	9x6	53
5THCU2-1	6x6	14x13.5	12x15	12x15	15x15	314
UTHCU2-1	6x3.5	25x7.5	2x2	2x2	25x7.5	311
UTHCU2-2	4.5x4.5	15x6.5	4x3	3.5x2	15x6.5	314
5THSU-1	5.3x5.5	6x6	3x3	6x6	6x6	314
UTHSU-1	12x3.8	7.3x4	12x1	0	12x4	18
5THNP-1	5.8x6	5.5x5.5	2.5x3	2x2	6.5x7	314
UTHNP-1	8x5	8.5x5.3	7x2	2x3	8.5x5.3	315

Table 6-21: Damage to Thick Panels with 5 mils Paint after Zone 2A Strikes

Panel ID	Shot #	Damage		Hole		Repair Area (in)	Damage Score
		Outer (in)	Inner (in)	Outer (in)	Inner (in)		
5TKCU1-3	1	1x1.5	0	0	0	3.8x2	1
5TKCU1-3	2	2x1.3	0	0	0	3.5x2	1
UTKCU1-3	1	1.75x3	0	0	0	3x4	1
UTKCU1-3	2	2x2	0	0	0	2.5x3.5	1
5TKCU2-3	1	1x1	0	0	0	2.5x2	1
5TKCU2-3	2	0.3x0.3	0	0	0	3.8x2	1
UTKCU2-3	1	1.5x1.5	0	0	0	2.5x1.5	1

Panel ID	Shot #	Damage		Hole		Repair Area (in)	Damage Score
		Outer (in)	Inner (in)	Outer (in)	Inner (in)		
UTKCU2-3	2	1.3x1.3	0	0	0	2.3x1.8	1
5TKSU-3	1	2.5x2.5	0	2.5x2.5	0	5x5.3	7
5TKSU-3	2	2x2.8	0	2x2.8	0	5.8x5.8	7
UTKSU-3	1	5x2.3	2.8x3	5x2.3	0	6x2.8	8
UTKSU-3	2	5x2.3	2.8x2.3	5x2.3	0	5.3x2.8	8
5TKNP-3	1	2.5x3	1.5x2	2.75x1.5	1x13	2.5x3.3	232
5TKNP-3	2	2.5x2.8	1x1	1.8x1.8	0.1x0.1	2.5x2.8	94
UTKNP-3	1	4.8x2.5	6x3	2.5x1.5	0	7.5x3	17
UTKNP-3	2	5.5x2.25	8x0.5	2.2x1.3	0.8x0.3	8x2	188

Table 6-22: Damage to Thin Panels with 5 mils Paint after Zone 2A Strikes

Panel ID	Shot #	Damage		Hole		Repair Area (in)	Damage Score
		Outer (in)	Inner (in)	Outer (in)	Inner (in)		
5THCU1-3	1	2.5x1	0.3x0.3	0	0	4x2	1
5THCU1-3	2	2x1.5	0.5x0.5	0	0	3x2	1
UTHCU1-3	1	2.5x2	1x0.8	1.5x0.5	0	3.8x2.3	4
UTHCU1-3	2	2x1	0.8x0.8	0	0	4.5x2	1
5THCU2-3	1	2x1	0.5x0.5	0	0	2.5x1.5	1
5THCU2-3	2	0.5x0.5	0	0	0	2.5x2.5	1
UTHCU2-3	1	1.3x1.5	3.5x2.3	1x0.8	0	4.3x2.3	46
UTHCU2-3	2	1.5x2	3.8x3.0	0.8x0.5	0	4x3	46
5THSU-3	1	3x3	2.5x2.5	2.5x2.3	1x1	5x5.3	178
5THSU-3	2	3.3x3.5	2x2	2.3x3	0.5x0.5	5.5x5.8	106
UTHSU-3	1	5.5x3	15x1	4.3x2.3	0.5x0.5	9x6.5	122
UTHSU-3	2	4.8x3.5	8x1	3.5x2.8	0.5x0.5	8.8x7.5	125
5THNP-3	1	2.5x3.5	2x2.5	1x2.3	2.5x3.5	2.5x3.5	304
5THNP-3	2	3x3.5	2x1.8	1.2x2.3	1.5x1.5	3x3.5	295
UTHNP-3	1	5.5x3.3	7.5x2.3	3.5x1.3	1x1.3	7x3.3	251
UTHNP-3	2	5.3x2.8	11.5x2	4.3x1.8	1x0.8	11.5x2.8	251

Table 6-23: Damage to Thick Panels with 8-10 and 12-14 mils Paint after Zone 2A Strikes

Panel ID	Paint (mils)	Shot #	Damage		Hole		Repair Area (in)	Damage Score
			Outer (in)	Inner (in)	Outer (in)	Inner (in)		
5TKCU1-2	8-10	1	1x1	0	0	0	2.5x1.8	1
5TKCU1-2	8-10	2	1x1.5	0	0	0	2x2.5	1
UTKCU1-2	8-10	1	2.5x3	0	0	0	2.5x3.5	1
UTKCU1-2	8-10	2	2x3.8	0	1x1	0	2.5x4.0	4
5TKCU2-2	8-10	1	2.5x2	0	0	0	3x2	1
5TKCU2-2	8-10	2	2.5x2.8	0	0	0	3x2	1
5TKCU2-2	12-14	3	2.3x1.3	0	0	0	2.5x1.8	1
5TKCU2-2	12-14	4	1.3x1	0	0.5x0.5	0	2.8x2.3	1

Panel ID	Paint (mils)	Shot #	Damage		Hole		Repair Area (in)	Damage Score
			Outer (in)	Inner (in)	Outer (in)	Inner (in)		
UTKCU2-2	8-10	1	1.5x1.5	0	0	0	2.3x1.8	1
UTKCU2-2	8-10	2	1.5x1.5	0	0	0	2x1.8	1
UTKCU2-2	12-14	3	2x1	0	0.5x0.5	0	2.3x1.5	1
UTKCU2-2	12-14	4	2.3x1.5	0	0.3x0.8	0	2x2	1
5TKSU-2	8-10	1	2.5x2.5	0	1.5x1.5	0	3x3	4
5TKSU-2	8-10	2	2.8x2.8	0	1.8x1.5	0	2.8x2.8	4
UTKSU-2	8-10	1	3.3x3	0	2.8x2	0	4x3	7
UTKSU-2	8-10	2	3.5x2.3	3x2	2.3x1.5	0	7x6	13
5TKNP-2	8-10	1	2.5x2.5	1.3x1.3	1.5x1.5	0.8x0.5	3x2.5	166
5TKNP-2	8-10	2	2.3x2.5	1.5x1.3	1.5x1.8	0.5x0.5	3x2.5	166
UTKNP-2	8-10	1	4.5x2.3	1x1.5	3.3x1.5	0	4.5x2.3	8
UTKNP-2	8-10	2	4x2	9.3x1	3.3x1.5	0.8x0.5	9.3x2	188

Table 6-24: Damage to Thin Panels with 8-10 and 12-14 mils paint after Zone 2A Strikes

Panel ID	LSP	Paint (mils)	Shot #	Damage		Hole		Repair Area (in)	Damage Score
				Outer (in)	Inner (in)	Outer (in)	Inner (in)		
5THCU1-2	ECF1	8-10	1	2.8x1.5	0	0	0	4x2.3	1
5THCU1-2	ECF1	8-10	2	2.3x1.8	0.5x0.8	0	0	3.5x2.5	1
UTHCU1-2	ECF1	8-10	1	2.5x1.3	4x4	1.5x0.5	1x1.5	3.5x2	193
UTHCU1-2	ECF1	8-10	2	3.0x1.3	3x2.3	0	0.8x0.8	4x2.3	127
5THCU2-2	ECF2	8-10	1	2.5x2	0	0	0	2.5x2	1
5THCU2-2	ECF2	8-10	2	2x2	0	0	0	2x2	1
5THCU2-2	ECF2	12-14	3	0.8x1	0	0.3x0.3	0	2.3x2	1
5THCU2-2	ECF2	12-14	4	1.5x1.5	0	0	0	3x2	1
UTHCU2-2	ECF2	8-10	1	2.3x2	5.8x2	2x1.5	0	3.5x4.5	13
UTHCU2-2	ECF2	8-10	2	3x2.3	5.5x4.3	2.5x1.5	0	4.5x4.5	16
UTHCU2-2	ECF2	12-14	4	2.8x3.3	5.5x4.5	2.5x1.8	0	3x2.5	61
5THSU-2	SU	8-10	1	2.8x2.3	2.8x2.5	1.3x1.3	1.3x1.3	5.5x5.5	229
5THSU-2	SU	8-10	2	3.3x2.3	2.3x2	1x1	0.5x0.3	6.8x6.3	103
UTHSU-2	SU	8-10	1	3x3.8	10.5x2.5	2x3	0.5x0.5	10.5x3.8	124
UTHSU-2	SU	8-10	2	3x3.3	11.3x2.8	2.3x2.3	1x1.5	11.3x3.3	250
5THNP-2	NP	8-10	1	2x2.3	2x2	1x1.5	0.5x0.5	4x4	166

Panel ID	LSP	Paint (mils)	Shot #	Damage		Hole		Repair Area (in)	Damage Score
				Outer (in)	Inner (in)	Outer (in)	Inner (in)		
5THNP-2	NP	8-10	2	3x2.5	2x2	1.3x2	1.5x1.5	3.3x3	292
UTHNP-2	NP	8-10	1	5.5x3	6.5x3	3.8x2	1x1	7x3	251
UTHNP-2	NP	8-10	2	4.3x2.3	7.3x2.5	3x1.5	0.5x0.8	7.5x2.5	188

6.7.5 Conclusions

- Paint did not adhere well to the thermoplastic composite substrate and tended to peel off easily in sheets indicating the need for better chemical or mechanical adhesion.
- Paint thickness did not appear to consistently have an effect on the damage.
- ECF results in the least damage of any LSP material tested.
- The thick Zone 1A 5HS panels sustained less damage than their unitape counterparts.
- The thin 5HS panels sustained less damage on average than the thin unitape panels when tested at Zone 2A.
- Thicker panels sustained less damage than thinner panels.
- The LSP and fiber orientation both have an influence over the shape of damage.
- Without LSP, the extent of damage is greatest along the fiber directions in both 5HS and unitape.
- Further research with comparable panels is needed before definite conclusions can be drawn between the behavior of TPCs and TSCs.
- Evidence of polymer melting corresponded in size with inside delamination.

6.8 Thermoplastic vs Thermoset Composites

6.8.1 Background

There are two types of polymer matrix composites: thermoset and thermoplastic. Thermoset composites (TSCs) are the traditional form of composites used in aircraft structure, and are largely epoxy based. Though they are cured through a heating process, they cannot be melted after cure, and do not have a melting temperature. TSCs have a glass transition temperature, which is a material property of all polymers which is defined as the temperature at which the polymer goes from behaving like glass to behaving like rubber, but it is not considered a phase change from solid to liquid. TSCs are cross linked during curing which is an irreversible chemical process. Once they are heated above their working temperature they are burned or vaporized. Thermoplastic composites (TPCs) on the other hand are not cross linked and have linear carbon chains so they can be melted after cure. TPCs have both a melting and crystallization temperature. This means that they can change into a liquid phase and given the right temperature environment, undergo a change in crystallinity which impacts material properties. As mentioned in section Background, the fact that TPCs can melt and re-solidify allows them to be welded, which is a major advantage to the aviation industry.

The lightning strike performance of TPCs was first evaluated in section 0. The test matrix was designed to explore the contribution of various factors to the damage caused by a direct lightning strike. These factors were the composite material, the LSP, the fiber arrangement (unidirectional or five harness satin (5HS) woven fabric), the laminate thickness, and the paint thickness. This helped establish a baseline behavior of thermoplastic composite panel in lightning strike environments.

Because of increasing interest in thermoplastic-based advanced composites for use in commercial aircraft structures, KART funded a new round of research to expand the database. The test matrix for this round of testing was expanded based on findings from the previous study. The number of data points for each test condition was doubled from two to four. Two additional matrix materials, polyphenylenesulfide (PPS), and epoxy were added to the test matrix along with LM PAEK. The number of paint thicknesses tested was increased from two to three, and the interval between paint thickness values was increased in order to further clarify the role paint thickness plays in lightning strike damage response. The interval between weights of LSP was also increased. Epoxy unitape panels were included to provide a direct lightning strike response comparison to that of the LM PAEK unitape panels. Conclusive evidence that composite panels without LSP perform poorly compared to those with LSP led to the removal of “unprotected” panels from this test matrix. The test matrix is provided in Table 6-26 to Table 6-28

6.8.2 Materials

Panel configurations included three matrix materials, two panel thicknesses for each matrix type, two lightning protection schemes, and three paint thicknesses.
The three matrix materials are:

1. TPC 1: Toray Cetex TC1100, 5HS T300JB PPS, 280 gsm FAW, 43%RC woven prepreg
2. TPC 2: Toray TC1225, T700-12K T1E LM PAEK, 145 gsm FAW 34%RC unidirectional

prepreg

3. TSC: TC275-1E/TR50S 15k, 150 gsm FAW, 35%RC unidirectional prepreg tape

The unidirectional tape carbon fiber panels had an individual ply thickness of 0.005”. Layups consisted of either 8 plies (0.04”) or 12 plies (0.06”) in a quasi-isotropic, symmetrical/balanced layup schedule for both LM PAEK and epoxy panels. Woven fabric panels were all PPS in a five harness satin (5HS) weave with a ply thickness of 0.012”, consisting of either 4 plies (0.048”) or 6 plies (0.072”).

Two different lightning strike protection schemes were equally represented in testing.

1. ECF: Dexmet 3CU7-100FA, 0.0030 thick, (195.3 gsm w/o resin) – (C2)
2. ECF: Dexmet 2CU4-100FA, 0.0020 thick, (73.3 gsm w/o resin) – (C3)

All panels were painted with aircraft industry standard paint over the LSP. The details of the coating are:

1. PPG CA-7501 epoxy primer
2. PPG F565-4010 epoxy intermediate coat
3. PPG CA8000 polyurethane topcoat

The panels were painted as follows:

1. Two panels of each configuration containing 5-7 mils of paint.
2. Two panels of each configuration containing 14-16 mils of paint.
3. Two panels of each configuration containing 23-25 mils of paint.

The nomenclature for the panel ID’s is specified in Table 6-25: Panel Serial ID below. The test matrix configurations for each matrix material are listed in Table 6-26, Table 6-27, and Table 6-28.

Table 6-25: Panel Serial ID

Naming Pattern - ABC##D	
A	Matrix material: E - epoxy, L - LM PAEK, P - PPS
B	Panel thickness: K – thick, N – thin
C#	LSP: C2 – ECF 195, C3 – ECF73,
#	Paint thickness: 1 – 5-7 mils, 2 – 14-16 mils, 3 – 23-25 mils
D	Panel No.: A – first panel, B – duplicate panel

Table 6-26: Test Matrix Configurations of Epoxy Panels

Matrix Material	Panel Thickness	LSP	Paint Thickness (mils)	Pair	Code
Epoxy	Thin (0.04 in)	C3: 73 gsm	14-16	A	ENC32A
				B	ENC32B
	Thick (0.06 in)			A	EKC32A
				B	EKC32B

Table 6-27: Test Matrix Configurations of LM PAEK Panels

Matrix Material	Panel Thickness	LSP	Paint Thickness (mils)	Pair	Code
LM PAEK	Thin (0.04 in)	C3: 73 gsm	5-7	A	LNC31A
				B	LNC31B
				A	LNC31A
				B	LNC31B
			14-16	A	LNC32A
				B	LNC32B
				A	LNC32A
				B	LNC32B
			23-25	A	LNC33A
				B	LNC33B
				A	LNC33A
				B	LNC33B
		C2: 195 gsm	5-7	A	LNC21A
				B	LNC21B
				A	LNC21A
				B	LNC21B
			14-16	A	LNC22A
				B	LNC22B
				A	LNC22A
				B	LNC22B
			23-25	A	LNC23A
				B	LNC23B
				A	LNC23A
				B	LNC23B
	Thick (0.06 in)	C3: 73 gsm	5-7	A	LKC31A
				B	LKC31B
				A	LKC31A
				B	LKC31B
			14-16	A	LKC32A
				B	LKC32B
				A	LKC32A
				B	LKC32B
			23-25	A	LKC33A
				B	LKC33B
				A	LKC33A
				B	LKC33B
		C2: 195 gsm	5-7	A	LKC21A
				B	LKC21B
				A	LKC21A
				B	LKC21B
			14-16	A	LKC22A
				B	LKC22B
				A	LKC22A
				B	LKC22B
			23-25	A	LKC23A
				B	LKC23B
				A	LKC23A
				B	LKC23B

Table 6-28: Test Matrix Configurations of PPS Panels

Matrix Ma	Panel Thickness	LSP	Paint Thickness (mils)	Pair	Code
PPS	Thin (0.048 in)	C3: 73 gsm	5-7	A	PNC31A
				B	PNC31B
				A	PNC31A
				B	PNC31B
			14-16	A	PNC32A
				B	PNC32B
				A	PNC32A
				B	PNC32B
			23-25	A	PNC33A
				B	PNC33B
				A	PNC33A
				B	PNC33B
		C2: 195 gsm	5-7	A	PNC21A
				B	PNC21B
				A	PNC21A
				B	PNC21B
			14-16	A	PNC22A
				B	PNC22B
				A	PNC22A
				B	PNC22B
			23-25	A	PNC23A
				B	PNC23B
				A	PNC23A
				B	PNC23B
	Thick (0.072 in)	C3: 73 gsm	5-7	A	PKC31A
				B	PKC31B
				A	PKC31A
				B	PKC31B
			14-16	A	PKC32A
				B	PKC32B
				A	PKC32A
				B	PKC32B
			23-25	A	PKC33A
				B	PKC33B
				A	PKC33A
				B	PKC33B
		C2: 195 gsm	5-7	A	PKC21A
				B	PKC21B
				A	PKC21A
				B	PKC21B
			14-16	A	PKC22A
				B	PKC22B
				A	PKC22A
				B	PKC22B
			23-25	A	PKC23A
				B	PKC23B
				A	PKC23A
				B	PKC23B

6.8.3 Methods/Procedures

All panels were struck twice at the high current Zone 2A test level. No Zone 1A strikes were completed in this round of testing. The deflection of the panel and thermal signature were recorded for each test point via laser deflection sensors and infrared (IR) imaging, respectively.

After direct effects of lightning (DEL) testing, the damage to the panels was recorded using the measurements described in section 6.4.1 Damage Code Measurements. Post-test pulse-echo ultrasonic inspection of the panels was completed and compared to the ultrasonic inspections of the pre-test pristine panels to determine the effect of the lightning strike through the depth of the panel. After ultrasonic inspection, Differential Scanning Calorimetry (DSC) of select panels was conducted to evaluate the changes in the crystallinity of the damaged panels by comparing the results to the data sheet for the pristine panels. Micrographs of select panels were completed to further evaluate the damage and delamination at the strike location.

6.8.4 Test Data

A summary of the test data can be found in Table 6-29 through Table 6-42 below.

Table 6-29: Summary of Damage Measurements to Epoxy Panels

Panel ID	Test Point	Outside Delamination		Outside Hole		Inside Damage			Inside Hole		Damage Score
		x (in)	y (in)	x (in)	y (in)	x (in)	y (in)	Type	x (in)	y (in)	
ENC32A	TP1	6.25	6.25	4.25	4	12	2.5	Damage	0	0	62
ENC32A	TP2	5.25	5	5	2.75	5	0.5	Damage	0	0	53
ENC32B	TP1	7.75	7.5	7.75	3.5	5.75	1.5	Damage	0	0	62
ENC32B	TP2	6.75	4.25	6.5	2	0.75	1.5	Delam.	0	0	8
EKC32A	TP1	1.75	2	2.25	1	0.5	0.25	Delam.	0	0	7
EKC32A	TP2	2.75	3.25	3.5	2.5	4.25	0.75	Damage	0	0	52
EKC32B	TP1	3.5	3.5	2	1.5	0	0	Delam.	0	0	4
EKC32B	TP2	2.5	3.75	2.5	2.25	3.25	0.5	Damage	0	0	52

Table 6-30: Summary of Damage Measurements to LM PEAK Panels with 5-7 mils of Paint

Panel ID	Test Point	Outside Delamination		Outside Hole		Inside Damage			Inside Hole		Damage Score
		x (in)	y (in)	x (in)	y (in)	x (in)	y (in)	Type	x (in)	y (in)	
LNC31A	TP1	4.5	4.5	1.5	0.5	0	0	Delam	0	0	5
LNC31A	TP2	4	4.5	1.25	0.75	0	0	Delam	0	0	5
LNC31B	TP1	3.5	2	1.25	0.25	0.5	0.5	Delam	0	0	4
LNC31B	TP2	3	4.25	1	0.25	0	0	Delam	0	0	2
LKC31A	TP1	4.5	4	2	2	0	0	Delam	0	0	5
LKC31A	TP2	5	4	3.25	2	0	0	Delam	0	0	8
LKC31B	TP1	3.75	4.75	4.5	2.5	0	0	Delam	0	0	8
LKC31B	TP2	4.5	4	4	1.5	0	0	Delam	0	0	8
LNC21A	TP1	2	2	0	0	0	0	Delam	0	0	1
LNC21A	TP2	3	3.25	0	0	0	0	Delam	0	0	1
LNC21B	TP1	1.75	3	0.25	0.25	0	0	Delam	0	0	1
LNC21B	TP2	2.5	2.5	1.5	0.5	0.75	0.5	Delam	0	0	4
LKC21A	TP1	2.25	2	0.25	0.25	0	0	Delam	0	0	1
LKC21A	TP2	2.25	1.75	0	0	0	0	Delam	0	0	1
LKC21B	TP1	2.75	1.5	1.5	0.75	0	0	Delam	0	0	4

LKC21B	TP2	2.75	1.5	1.25	0.5	0	0	Delam	0	0	4

Table 6-31: Summary of Damage Measurements to LM PEAK Panels with 14-16 mils of Paint

Panel ID	Test Point	Outside Delamination		Outside Hole		Inside Damage			Inside Hole		Damage Score
		x (in)	y (in)	x (in)	y (in)	x (in)	y (in)	Type	x (in)	y (in)	
LNC32A	TP1	3	3.5	1.75	1.25	0.5	0.5	Delam	0	0	4
LNC32A	TP2	3.5	4	2.25	1	0	0	Delam	0	0	7
LNC32B	TP1	4	3.75	3.75	3	0.75	0.75	Delam	0	0	7
LNC32B	TP2	3.75	5	1.75	2.5	0.5	0.5	Delam	0	0	8
LKC32A	TP1	4.5	4.25	3.25	1.5	0	0	Delam	0	0	8
LKC32A	TP2	5	3.5	2	1.5	0	0	Delam	0	0	5
LKC32B	TP1	4.75	4.75	1.75	2	0	0	Delam	0	0	5
LKC32B	TP2	4.25	5	1.25	2.5	0	0	Delam	0	0	8
LNC22A	TP1	2.25	2	1.25	0.75	1.75	2.25	Delam	0	0	4
LNC22A	TP2	2.5	2.5	1	1	3.5	3.5	Delam	0	0	1
LNC22B	TP1	2.5	2.5	1	0.75	3	1.75	Delam	0	0	1
LNC22B	TP2	2.25	2	0.25	0.25	3	2	Delam	0	0	1
LKC22A	TP1	2.5	1.5	0	0	0	0	Delam	0	0	1
LKC22A	TP2	2.75	1.5	1.25	0.75	0	0	Delam	0	0	4
LKC22B	TP1	2	2.5	0	0	0	0	Delam	0	0	1
LKC22B	TP2	1.75	2.25	0	0	0	0	Delam	0	0	1

Table 6-32: Summary of Damage Measurements to LM PEAK Panels with 23-25 mils of Paint

Panel ID	Test Point	Outside Delamination		Outside Hole		Inside Damage			Inside Hole		Damage Score
		x (in)	y (in)	x (in)	y (in)	x (in)	y (in)	Type	x (in)	y (in)	
LNC33A	TP1	5	4.5	2	1.25	8.5	6.5	Damage	0	0	59
LNC33A	TP2	5	5	2	1.75	11	4	Damage	0	0	59
LNC33B	TP1	5.5	6.5	2.5	1.5	7.5	5	Damage	0	0	62
LNC33B	TP2	4.25	5.5	2.25	1.75	11.75	5	Damage	0	0	62
LKC33A	TP1	5.5	6	1.75	1.5	3	5.75	Delam	0	0	14
LKC33A	TP2	5.75	5.5	2	1.5	0	0	Delam	0	0	5
LKC33B	TP1	4.75	4.5	2	1	6	0.5	Delam	0	0	14
LKC33B	TP2	5.5	5	1.75	1.25	2	0.5	Delam	0	0	5
LNC23A	TP1	3.5	4.25	0	0	1.5	1.5	Delam	0	0	2
LNC23A	TP2	6	4	0	1	4.75	4.25	Delam	0	0	11
LNC23B	TP1	3.75	4	1.75	1	4.25	4.25	Delam	0	0	13
LNC23B	TP2	3.75	2.5	1.75	1	4.5	3	Delam	0	0	13
LKC23A	TP1	3.5	3.75	0	0	4.25	4	Delam	0	0	10
LKC23A	TP2	3.25	3	0	0	3.5	3	Delam	0	0	1
LKC23B	TP1	3.75	3.5	0	0	0	0	Delam	0	0	1
LKC23B	TP2	2.5	2.5	0	0	0	0	Delam	0	0	1

Table 6-33: Summary of Damage Measurements to PPS Panels with 5-7 mils of Paint

Panel ID	Test Point	Outside Delamination		Outside Hole		Inside Damage			Inside Hole		Damage Score
		x (in)	y (in)	x (in)	y (in)	x (in)	y (in)	Type	x (in)	y (in)	
PNC31A	TP1	1	1.5	0.5	0.75	0	0	Delam	0	0	1
PNC31A	TP2	0.5	0.75	0.5	0.75	0	0	Delam	0	0	1
PNC31B	TP1	3.75	2	0.75	1	0	0	Delam	0	0	1
PNC31B	TP2	3	3.5	0.75	0.5	0	0	Delam	0	0	1
PKC31A	TP1	1	1.5	1	0.75	0	0	Delam	0	0	1
PKC31A	TP2	0.75	0.5	1	0.75	0	0	Delam	0	0	1
PKC31B	TP1	1	1	0.5	0.5	0	0	Delam	0	0	1
PKC31B	TP2	1	1.25	0.5	0.25	0	0	Delam	0	0	1
PNC21A	TP1	0.75	1.25	0	0	0	0	Delam	0	0	1
PNC21A	TP2	1.5	1.75	0	0	0	0	Delam	0	0	1
PNC21B	TP1	2	1.5	0	0	0	0	Delam	0	0	1
PNC21B	TP2	1	1	0	0	0	0	Delam	0	0	1
PKC21A	TP1	1	1.5	0	0	0	0	Delam	0	0	1
PKC21A	TP2	1.5	0.75	0	0	0	0	Delam	0	0	1
PKC21B	TP1	0.75	0.5	0	0	0	0	Delam	0	0	1
PKC21B	TP2	1.25	0.75	0	0	0	0	Delam	0	0	1

Table 6-34: Summary of Damage Measurements to PPS Panels with 14-16 mils of Paint

Panel ID	Test Point	Outside Delamination		Outside Hole		Inside Damage			Inside Hole		Damage Score
		x (in)	y (in)	x (in)	y (in)	x (in)	y (in)	Type	x (in)	y (in)	
PNC32A	TP1	2	3.5	1.5	1.75	3.75	4	Delam	0	0	4
PNC32A	TP2	4.75	4.25	2.25	2	4.25	4	Delam	0	0	17
PNC32B	TP1	3	4.75	1.5	2	3.5	4.75	Delam	0	0	14
PNC32B	TP2	3	5	1.75	1.75	4	4.25	Delam	0	0	14
PKC32A	TP1	2	1.75	0.75	1.25	2	2	Delam	0	0	4
PKC32A	TP2	5	3	1.75	1.5	2	1.5	Delam	0	0	5
PKC32B	TP1	3	2.5	2.25	1.5	0.75	1.5	Delam	0	0	7
PKC32B	TP2	2.75	3	2.75	2.5	0	0	Delam	0	0	7
PNC22A	TP1	3	3	0.5	0.25	3	2.25	Delam	0	0	1
PNC22A	TP2	2.5	2	0	0	2.5	1.5	Delam	0	0	1
PNC22B	TP1	3.5	4	0	0	4	3	Delam	0	0	1
PNC22B	TP2	3	3.5	0	0	3	2.5	Delam	0	0	1
PKC22A	TP1	3.5	1.25	0	0	0.25	0.5	Delam	0	0	1
PKC22A	TP2	0.5	1.25	0	0	0	0	Delam	0	0	1
PKC22B	TP1	1	0.75	0	0	1.5	1.75	Delam	0	0	1
PKC22B	TP2	1.25	1	0	0	0	0	Delam	0	0	1

