# COMMON PRACTICE LIGHTNING STRIKE PORTECTION CHARACTERIZATION TECHNIQUE TO QUANTIFY DAMAGE MECHANISMS ON COMPOSITE SUBSTRATES

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## ABSTRACT

To support FAA certification airworthiness standards, composite substrates are subjected to lightning direct-effect electrical waveforms to determine performance characteristics of the lightning strike protection (LSP) conductive layers used to protect composite substrates. Test results collected from independent LSP studies are often incomparable due to variability in test procedures & applied practices at different organizations, which impairs performance correlations between different LSP data sets. Under a NASA supported contract, The Boeing Company developed technical procedures and documentation as guidance in order to facilitate a test method for conducting universal common practice lightning strike protection test procedures. The procedures obtain conformity in future lightning strike protection evaluations to allow meaningful performance correlations across data sets.

This universal common practice guidance