Table 6-35: Summary of Damage Measurements to PPS Panels with 23-25 mils of Paint

Panel ID	Test Point	Outside Delamination		Outside Hole		Inside Damage			Inside Hole		Damage Score
		x (in)	y (in)	x (in)	y (in)	x (in)	y (in)	Type	x (in)	y (in)	
PNC33A	TP1	4	4	1.5	1.75	0.5	0.25	Damage	0	0	31
PNC33A	TP2	2.5	3.25	1.75	2	3.25	2.75	Damage	1	0.75	175
PNC33B	TP1	3.5	3	1.75	2	3.5	2.75	Damage	1	1.25	238
PNC33B	TP2	4.5	4.5	1.5	1.75	3.5	3	Damage	0.75	1	176
PKC33A	TP1	2.75	2.5	1.75	1.75	1.75	1.75	Delam	0	0	4
PKC33A	TP2	2.5	3	1.75	1.75	2.25	1.5	Delam	0	0	4
PKC33B	TP1	2.25	2.75	1.25	2	2	2.25	Delam	0	0	4
PKC33B	TP2	3	2.75	1.5	1.75	1.75	2	Delam	0	0	4
PNC23A	TP1	2.5	2.5	0.25	0.25	3	2.75	Delam	0	0	1
PNC23A	TP2	2.5	2	0	0	0	0	Delam	0	0	1
PNC23B	TP1	3	3.5	0	0	3.75	3.75	Delam	0	0	1
PNC23B	TP2	3.25	2.75	1	0.5	3.5	3	Delam	0	0	1
PKC23A	TP1	1.5	2.25	0	0	1.75	1.75	Delam	0	0	1
PKC23A	TP2	1.25	1	0	0	1.5	1.25	Delam	0	0	1
PKC23B	TP1	1.25	1	0	0	1.5	1	Delam	0	0	1
PKC23B	TP2	1.25	1.5	0	0	2	2	Delam	0	0	1

Table 6-36: Thermal and Deflection Measurements of Epoxy Panels

Panel ID	Test Point	Peak Temperature (°C)	Max Deflection (mm)
ENC32A	TP1	267.6	13.4281
ENC32A	TP2	205.9	12.3745
ENC32B	TP1	226.6	12.9784
ENC32B	TP2	236.6	13.1564
EKC32A	TP1	203.2	9.2503
EKC32A	TP2	182.6	9.7274
EKC32B	TP1	185.1	9.658
EKC32B	TP2	185.6	9.6551

Table 6-37: Thermal and Deflection Measurements of LM PAEK Panels with 5-7 mils of paint

Panel ID	Test Point	Peak Temperature (°C)	Max Deflection (mm)
LNC31A	TP1	160.2	8.6833
LNC31A	TP2	257.5	7.58
LNC31B	TP1	266.7	7.0813
LNC31B	TP2	187.4	7.3696

Panel ID	Test Point	Peak Temperature (°C)	Max Deflection (mm)
LKC31A	TP1	152.7	6.6232
LKC31A	TP2	148.7	5.3124
LKC31B	TP1	154.6	5.9186
LKC31B	TP2	176.3	6.1796
LNC21A	TP1	135.4	6.3102
LNC21A	TP2	113	7.4234
LNC21B	TP1	224.7	7.3846
LNC21B	TP2	260.9	7.4841
LKC21A	TP1	117.2	5.751
LKC21A	TP2	91.7	Data Not Recorded
LKC21B	TP1	199.1	6.8967
LKC21B	TP2	190.8	5.6275

Table 6-38: Thermal and Deflection Measurements of LM PAEK Panels with 14-16 mils of paint

Panel ID	Test Point	Peak Temperature (°C)	Max Deflection (mm)
LNC32A	TP1	259.2	8.7328
LNC32A	TP2	233.5	7.9697
LNC32B	TP1	239.1	9.1298
LNC32B	TP2	256	8.1775
LKC32A	TP1	162.2	6.5
LKC32A	TP2	192.1	6.1396
LKC32B	TP1	165.8	7.6835
LKC32B	TP2	140.3	7.7068
LNC22A	TP1	264.5	7.1941
LNC22A	TP2	245.4	Data Not Recorded
LNC22B	TP1	260.9	6.1116
LNC22B	TP2	252.3	7.0607
LKC22A	TP1	102.2	5.7061
LKC22A	TP2	186.3	5.8968
LKC22B	TP1	91.7	5.8198
LKC22B	TP2	83.2	5.5733

Table 6-39: Thermal and Deflection Measurements of LM PAEK Panels with 23-25 mils of paint

Panel ID	Test Point	Peak Temperature (°C)	Max Deflection (mm)
LNC33A	TP1	212.2	9.1144
LNC33A	TP2	331.4	9.7932
LNC33B	TP1	265.9	9.9428
LNC33B	TP2	219.1	11.577
LKC33A	TP1	184.7	9.0205

Panel ID	Test Point	Peak Temperature (°C)	Max Deflection (mm)
LKC33A	TP2	187	8.9891
LKC33B	TP1	179.7	9.1016
LKC33B	TP2	187.3	9.1335
LNC23A	TP1	111	6.5826
LNC23A	TP2	119.6	7.1265
LNC23B	TP1	127.1	6.2021
LNC23B	TP2	123.8	6.6435
LKC23A	TP1	95.4	5.8681
LKC23A	TP2	107.6	6.1951
LKC23B	TP1	86.7	6.0495
LKC23B	TP2	87.6	4.9191

Table 6-40: Thermal and Deflection Measurements of PPS Panels with 5-7 mils of paint

Panel ID	Test Point	Peak Temperature (°C)	Max Deflection (mm)
PNC31A	TP1	234.9	7.9805
PNC31A	TP2	251.4	7.3145
PNC31B	TP1	241.3	8.3263
PNC31B	TP2	252.4	8.5744
PKC31A	TP1	204.1	5.9568
PKC31A	TP2	152.1	6.4646
PKC31B	TP1	214.2	6.5436
PKC31B	TP2	196	6.4264
PNC21A	TP1	130.4	6.0157
PNC21A	TP2	221.1	7.1663
PNC21B	TP1	256.6	5.8232
PNC21B	TP2	254.1	6.7263
PKC21A	TP1	134.1	Data Not Recorded
PKC21A	TP2	132.9	5.1801
PKC21B	TP1	130.6	5.4287
PKC21B	TP2	116.4	5.682

Table 6-41: Thermal and Deflection Measurements of PPS Panels with 14-16 mils of paint

Panel ID	Test Point	Peak Temperature (°C)	Max Deflection (mm)
PNC32A	TP1	301.7	8.5736
PNC32A	TP2	275.9	9.3622
PNC32B	TP1	225.4	10.2329
PNC32B	TP2	204.1	9.2083
PKC32A	TP1	209.4	7.9221
PKC32A	TP2	177.7	7.8575

Panel ID	Test Point	Peak Temperature (°C)	Max Deflection (mm)
PKC32B	TP1	188.3	7.0805
PKC32B	TP2	182.7	7.6639
PNC22A	TP1	153.9	6.9547
PNC22A	TP2	122.8	6.978
PNC22B	TP1	127.7	7.0973
PNC22B	TP2	128.7	6.5369
PKC22A	TP1	80.5	5.6845
PKC22A	TP2	78.1	5.7819
PKC22B	TP1	83.5	5.657
PKC22B	TP2	73.7	5.2211

Table 6-42: Thermal and Deflection Measurements of PPS Panels with 23-25 mils of paint

Panel ID	Test Point	Peak Temperature (°C)	Max Deflection (mm)
PNC33A	TP1	259.9	9.1043
PNC33A	TP2	660.1	N/A
PNC33B	TP1	660	N/A
PNC33B	TP2	660.1	N/A
PKC33A	TP1	202.2	6.6697
PKC33A	TP2	190.9	7.1657
PKC33B	TP1	195.1	7.8051
PKC33B	TP2	197.3	7.7341
PNC23A	TP1	116.2	6.8001
PNC23A	TP2	128.9	6.5649
PNC23B	TP1	177.9	8.077
PNC23B	TP2	173.4	8.077
PKC23A	TP1	83.9	6.1469
PKC23A	TP2	85.4	5.9354
PKC23B	TP1	133	5.5559
PKC23B	TP2	84.5	5.8552

6.8.5 Damage Analysis

Damage Codes

Of all the configurations tested, only one scored higher than the acceptable damage threshold of 64. This configuration had four test points, three of them failed the damage code assessment, while the one other test point did not sustain as much damage. These three test points were PNC33A-TP2 and PNC33B-TP1 and TP2 and they scored 175, 238, and 176 respectively. All four test points had roughly the same area of outside delamination (between 2.5 - 4.5” x 3 - 4.5”) and outside hole (between 1.5 - 1.75” x 1.75 - 2”). The difference was on the inside of the panels. The test point that passed the damage code assessment (PNC33A-TP1) had an inside delamination of 0.5 x 0.25” with no holes on the inside of the panel giving it a score of 31, while the other three test points had inside delamination between 3.25 - 3.5” x 2.75 - 3” and punctures all the way through the composite. This configuration contained thin panels with the lighter weight of copper LSP and the thickest amount of paint. In other words, these were the worst case scenario panels of the PPS matrix material configuration, so their failure is not unexpected. It is worth noting that their LM PAEK counterparts scored 59 on both test points of the LNC33A panel and 62 of the LNC33B panel, which is close to the failure threshold of 64.

IR Imaging

IR imaging allowed for real-time capture of the temperature progression profile of the panel. Using an IR camera that is mounted below the panels to avoid oversaturating the sensors with the arc, videos were taken that show the temperatures across the whole underside of the panel. See Figure 6-78 for the test setup. Using a program called ExaminIR, a frame-by-frame analysis was done to determine the highest temperature on the inside of the panel. The peak-temperature frame was analyzed in the ImageJ image analysis program, which allowed measurement of the areal heat distribution throughout the panel. The IR imaging demonstrated that the insulating properties of the matrix material confine the heating to a relatively small primary damage zone (PDZ). No location more than two inches outside of the PDZ boundaries exceeded 30 °C. It is unlikely that regions of the panel outside the PDZ were affected by heating due to lightning strike events. To confirm this point, the DSC samples were taken from areas both inside and outside the PDZ and compared to determine whether there was a change in crystallinity.

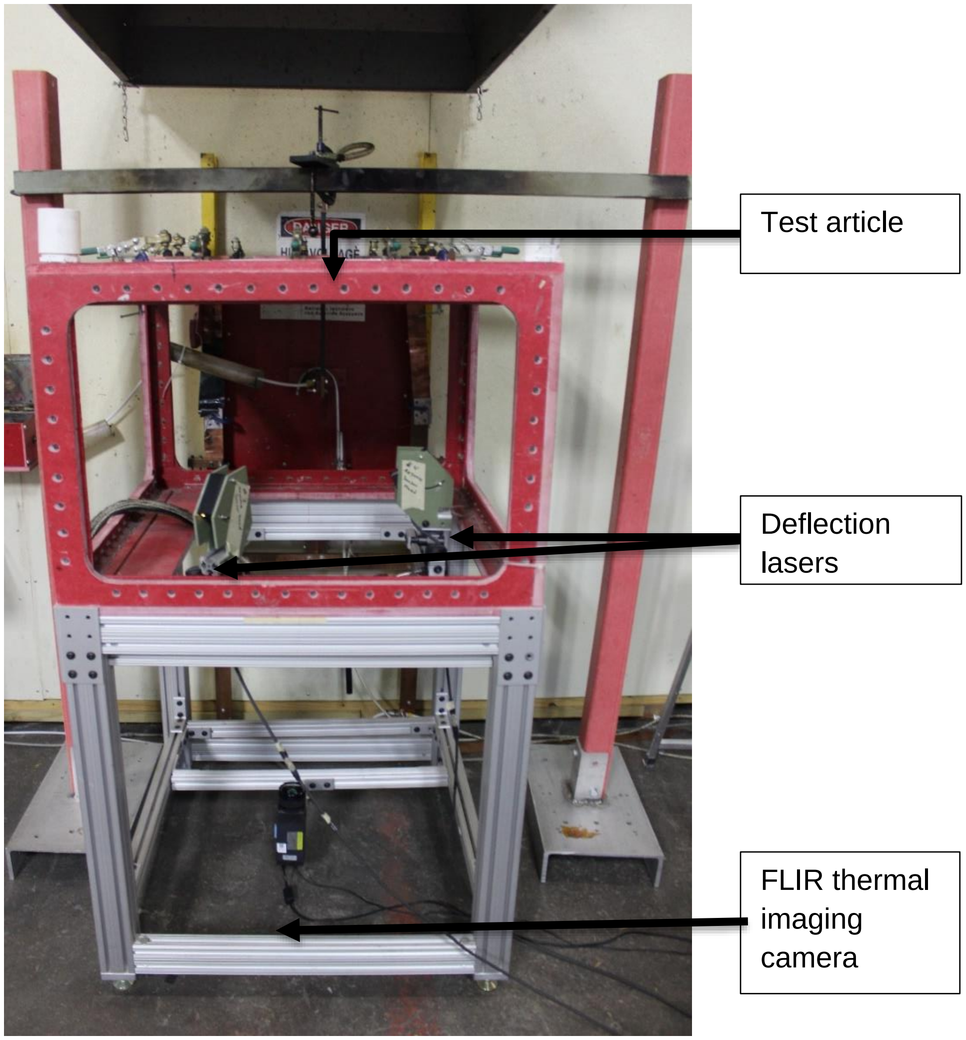


Figure 6-78: Labeled photo of the test set up

The three test points that resulted in holes all the way through the panel were excluded from the thermal analysis because the recorded temperatures exceeded the range of the IR sensor. The peak temperatures within the PDZ, which were measured from the back of the panels, typically approached or exceeded the glass transition temperatures (T_g) for each of the three matrix materials. Peak temperatures rarely approached or exceeded the melting temperature (T_m) of the PPS or LM PAEK thermoplastics. As for the epoxy panels, though they do not have a melting temperature, the thin panels did exceed the glass transition temperature while the thick panels were almost always 20 °C below the glass transition temperature. Four test points of the LM PAEK panels, namely LNC31B-TP1, LNC33A-TP2, LNC33B-TP1, and LNC22A-TP1-reached the matrix crystallization temperature (T_c). There was no discernable trend between damage score and peak temperature or areal heat distribution. For thermoplastic panels, the peak temperature achieved is inversely proportional to the distribution of the heat through and across the panel. This phenomenon was not observed with the thermoset panels. This is shown in Figure 6-79 below. Additionally, there is no discernable correlation between the heat distribution and the area of outside or inside delamination. This implies that heating alone does not define the delamination area, nor is the distribution of heat directly proportional to delamination.

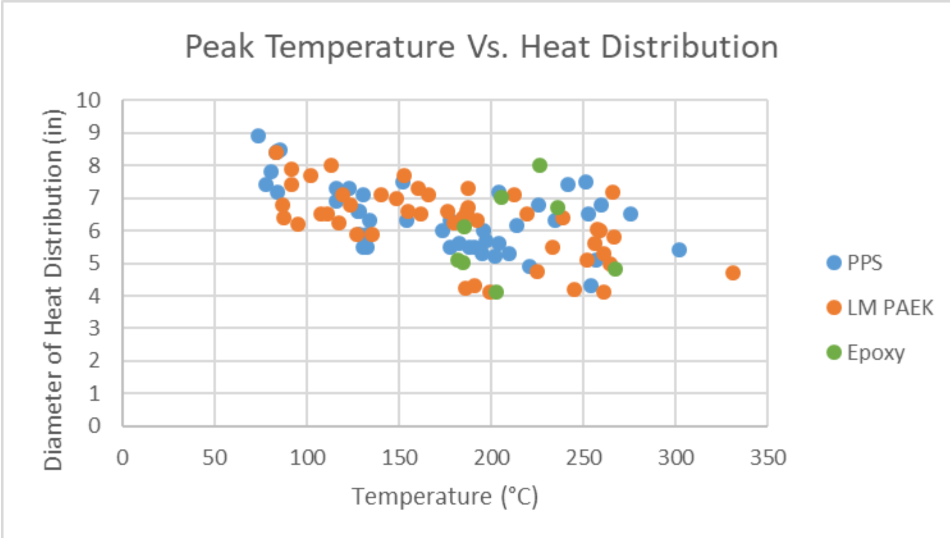


Figure 6-79: Graph of the peak temperature versus heat distribution

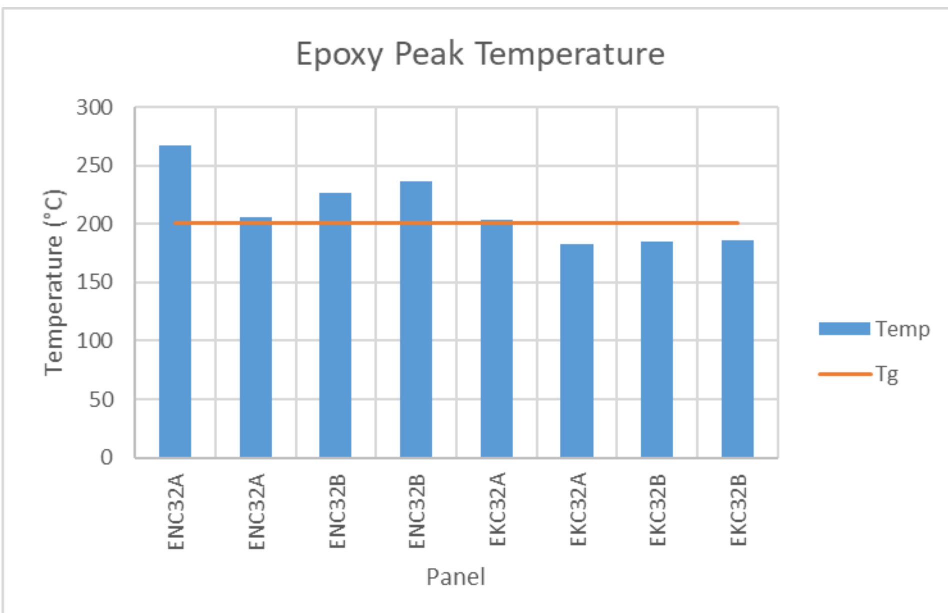


Figure 6-80: Graph of the peak temperatures obtained by epoxy panels

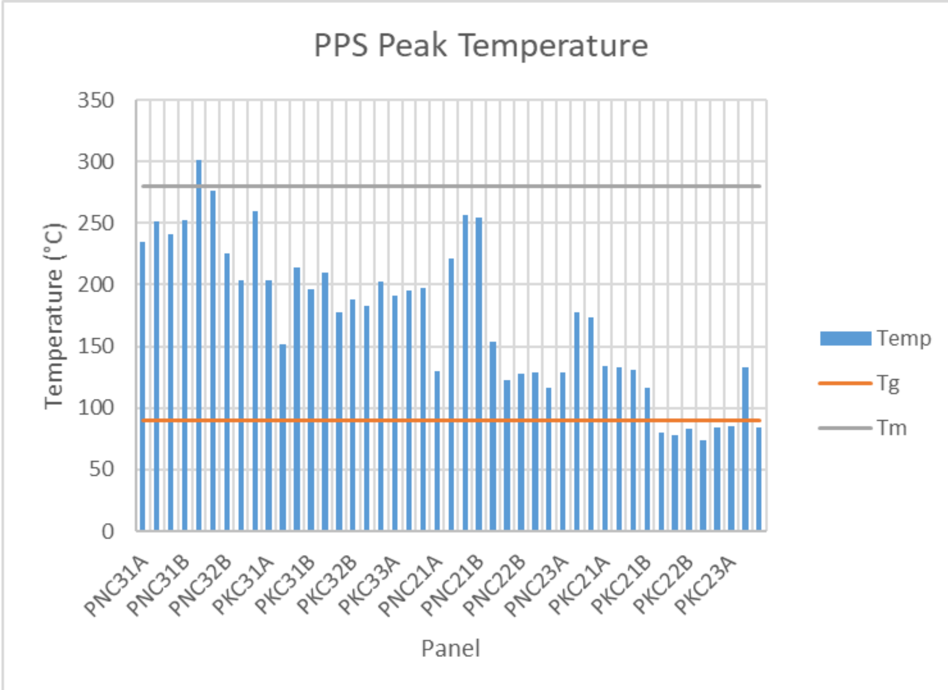


Figure 6-81: Graph of the peak temperatures obtained by PPS panels

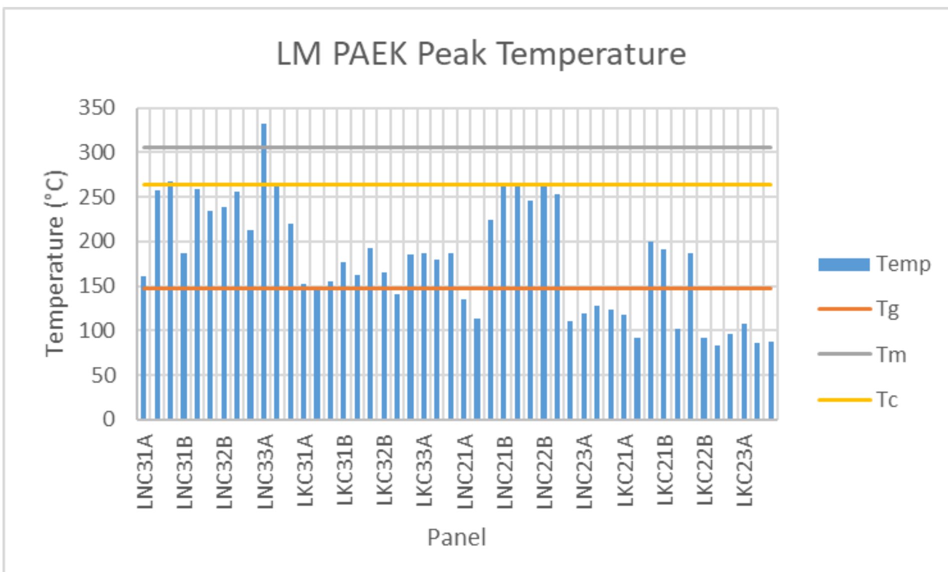


Figure 6-82: Graph of the peak temperatures obtained by LM PAEK panels

Deflection

The impact and subsequent shockwave of a lightning strike event can cause the panels to deflect. Laser deflection sensors mounted beneath the panels were used to measure the maximum amplitude of deflection that occurred at a reference point at the center of each panel by collecting a measurement every 20 microseconds throughout the lightning test. See Figure 6-78 for the test setup. Deflection data was compared to the amount of damage a panel sustained to determine whether there was any correlation. This was done by comparing the deflection to the damage scores, outside delamination, outside hole, inside delamination, and inside damage areas. Inside holes were not analyzed for deflection because debris falling through the hole skewed the deflection measurements in these cases. Looking at Figure 6-83 below, there appears to be a trend between amount of deflection and the damage score, though there is not enough evidence to say this conclusively. The only test factors that independently impacted the amplitude of deflection were the matrix material and panel thickness. As seen in Figure 6-84, the thermoplastic panels (PPS and LM PAEK) performed similarly, while the thermoset panels (epoxy) had a greater deflection amplitude. It is also clear that the panel thickness impacted the deflection amplitude. As one would expect, the thinner panels had a greater peak amplitude of deflection than their thick counterparts. No other independent factors had a statistically significant difference in deflection behavior. However, when factors are combined, there is a clear trend within the various configurations which can be seen in Figure 6-85. While it appears that the paint thickness may have also made a difference in deflection within each configuration, it is not by an appreciable/statistically significant amount or always in the same trend. Figure 6-86 shows that the maximum temperature is directly proportional to the maximum amplitude of deflection. This makes sense as the higher temperature events would correlate with more vaporization and explosion of material, thereby increasing the amplitude of deflection.

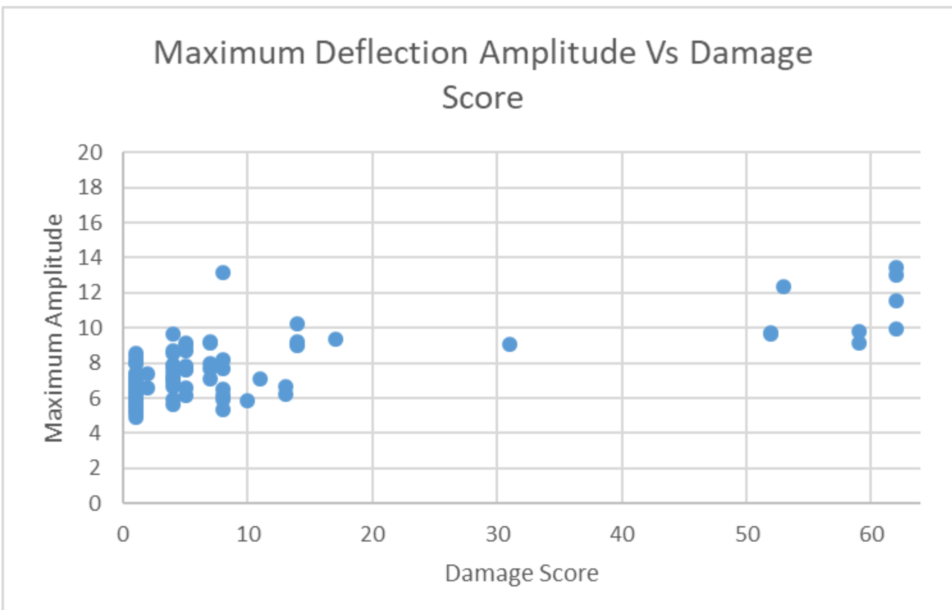


Figure 6-83: Graph of the maximum amplitude of deflection versus damage score

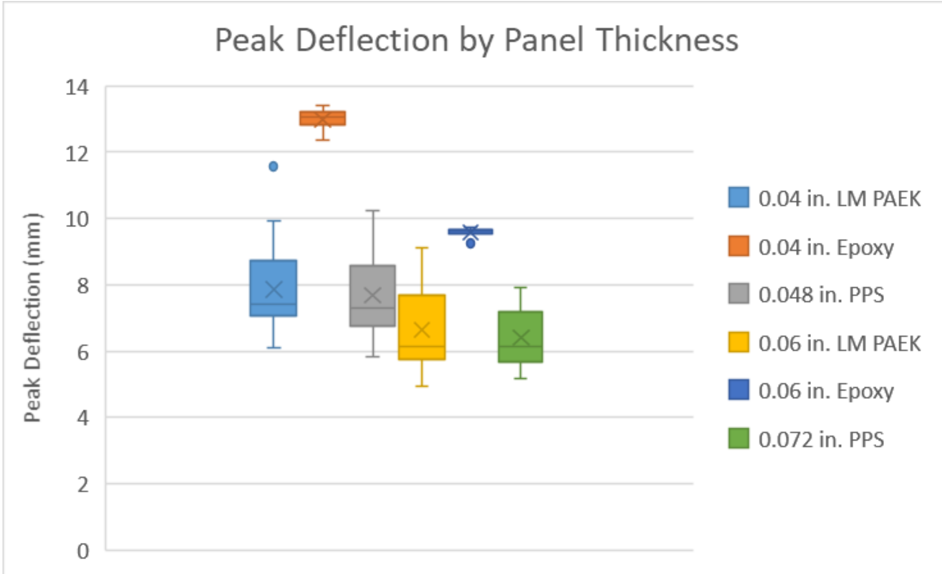


Figure 6-84: Average amplitude of deflection by matrix material.

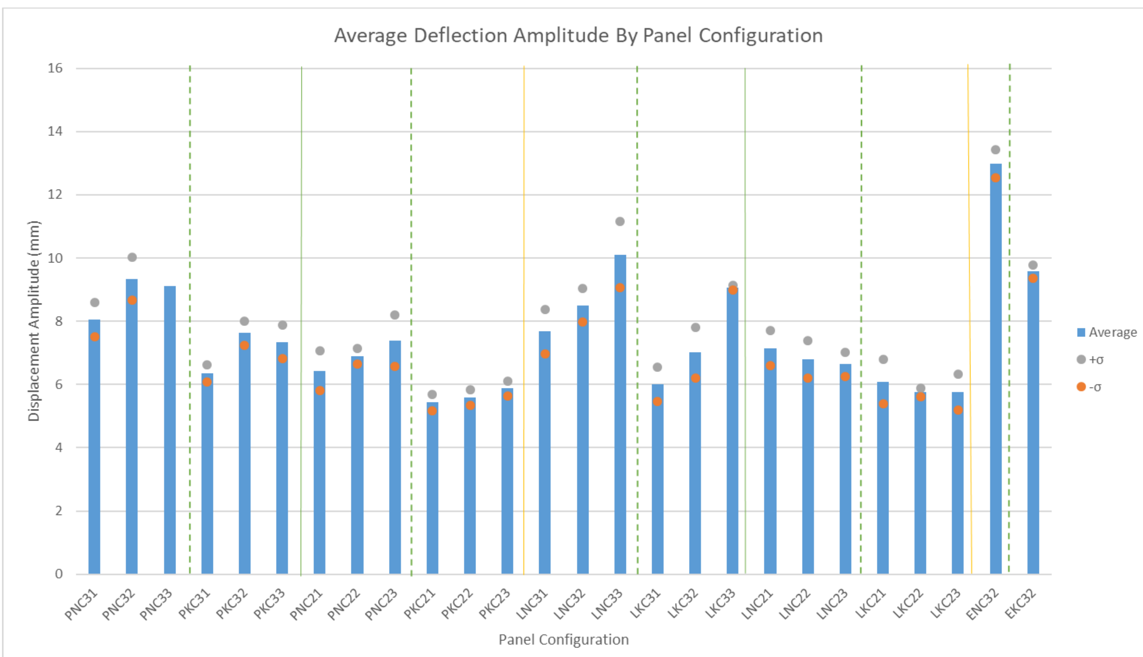


Figure 6-85: Average amplitude of deflection by panel configuration
Note: σ denotes one standard deviation.

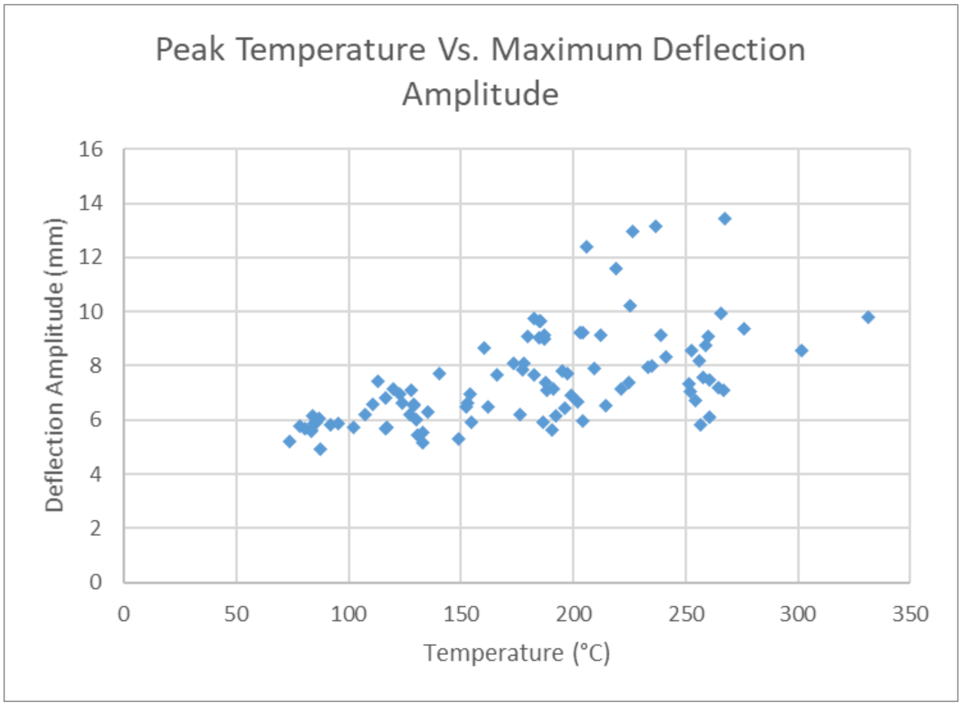


Figure 6-86: Graph of the peak temperature obtained during testing versus the peak deflection

C-Scans

Due to warping of the panels after lightning strike, the data from the pulse echo scans is deceptive because the panels no longer lay flat. The scans show what looks like internal damage when there isn't any, and from depths deeper than the panel thickness. However, looking at the area of damage near the strike on the C-scans, and ignoring the secondary area (i.e. the ring around the most severe damage that is the same thickness as the unpainted panel border shown in Figure 6-87) outside of that shows that the PDZ is indeed limited to the area near the strike. On average, the size of damage on the PPS panels measured from the C-scans was the smallest while the epoxy panels had nearly double the diameter of damage. The damage through the depth of the panel was also the lowest on the PPS panels while the PAEK and epoxy panels both sustained more damage to deeper plies.

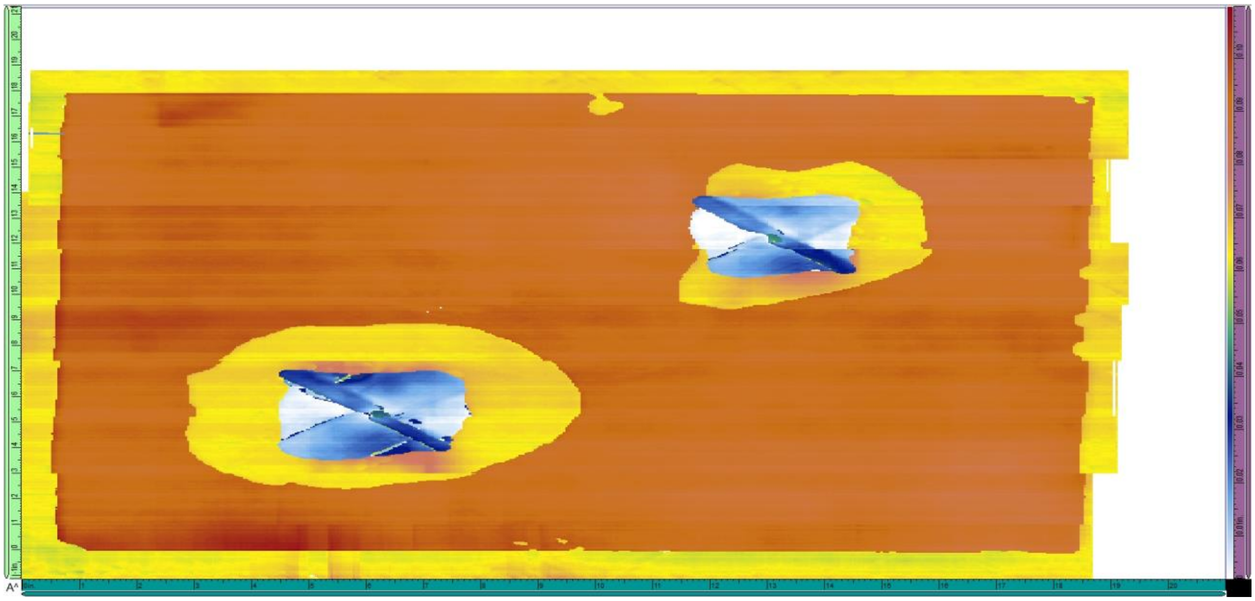
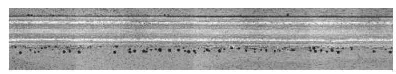
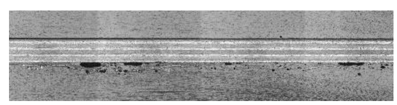
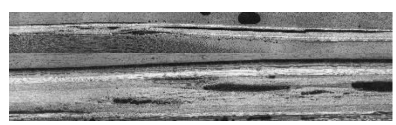
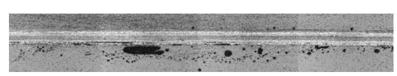
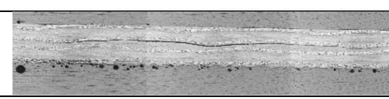
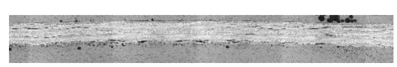
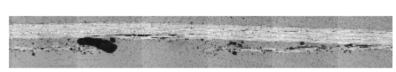
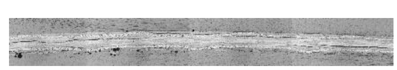


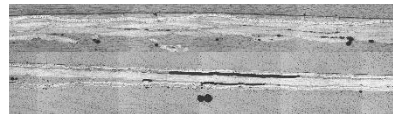
Figure 6-87: Pulse echo scan of LKC23A

Micrographs

Micrographs of the cross section of select panels were taken to confirm the findings of the ultrasonic C-scans and to determine the void content of the panels. The photomicrograph delamination samples may look quite different from the C-scan and tap test delamination areas due to being represented in three dimensions instead of two. All photomicrograph coupons look at the plies in the very center of the damage area to demonstrate what the worst damage would look like. The micrographs also showed that the delamination area sometimes exceeds that of the delamination measured via tap testing. This is not surprising as it can be difficult to identify delamination via tap test at the center of the panel if the surface plies are not delaminated. The void content percentages were calculated by excluding the immediate damage area of the strike, as the voids due to damage were large and would skew the data. For ease of comparison and normalization, the void area was calculated from the void content percentages. It is important to note that this is all from one cross sectional slice of the damage area From the void content analysis summarized in Table 6-43, generally the thin panels had a greater void content, and thus more delamination between the plies than the thick panels, as one would expect. Interestingly, the LM PAEK panels had less delamination in three out of four cases than their PPS counterparts. This may be due to the higher working temperature of LM PAEK as compared to PPS. The one exception to this is the photomicrograph from panel LNC22B which had significantly more delamination than the other samples, though this is not reflected in the damage measurements. The micrographs also revealed that in addition to delamination and fiber breakage, the PPS panels also had matrix cracking and fiber-matrix debonding, which in this study, was more common in woven panels than in unitape panels. Since all the PPS panels were fabric and all of the LM PAEK panel were tape, it is difficult to determine if this phenomena is an effect of the matrix or the fiber form. Table 6-43 below has a summary of the extent and type of damage observed in the micrographs. Of the panels selected for micrographs, the damage generally seems to go either through all the plies or only to within one ply of the center, regardless of the number of plies present. The last thing the photomicrographs revealed was related to the visible melting signature seen on the back of some panels. This melting was first observed and noted in section Analysis and was thought to be related to the inside delamination of the panel. Among the photomicrograph coupons were samples both with and without this visible melting signature present. Of the samples with visible melting, some of them lined up with delamination and some did not. There was no consistent correlation to delamination seen on the micrographs Since thermoplastics have more plastic properties than thermosets, it makes sense that they would end up with such a deformation from the melting and re-solidifying.

Table 6-43: Summary of Photomicrograph Data

Coupon	Void Content (%)	Void Area (in^2)	No. of Plies Damaged	Notes	Photomicrograph*
EKC32A-TP1	0.7	0.003	6/12	Delamination and only top ply fiber breakage	
ENC32A-TP2	1.43	0.003	8/8	Delamination and fiber breakage	
LKC22B-TP1	0.461	0.001	1/12	Only minor fiber damage, and LSP damage	
LKC23A-TP1	0.523	0.002	7/12	Delamination and fiber breakage	
LKC32B-TP1	0.257	0.001	1/12	Delamination and only top ply fiber breakage	
LNC22B-TP1	7.245	0.018	8/8	Delamination, fiber breakage, and more voids in last ply.	
LNC32B-TP2	0.463	0.001	3/8	Delamination and only top ply fiber breakage	
PKC22A-TP2	0.719	0.002	3/6	Delamination	
PKC22B-TP1	1.026	0.003	6/6	Delamination, fiber-matrix debonding, and matrix cracking	
PKC32B-TP2	1.193	0.004	5/6	Delamination and matrix cracking	
PNC22B-TP2	2.209	0.005	4/4	Delamination, fiber breakage, and matrix cracking	

Coupon	Void Content (%)	Void Area (in²)	No. of Plies Damaged	Notes	Photomicrograph*
PNC32B-TP1	7.174	0.002	4/4	Delamination, fiber breakage, and matrix cracking	

*Note: The photos included in the photomicrograph column do not contain the entire micrograph. These photos show selected regions of the micrograph that best display the damage discussed in the notes column.

DSC

DSC is an analytic method used to determine the percent crystallinity of a non- or semi-crystalline material. Given that thermoplastics melt when taken above their working temperature and re-solidify as they cool back down, their percent crystallinity may change depending on how quickly the temperature changes. Multiple samples were extracted from the panels after DEL testing, both within and far away from the expected heat affected zone. In thermoplastics, the heat-affected zone is defined as the region where material properties have changed because of a non-melting, heat treatment process. The heat-affected zone was expected to be contained within the PDZ. See Figure 6-88for a schematic of sample locations and numbering. The DSC from the area outside the PDZ was compared to the expected crystallinity from the control point to determine if the whole panel is affected or not. As shown in Table 6-44 below, the change in percent crystallinity is not significant enough to cause changes to material property or behavior outside the PDZ. Even inside the PDZ, where intact, the matrix material crystallinity did not change enough to affect the material properties. This is not surprising as the panel would need to have a much slower cooling rate to have an effect on the crystallinity[6.1]. It is interesting to note that in our DSC samples the crystallinity of the PPS composite was nearly twice that of the LM PAEK composite.

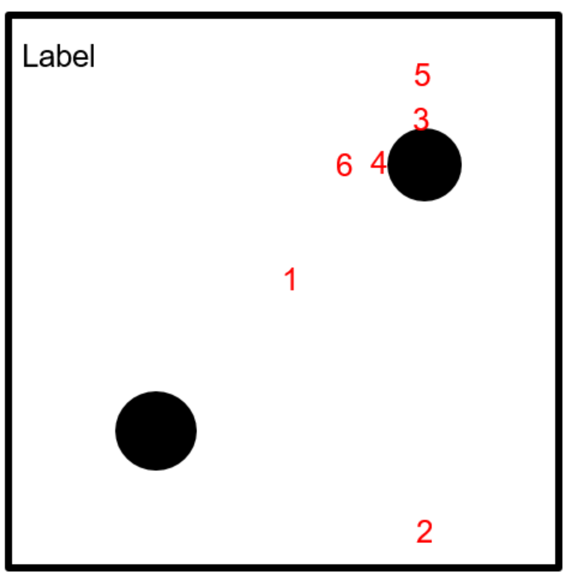


Figure 6-88: Schematic showing the relative locations of each DSC sample

Table 6-44: Percent crystallinity after lightning strike

Sample Number	LNC33A	PNC33A
1	21.16%	48.10%
2	21.81%	47.68%
3	22.06%	47.63%
4	23.45%	45.62%
5	22.45%	48.22%
6	23.06%	45.34%

6.8.6 Discussion

There were four factors in this test that influenced the outcome of a lightning strike event. These factors were:

1. Matrix Material
2. LSP
3. Panel Thickness
4. Paint Thickness

The impacts of each factor on the results of the lightning strike are discussed below in greater detail.

Matrix Material

Three different matrix materials were tested for comparison. Except for one PPS configuration which far exceeded the failure threshold, typically, epoxy panels sustained the most damage, followed by LM PAEK and PPS panels. This is shown in Figure 6-89 below. The performance of each specific matrix material is discussed further in the following sections.

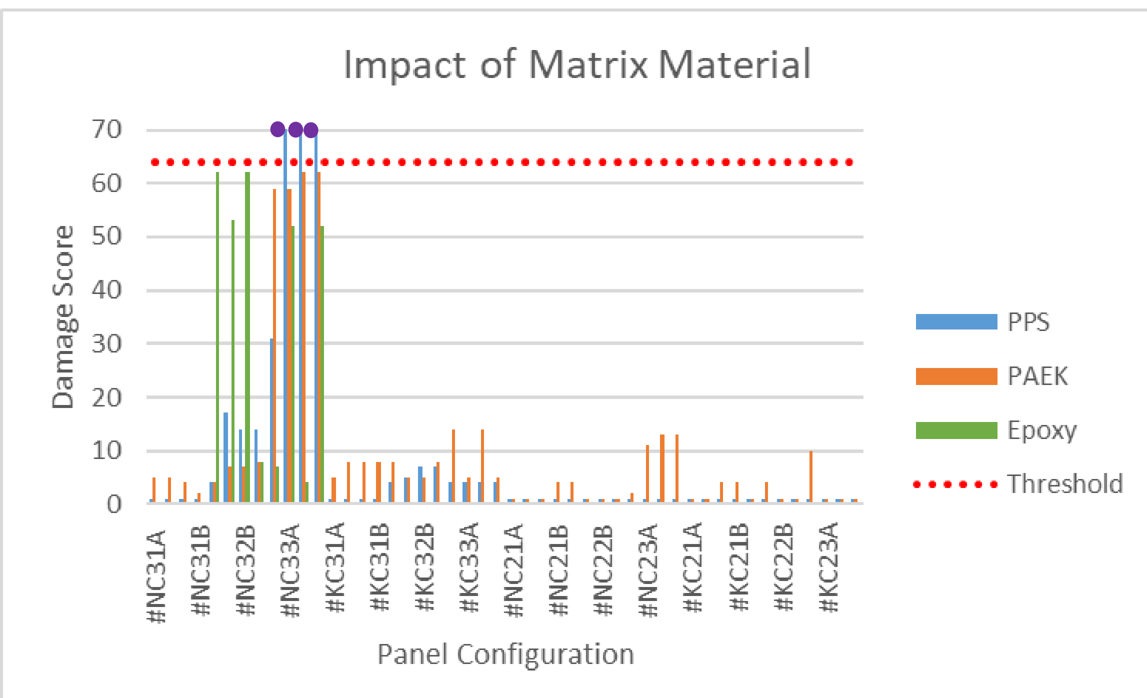


Figure 6-89: Graph of the impact of the matrix material on the damage score
Note: bars with purple marker exceeded the threshold and are cut off the graph. Please refer to the tables in section 6.8.4

Thermoset

While the epoxy panels in this round of testing did not exceed the failure threshold, they did score near it, with the majority of test points receiving damage to the fibers on the inside of the panel. The outside delamination and outside hole of the thin epoxy panels tend to be larger than that of their LM PAEK and PPS counterparts but the size of the outside hole on the thick epoxy panels was about the same as the comparable LM PAEK and PPS panels.

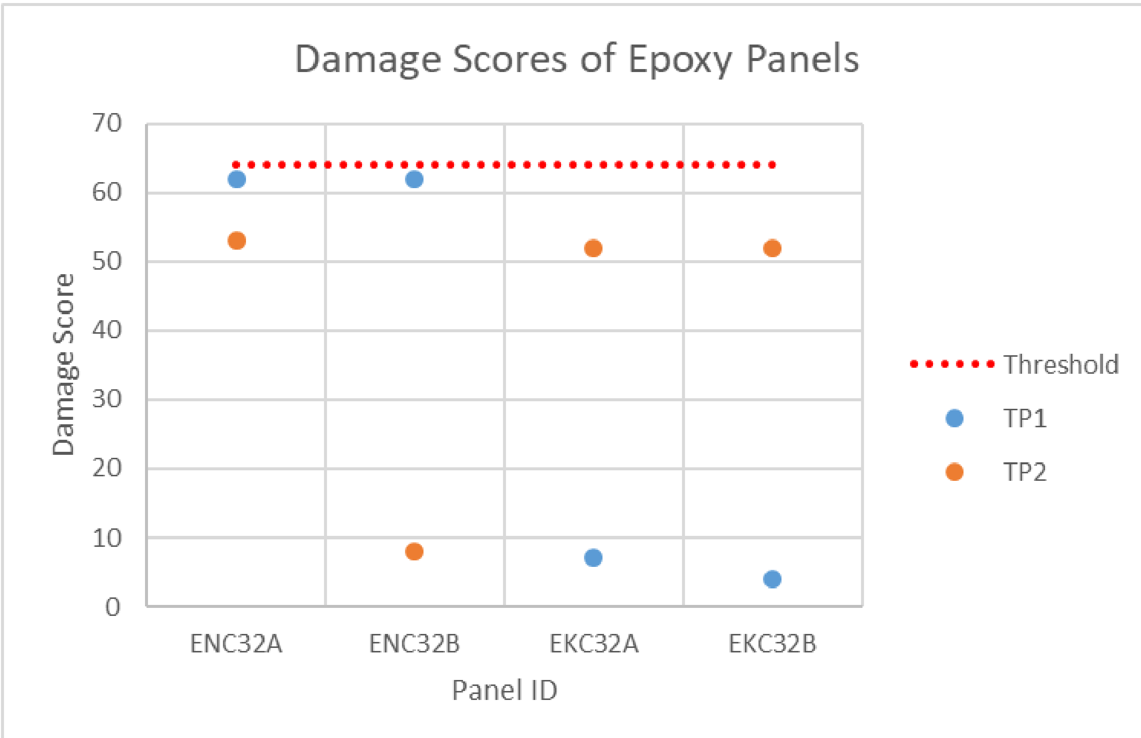


Figure 6-90: Graph of the damage scores of epoxy panels

Thermoplastic

LM PAEK and PPS panels scored identically in 16 of 48 comparable test points. Of the 48 test points, 15% of the LM PAEK panels did better than their PPS counterparts, which had three instances of catastrophic failures. Conversely, 52% of test points for the PPS panels performed better than their LM PAEK counterparts. This seems to indicate that the PPS panels do better, if not just as well, as the LM PAEK panels. However, as the LM PAEK panels were all made from unidirectional tape while the PPS panels were all five harness satin panels, it is difficult to say if this is due to the matrix material or the fiber arrangement.

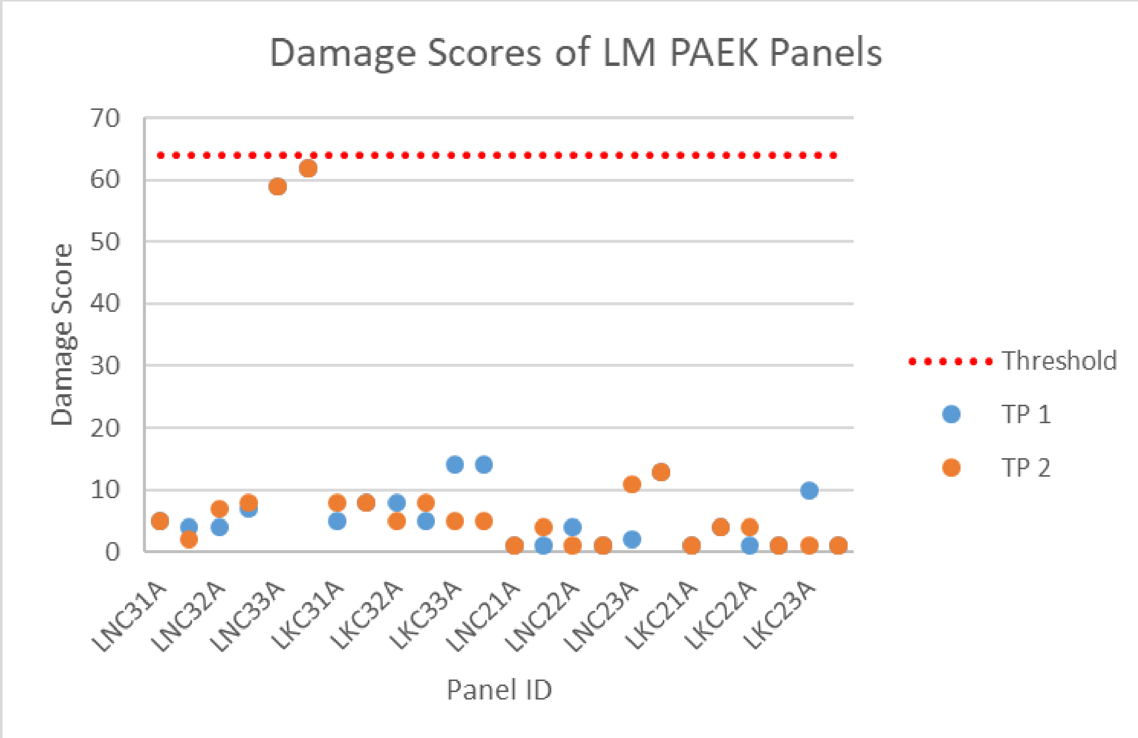


Figure 6-91: Graph of the damage scores of LM PAEK panels

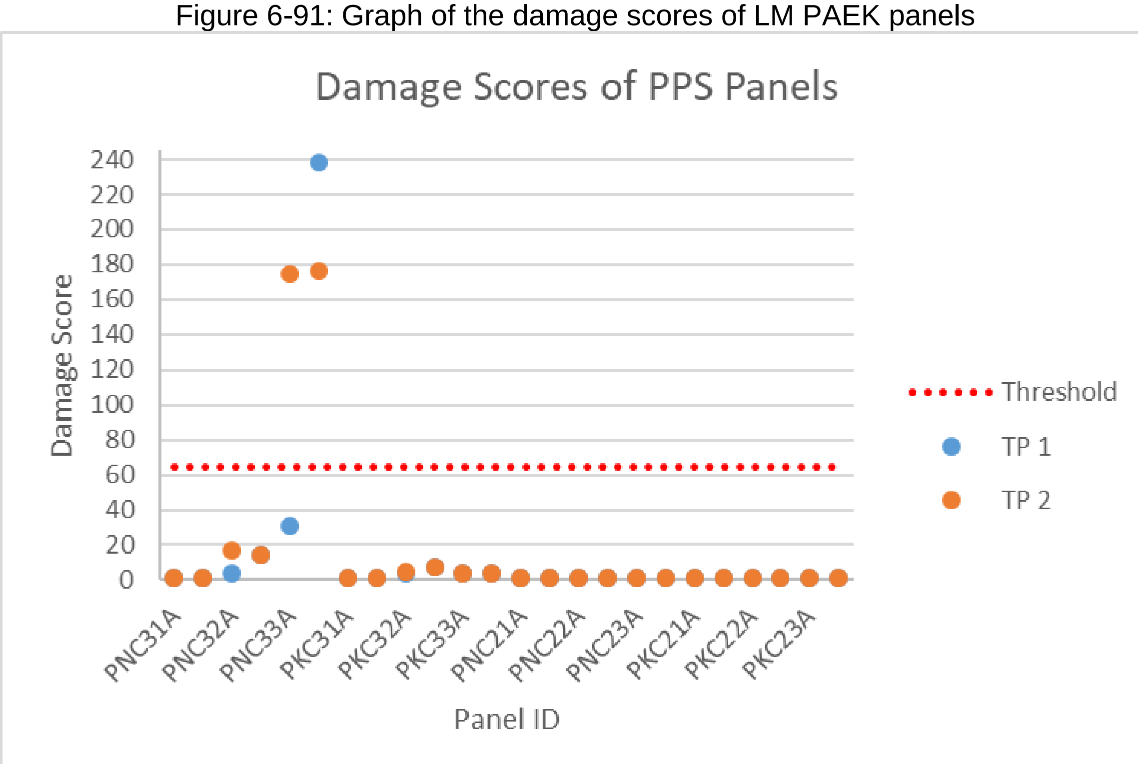


Figure 6-92: Graph of the damage scores of the PPS panels.

LSP

As seen in Figure 6-93, the heavier weight of copper outperformed the lighter weight in nearly every configuration in terms of damage score, with the only three failures (in terms of damage scores) having the lighter weight of ECF. In fact, the lighter ECF only performed better in one particular instance: on the Panel "B" test point 2, of the thin LM PAEK panels with 5-7 mils of paint. The panel code for this configuration is LNC**3**1B-TP2 (lighter), and the corresponding equivalent panel with heavier ECF is panel LNC**2**1B-TP2 (heavier). LNC**3**1B-TP2 (lighter) actually had a greater area of outside delamination, but a smaller outside hole and no inside delamination. LNC**2**1B-TP2 (heavier) had a larger outside hole and inside delamination area. For panel “A” of these configurations, LNC**3**1A-TP2 (lighter) similarly had a larger outside delamination area than the LNC**2**1A-TP2 (heavier), but the heavier weight of copper on the “A” panel in this configuration did not have an outside hole, and thus scored lower. In comparison, test point 1 on each of these four panels, the heavier ECF yielded less damage on all damage criteria. On the thick panels in general, the LSP seemed to be less important as both weights of copper performed equally well. In general, the difference in damage from one LSP scheme to another suggests that, for thick panels, the LSP has less of an impact on the damage because the thickness of the panel outweighs it. However, with the thin panels there was a bigger difference between the damage sustained by the panels protected by the different weights of copper. This indicates that LSP plays a more important role on thinner panels.

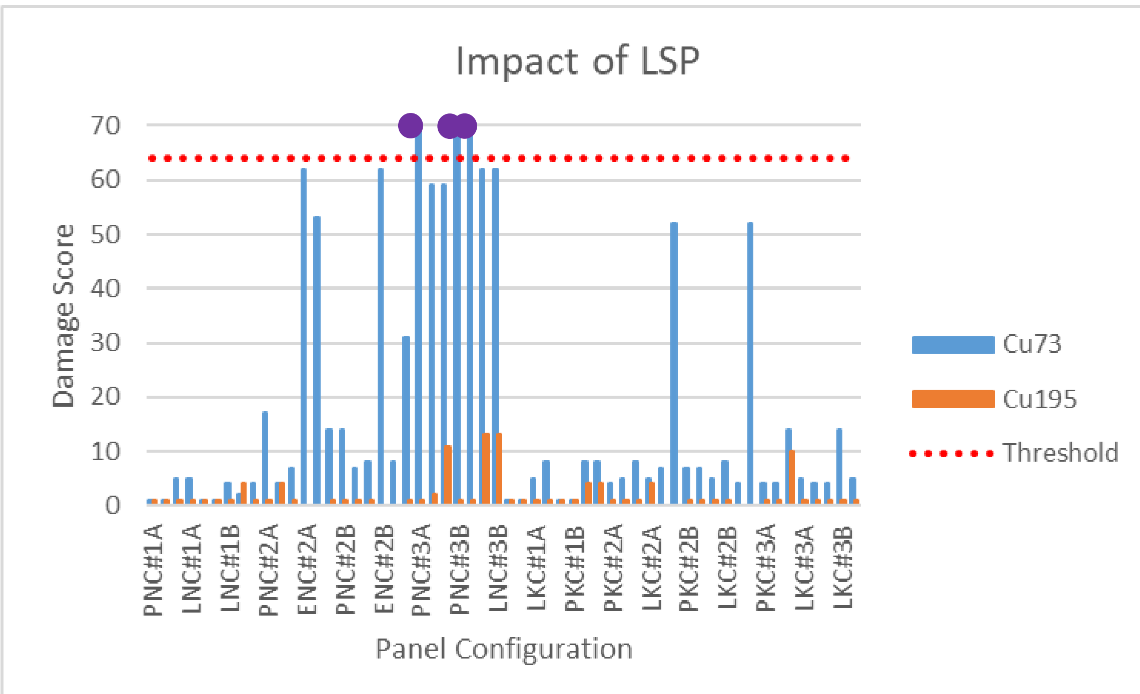


Figure 6-93: Graph of the impact of LSP on damage score.
Note: bars with purple marker exceeded the threshold and are cut off the graph. Please refer to the tables in section6.8.4.

Panel Thickness

Figure 6-94 below shows the impact of panel thickness on the amount of damage sustained due to a lightning strike event.

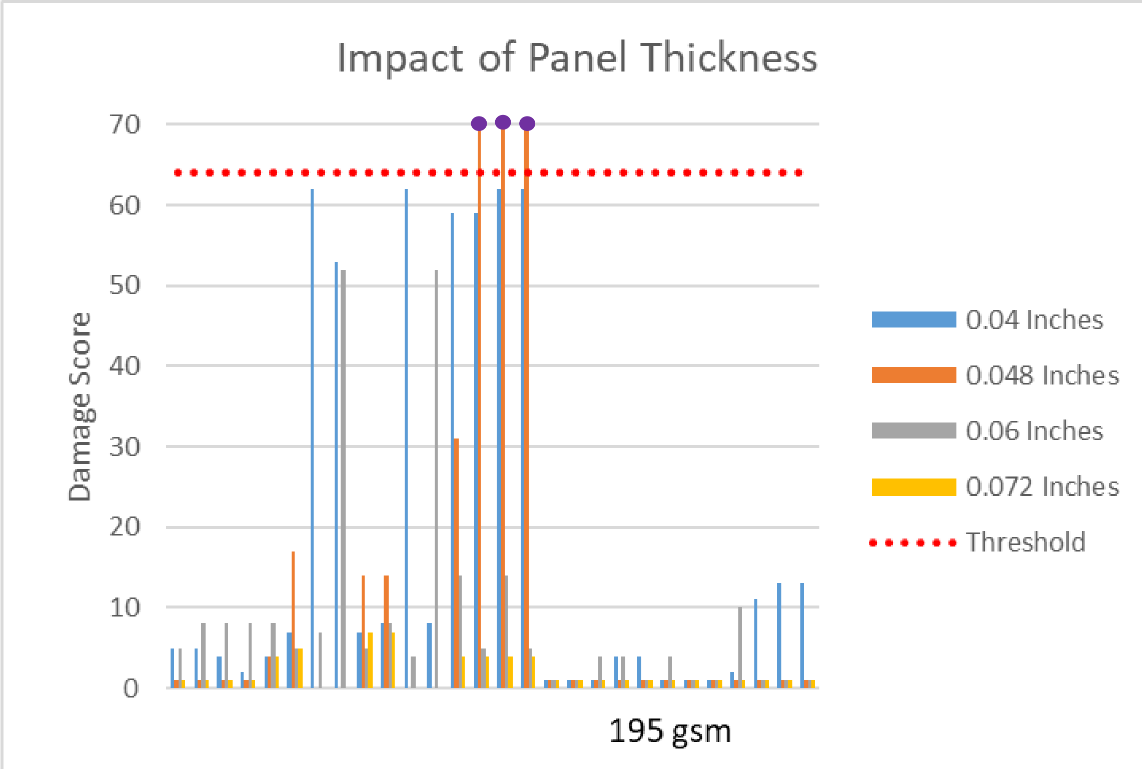


Figure 6-94: Graph of the impact of panel thickness on damage score.
Note: bars with purple marker exceeded the threshold and are cut off the graph. Please refer to the tables in section 6.8.4.

Thick panels sustained equal to or less damage than thin panels across all measurements on 28 out of 52 comparable test points. Of the 24 times, the thick panels did not perform better than or equal to the thin panels across all the damage criteria, only twice did that include thick panels having more delamination on the inside of the panel. The remaining 22 instances resulted in the thick panels having larger outside hole or delamination area, but equal or less inside damage/delamination or hole. In total, there were only 19 instances of inside delamination, 31 instances of no inside delamination at all, and two instances of inside damage to the thick panels out of 52.

On average, the thin panels had 1.68 inches larger outside delamination diameter and 1.15 inches larger outside hole diameter than their thick counterparts. Inside delamination areas of thin panels on average were 2.19 inches. Only the thin panels had inside holes, which were no bigger than 1.25 inches. The three test points resulting in holes all the way through the panel were PPS matrix panels with 23-25 mils of paint and the lighter weight of expanded copper foil. Out of the 52 comparable test points, only 11 times did a thin panel have inside damage, while the equivalent thick panels had at most inside delamination with no inside damage. In nine of those 11 cases the damage was considerably larger than the delamination. The only thick panels to sustain any inside damage were epoxy panels, which indicates it is more likely due to the matrix material than the panel thickness.

Paint Thickness

Figure 6-95 shows the impact of paint thickness on the damage sustained after lightning strike. Paint acts as a dielectric, which can cause an increase in the dwell time and heating by containing the arc to a limited area instead of allowing it to spread out. Typically thinner paint performs better, as depicted in Figure 6-96.

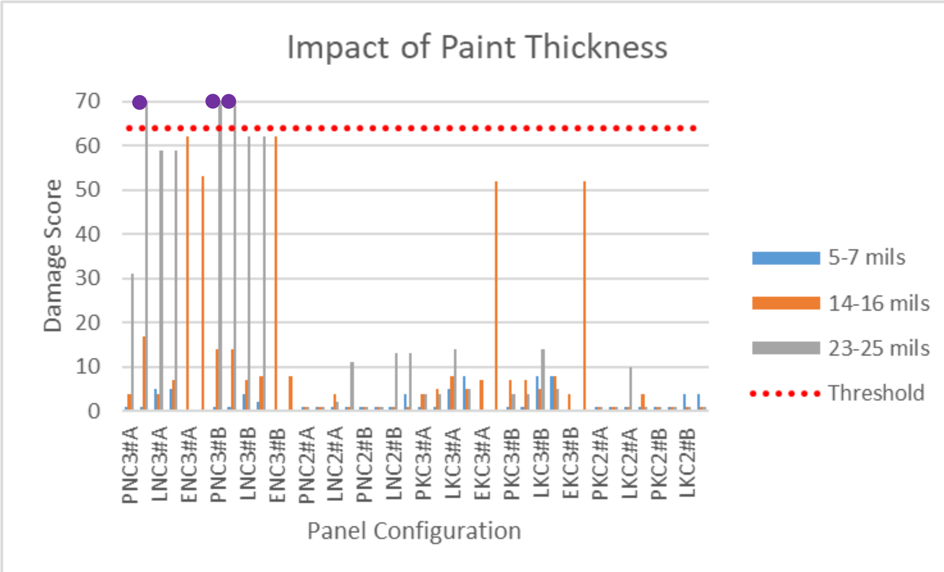


Figure 6-95: Graph of the impact of paint thickness on damage score
Note: bars with purple marker exceeded the threshold and are cut off the graph. Please refer to the tables in section 6.8.4.

<u>5-7 mils</u>

The panels with 5-7 mils of paint sustained the least damage of all three paint classes. After lightning strike, the paint thickness of the area around the strike was measured at 4.1 ± 0.6 mils of paint on average. These panels only had two out of a possible 32 instances of inside delamination and the size of the delamination was approximately 0.5 inches. These panels had small to no outside holes and small areas of outside delamination.

<u>14-16 mils</u>

The thick panels with 14-16 mils of paint usually sustained minimal damage, but the corresponding thin panels sustained more damage to both the inside and outside of the panel. After lightning strike, it was observed that the area around the strike on these panels had an average of 8.0 ± 2.3 mils of paint. These panels had slightly larger damage measurements than their 5-7 mils counterparts, especially in terms of inside delamination. Only 13 of 40 (three PPS, nine LM PAEK, and one epoxy) test points had no inside delamination, and five epoxy test points (of the 40 total test points) sustained fiber damage to the inside of the panel. This is evidence that with the same amount of paint, thermoplastics sustain less fiber damage to the inside of the panel than thermoset panels.

<u>23-25 mils</u>

After DEL testing, paint measured in the area around the test points had on average 14.2 ± 1.8 mils of paint. Looking at the size of outside delamination and hole, the panels in this paint class sustained around the same amount of damage as the panels in the 14-16 mils. The difference comes in the size and type of damage to the inside of the panel. Of the 32 test points on panels with thicker paint, only four resulted in no inside delamination. There were eight test points that resulted in fiber damage to the inside of the panel. The area of damage sustained by the thermoplastic panels with 23-25 mils of paint was approximately the same as the damage sustained by the epoxy panels with 14-16 mils of paint. This confirms that thermoplastics sustain less inside fiber damage than thermosets with the same amount of paint. Of all 52 panels, the only three test points to result in holes all the way through the panel were thin panels in this paint class with the lightest weight of ECF.

In order to determine the type of relationship between paint thickness and the magnitude of damage, the average damage score for each paint class was plotted against the average measured paint thickness. Seen in Figure 6-96 below, there is a linear relationship between paint thickness and damage score.

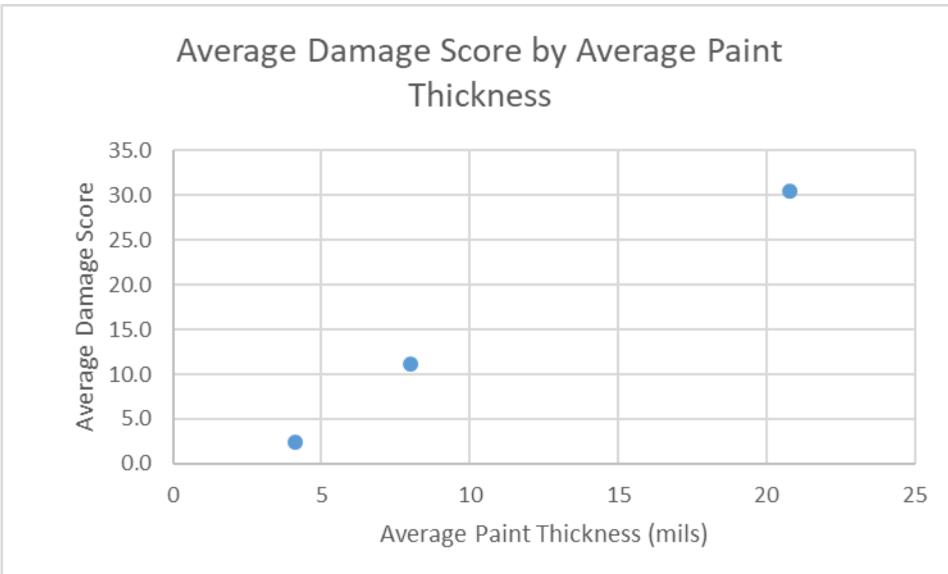


Figure 6-96: Average Damage Score vs. Average Paint Thickness

6.8.7 Conclusions

- IR imaging showed that in the hottest frame of the recordings, the PDZ area is inversely proportional to the maximum temperature, and the rest of the panel (outside of the PDZ) does not experience significant heating during or after a Zone 2A lightning strike.
- Deflection of the panels during strike is most heavily impacted by matrix material. Overall, thermoplastics deflect less than thermosets.
- C-scans confirm that the damage is limited to the area near the strike and does not affect the whole panel.
- Photomicrographs revealed that thinner panels have more delamination through the depth of the panel than thicker panels.
- The 5HS PPS panels resulted in matrix cracking and fiber-matrix debonding whereas the unitape LM PAEK panels did not, it is unclear if this is due to the fiber form or the matrix material.
- The visible melting signature on the inside of some panels does not always coincide with delamination.
- DSC showed that there is no significant change in the crystallinity of the matrix materials at the strike location or near the edges of the panels. This is likely because the lightning

strike event is too quick to allow a change to take place[6.1].

- Thermoplastic panels sustained less damage on the inside of the panels than their thermoset counterparts.
- The heavier weight of expanded copper foil protected the panels better than the lighter weight.
- The thicker panels sustained less damage, and did not heat up as much as the thinner panels on the inside.
- The impact of increasing paint thickness on resulting panel damage tends to be more significant for thermoset panels than it does compared to thermoplastic panels.

6.9 Aged Thermoplastic Composite Lightning Strike Evaluation

6.9.1 Background

Lightning strike performance of thermoplastic composites (TPC) has been evaluated in earlier sections of this document (sections 0 and 6.8). Previous research focused on the behavior of various matrix materials, panel thicknesses, and lightning strike protection schemes. In all cases, the evaluations were performed on newly fabricated panels. Although studies have been conducted on the mechanical durability of composite structures subject to fatigue cycling and other in-service types of material degradation, no known study has been conducted which explores the behavior of environmentally aged TPC aircraft structures when subject to lightning strike. This research intends to provide a data-based analysis to help shed light on a few questions. How does a TPC panel perform when struck by lightning after several years in service? How does the performance of TPC differ from TSC when struck by lightning, both before and after years of environmental degradation?

This study compared equal sets of TPC and TSC panels. Both sets of panels were environmentally aged. A control group, equal in size, of both TPC and TSC panels remained in newly fabricated condition. Environmental aging included five of the major sources of environmental, in-service, degradation of exterior aircraft components. These sources are airborne sand, vibration, hot/cold cycling, humidity, and salt air. The five environmental aging sources were simulated with three environmental aging tests performed consecutively on each panel without variation. The tests were blown sand, salt-fog, and HALT chamber HASS testing (which combines random vibration and hot/cold cycling). The magnitude and duration of environmental aging tests was selected to exceed expected long term commercial aircraft service (cycles). As a result, any damage will surpass what is normally seen during the routine paint service life of a commercial aircraft. Test results represent the “worst case” scenario for environmentally aged panels. The test matrix is provided in Table 6-45.

6.9.2 Materials

Panel configurations included two matrix materials, one panel thickness, two lightning protection schemes, and two paint thicknesses. Each configuration had two aged panels and two additional control panels to be lightning tested.

The two matrix materials evaluated were:

1. TPC 1: Toray TC1225/T700-12K T1E LM PAEK, 145 gsm FAW 34%RC unidirectional prepreg
2. TSC: TC380/T700 12K, 145 gsm FAW, 34%RC unidirectional prepreg tape. This is a new, toughened epoxy resin system.

The unidirectional tape carbon fiber panels with a ply thickness of 0.005”. Layups consisted of 12 plies (0.06”) in a quasi-isotropic, symmetrical/balanced layup schedule for both thermoplastic and thermoset panels.

The two distinct lightning strike protection schemes tested were both copper foil, but the geometry of the grid pattern and method of manufacturing differ. The LSPs were:

1. Expanded Copper Foil - ECF: Dexmet 2CU4-100FA (73.3 gsm)
2. Perforated Copper Foil - PCF: 3M PF060 (60 gsm) was used on the LM PAEK panels
3. Perforated Copper Foil – PCF: 3M AF 536 137 PCF 060 (60 gsm) was used on the epoxy panels. Henkel PL 7000 adhesive film was used to apply this LSP to the panels.

All panels were painted with aircraft industry standard paint over the LSP. The details of the coating were:

1. PPG CA-7501 epoxy primer
2. PPG F565-4010 epoxy intermediate coat
3. PPG CA8000 polyurethane topcoat

The panels were painted as follows:

1. Two panels of each configuration were painted with 5-7 mils of standard coating
2. Two panels of each configuration were painted with 11-13 mils of standard coating

Table 6-45: Test Matrix and Panel ID Numbers

Matrix Material	LSP	Paint Thickness (mils)	Aged	Panel #
LM PAEK	ECF 73 gsm	5-7	✓	1
LM PAEK	ECF 73 gsm	5-7	✓	2
LM PAEK	ECF 73 gsm	5-7		3
LM PAEK	ECF 73 gsm	5-7		4
LM PAEK	ECF 73 gsm	11-13	✓	5
LM PAEK	ECF 73 gsm	11-13	✓	6
LM PAEK	ECF 73 gsm	11-13		7
LM PAEK	ECF 73 gsm	11-13		8
LM PAEK	3M PCF060	5-7	✓	10
LM PAEK	3M PCF060	5-7	✓	11
LM PAEK	3M PCF060	5-7		12
LM PAEK	3M PCF060	5-7		13
LM PAEK	3M PCF060	11-13	✓	14
LM PAEK	3M PCF060	11-13	✓	15
LM PAEK	3M PCF060	11-13		16
LM PAEK	3M PCF060	11-13		17
Epoxy	ECF 73 gsm	5-7	✓	19
Epoxy	ECF 73 gsm	5-7	✓	20
Epoxy	ECF 73 gsm	5-7		21
Epoxy	ECF 73 gsm	5-7		22
Epoxy	ECF 73 gsm	11-13	✓	23
Epoxy	ECF 73 gsm	11-13	✓	24
Epoxy	ECF 73 gsm	11-13		25
Epoxy	ECF 73 gsm	11-13		26
Epoxy	3M AF 536 137 PCF 060	5-7	✓	27
Epoxy	3M AF 536 137 PCF 060	5-7	✓	28
Epoxy	3M AF 536 137 PCF 060	5-7		29
Epoxy	3M AF 536 137 PCF 060	5-7		30

Matrix Material	LSP	Paint Thickness (mils)	Aged	Panel #
Epoxy	3M AF 536 137 PCF 060	11-13	✓	31
Epoxy	3M AF 536 137 PCF 060	11-13	✓	32
Epoxy	3M AF 536 137 PCF 060	11-13		33
Epoxy	3M AF 536 137 PCF 060	11-13		34

6.9.3 Methods/Procedures

It is important to note that DO-160G test specifications are designed to far exceed any in-service environmental condition. Test specifications are intentionally scaled up so that a component that still functions properly after a DO-160G test will survive normal flight conditions. No scaling factor or relative time to service life is offered. In fact, it is explicitly stated that the tests are not designed for this purpose, but rather for design qualification.

Half of the test panels were environmentally aged prior to lightning testing. The test parameters for the environmental aging were selected to simulate the worst-case scenario seen within the scope of one paint lifespan of a commercial aircraft – i.e. 7 years at 3000 hours per year. The first step in the aging process was sand testing per DO-160G section 12 category – S, which was worst-case scenario test. The test was a total of 2 hours in duration with a sand velocity of 18 m/s. The sand test was conducted at 25 °C for one hour and 55 °C for another hour. After sand testing, the panels were subject to salt-fog DO-160G section 14 category T, which was the worst-case test. This test used a 5% salt-water solution, which was atomized and misted over the panels. The panels were cycled through the chamber twice for 48 hours in each cycle with a 24-48 hour drying period in between misting cycles. The panels then went through a highly accelerated stress screening (HASS) test in a highly accelerated life test (HALT) chamber. As testing parameters are not specified for this in DO-160G, a literature review was done to determine a reasonable worst-case scenario vibration rate and temperature cycling[6.2, 6.3, 6.4]. Based on this review, it was decided that the vibration would be 50 GRMS and the temperature was cycled through -55 °C to 70 °C at a rate of 30 °C/min and dwelled at each end of the extremes for approximately 1.5 minutes, thus each cycle was about 11.5 minutes long with the profile running for 36 hours total.

After completing the aging processes, as shown in Figure 6-97 below, all panels were struck twice at the high current Zone 2A test level; no Zone 1A strikes were conducted in this round of testing. The deflection of the panel and thermal signature were recorded for each test point via laser tracking and IR imaging respectively. After the direct effects of lightning (DEL) testing, the damage to the panels was measured according to the directions laid out in section 6.4.1. Pulse-echo ultrasonic inspection of the panels was then carried out to determine the effect of the lightning strike through the depth of the panel. When this was completed, photomicrographs and dynamic mechanical analysis (DMA) of select panels were conducted to evaluate the changes in the stiffness of the damaged panels by comparing the results of the aged panels back to the control panels.

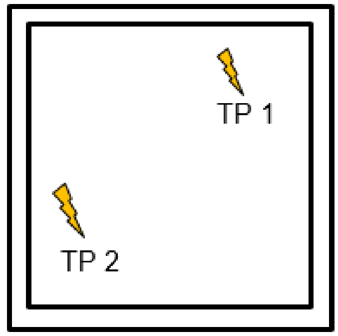


Figure 6-97: Schematic of Test Point Locations

6.9.3 Test Data

Table 6-46 below contains the damage measurement data from lightning testing. Panels 9 and 18 were extra panels that were never manufactured.

Table 6-46: Damage Measurements

ID #	Test Point	Outside Delamination		Outside Hole		Inside Delamination		Inside Hole (in)	Damage Score
		x (in)	y (in)	x (in)	y (in)	x (in)	y (in)		
1	1	4.25	3.5	4	2.75	0	0	0	8
1	2	3.25	3	3	2.5	0	0	0	7
2	1	2.5	2	1.75	1.25	0	0	0	4
2	2	2.5	1.5	1.25	1	0	0	0	4
3	1	2.5	2.5	1.5	0.25	0	0	0	4
3	2	2.5	1.25	2	0.75	0	0	0	4
4	1	2	3.5	1.25	0.5	0	0	0	4
4	2	2	1.5	2	0.5	0	0	0	4
5	1	2.75	3	1.75	2	0	0	0	4
5	2	3.25	2.75	2	1.75	3.5	1.25	0	4
6	1	4	3.75	3	2.5	0	0	0	7
6	2	3.25	4	2.25	2.75	3	1.25	0	7
7	1	2.5	2	3	1.25	0	0	0	7
7	2	3	1.75	2.75	1	0	0	0	7
8	1	2.5	2	2.5	2	0	0	0	7
8	2	2.5	1.75	2.5	1.25	0	0	0	7
10	1	4	3.75	2.25	1.75	0	0	0	7
10	2	4.25	4.5	2	1.75	0	0	0	5
11	1	4.25	5	3.25	2.25	0	0	0	8
11	2	4.25	5.75	2.5	2	0	0	0	8
12	1	2.5	1.75	0.75	0.75	0	0	0	1
12	2	2.5	2.75	0.75	0.5	0	0	0	1
13	1	3.25	3	2.5	1.25	0	0	0	7
13	2	4.25	3	3.5	1.25	0	0	0	8
14	1	3.75	4.25	3	2	0	0	0	8
14	2	3.75	4.25	3	3.25	0	0	0	8
15	1	4.5	4	1.75	1.25	0	0	0	5
15	2	3.75	4.5	1.75	1.75	0	0	0	5
16	1	4	4	3	1	0	0	0	7
16	2	3.75	3.25	2.5	1.25	0	0	0	7
17	1	2.25	2.5	2	1.5	0	0	0	4
17	2	3	4	2.5	1.75	0	0	0	7

ID #	Test Point	Outside Delamination		Outside Hole		Inside Delamination		Inside Hole (in)	Damage Score
		x (in)	y (in)	x (in)	y (in)	x (in)	y (in)		
19	1	3.5	1.75	1	0.5	0	0	0	1
19	2	2.5	2.75	0	0	0	0	0	1
20	1	2.75	3	0	0	0	0	0	1
20	2	2.25	2.25	0	0	0	0	0	1
21	1	1.25	1.75	1.25	1	0	0	0	4
21	2	2.75	0.5	1.25	0.5	0	0	0	4
22	1	0	0	0	0	0	0	0	1
22	2	0.75	0.75	0	0	0	0	0	1
23	1	3.75	3.75	0	0	0	0	0	1
23	2	2.75	3.5	0	0	0	0	0	1
24	1	3.75	3.75	0	0	0	0	0	1
24	2	3.75	3.75	0	0	0	0	0	1
25	1	2.5	2.75	0	0	0	0	0	1
25	2	1.25	2.75	1	0.75	0	0	0	1
26	1	5.25	3.75	1	0.75	0	0	0	2
26	2	4.25	5	2.25	2	0	0	0	8
27	1	3.25	2.75	2	1.25	0	0	0	4
27	2	3.25	4	2.25	0.75	0	0	0	7
28	1	3.5	2.5	2	1.5	0	0	0	4
28	2	4.5	3.25	1.25	0.25	0	0	0	5
29	1	2.75	2	2.75	1	0	0	0	7
29	2	3.75	3.25	2	1	0	0	0	4
30	1	4	2.5	2.5	1	0	0	0	7
30	2	1.5	1	1.5	0.75	0	0	0	4
31	1	4.75	3.75	1.75	0.75	0	0	0	5
31	2	5	4.75	2	0.5	0	0	0	5
32	1	3.5	4.75	3	1.25	0	0	0	8
32	2	4	5.5	2.5	1.25	0	0	0	8
33	1	3.5	1.75	2	1	0	0	0	4
33	2	3.75	2.25	2.5	1.25	0	0	0	7
34	1	4.25	3	3	1.5	0	0	0	8
34	2	2.75	3	2.5	1.75	0	0	0	7

6.9.4 Discussion

Aging

This first step in the aging process was sand testing. As called out in DO-160G section 12 category – S, the panels were bombarded at a 90° angle by sand moving at a velocity of 18 m/s at 25 °C for one hour and then again at 55 °C for another hour. As traditional aircraft paint does not adhere well to thermoplastic panels, there was concern that if a small hole was made in the paint due to the velocity of the sand, then larger sections of paint might peel off the panel. This type of paint loss would warrant repainting the panel before lightning strike, which would cancel out any effects of the aging process on the painted panel. To avoid excessive paint loss, the edges of the panels were first taped off with a layer of packing tape and then a layer of duct tape to protect the exposed painted edge of the panels at the unpainted panel border, as seen in Figure 6-98: Taped panel ready for sand testing. After sand testing, this tape was removed and the panels were inspected for signs of degradation. Aside from a residual layer of sand that came off easily and minor nicks in the paint surface only noticeable through touch, there were no signs of damage or degradation. However, there was a small amount of adhesive residue left behind on the edges of the panel from the tape because of the high temperature cycle. This residue was outside of lightning strike locations and was not expected to have any effect on further testing of the panels.

Figure 6-98: Taped panel ready for sand testing

The panels were then subject to the salt-fog stage of the aging process. As seen in Figure 6-99, the panels were placed on racks in a chamber containing a 5% salt-water solution at 35 °C. The solution was then atomized and misted on the panels for 48 hours before being taken out to dry for at least 24 hours. This procedure was repeated one more time before the panels were inspected. After the panels dried for the second time, the residual layer of salt was wiped off and no noticeable damage or degradation to the paint, LSP, or the panel was observed.

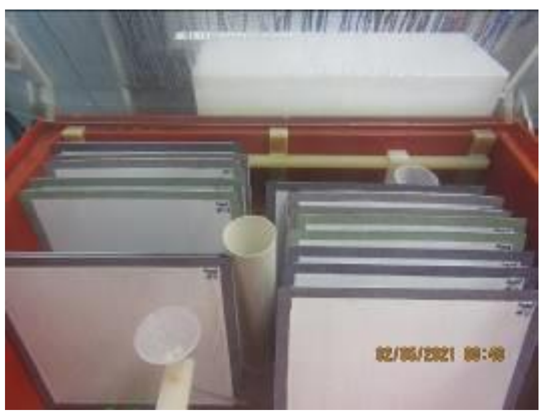


Figure 6-99: Aged panels after the first cycle in the salt-fog chamber

The final step in the aging process was the HALT chamber HASS testing. The panels were placed inside the fixture seen in Figure 6-100 that can hold four panels at a time. The panels were simultaneously subjected to random vibration at 50 GRMS and thermal cycling from -55 to 70 °C for a total of 36 hours. A thermocouple monitored the ambient temperature between the panels. Thermoplastics are excellent thermal insulators and preliminary testing revealed that not all the panels receive the same thermal conditioning at each position in the test fixture, as each layer in the test fixture is subsequently more insulated than the one above it. To counter this, every 8 hours the test was paused and the panels rotated cyclically through each position in the fixture so that by the end of the 36 total hours, each panel had seen the same thermal condition. Each set of four panels went through one 36-hour HALT. Upon subsequent inspection, no significant visible damage or degradation was seen at the end of this step in the aging process.

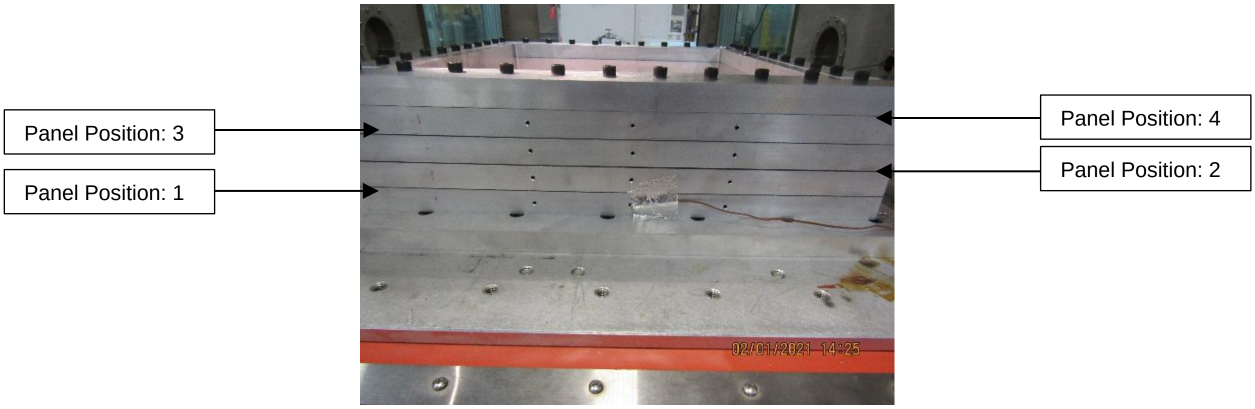


Figure 6-100: HALT fixture assembly

IR Imaging

An infrared camera was mounted below the panels to monitor the temperature of the panel during the lightning strike event (for more details, refer back to section 6.8.5. Several data points found in Table 6-47 below were analyzed separately from the rest of the data, as Component C* did not fire appropriately. Component C* is the waveform that generates most of the heat of the lightning event. In the cases that C* extinguished early, the temperatures stayed relatively low and would skew the rest of the data for panels that received the correct C* waveform requirement. Looking at the remaining data, there was no consistent and distinct heat dispersal between the aged and control panels. The matrix material and lightning strike protection scheme had a bigger impact on the temperatures obtained by the panel in the location of the lightning strike attachment. The LM PAEK panels reached an average of 218.8 ± 32.1 °C while the epoxy panels reached 183.1 ± 30.3 °C. On average, the LM PAEK panels exceeded their glass transition temperature (T_g, see section 6.8.1 for more details) of 147 °C, but the epoxy panels stayed below their T_g of 201 °C. The 70-gsm ECF panels heated to higher temperatures than the 60 gsm PCF protected panels for 75% of cases. As the LM-PAEK panels reached higher peak temperatures than the epoxy panels while maintaining the same size PDZ, this implies that for equal peak temperatures, the LM PAEK panels will contain the PDZ to a smaller relative area than the epoxy panels will. There is no correlation between amount of paint, aging, or LSP with the peak temperature or PDZ diameter.

Table 6-47: List of Thermal Data Excluded From Analysis and Report

Excluded Test Points	Reason For Exclusion From Analysis	Temp. °C
Panel 1 – TP 2	No IR data, camera did not trigger	-
Panel 5 – TP 2	No IR data, camera did not trigger	-
Panel 19 – TP 2	No C bank, temperature data is anomalous. No deflection data	41.8
Panel 20 – TP 1	No C bank, temperature data is anomalous	42.1
Panel 20 – TP 2	No C bank, temperature data is anomalous	42.7
Panel 22 – TP 1	No C bank, temperature data is anomalous	58.9
Panel 22 – TP 2	No C bank, temperature data is anomalous	42.6

Excluded Test Points	Reason For Exclusion From Analysis	Temp. °C
Panel 23 – TP 1	No C bank, temperature data is anomalous	41.3
Panel 23 – TP 2	No C bank, temperature data is anomalous	43.1
Panel 24 – TP 1	No C bank, temperature data is anomalous	46.1
Panel 24 – TP 2	No C bank, temperature data is anomalous	43.2
Panel 25 – TP 1	No C bank, temperature data is anomalous	47.6
Panel 28 – TP 1	No IR, camera froze	-
Panel 28 – TP 2	No C bank, temperature data is anomalous	60.5

For most of the panels in Table 6-47, the Component C* waveforms did not meet the requirements, likely due to the non-woven polyester scrim in the adhesive film used to consolidate the ECF to the epoxy panels. Of all the panels in Table 6-47, where the Component C* waveforms did not meet the requirements, only one of them was a PCF protected panel (28). While no thermal data was collected for the first test point on panel 28, the Component C* waveform was typical for TP 1 and for both test points on the duplicate panel (27) of that particular configuration (epoxy, aged, 60 gsm PCF, 5-7 mils of paint). Therefore, it is likely that the Component C* waveform of panel 28-TP 2 was truly anomalous, while the Component C* waveforms of the other panels were characteristic to those panel configurations. Of the anomalous epoxy test points, 70% were aged panels while the other 30% were from the control group.

Displacement

Displacement measurements were taken during lightning strike testing via laser displacement sensors. Two lasers tracked the motion of the center of the back of the panel to determine how much the panel deflected from lightning strike. As seen in Figure 6-101 below, the aged panels did not deflect more or less than their control group counterparts by a significant amount. The paint thickness did make an impact on deflection. In all but one configuration, (specifically the aged, 60 gsm PCF, LM PAEK), the panels with 5-7 mils of paint deflected less than the panels with 11-13 mils of paint. This is consistent with the findings in section 6.8.5. There were not consistent behavioral differences between the PCF protected panels and their traditional ECF protected counterparts. The study conducted in section 6.8 found that there was a linear relationship between the maximum displacement amplitude and the peak temperature of the panel. This trend could not be confirmed by the findings of this study where, as shown in Figure 6-101 and Figure 6-102, no conclusive trend was seen.

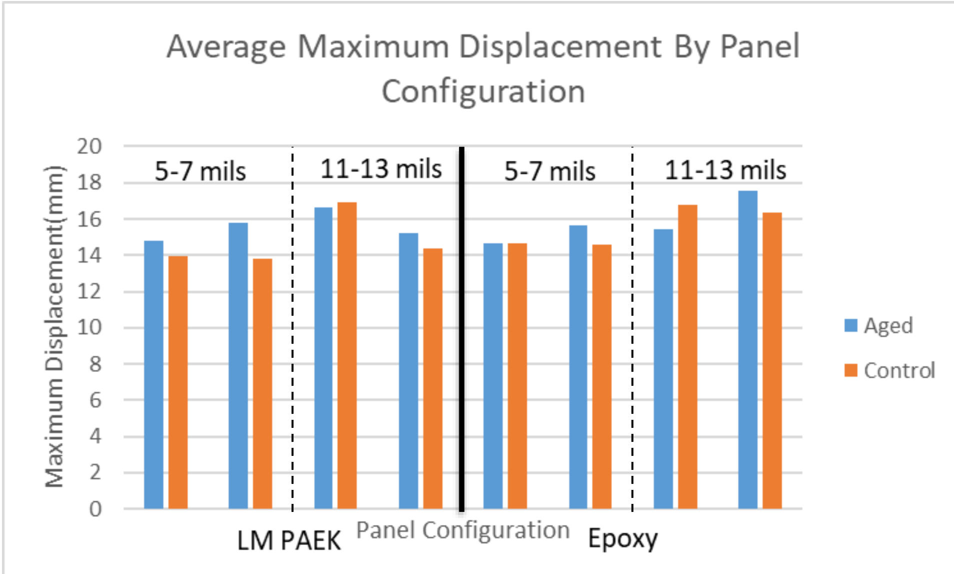


Figure 6-101: Average Maximum Displacement by Panel Configuration

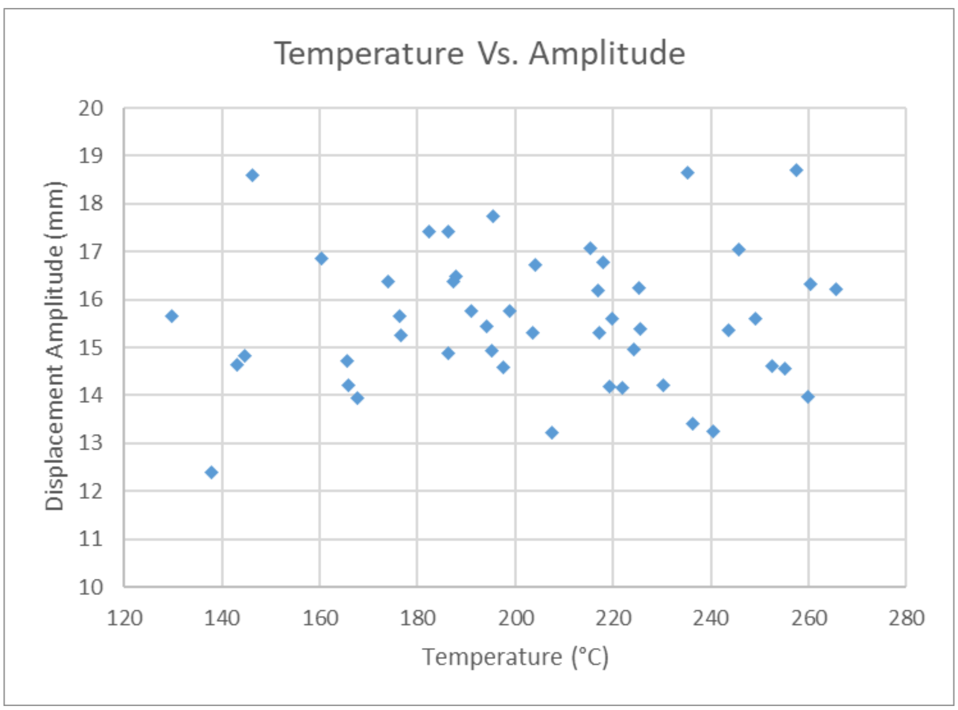


Figure 6-102: Peak Temperature vs. Max Displacement Amplitude

Damage Measurements

As seen in Figure 6-103 and Figure 6-104 below, no panel exceeded the damage score-based failure threshold of 64 points. The damage code system in section 6.4 was designed to give more information about failures than passes, so there is little variation in the damage scores of these panels. Conclusions from the scores alone show that aging made no difference, epoxy panels may have sustained slightly less damage than the LM PAEK, the ECF protected the panels better than the PCF, and panels with 5-7 mils of paint sustained less damage than panels with 11-13 mils. As discussed further in this report, when looking at other metrics, a more nuanced picture emerges. This is not surprising as the range in damage scores is too small relative to the full extent of the damage scores.

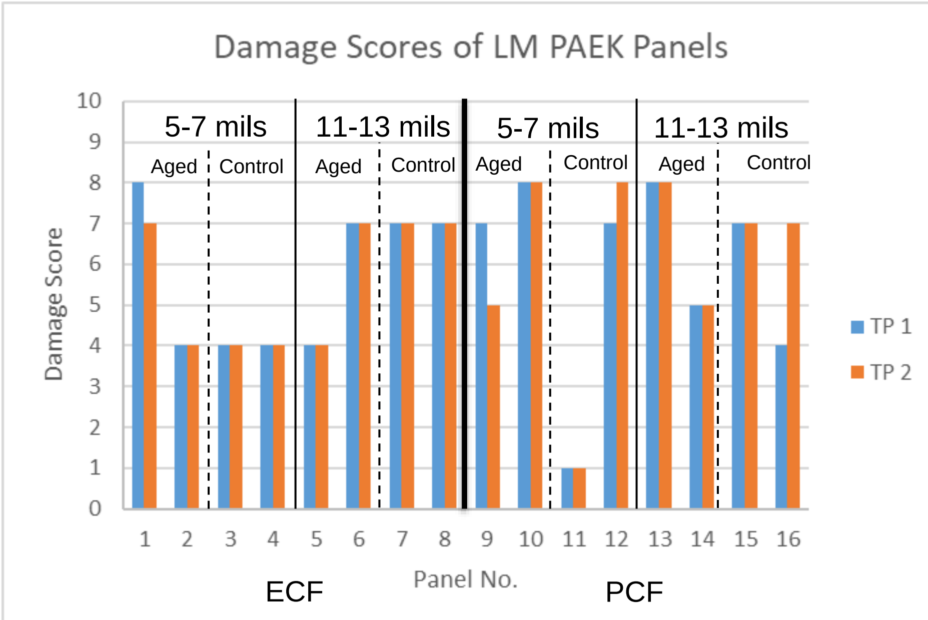


Figure 6-103: Damage Scores of LM PAEK Panels

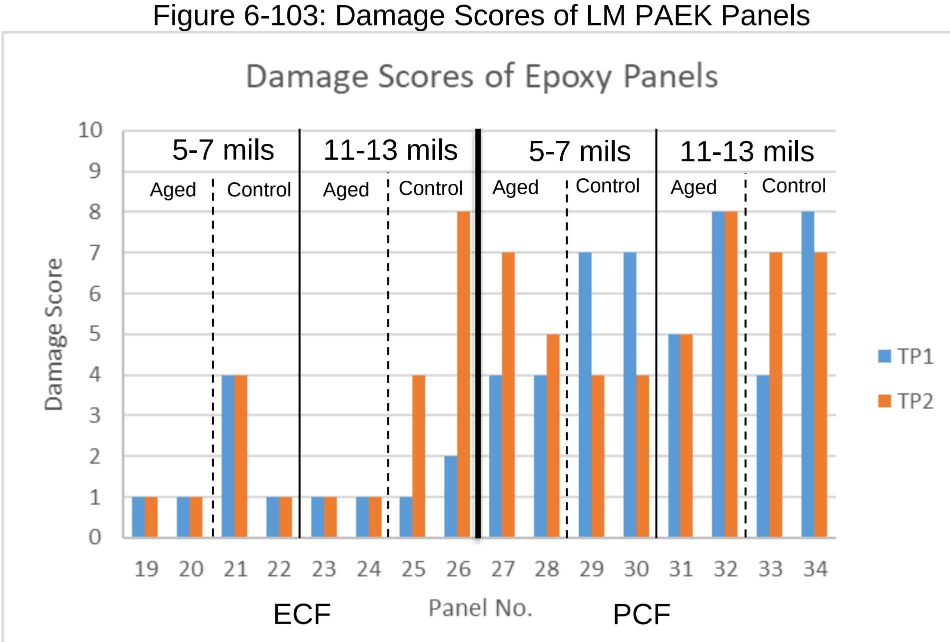


Figure 6-104: Damage Scores of Epoxy Panels

Test Variables

The impacts of each of the following factors on the results of the lightning strike are discussed below in detail:

1. Matrix Material
2. LSP
3. Paint Thickness
4. Aging

Matrix Material

The LM PAEK panels had an average outside delamination of 3.5 inches, outside hole of 2.3 inches, and an inside delamination of 0.2 inches. On average, the epoxy panels had an outside delamination measurement of 3.4 inches, outside hole measurement of 1.4 inches and no inside delamination. Given that measurements are only accurate to 0.25 inches, and looking at the average area for each damage criterion for LM PAEK compared to epoxy, the two matrix materials performed comparably in all but the outside hole criterion. The LM PAEK average outside hole was 2.3 inches while for epoxy it was 1.4 inches. Further investigation shows that the LM PAEK and epoxy panels with 60 gsm PCF had similar outside hole measurements. The epoxy panels with 73 gsm ECF had significantly smaller outside hole measurements than their PAEK counterparts, on average. This may be due to the non-wove polyester scrim in the film adhesive layer which was used to adhere the LSP to the epoxy panels. During lightning testing, the Component C*, which is where most of the heat comes from, did not fire correctly on multiple instances and was frequently extinguished before any significant heat could be transferred to the panel. This is likely due to the added adhesive dielectric layer making it harder for the C* component to remain attached for the required duration. This could account for the smaller outside hole on these panels, thus it is likely that the matrix material itself did not really make much of a difference in behavior noted through the damage measurements. The average repair areas of the LM PAEK and epoxy panels protected by the PCF can be seen in Table 6-48 below. From this table it is clear that the epoxy panels had a much larger average repair area than the LM PAEK panels did. This implies that there was more LSP and cosmetic damage to the epoxy panels than the LM PAEK panels. The effect of matrix material on the overall damage score for each panel is plotted in Figure 6-105.

Table 6-48: Average Repair Areas of PCF Protected Panels

Matrix Material	Average (in^2)	Standard Deviation (in^2)
LM PAEK	21.6	2.1
Epoxy	34.1	7.0

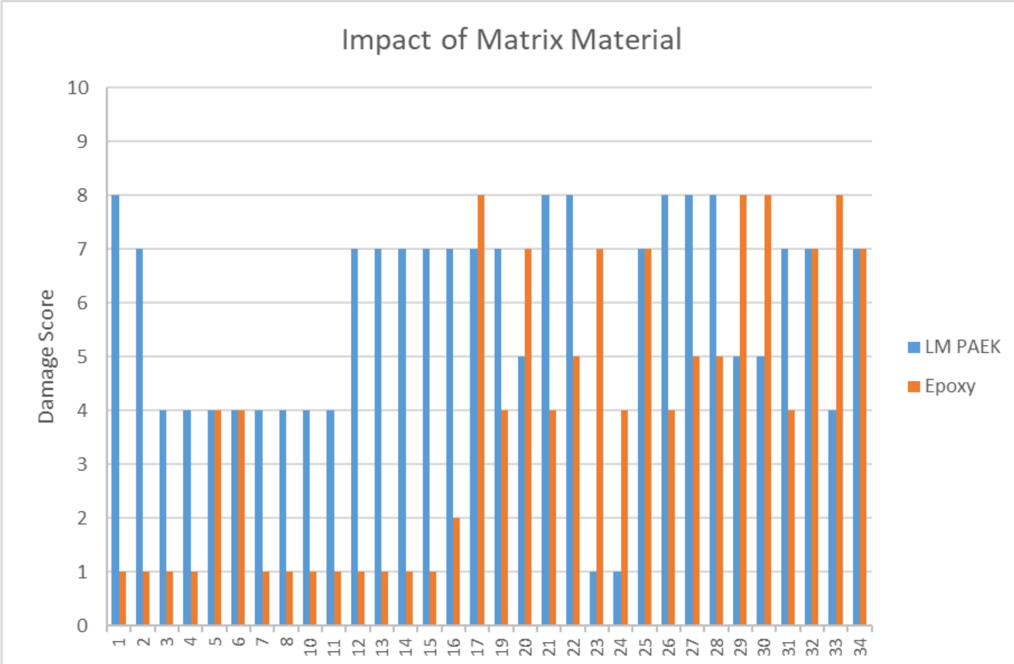


Figure 6-105: Impact of Matrix Material

<u>LSP</u>

The panels protected by 73 gsm ECF on average sustained 3.0 inches of outside delamination, 1.4 inch hole, and 0.2 inches of inside delamination. By contrast, the panels protected by 60 gsm PCF on average sustained 3.9 inches of outside delamination, 2.3 inch hole, and no inside delamination. As expected, the panels with more copper mass per unit area had smaller outside delamination and outside hole measurements as it carried the current away more efficiently. Repair area is the metric most tied to LSP damage so the average repair area for each LSP was plotted in Figure 6-106 to determine if any other trends were present. As the epoxy panels protected by the ECF had an extra dielectric layer that skewed the data, this graph only contains data from the LM PAEK panels. On average, the PCF provided the same or slightly better protection of the composite panel (as demonstrated by the damage scores in Figure 6-107) than the ECF per unit weight of LSP material. This may indicate potential weight savings when PCF type LSP is used. The repair area of the PCF on average was proportionally larger than the ECF, as would be expected for the lighter (60 gsm) areal weight.

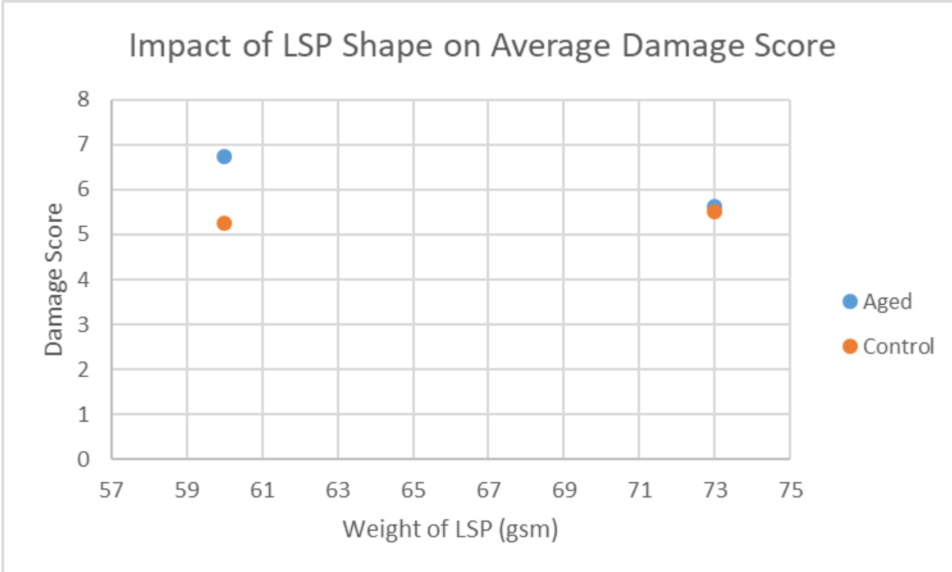


Figure 6-106: Impact of LSP Shape on Average Damage Score

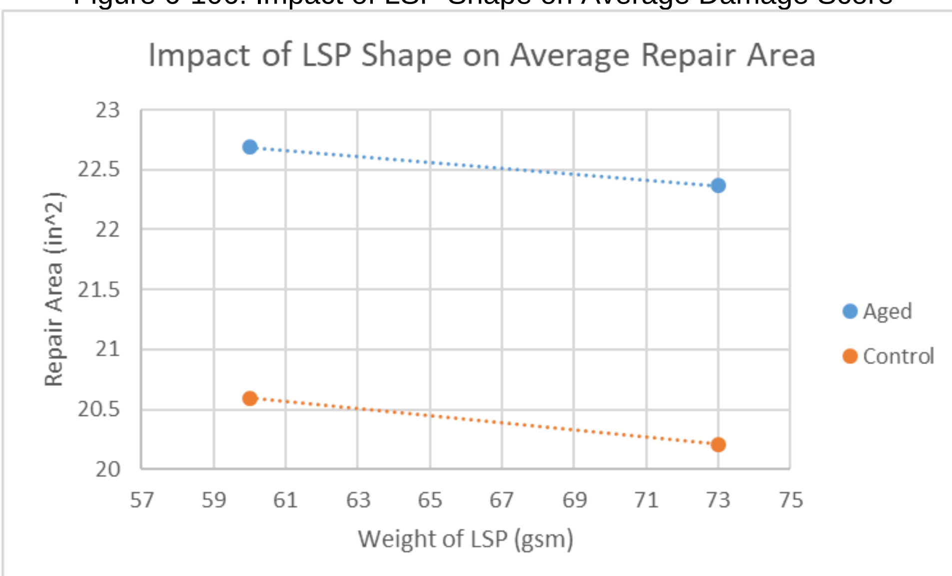


Figure 6-107: Impact of LSP Shape on Average Repair Area

<u>Paint Thickness</u>

On average, panels with 5-7 mils of paint had 3.1 inches of outside delamination, 1.7 inch outside hole, and no inside delamination or hole. Panels with 11-13 mils of paint had 3.8 inches of outside delamination, 2.0 inch outside hole, and 0.2 inches of inside delamination. Measurements are only accurate to 0.25 inches, so the only significant difference in damage between the 5-7 mils and the 11-13 mils panels was the size of the outside delamination. As shown in Figure 6-108 below, the panels with more paint had nearly an inch more outside delamination than the panels with less paint. This implies that the panels with less paint did a better job at containing the damage on the top of portion of the panel, which is consistent with the findings in section 6.8.6.

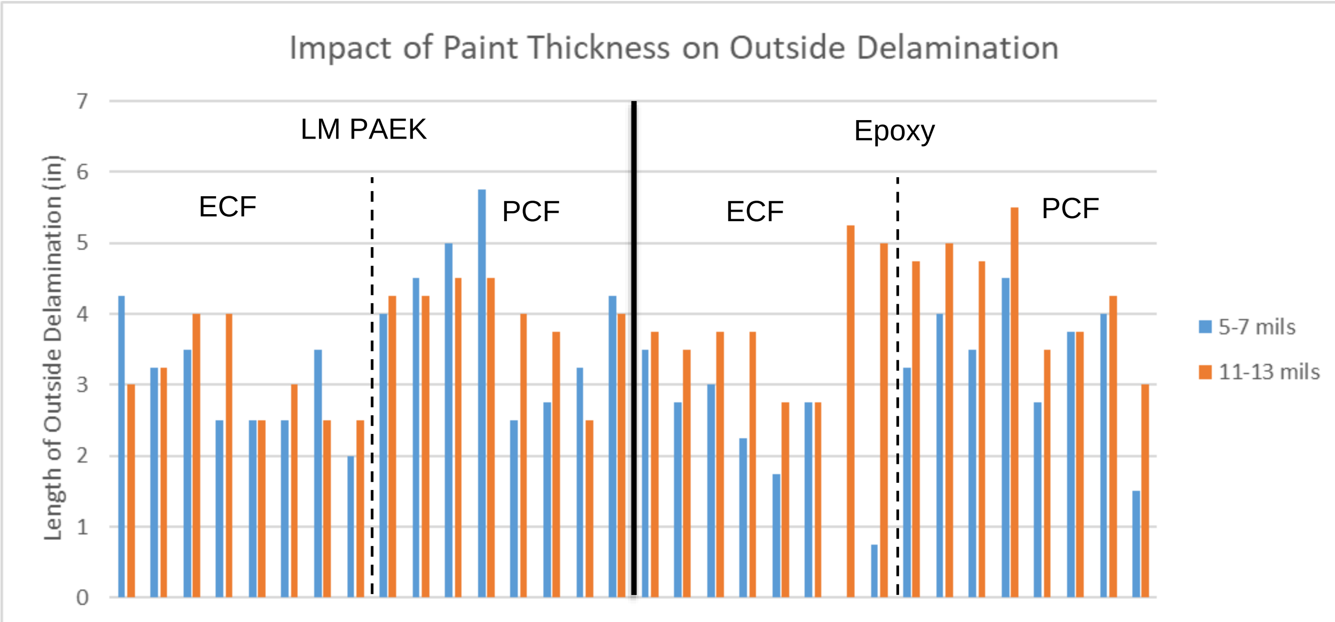


Figure 6-108: Impact of Paint Thickness on Outside Delamination

<u>Aging</u>

The environmentally aged panels had an average outside delamination of 3.9 inches, outside hole of 1.8 inches, and an inside delamination of 0.2 inches. The control panels on average had an outside delamination measurement of 3.0 inches, outside hole measurement of 1.9 inches and no inside delamination. Measurements are only accurate to 0.25 inches. The only significant difference in damage between the aged and control group panels was in the outside delamination, which implies that the aged panels sustained more damage than the control group, though not significantly. The graph of the average repair areas, can be found in Figure 6-109. The epoxy 73 gsm ECF is not included in the graph due to the adhesive dielectric layer leading to the component C* waveform anomalies. In 19 of the 24 comparable cases, the aged panels had larger repair areas than their control group counterpart panels. The repair area metric mostly reflects the state of the LSP, so aging had an impact on the LSP material.

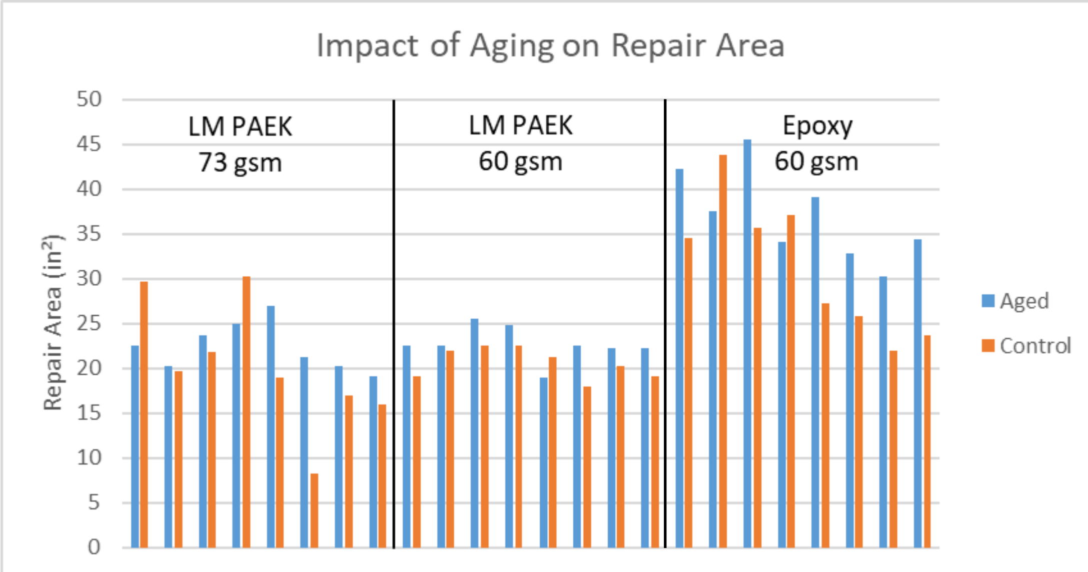


Figure 6-109: Impact of Aging on Repair Area

Post-Test Damage Evaluation Methods

<u>C-Scans</u>

Pulse echo ultrasonic inspection showed that damage is limited to the few inches surrounding the strike location. The damage area was determined by noting where the color of the panel changes to match the areas far away from the strike zone. More specifically, the average damage area of the LM PAEK panels was 4.2 square inches and the average damage area of the epoxy panels was 2.0 square inches. While both matrix materials contained the damage, the epoxy panels had consistently smaller damage areas on the scans. Based on depth measurements from the pulse echo scans, not only did the epoxy panels have smaller damage areas, but the damage also seemed to penetrate through fewer plies than on the LM PEAK panels. Photomicrographs were taken to further evaluate this finding, detailed in the photomicrograph section below. LSP did not affect the damage area significantly, which was expected, as the two LSPs were close in weight. The aged panels did sustain slightly more damage than the control group panels, though not by a significant amount, implying that the paint protected the LSP and composite materials from aging. It is important to note that the damaged paint near the panel damage areas was removed before the scans were taken, and thus, this modification appears on the scans.

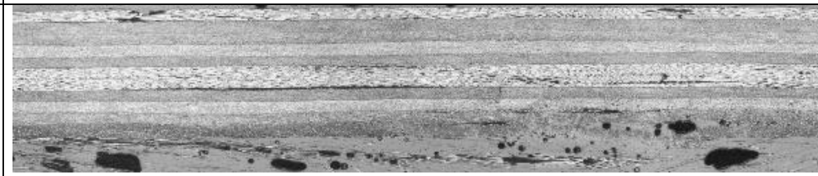
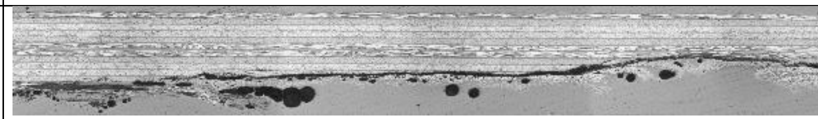
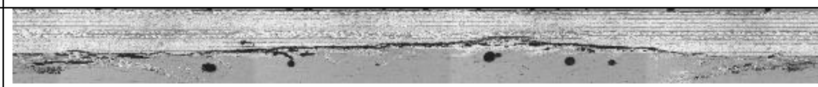
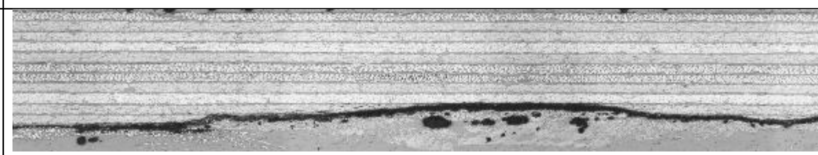
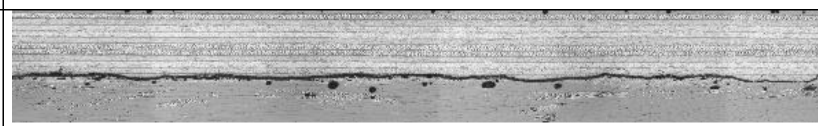
<u>Photomicrographs</u>

Photomicrographs (PMs) were taken as cross sections of the strike location for eight configurations (one from each type of configuration with 5-7 mils of paint) to determine the effects of aging and lightning strike protection. A summary of the PM coupons from panels 2, 4, 11, 13, 19, 20, 27, and 29 can be found in Table 6-49 below. As it was not possible to take PMs of these coupons before lightning testing, the void content analysis could not differentiate small delamination areas from areas of trapped air that resulted from the manufacturing process with certainty. The results of the PMs showed that the lighter weight of LSP (60 gsm PCF) sustained more damage both in terms of cross-sectional diameter and depth, but had smaller void content than the 73 gsm ECF counterparts. This implies that the separation between each pair of delaminated plies is less. Comparing the PMs from the aged versus control panels showed that, on average, the control panels sustained very similar depth and diameter of damage, as well as void contents to the samples from the aged panels. This is only the case if the PM from panel 13, discussed below, is disregarded.

Comparing the two matrix materials to each other, the diameter of damage was comparable between the LM PAEK and epoxy panels, but the void content was higher in the LM PAEK panels, indicating the delamination in these panels was greater. As seen in Table 6-49 below, the LM PAEK panels generally sustained less damage through the depth of the panel than their epoxy counterparts in all but one configuration did. As discussed above, the C-scans show that, on average, the epoxy panels sustained less damage through the depth than LM PAEK panels. The PM finding contradicts what the pulse echo C-scans showed. Given that the C-scans look at the whole panel, while the PMs look at only a local cross section, a more complete analysis would take more PM samples from similar panels to determine whether there is a trend.

The extent of damage in panel 13 is greater than expected, with the presence of defects further through the panel than the center ply and fiber breakage on the back of the panel that was not initially noted upon visual/damage inspection or through the C-scans of the panel after lightning strike. The fiber breakage could not be seen by the naked eye when visually inspecting the sample after looking at the PM. Further PMs of panel 13 and similar panels would be needed to determine whether this damage is anomalous. The sample from panel 13 sustained the most damage through the depth of the panel, though the damage is not continuous. The top seven plies show more consistent damage, but plies eight through 11 are all intact with no delamination or fiber breakage. Near the center of the damage on the bottom of ply 12 there is some delamination and fiber breakage. Since all other LM PAEK samples sustained less damage, the damage to panel 13 may be anomalous, but there is insufficient data to determine this conclusively.

Table 6-49: Summary of Photomicrograph Analysis

Sample	Void Content (%)	Depth of Damage (ply)	Diameter of Damage	Type of Damage	Photomicrograph
Panel 2 (LM PAEK, ECF, Aged)	4.512	3	1.45	Delamination	
Panel 4 (LM PAEK, ECF, Control)	4.988	3	1.65	Delamination	
Panel 11 (LM PAEK, PCF, Aged)	1.251	2	1.76	Delamination	
Panel 13 (LM PAEK, PCF, Control)	3.623	12	3.21	Delamination , Fiber Breakage	
Panel 19 (Epoxy, ECF, Aged)	1.846	5	1.15	Delamination	
Panel 21 (Epoxy, ECF, Control)	1.477	6	1.37	Delamination	
Panel 27 (Epoxy, PCF, Aged)	2.306	4	2.58	Delamination	
Panel 29 (Epoxy, PCF, Aged)	1.875	2	3	Delamination	

Another phenomenon observed through the PMs that must be discussed is the state of the epoxy matrix. The epoxy panels in this study were made with a new epoxy resin system (TC380) that was designed to increase the toughness of the interply region. This modification caused the appearance of irregularities appearing as “ply separation” and “fiber damage” like phenomena seen in the PMs, when in reality the composite has not sustained any such damage and rather this phenomena is characteristic of the TC380 epoxy system.

DMA

Dynamic mechanical analysis is an analytical method used to obtain various material properties of polymers and other viscoelastic materials. A cyclic stress and temperature load is applied to the sample material and the material response to these loads is measured. This allows the glass transition temperature as well as the storage and loss modulus of the sample to be determined. The storage modulus relates to the spring-like behavior of viscoelastic materials and is an indicator of mechanical strength, or the ability of the material to store energy. The loss modulus is a measure of how well the sample material dissipates energy, typically in the form of heat. The tangent delta function is a measure of the material dampening. It is a ratio of the loss modulus to storage modulus.

Five panels in particular (1, 3, 10, 12, and 32) were selected prior to the aging process to be part of further material testing (DMA) after the direct attachment test. A sample was taken before and after aging, and before and after lightning strike to understand how these composites change as a result of aging and lightning strike. A sample was cut from the corner of two control panels (3 and 12) and from three aged panels (1, 10, and 32) before lightning testing. After DEL testing was completed, another sample was taken from within the PDZ of each of these panels and a few additional panels (specifically 24, 26, and 34). The results of the DMA are in Table 6-50 below. As expected, the LM PAEK panels are stronger than the epoxy panels for all samples by 28% on average. Though the data points are few, it appears that the aging process and the lightning strike both affected the material strength. In terms of aging, the aged panels had a lower storage modulus than their control group counterparts for the six comparable configurations, indicating that aged panels were weaker than the corresponding control panels. In terms of the effects of lightning strike, three out of four instances of the samples from the PDZ had a higher storage modulus than the corresponding sample from the corner of the same panel. This implies that in those cases, the composite became stronger in the PDZ. It is important to note that these three instances were all from the LM PAEK panels and this might be a result of the matrix material being plasticized through the heat cycling experienced through the lightning strike event, which can increase the toughness[6.5]. There was only one thermoset data point, so no conclusions can be drawn about the behavior of the epoxy panels. Comparing the aged samples to their control counterparts, the control panels had a higher storage modulus four out of six times. This implies that the aging process weakened the composite by an average of 12%. This is consistent with the results of the PMs and pulse echo scans.

Table 6-50: Summary of DMA Results

Location	Panel ID	Configuration				T_g (°C)	Storage Modulus (Mpa)	Loss Modulus (Mpa)	Peak tan(δ)
Within PDZ	1	LM PAEK	73 gsm ECF	5-7 mils	Aged	141.60	60000	960	0.02
	3	LM PAEK	73 gsm ECF	5-7 mils	Control	140.85	58000	835	0.01
	10	LM PAEK	3M ABS_36	5-7 mils	Aged	145.76	58000	1508	0.03
	12	LM PAEK	3M ABS_36	5-7 mils	Control	141.51	62000	856	0.01
	24	Epoxy	73 gsm ECF	11-13 mils	Aged	190.17	41000	8610	0.21
	26	Epoxy	73 gsm ECF	11-13 mils	Control	191.79	50000	10500	0.21
	32	Epoxy	3M ABS_36	11-13 mils	Aged	190.79	37000	7770	0.21
	34	Epoxy	3M ABS_36	11-13 mils	Control	193.91	42000	9660	0.23
Corner	1	LM PAEK	73 gsm ECF	5-7 mils	Aged	140.15	45000	698	0.02
	3	LM PAEK	73 gsm ECF	5-7 mils	Control	141.38	52000	718	0.01
	10	LM PAEK	3M ABS_36	5-7 mils	Aged	140.86	59000	915	0.02
	12	LM PAEK	3M ABS_36	5-7 mils	Control	141.12	48000	744	0.02
	32	Epoxy	3M ABS_36	11-13 mils	Aged	190.01	40000	7600	0.19

6.9.5 Conclusions

- The aged TPC materials took on slightly more damage from lightning strike than their control group counterparts. TPC's had 33% larger outside delamination, as well as an average inside delamination of 0.4 inches while the control panels had no inside delamination.
- The aged epoxy panels, on average, had larger areas of outside delamination than the control group (3.8 inches and 3.0 inches respectively), but smaller outside hole size (1.1 inches and 1.6 inches respectively).
- Thermally, the LM PAEK contained the heat from lightning strike to a smaller relative area than the epoxy panels when the same peak temperature was recorded.
- With respect to displacement, the paint thickness was the only variable that influenced the results. Panels with more paint had larger displacements.
- DMA showed that the LM PAEK is still stronger than the epoxy after lightning strike. DMA also showed that the aging process did lessen the stiffness both the LM PAEK and the epoxy panels.

- The photomicrographs indicated the LM PAEK panels sustained less damage through the depth of the panels than the toughened epoxy panels, but the LM PAEK panels had higher void content.
- The physical damage measurements, on the toughened TSC panels, on average, were smaller than their TPC counterparts were.
- Panels protected by the 73 gsm ECF had outside hole and delamination measurements that were, on average, one inch smaller than the outside hole and delamination measurements on the panels protected by the 60 gsm PCF. By repair area, the PCF performed better per unit weight of copper. By damage scores, the PCF performed as well as the heavier weight of ECF.
- Panels with thinner paint coatings (5-7 mils) sustained 0.7 inches less outside delamination than the panels with the thicker paint (11-13 mils).
- Environmentally aged panels had on average 0.9 inches larger outside delamination than the control group panels, but none failed the damage threshold.

6.10 Spliced Lightning Strike Protection on Thermoplastic Composites

6.10.1 Background

Previous research on spliced LSP discussed in section 6.6 focused on the effects of spliced lightning strike protection on thermoset panels. This section delves deeper into the behavior of spliced LSP on thermoplastic panels by aiming to answer the following questions:

- How does the LSP splice configuration affect the damage sustained?
- How do various splice configurations affect current and temperature flow through the panel?
- Does the underlying matrix material significantly affect the damage sustained?

To answer these questions, the resistivity of the panel surface, thermal signature, current distribution, and physical and paint damage were studied in response to Zone 2A direct attachment tests carried out on flat panels described in Table 6-51 per SAE ARP 5416A.

6.10.2 Materials

Panel configurations included two matrix materials, one panel thickness, three LSP schemes, and six types of LSP splices. Each configuration had three duplicate panels, except the baseline (no-splice) configuration of PEKK matrix materials. Figure 6-110 below shows the various LSP configurations. The full test matrix can be found below in Table 6-51.

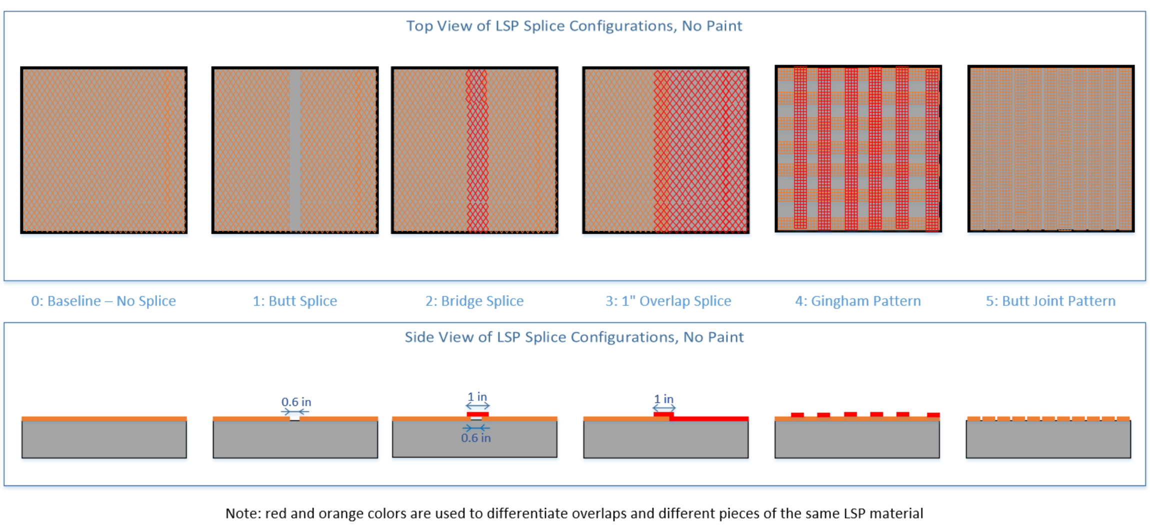


Figure 6-110: Schematic Representation of LSP Splice Configurations

The two matrix materials evaluated were:

1. TPC 1: Toray TC1225/T700-12K T1E LM PAEK, 145 gsm FAW 34%RC unidirectional prepreg
2. TPC 2: Solvay APC (PEKK-FC)/AS4D 12K, 145 gsm FAW 34%RC unidirectional prepreg

The unidirectional tape carbon fiber panels had a ply thickness of 0.005”. Layups consisted of 12 plies (0.06”) in a quasi-isotropic, symmetrical/balanced layup schedule for both matrix materials.

The three LSP schemes all used copper as the conducting material, but the geometry of the grid pattern and method of manufacturing differ. The LSP varieties tested were:

1. Expanded Copper Foil - ECF: 73.3 gsm anisotropic diamond mesh pattern
2. Woven Copper Mesh – WCM: 72 gsm isotropic square mesh pattern
3. Woven Copper Mesh – WCM: 182 gsm isotropic square mesh pattern

The 182 gsm WCM LSP was applied with an automatic fiber placement (AFP) machine. Using AFP for LSP application makes it possible to automate the LSP application process. This allows more flexibility to apply the LSP tape in unique patterns, which can help reduce weight and can lower manufacturing costs for OEMs, especially in instances that the underlying structure is also built using AFP. The typical method of hand-laying LSP is a labor-intensive process, which requires precise cutting and handling of the LSP and then curing the whole part, which is not ideal for compatibility with AFP composite processes. Panels made using the AFP process for LSP application are referred to throughout this report as “tape laid.”

All panels were painted with 11-13 mils of aircraft industry standard paint over the LSP. The details of the coating were:

1. PPG CA-7501 epoxy primer
2. PPG F565-4010 epoxy intermediate coat
3. PPG CA8000 polyurethane topcoat

Table 6-51: Test Matrix and Panel ID Numbers

Matrix Material	Splice Type	LSP	Panel ID
LM PAEK	0: Baseline – No Splice – Hand Laid	WCM 182 gsm	A0-182-1
			A0-182-2
			A0-182-3
	1: Butt Splice– Hand Laid	WCM 72 gsm	A1-72-1
			A1-72-2
			A1-72-3
		ECF 73 gsm	A1-73-1
			A1-73-2
			A1-73-3
	2: Bridge Splice – Hand Laid	WCM 72 gsm	A2-72-1
			A2-72-2
			A2-72-3
	3: 1" Overlap– Hand Laid	WCM 72 gsm	A3-72-1
			A3-72-2
			A3-72-3
	4: Gingham Pattern – Tape Laid	WCM 182 gsm	A4-182-1
			A4-182-2
			A4-182-3
	5: Butt Joint Pattern – Tape Laid	WCM 182 gsm	A5-182-1
			A5-182-2
			A5-182-3
PEKK	0: Baseline – No Splice– Hand Laid	ECF 73 gsm	E0-73-1
	1: Butt Splice– Hand Laid	WCM 72 gsm	E1-72-1
			E1-72-2
			E1-72-3
		ECF 73 gsm	E1-73-1
			E1-73-2
			E1-73-3
	2: Bridge Splice – Hand Laid	WCM 72 gsm	E2-72-1
			E2-72-2
			E2-72-3
	3: 1" Overlap– Hand Laid	WCM 72 gsm	E3-72-1
			E3-72-2
			E3-72-3

6.10.3 Methods/Procedures

Each panel was to be tested once at the high current Zone 2A test level. Prior to testing, the surface resistance of each panel was measured over a five inch distance across the splice to determine the resistivity.

During testing, current distribution across the panel was recorded by four current probes, one located at each panel corner. The thermal signature of the back of the panel during testing was recorded via infrared (IR) imaging. The IR camera system experienced intermittent failure during the course of testing and thus data is missing for certain test points.

After DEL testing, the damage to the panels was recorded using the parameters discussed throughout section 6.10.4. These parameters assess the extent of fiber damage, delamination, holes through the composite, and paint and LSP damage. The surface resistance measurement was repeated after lightning test to determine how the resistivity of the material may have changed. Post-test through-transmission ultrasonic inspection of the panels was done to determine the effect of the lightning strike through the depth of the panel.

6.10.4 Discussion and Data

IR Imaging

The FLIR thermal imaging camera recorded the thermal signature resulting from the lightning strike tests. The camera was positioned to view the backside of the panel. From studies in the preceding sections of chapter 6, the thermal insulating properties of 12 ply, quasi-isotropic LM PAEK thermoplastic panels combined with 73 gsm ECF and 11-13 mils of paint were determined to result in an average PDZ of 4.9 ± 0.5 inches in diameter from a Zone 2A lightning attachment.

The aim in this study was to determine whether the presence of a splice in the LSP changes the heat signature compared to panels with continuous LSP. For most splice configurations, the region of the panel immediately beneath the splice did not show signs of heating. Splice heating was evident in A1 and E1 (hand laid butt splice), and A5 (tape laid butt splice) configurations, where the splices reached higher temperatures than other panel configurations did. An example of this is shown in Figure 6-111, and splice temperatures are contained in Table 6-52. It is important to note that due to intermittent failure of the IR camera system, thermal data is missing from 16 of the 34 test points.

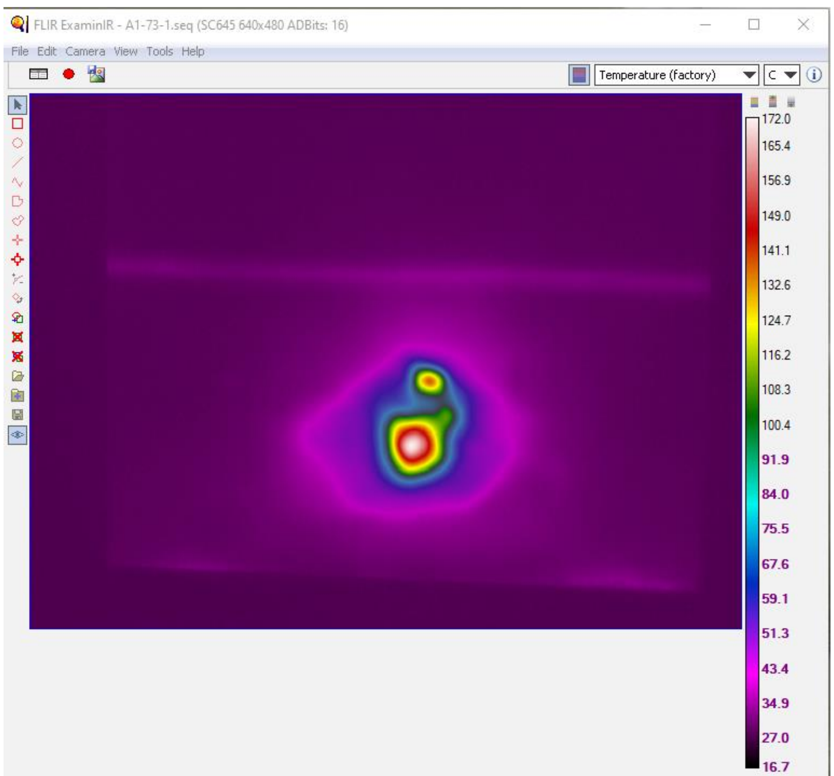


Figure 6-111: Frame from Thermal Imaging of Panel A1-73-1

Table 6-52 below contains the peak temperature and size of the PDZ at the time the peak temperature occurred. Splice temperature indicates heating observed outside the PDZ due to the discontinuities along the LSP.

Table 6-52: Summary of FLIR Data

Panel ID	Max Temperature (°C)	PDZ Diameter (in)	Splice Temperature (°C)
A0-182-1	Data Not Recorded	Data Not Recorded	Data Not Recorded
A0-182-2	154.6	3.4	No Heating Observed
A0-182-3	Data Not Recorded	Data Not Recorded	Data Not Recorded
A1-72-1	Data Not Recorded	Data Not Recorded	Data Not Recorded
A1-72-2	Data Not Recorded	Data Not Recorded	Data Not Recorded
A1-72-3	212.7	5.5	32
A1-73-1	172	6.5	30.5
A1-73-2	Data Not Recorded	Data Not Recorded	Data Not Recorded
A1-73-3	225.8	4.2	37
A2-72-1	219.5	4.7	No Heating Observed
A2-72-2	186.2	4.89	No Heating Observed
A2-72-3	183.6	5.6	No Heating Observed
A3-72-1	173.5	5.6	No Heating Observed
A3-72-2	202	5	No Heating Observed
A3-72-3	195.9	5.1	No Heating Observed
A4-182-1	Data Not Recorded	Data Not Recorded	Data Not Recorded
A4-182-2	173.2	3.9	No Heating Observed
A4-182-3	Data Not Recorded	Data Not Recorded	Data Not Recorded
A5-182-1	Data Not Recorded	Data Not Recorded	Data Not Recorded
A5-182-2	138.9	5.1	32
A5-182-3	173.9	4.73	34
E0-73-1	Data Not Recorded	Data Not Recorded	Data Not Recorded
E1-72-1	156.5	3.99	38
E1-72-2	200.2	3.8	36
E1-72-3	149.2	4.5	32
E1-73-1	Data Not Recorded	Data Not Recorded	Data Not Recorded
E1-73-2	160.2	5.1	34
E1-73-3	Data Not Recorded	Data Not Recorded	Data Not Recorded
E2-72-1	132.9	5.7	No Heating Observed
E2-72-2	Data Not Recorded	Data Not Recorded	Data Not Recorded
E2-72-3	Data Not Recorded	Data Not Recorded	Data Not Recorded
E3-72-1	Data Not Recorded	Data Not Recorded	Data Not Recorded
E3-72-2	Data Not Recorded	Data Not Recorded	Data Not Recorded
E3-72-3	Data Not Recorded	Data Not Recorded	Data Not Recorded

Table 6-53 below details the average diameter of the PDZ in the attachment region for each configuration.

Table 6-53: Average Continuous Diameter of PDZ in Attachment Region

Matrix Material	LSP Configuration	Average PDZ Diameter (in.)
LM-PAEK	Hand-laid, 73 gsm, Butt Splice	5.35 ± 1.63
	Hand-laid, 72 gsm, Butt Splice	5.50
	Hand-laid, 72 gsm, Bridge Splice	5.06 ± 0.47
	Hand-laid, 72 gsm, Overlap Splice	5.23 ± 0.32
	Tape-laid, 72 gsm, Butt Joint	4.92 ± 0.26
	Tape-laid, 72 gsm, Gingham	3.90
PEKK	Hand-laid, 73 gsm, Butt Splice	5.10
	Hand-laid, 72 gsm, Butt Splice	4.10 ± 0.36
	Hand-laid, 72 gsm, Bridge Splice	5.70

Current Distribution

Four current probes measured the current distribution across the panel and across the splice. Figure 6-112 below shows the placement of each probe relative to the orientation of the panel and the attachment point and the generator return.

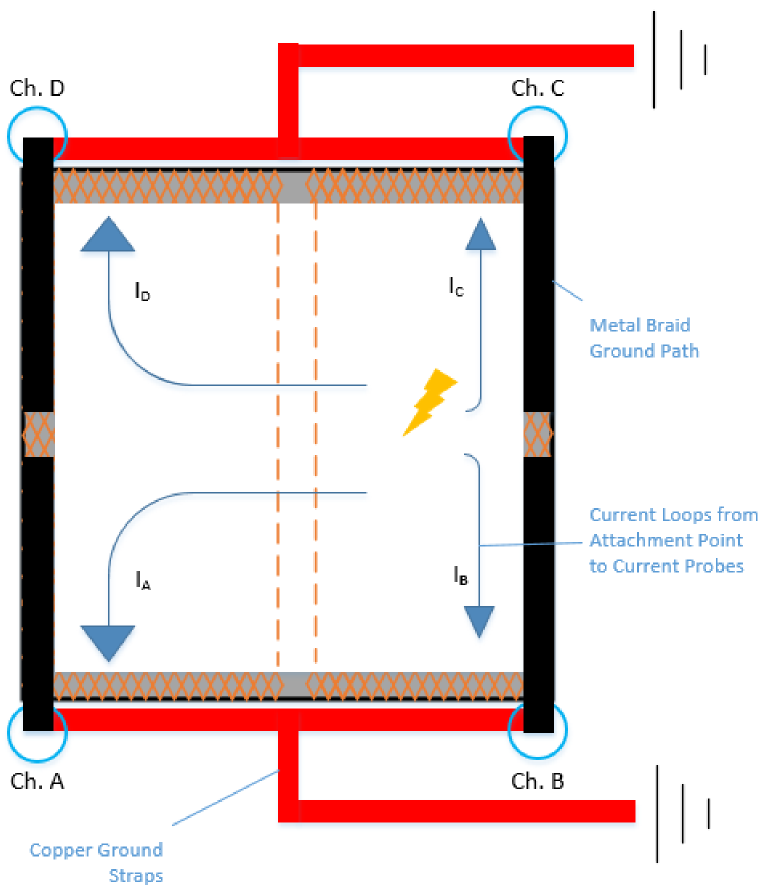


Figure 6-112: Current Probe Configuration

The distance from the panel edge through the copper ground straps from each current probe to the generator return was the same. The strike location on the panel was not centered so the distance from the strike location to the current probes was offset.

For all panels, the majority of the current was biased toward probes B and C, while a lower current amplitude crossed the splice and was detected by probes A and D. The peak current amplitude of probe B was summed with the peak current from probe C. This represented the current flow on the near-side of the splice. Likewise, the peak current amplitudes measured on probes A and D were summed to represent the current flow on the far-side of the splice. The far-side current was subtracted from the near-side current, resulting in a delta representing the amount of bias in current flow between the two sides. The average value of this current bias is summarized in Table 6-54 below.

The type of splice had an influence on the current distribution. As seen in Table 6-54 below, the hand laid butt splice (A1 and E1) panels saw the largest amount of current bias toward probes B and C. This was expected since the butt splice had the least continuous LSP path. Hand laid splices had a larger current distribution bias than tape-laid (A4, A5) splice configurations. The tape laid configurations had more homogenous splice patterns than hand laid configurations. Additionally, the gingham (A4) configuration had the largest amount of overlap between each tow of LSP, which may have contributed to its lower magnitude of current distribution bias than other LM PAEK configurations, and its similar behavior to the baseline (A0) panel.

For all comparable configurations, the LM PAEK panels showed a larger current bias toward the B and C probes than the PEKK panels did. This may be due to the matrix materials' dielectric properties. The measured surface resistivity (discussed further below) of the PEKK panels was approximately half that of the LM PAEK panels, which may have allowed the current to flow more uniformly across the PEKK panels. Table 6-55 summarizes the observed current distributions. It should be noted that the total amount of current distributed across each panel resulted from the 100 kA ± 10% peak current delivered by a Zone 2A test.

Table 6-54: Summary of Current Distribution Data

Matrix Material	Splice Type	Average BC - Average AD (kA)
LM PAEK	Baseline	30.9
	Butt Splice	50.6
	Bridge Splice	44.5
	Overlap	43.1
	Gingham	30.3
	Butt Joint	33.2
PEKK	Butt Splice	36.1
	Bridge Splice	29.3
	Overlap	32.3

Table 6-55: Summary of Current Distribution Data

Panel ID	Current Distribution (kA)			
	Ch. A	Ch. B	Ch. C	Ch. D
A0-182-1	Data Not Recorded	Data Not Recorded	Data Not Recorded	Data Not Recorded
A0-182-2	17.71	31.61	34.73	15.03
A0-182-3	18.35	29.24	33.15	15.82
A1-72-1	11.81	42.96	Data Not Recorded	15.93
A1-72-2	12.29	41.36	38.23	15.13
A1-72-3	12.29	1.587	35.23	15.29
A1-73-1	13.25	39.78	Data Not Recorded	17.52
A1-73-2	12.93	39.78	38.23	16.09
A1-73-3	6.705	22.27	27.07	10.35
A2-72-1	13.89	39.78	35.04	17.52
A2-72-2	13.73	39.78	36.63	17.04
A2-72-3	13.89	0	36.63	17.2
A3-72-1	13.73	39.78	35.04	17.68
A3-72-2	13.89	38.18	36.63	17.52
A3-72-3	14.53	38.18	36.63	17.68
A4-182-1	Data Not Recorded	Data Not Recorded	Data Not Recorded	Data Not Recorded
A4-182-2	18.55	29.24	33.94	15.82
A4-182-3	15.57	29.24	33.15	15.03
A5-182-1	14.35	28.44	34.73	14.23
A5-182-2	15.57	30.03	33.15	15.03
A5-182-3	16.55	30.82	33.15	15.03
E0-73-1	19.49	37.89	Data Not Recorded	Data Not Recorded
E1-72-1	13.13	30.82	33.15	15.03
E1-72-2	16.54	31.58	36.31	13.44
E1-72-3	17.31	30	34.73	14.23
E1-73-1	14.35	29.24	34.73	14.23
E1-73-2	14.35	31.61	34.73	14.23
E1-73-3	31.43	26.84	Data Not Recorded	14.21
E2-72-1	15.57	30.03	32.36	15.03
E2-72-2	17.42	30.03	33.94	16.61
E2-72-3	20.38	30.03	33.15	16.61
E3-72-1	15.57	28.44	33.15	15.03
E3-72-2	17.73	30	33.15	15.82
E3-72-3	15.11	30.82	34.73	14.23

Resistivity

DC resistance measurements were taken on the panel surface before and after lightning testing at a separation of five inches between measurement points A and B, centered on the centerline of the panel. These measurements are shown in Table 6-56. Pre-test resistivity measurements were of similar orders of magnitude for all panels except the LM PAEK butt splice (A1) configurations, which were three to four orders of magnitude higher. Resistivity changed for all panels between the pre-test and post-test measurements, as seen in Figure 6-113 and Figure 6-114 (plots which contain the same data with two different vertical scales.) The magnitude of the change in resistivity was only significant for butt splice LM PAEK (A1) configurations, which decreased by three orders of magnitude and came within range of the resistivity of the other configurations. The pre-test values of the LM PAEK hand laid butt splice (A1) panels were much higher than the values for the PEKK hand laid butt splice (E1) panels despite containing the same LSP configurations. This may have been due to the surface preparation of the measurement area not being uniform and possibly maintaining a thin layer of dielectric matrix material on the LSP.

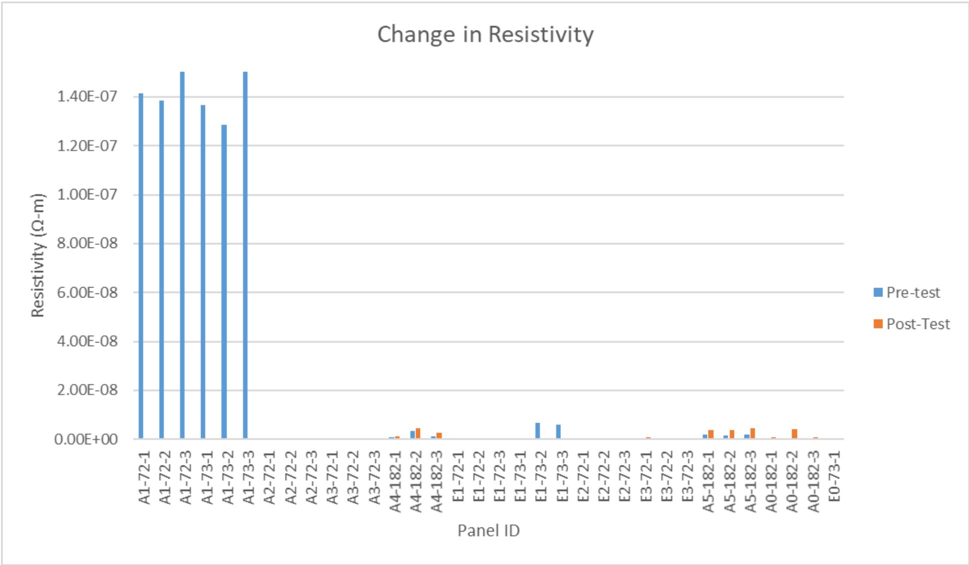


Figure 6-113: Graph of Pre and Post-Test Resistivity Measurements (Scaled for Higher Resistivity Values)

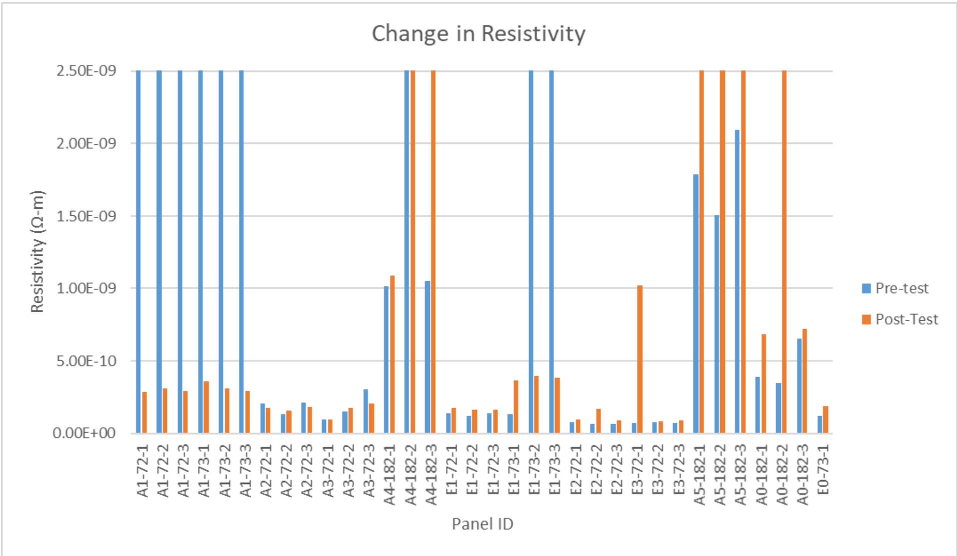


Figure 6-114: Graph of Pre and Post-Test Resistivity Measurements (Scaled for Lower Resistivity Values)

The panel configurations with some type of overlap in the LSP splice changed the least in their pre- and post-test resistivity. The butt joints that had no overlap between the pieces of LSP had the greatest change in their resistivity measurements. The tape laid (A4 and A5) splice configurations generally had higher pretest resistivity than other configurations (aside from the A1 configurations), and increased in resistance in the post-test measurements. Figure 6-115 shows the locations of the DC resistance measurements described in Table 6-56.

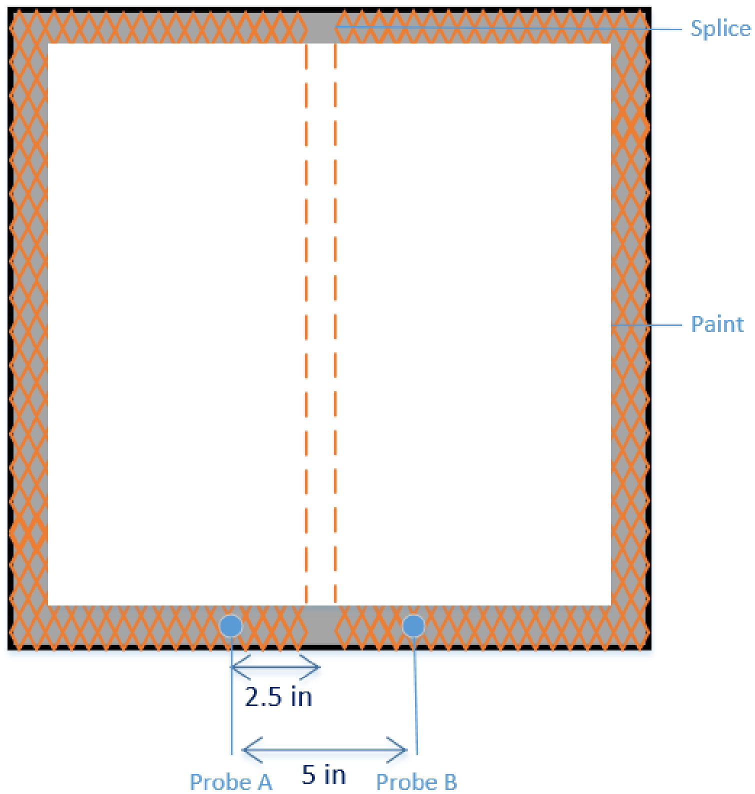


Figure 6-115: Schematic of Probe Placement for Resistivity Measurements

Table 6-56: Summary of Pre- and Post-Test DC Resistance Measurements

Panel ID	Pre-Test Resistivity (Ω-m)	Post-Test Resistivity (Ω-m)
A0-182-1	3.92E-10	6.821E-10
A0-182-2	3.45E-10	4.114E-09
A0-182-3	6.55E-10	7.214E-10
A1-72-1	1.41E-07	2.869E-10
A1-72-2	1.39E-07	3.092E-10
A1-72-3	1.54E-07	2.889E-10
A1-73-1	1.37E-07	3.571E-10
A1-73-2	1.3E-07	3.12E-10
A1-73-3	2.53E-07	2.94E-10
A2-72-1	2.06E-10	1.741E-10
A2-72-2	1.33E-10	1.54E-10
A2-72-3	2.1E-10	1.841E-10
A3-72-1	9.5E-11	9.707E-11
A3-72-2	1.48E-10	1.777E-10
A3-72-3	3.02E-10	2.048E-10
A4-182-1	1.01E-09	1.092E-09
A4-182-2	3.36E-09	4.589E-09
A4-182-3	1.05E-09	2.849E-09
A5-182-1	1.79E-09	3.785E-09
A5-182-2	1.51E-09	3.916E-09
A5-182-3	2.09E-09	4.541E-09

Panel ID	Pre-Test Resistivity (Ω-m)	Post-Test Resistivity (Ω-m)
E0-73-1	1.19E-10	1.89E-10
E1-72-1	1.38E-10	1.767E-10
E1-72-2	1.19E-10	1.6E-10
E1-72-3	1.39E-10	1.638E-10
E1-73-1	1.33E-10	3.629E-10
E1-73-2	6.76E-09	3.941E-10
E1-73-3	5.82E-09	3.854E-10
E2-72-1	7.74E-11	9.42E-11
E2-72-2	6.53E-11	1.708E-10
E2-72-3	6.68E-11	8.895E-11
E3-72-1	7.36E-11	1.021E-09
E3-72-2	7.72E-11	8.47E-11
E3-72-3	7.12E-11	9.004E-11

Paint, LSP, and Laminate Damage

Paint damage in this study describes two different measurements: (1) the damage to the paint near the lightning attachment point (in the PDZ), and (2) any paint damage outside of the lightning attachment point which resulted from the LSP splice. The extent of the paint damage on the panels with hand laid LSP (all configurations except A4 and A5) was limited to minor bubbling observed beneath the paint (no paint puncture) along the splice as seen in Figure 6-116. Out of all configurations, the tape laid butt splice (A5-182) panels had the most extensive paint damage outside the PDZ. As shown in Figure 6-117 below, small circles of paint were ejected from the test article over the majority of the panel area in a pattern consistent with the splicing. This was likely due to sparking that occurred where LSP discontinuities required the current to jump from one piece of LSP to the next. Table 6-57 contains the paint damage measurements.

Figure 6-116: Paint Bubbling Above Splice on A1-73-2, Paint Intact

Figure 6-117: Paint Damage on A5-182-1 Panel Resulting from Lightning, Paint Ejected

Table 6-57: Paint Damage from Lightning Strike

Panel ID	Paint Damage Diameter in PDZ (in)	Paint Damage Beyond PDZ (in)
A0-182-1	3	N/A
A0-182-2	2.5	N/A
A0-182-3	2.5	N/A
A1-72-1	5.25	N/A
A1-72-2	5.75	N/A
A1-72-3	5.25	N/A
A1-73-1	9.25	N/A
A1-73-2	3.5	N/A
A1-73-3	6	N/A
A2-72-1	8.5	N/A
A2-72-2	6	N/A
A2-72-3	5.5	N/A
A3-72-1	6	N/A
A3-72-2	6.5	N/A
A3-72-3	6	N/A
A4-182-1	8.25	N/A
A4-182-2	4.25	N/A
A4-182-3	4.5	N/A
A5-182-1	4	N/A
A5-182-2	4.5	18
A5-182-3	4	18
E0-73-1	4	18
E1-72-1	5.25	N/A
E1-72-2	4	N/A
E1-72-3	5.25	N/A
E1-73-1	5.5	N/A
E1-73-2	5.25	N/A
E1-73-3	5.5	N/A

Panel ID	Paint Damage Diameter in PDZ (in)	Paint Damage Beyond PDZ (in)
E2-72-1	5.5	N/A
E2-72-2	4.25	N/A
E2-72-3	6.25	N/A
E3-72-1	4.25	N/A
E3-72-2	5.25	N/A
E3-72-3	4.5	N/A

Most configurations did not show evidence of LSP damage outside of the PDZ. The two configurations with damage to the LSP at the location of the splices were the hand (A1, E1) and tape (A5) laid butt splices. As shown in Figure 6-118, there was evidence of vaporization and damage to the LSP along the discontinuous edges on the hand laid butt splice panels. In Figure 6-119 below, another type of LSP damage can be seen under a microscope. On all of the A5-182 (tape laid butt splice) panels where the paint was ejected along the splices, there were small holes and cracks observed in the LSP layer. In both butt splice configurations, the LSP damage was likely due to LSP vaporization that occurred when current jumped across the splice from one piece of LSP to the next.

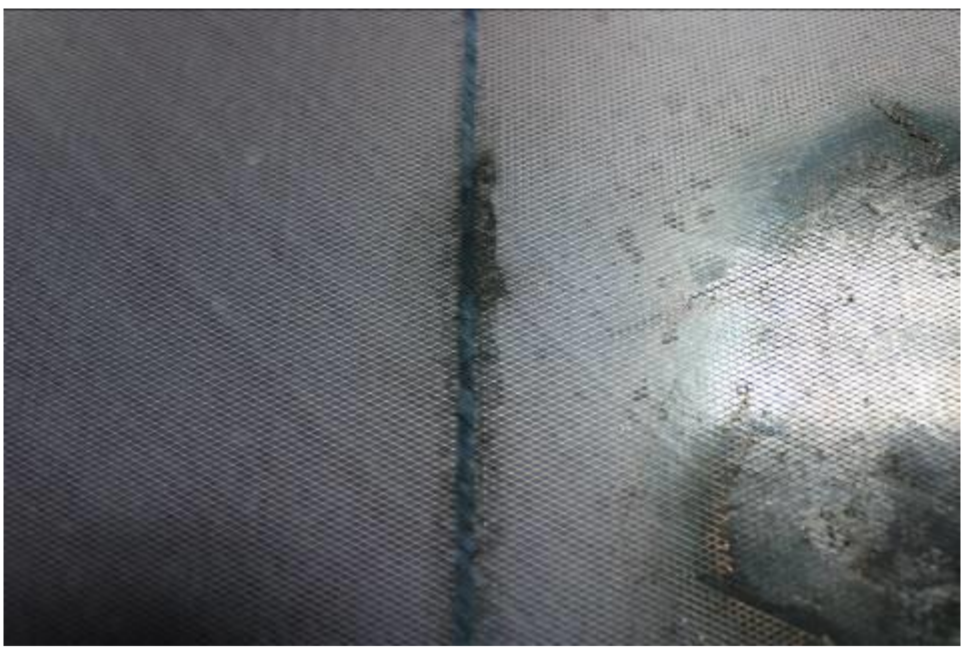


Figure 6-118: Damage to LSP at Splice Location, A1-73-1

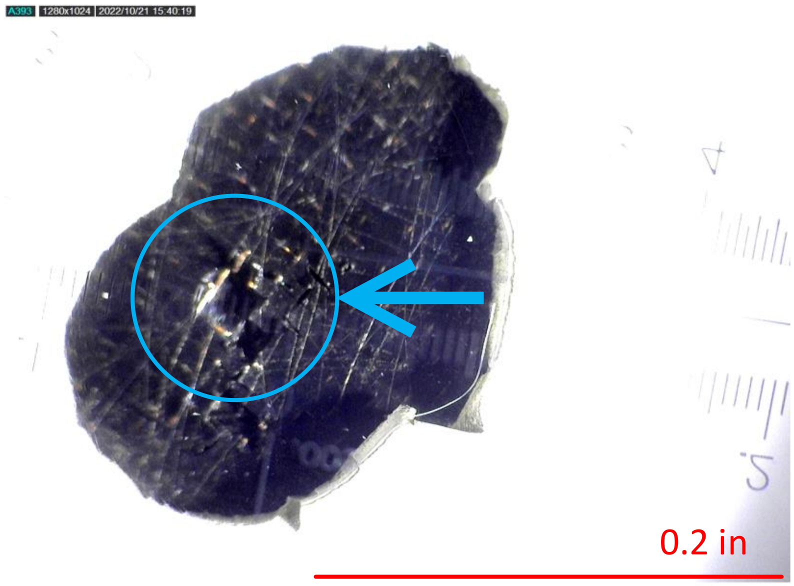


Figure 6-119: LSP Damage on the A5-182 Panels

Laminate damage in the LM PAEK panels was limited to outside fiber breakage and delamination. Fiber breakage on average was 2.23 ± 0.75 inches in length. Outside delamination was 2.83 ± 0.80 inches long on average. Only four panels had inside delamination, which averaged to 1.25 ± 0.54 inches long.

The PEKK panels sustained larger amounts of damage. The fiber breakage on the top ply averaged to 2.44 ± 0.41 inches in length and the outside delamination was 3.25 ± 0.82 inches long on average. Two of the three panels from each of the E1-72, E2-72, and E3-72 (all containing woven copper mesh, 72 gsm) configurations had fiber damage on the inside of the panel. Those six cases averaged 2.79 ± 1.43 inches of damage. The E1-73 panels (containing expanded copper foil, 73 gsm) had no inside delamination. The remaining four PEKK panels (E0-73-1, E1-72-2, E2-72-1, and E3-72-2) had an average inside delamination diameter of 4.00 ± 1.90 inches. PEKK panels had larger inside and outside delamination diameters than the equivalent LM PAEK panels.

Based on the damage scores listed in Table 6-58, the following was determined. Of all configurations tested, the A5 (tape laid butt joint, 182 gsm) configuration performed the best, with an average damage score of three. This was slightly better than the A0 (baseline 182 gsm) configuration, which had an average damage score of four. The configurations that performed the worst were the E1-72, E2-72, and E3-72 (woven copper mesh 72 gsm) configurations, which had average damage scores of 27, 38, and 40.3 respectively. All other configurations performed well and had average damage score ranging between 5.8 and 7.3. For more information on how damage scores are determined, please refer to section 6.4.

There was no hole on the inside of any panel. No delamination or fiber damage was observed along the splices. Table 6-58 contains the laminate damage measurements.

Table 6-58: Laminate Damage Measurements Sustained from Lightning Strike

Panel ID	LSP Damage (in)	Outside Delamination		Outside Hole		Inside Delamination/ Damage			Inside Hole (in)	Damage Score
		x (in)	y (in)	x (in)	y (in)	x (in)	y (in)	Type		
A0-182-1	3.25	1.25	2	1.5	0.75	0.5	1.25	Delamination	0	4
A0-182-2	2.5	2	1.75	1.5	1	1.5	1.75	Delamination	0	4
A0-182-3	2.5	2	1.5	1.5	1	0	0	Delamination	0	4
A1-72-1	5.5	2.25	2	2.25	1.25	0	0	Delamination	0	7
A1-72-2	5.5	2.75	1.25	2.5	1.75	0	0	Delamination	0	7
A1-72-3	5.5	2.5	1.75	1.75	0.25	0	0	Delamination	0	4
A1-73-1	6	4	4.25	2.25	1.5	1.5	1.25	Delamination	0	8
A1-73-2	5.5	3.75	3	3.5	1.25	0	0	Delamination	0	7
A1-73-3	6	3	3.25	2.75	1.5	0	0	Delamination	0	7
A2-72-1	5	2.75	2	2.25	1	0	0	Delamination	0	7
A2-72-2	5.5	3.75	3	2.5	1.5	0	0	Delamination	0	7
A2-72-3	5.75	4.75	2.5	3	2.7	0	0	Delamination	0	8
A3-72-1	6.5	3.75	1	3.25	0.5	0	0	Delamination	0	7
A3-72-2	5.75	2.25	1.5	2	1.5	0	0	Delamination	0	4
A3-72-3	5.5	2.5	2	3.25	0.75	0	0	Delamination	0	7
A4-182-1	4	3	2.25	1.5	1.25	0.5	0.5	Delamination	0	4
A4-182-2	4.75	2.5	2	2.5	2	0	0	Delamination	0	7
A4-182-3	3.5	3	2.25	3.25	2.25	0	0	Delamination	0	7
A5-182-1	4	1.75	2.25	1.25	1	0	0	Delamination	0	4
A5-182-2	4	2.25	1	1	0.25	0	0	Delamination	0	1
A5-182-3	3.75	2	1.25	1.5	1.5	0	0	Delamination	0	4
E0-73-1	5.25	2.75	2	1.25	2.5	5.5	4	Delamination	0	16
E1-72-1	4	3	2	3	2	1.25	0.25	Damage	0	43
E1-72-2	4.75	2.5	3.25	2	2	1.25	1	Delamination	0	4
E1-72-3	4.5	3	4	3	2	1	0.5	Damage	0	34
E1-73-1	4.5	2.25	1.5	2.5	2	0	0	Delamination	0	7
E1-73-2	5.5	3	2.5	3.25	3	0	0	Delamination	0	7
E1-73-3	5.75	2.25	2	2.5	2	0	0	Delamination	0	7
E2-72-1	4.25	2.25	2	2	1.5	4.25	1.25	Delamination	0	13
E2-72-2	6.5	4	3	2.25	2.25	4.25	0.5	Damage	0	52
E2-72-3	4.5	3.25	4	2	1.75	4	0.5	Damage	0	49
E3-72-1	4.5	3.25	3.25	2.25	1.75	2.5	0.75	Damage	0	52
E3-72-2	4.5	3.25	2	2.25	1.75	5	2.25	Delamination	0	16
E3-72-3	6.75	5	4.5	2.25	2	3.75	0.5	Damage	0	53

C-Scans

For all panels, the damage region recorded on the c-scans was contained to the lightning attachment area. No damage was seen beneath the splices or anywhere outside of the attachment area in any of the configurations. The larger delamination area of the PEKK panels as compared to the LM PAEK panels can be seen in Figure 6-120 below, which graphs the delamination area as measured via c-scan.

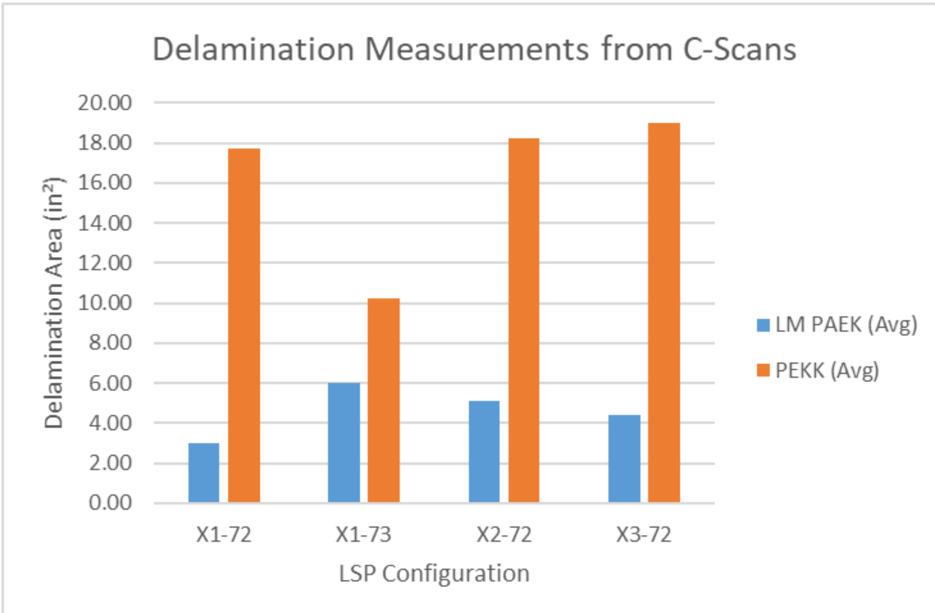


Figure 6-120: Graph of Delamination Measurements from C-Scans - LM PAEK vs PEKK Configuration

Impact of Matrix Material

The most notable difference was the larger inside and outside delamination area and the inside damage of PEKK panels, as previously discussed. Another difference was the amount of LSP damage. Comparing only the panels with the same LSP and splice configurations, the average length of LSP damage was 5.68 inches for LM PAEK panels and 5.0 inches for PEKK panels. The LM PAEK panels showed a larger bias of approximately 10 to 15 kA in current distribution toward the B and C current probes than the comparable PEKK panels did.

Impact of Splice Type

Minimal differences were observed between the hand laid configurations with regard to LSP damage, paint damage, and laminate damage. The butt splice configuration had less current transfer across the splice and a greater change in resistivity than the other configurations.

Between the tape laid configurations, the gingham pattern had a larger PDZ than the butt joint pattern; however, the extent of the LSP and paint damage was more contained within the PDZ of the gingham pattern.

6.10.5 Conclusions

- The presence of some amount of overlap or physical continuity between two different sections of LSP reduced the amount of damage outside the PDZ in both hand and tape laid splice configurations.
- PEKK panels had larger areas of inside and outside delamination than LM PAEK panels.
- When a small (<0.06”) discontinuity (splice) is present in the LSP a larger amount of the current remained on the side of the splice the lightning attachment occurred on.
- The presence of a splice in the LSP did not alter the type or extent of damage to the laminate.
- Hand and tape laid butt splice configurations sustained more damage to paint and LSP than other configurations.
- The hand and tape laid butt splice configurations consistently had thermal signatures that showed heating beneath the splice, which was absent from all other configurations.

6.11 Novel Lightning Strike Protection Methods

6.11.1 Background

The goal of this research was to study the effectiveness of novel LSP configurations on thermoplastics to minimize damage to aircraft as a result of lightning direct attachment. This section takes a closer look at how different novel LSP configurations compare to traditional LSP methods by answering the following questions:

- How does the novel LSP configuration affect the damage sustained to the thermoplastic?
- How does the damage sustained with the novel LSP compare to the damage sustained with traditional LSP?

Data collected included test photographs, resistivity of the panel surface at the LSP layer, waveform parameters during lightning test, post-test physical damage measurements, and paint damage measurements. Test points were performed per the procedure in SAE ARP 5416A on flat panels using Zone 1A and Zone 2A waveforms, as listed in Table 6-59.

6.11.2 Materials

Panel configurations included two matrix materials, two panel thicknesses, and three novel LSP types. The Zone 1A and Zone 2A panels had two duplicate panels per configuration. All baseline information regarding traditional LSP (ECF) was referenced from previous research studies from sections 6.8 and 6.9 of this document, and no additional baseline configurations were tested for this research study. The full test matrix can be found below in Table 6-59.

The two matrix materials evaluated were:

1. Unitape: Toray TC1225 unidirectional tape, T700-12K T1E 145 gsm FAW 34% RC
2. Unitape: Park E-752 unidirectional tape, 12K C12HTS45 145 gsm FAW 35% RC

The unidirectional tape carbon fiber panels had a ply thickness of 0.005”. Layups consisted of either 8 plies (0.04”) or 12 plies (0.06”) in a quasi-isotropic, symmetrical/ balanced layup schedule for both matrix materials.

The three novel LSPs tested were:

1. Graphene based coating
2. ElectroVeil: nickel coated chopped carbon fiber mat, 70 gsm from Park Aerospace
3. Nickel nanostrands: 3AA150 from Conductive Composites

The graphene coating was applied via bar coating to the bare panel surface. Standard aircraft paint was applied over the graphene coating, with a target thickness of 11-13 mils. Due to the brittle nature of the graphene coating, a different surface preparation procedure was used prior to the application of the standard aircraft paint, wherein low pressure air was flowed across the surface, followed by an alcohol flow, and lastly low pressure air flow again.

ElectroVeil LSP was supplied as a dry material, which was co-consolidated with the panels as the top ply using an additional surfacing film of the same matrix material as the panel both above and below the LSP ply. Standard aircraft paint was applied to the laminates at a target thickness of 11-13 mils.

The nickel nanostrands (NNS) were manufactured via a chemical vapor deposition process which resulted in the three dimensionally branched, loose powder material with a bulk density ranging from 0.14 – 0.18 g/cm^3. NNS LSP was applied as part of the standard aircraft coating process. Primer and intermediate coat were applied as normal, but the topcoat layer was mixed with 7% by volume of nickel nanostrands. The target thickness of the coatings was 11-13 mils.

Table 6-59: Test Matrix and Panel ID

Lightning Strike Protection (LSP)	Matrix Material	Zone	Plies	Panel ID	Number of Test Points
Graphene Coating	LM PAEK	1A	12	LGrZ1-K1	1
				LGrZ1-K2	1
		2A	12	LGrZ2-K1	2
				LGrZ2-K2	2
Nickel Nanostrands	LM PAEK	1A	12	LNiZ1-K1	1
				LNiZ1-K2	1
		2A	12	LNiZ2-K1	2
				LNiZ2-K2	2
			8	LNiZ2-N1	2
				LNiZ2-N2	2
	Epoxy	2A	12	ENiZ2-N1	1
				ENiZ2-N2	1
ElectroVeil	LM PAEK	1A	12	LEZ1-K1	1
				LEZ1-K2	1
		2A	12	LEZ2-K1	2
				LEZ2-K2	2
			8	LEZ2-N1	2
				LEZ2-N2	2
	Epoxy	2A	8	EEZ2-N1	2

All panels were painted with 11-13 mils of aircraft industry standard paint over the LSP, except the NNS panels which had an additive mixed into the topcoat layer. The details of the coating were:

1. PPG CA-7501 epoxy primer
2. PPG F565-4010 epoxy intermediate coat
3. PPG CA8000 polyurethane topcoat

6.11.3 Methods/Procedures

The surface resistance of each panel was measured on the conductive LSP layer of each panel before lightning testing. A DC milliohm meter was used with a distance of one inch between the probe tips.

During lightning testing, the waveform information from the lightning generator was collected for each test point, which described the current components delivered. Test panels designated for Zone 1A received only one test point while those designated for Zone 2A received two test points per panel as described in Table 6-59.

After testing, the surface resistance measurements were repeated to determine any changes in resistivity due to testing. Physical damage to the panels was measured using the parameters discussed in section 6.4. These parameters were used to assess the extent of fiber damage, delamination, holes through the composite, and paint damage. Post-test B and C ultrasonic scans of the panels were done to determine the extent of the damage caused by the lightning strike in terms of the area and depth. Paint adhesion tests were conducted after the ultrasonic scans. The paint adhesion testing was performed per ASTM D3359 using both method A and method B.

6.11.4 Discussion and Data

Lightning Performance

All panel damage measurements were taken to the nearest quarter inch. All average values reported in this section are rounded to the nearest decimal place.

Graphene Coating: All of the graphene protected panels were 12 ply laminates. The graphene coating on the panels was applied first onto the panels via bar coating and then painted with standard aircraft paint. The graphene coating was brittle and had to be handled with care, thus the standard surface preparation techniques could not be used prior to the application of standard aircraft paint. Figure 6-121 shows a cross sectional schematic of the graphene LSP panels.

The pre-test surface resistance of the panels ranged from 7.7 -13.1 Ω. The post-test resistance measurements after testing at Zone 1A did not consistently trend in either an increase or decrease. After testing at Zone 2A, the average resistance value increased by 1.7 Ω or 21%.

For Zone 1A test points, there was extensive damage to the inside of the panel (dimensions averaging 18.6 x 4.8 inches) and the presence of a through hole on both test points. As shown in Figure 6-122, several tows of the unitape on the inside of the panel (bottom ply) separated from the laminate. The Zone 1A panels also sustained extensive fiber damage and delamination on the outside (top ply) of the laminates. This damage to the inside of the test article was still present even while testing in Zone 2A, though the average area was less, at 12.1 x 1.8 inches. Similarly, the average inside hole size on the Zone 2A panels were smaller than the average inside holes on the Zone 1A panels (0.3 x 0.2 inches versus 0.2 x 1 inches respectively) with one of the test points, LGrZ2-K1 TP1, having no through hole. Based on these results where 12 ply graphene protected panels received extensive damage, it was decided that the thinner 8 ply laminates would not be fabricated or tested because they were expected to perform worse.

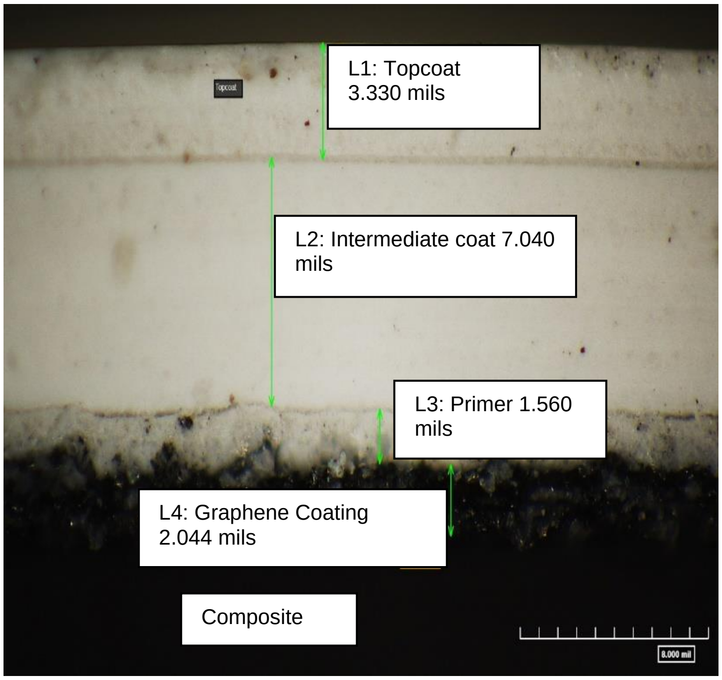


Figure 6-121: Cross Sectional Photomicrograph of Graphene Protected Panels

Figure 6-122: LGrZ1-2 Post-Test – Inside Damage Photo

ElectroVeil: The ElectroVeil LSP material is a nickel coated carbon fiber mat that must be co-consolidated with the laminate. The pre-test surface resistance of the material on the LM PAEK panels ranged from 27.4 – 42 mΩ, which is three to four orders of magnitude more conductive than the graphene coating. The post-test surface resistance results from Zone 1A testing did not consistently trend in either an increase or decrease when compared to the pre-test values. Post-test resistance measurements after Zone 2A testing showed that the resistance decreased by 5.9 mΩ on average or 18%.

In Zone 1A testing, there was no fiber damage to the inside of the panel or a through hole on any test point. The inside delamination was 0.9 x 1.1 inches on average. The outside delamination and outside hole measured on average 6.3 x 3.8 inches and 4.3 x 3.8 inches respectively.

The Zone 2A, 12 ply panels protected with the ElectroVeil material sustained no inside damage, delamination, or through holes. The outside delamination was 3.4 x 2.9 inches on average, while the outside hole measured 2.1 x 1.3 inches on average. Due to limited test panels and invalid test points, there was insufficient data recorded for epoxy panels protected with ElectroVeil, so the comparison between LM PAEK and epoxy panels protected with ElectroVeil will not be made in this report.

Nickel Nanostrands: The branch structured nickel nanostrand (NNS) material was supplied in loose powder form and was mixed into the topcoat layer of the aircraft coating at 7% by volume as represented in Figure 6-123. The DC milliohm-meter used for surface resistance measurements on other panels was unable to measure the resistance of the coating before or after lightning testing, demonstrating that this LSP was the most electrically resistive of the three materials tested. Due to a shortage of materials, two of the spare 8 ply epoxy panels were painted with nickel nanostrands on the back ply of the panels. The metal braid used to electrically connect the panels to the generator ground path was clamped only on the top (NNS) surface of the panel to isolate the ElectroVeil on the other side from the generator ground path.

On average in the Zone 1A testing, the inside damage measured 22 x 3.5 inches and the inside hole measured 2.6 x 2.4 inches. The outside delamination and outside hole measured on average 7.3 x 5.6 inches and 5.9 x 3.8 inches respectively.

The Zone 2A, 12 ply panels protected with NNS material sustained on average 4.1 x 3.2 inches of outside delamination, outside holes averaging 3.1 x 2.1 inches, 11.7 x 1.3 inches for the inside damage, and 1.1 x 0.8 inches for the inside holes. The four Zone 2A test points on 8 ply LM PAEK panels protected with NNS material had an average inside damage measurement of 17 x 2.2 inches, and an average of 1 x 1 inches for the inside hole measurement. The outside delamination was 5.2 x 3.1 inches on average. The outside hole was 4.3 x 1.9 inches on average.

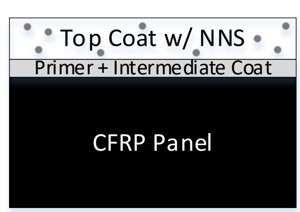


Figure 6-123: Schematic of NNS Panel Cross Section – Not Drawn to Scale

All four Zone 2A test points on 8 ply epoxy panels protected with NNS material had inside damage, measuring 19.3 x 2.3 inches on average. The through holes of those four test points had an average measurement of 0.4 x 0.3 inches. The outside delamination was 13.8 x 2.9 inches on average. The outside hole was 13.8 x 2.5 inches on average. The outside delamination, outside hole, and inside damage areas were smaller by 60%, 76%, and 44% respectively on the equivalent LM PAEK panels as compared to the epoxy panels, however the epoxy panels with NNS had an 76% reduction in the inside hole area on average.

Comparison with Baseline Panels: Data from similar panels (12 ply, unitape, LM PAEK panels tested at Zone 2A) containing ECF or no LSP reported in previous sections of this report has been consolidated for convenience below to compare with the results of the novel LSP protected panels. The numbers reported in the “No LSP” column were linearly extrapolated based on measurements taken on panels that were 8 plies and 16 plies, as no direct comparison data on 12 ply laminates was available.

Though the outside delamination of the graphene protected Zone 2A panels was smaller on average than the panels protected by ECF, the outside hole and all inside measurements being larger on graphene panels showed that the ECF was a more effective LSP. As shown in Table 6-60 below, the graphene protected panels performed slightly better than the panels with no LSP. The ElectroVeil material performed slightly better than the panels with a similar weight of ECF dry material when protecting a 12 ply laminate, and substantially better than panels with no LSP. The NNS material performed worse than ECF for all damage types. NNS material performed slightly better than panels with no LSP on the outside damage measurements, however because the NNS panels had more severe inside damage, it was not considered an effective LSP.

Table 6-60: Comparison of Average Damage Measurements on 12 Ply LM PAEK Composite in Zone 2A

Parameter	**73 gsm ECF**	**ElectroVeil**	**Graphene**	**NNS**	**No LSP**
Outside Delamination	3.5 x 3.2 inches	3.4 x 2.9 inches	4.1 x 2 inches	4.1 x 3.2 inches	*5.4 x 3.4 inches
Outside Hole	2.3 x 1.8 inches	2.1 x 1.3 inches	2.8 x 1.1 inches	3.1 x 2.1 inches	*4.2 x 2.2 inches
Inside Delamination	0.5 x 0.2 inches	0 x 0 inches	N/A	N/A	*4.3 x 2.6 inches
Inside Damage	0 x 0 inches	0 x 0 inches	12.1 x 1.8 inches	11.7 x 1.3 inches	*10.5 x 3.15 inches
Inside Hole	0 x 0 inches	0 x 0 inches	0.25 x 0.2 inches	1.1 x 0.8 inches	*0.8 x 0.9 inches

*Values were linearly extrapolated using the average values from eight and 16 ply composite panels with no LSP

Table 6-61 compares the 8 ply LM PEAK laminates and shows that ECF protected the panel more effectively than a comparable dry weight of the ElectroVeil material by 33% and 44% for the outside hole and inside delamination respectively, and by 100% for inside damage and inside hole parameters. The panels with no LSP material had smaller areas of outside delamination, outside hole, and inside damage by 26%, 49%, and 25% respectively when compared to the NNS protected panels.

Table 6-61: Comparison of Average Damage Measurements on 8 Ply LM PAEK Composite in Zone 2A

Parameter	**73 gsm ECF**	**ElectroVeil**	**NNS**	**No LSP**
Outside Delamination	3.6 x 4.1 inches	3 x 2.7 inches	9.5 x 3 inches	6.0 x 3.5 inches
Outside Hole	2.4 x 1.9 inches	2.9 x 2.4 inches	9.0 x 2.2 inches	5.0 x 2.0 inches
Inside Delamination	0.4 x 0.4 inches	1 x 1 inches	N/A	7.3 x 4.0 inches
Inside Damage	0 x 0 inches	9.8 x 1.5 inches	17 x 2.2 inches	8.8 x 3.2 inches
Inside Hole	0 x 0 inches	0.1 x 0.1 inches	0.7 x 0.7 inches	0.8 x 1.1inches

NDI

The B-scans of the graphene and NNS panels showed that the damage went through the entire depth of the panel for both Zone 1A and Zone 2A test points. The B-scans of the ElectroVeil panels showed that the damage went through the entire depth of the panel for all Zone 2A test points on 8 ply panels except the LEZ2-N2 test point 2. The B-scans were used to determine the maximum depth of damage for every test point. This data is reported in Table 6-62 as the average of those measurements by configuration.

Table 6-63 below, which contains a summary of the average delamination area for each tested configuration as determined via C-scans, shows that the LM PAEK panels had smaller delamination areas by 46% when protected by ElectroVeil and 41% when protected by NNS as compared to the equivalent epoxy panels.

Table 6-62: Average Maximum Depth of Damage (in) via B-Scans

B-Scans			Average Maximum Depth of Damage (in)					
			Zone 1A			Zone 2A		
Matrix Material	Ply Count	Average Panel Thickness (in)*	Graphene	ElectroVeil	NNS	Graphene	ElectroVeil	NNS
LM PEAK	8	0.0570 ± 0.004	N/A	N/A	N/A	N/A	0.0592**	0.0530
Epoxy	8	0.0594 ± 0.002	N/A	N/A	N/A	N/A	N/A	0.0594
LM PEAK	12	0.0802 ± 0.004	0.075	0.0523	0.081	0.075	0.0459	0.081

*Note: The panel thickness is dependent on paint thickness.
**Note: three of four test points in this configuration had damage through the entire depth of panel, this average excludes the one test point that did not. The maximum depth of damage on LEZ2-N2 TP2 was 0.185 inches.

Table 6-63: Average Area (sq. in) via C-Scans

C-Scans		Average Area (sq. in)					
		Zone 1A			Zone 2A		
Matrix Material	Ply Count	Graphene	ElectroVeil	NNS	Graphene	ElectroVeil	NNS
LM PEAK	8	N/A	N/A	N/A	N/A	6.948	9.299
Epoxy	8	N/A	N/A	N/A	N/A	N/A	15.740
LM PEAK	12	20.953	6.193	26.435	6.709	6.627	7.953

Paint Adhesion

As discussed in section 6.7.3, the standard aircraft paint and surface preparation methods typically do not result in good adhesion between the paint and the laminate on LM PAEK panels. Novel LSP methods discussed in this section introduce additives mixed into the topcoat in the case of NNS, or a new material layer between the paint and the laminate in the case of the graphene coating that may alter the paint system's adhesion to the LM PAEK panels. Thus it was decided to conduct paint adhesion testing per ASTM D3359 on the LM PAEK panels to determine the effects these LSPs may have had on the paint adhesion.

ASTM D3359 indicates that for coating systems thicker than 5 mils to use the x-cut method as to prevent the paint cracking that occurs along the scribes in thicker paints with the cross-hatch method. Despite the paint thickness being greater than 5 mils, it was decided to perform both the x-cut and cross-hatch methods of paint adhesion testing because this paint cracking was not observed in the cross-hatch test points and the x-cut method did not yield differentiable results between the different LSP materials. The full table of results, including the measured paint thicknesses, can be found in Table 6-64 and Table 6-65 for the cross-hatch and x-cut methods respectively. A legend for interpreting the results based on the ASTM definitions can be found in Table 6-66. No epoxy panels were included in this examination.

The brittle graphene coating required careful handling. The cross-hatch testing showed that in the places that the paint was removed, it was actually the graphene coating that lifted off of the surface of the composite first rather than the paint disbonding from the graphene coating. Taking an average from all 12 cross-hatch data points of the area of paint removed, the overall removal area for the paint adhesion test on the graphene coating protected panels was 22.66%, or a 2B classification. No paint removal was observed in the x-cut method. Figure 6-124 shows representative photos of the cross-hatch and x-cut methods.

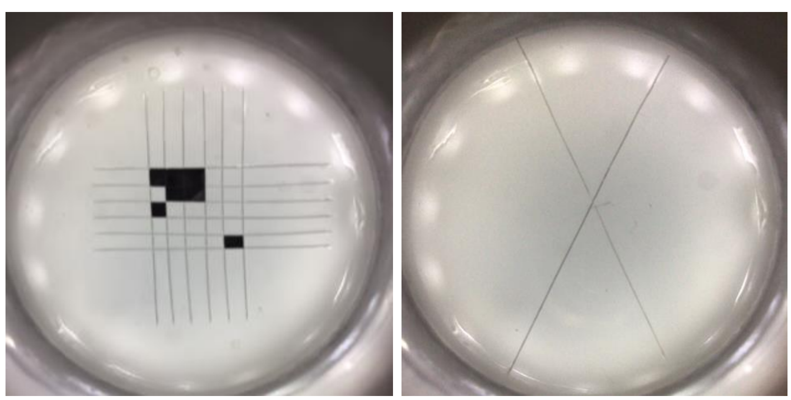


Figure 6-124: Cross-Hatch (left) and X-Cut (right) Paint Adhesion on LGrZ1-K1

The ElectroVeil protected panels can be considered the baseline for the paint adhesion test as there were no non-standard materials present between the panel and the paint, or within the paint system. The ElectroVeil panels contained the LSP embedded in a layer of surfacing film which is chemically identical to ECF protected panels in terms of paint adhesion. Averaging the results from the six cross-hatch data points, the area of paint removed from the ElectroVeil panels was 57%, corresponding to a 1B classification. No paint removal was observed in the x-cut method. Figure 6-126 shows representative photos of the cross-hatch and x-cut methods.

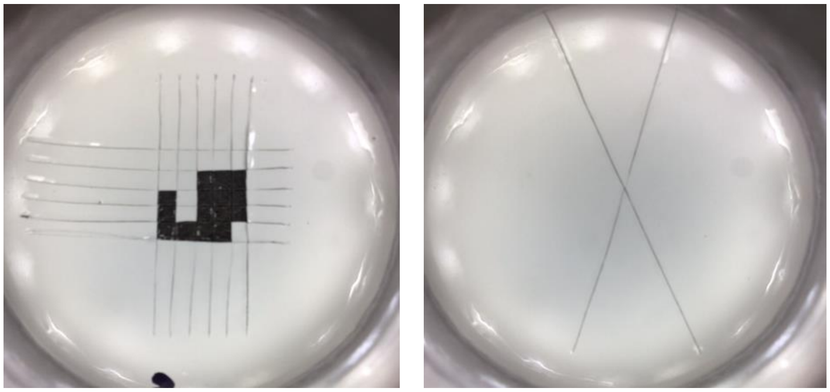


Figure 6-125: Cross-Hatch (left) and X-Cut (right) Paint Adhesion on LEZ2-N2

The presence of the NNS in the topcoat layer of the standard aircraft paint negatively altered the results on the paint adhesion as compared to the ElectroVeil material. Taking an average from all six cross-hatch data points of the area of paint removed, the overall removal area for the paint adhesion on the NNS protected panels was 99.33%, or a 0B classification. No paint removal was observed in the x-cut method. Figure 6-126 shows representative photos of the cross-hatch and x-cut methods.

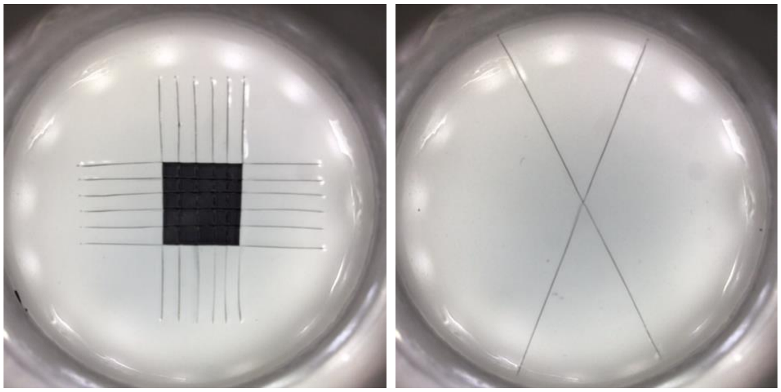


Figure 6-126: Cross-Hatch (left) and X-Cut (right) Paint Adhesion on LNiZ1-K1

Table 6-64: Paint Adhesion Results via Cross-Hatch Method

LSP	Paint Thickness (mils)		Paint Adhesion Result		
	Average	St. Dev.	Location 1	Location 2	Location 3
Graphene	11.68	0.2	2B	3B	2B
Graphene	10.75	0.15	2B	2B	1B
Graphene	12.03	0.48	4B	4B	2B
Graphene	9.98	0.43	1B	5B	1B
NNS	10.15	0.34	0B	0B	0B
NNS	9.6	0.29	0B	0B	0B
ElectroVeil	12.76	0.26	2B	4B	1B
ElectroVeil	13.44	0.81	0B	1B	0B

Table 6-65: Paint Adhesion Results via X-Cut Method

LSP	Paint Thickness (mils)		Paint Adhesion Result		
	Average	St. Dev.	Location 1	Location 2	Location 3
Graphene	10.35	0.48	5A	5A	5A
Graphene	10.36	0.14	5A	5A	5A
Graphene	10.99	0.48	5A	5A	5A
Graphene	10.07	0.42	5A	5A	5A
NNS	9.5	0.57	5A	5A	5A
NNS	10.09	0.34	5A	5A	5A
ElectroVeil	11.67	0.45	5A	5A	5A
ElectroVeil	13.46	0.54	5A	5A	5A

Table 6-66: Classification of Adhesion Test Results Legend – From ASTM D3359 [6.7]

Cross Hatch		X-Cut	
Classification	% Area Removed	Classification	Description
5B	0%	5A	No peeling or removal
4B	<5%	4A	Trace peeling or removal along incision or at their intersection
3B	5-15%	3A	Jagged removal along most of incisions up to 1/16” on either side
2B	15-35%	2A	Jagged removal along incision up to 1/8” on either side
1B	35-65%	1A	Removal from most of the area of the X under the tape
0B	>65%	0A	Removal beyond the area of the X

6.11.5 Conclusions

- The graphene based coating did not provide sufficient lightning strike protection in Zone 1A or Zone 2A test points.
- The ElectroVeil material performed as well as a comparable dry weight of ECF on the 12 ply laminate in Zone 2A.
- The NNS material at a 7 v/v% did not provide sufficient lightning strike protection in Zone 1A or Zone 2A test points.
- The LM PAEK NNS panels sustained less damage than the equivalent epoxy panels.
- The graphene protected panels had the best paint adhesion of all three LSP materials, and the NNS material performed the worst.

Chapter 6 References

[6.1] D.W. Van Krevelen and K. Te Nijenhuis, 'Crystallization and Recrystallization' *Properties of Polymers Their Correlation with Chemical Structure; Their Numerical Estimation and Prediction from Additive Group Contributions.* The Netherlands: Elsevier, 2009

[6.2] McKelvey, T., et al. "Vibration Data Analysis for a Commercial Aircraft." *Automatica*, vol. 32, no. 12, Dec. 1996, pp. 1689–1700., doi:10.1016/s0005-1098(96)80005-7.

[6.3] Okur, E., et al. "Investigation of Fatigue Behaviour of External Stores Under Fixed Wing Aircraft Platforms During Random Vibration."2011. Middle East Technical University, Master's Thesis.

[6.4] Galef, A. E. "Literature Review : AIRCRAFT EQUIPMENT RANDOM VIBRATION TEST CRITERIA BASED ON VIBRATIONS INDUCED BY TURBULENT AIRFLOW ACROSS AIRCRAFT EXTERNAL SURFACES Dreher, J. F. U.S. Naval Res. Lab., Shock Vib. Bull. 43 (3), 127-138 (June. 1973) 16 Refs Refer to Abstract No. 73-1686." *The Shock and Vibration Digest*, vol. 6, no. 5, 1974, pp. 61–61., doi:10.1177/058310247400600523.

[6.5] Adams, Daniel. "Environmental Testing of Composites." *CompositesWorld*, CompositesWorld, 12 Nov. 2019, www.compositesworld.com/articles/environmental-testing-of-composites.

[6.6] Fisher, Franklin A., et al. *Lightning Protection of Aircraft*. Lightning Technologies Inc., 2004.

[6.7] ASTM Standard D3359-22, "Standard Test Methods for Rating Adhesion by Tape Test," ASTM International, West Conshohocken, PA, 2023, DOI: 10.1520/D3359-22, www.astm.org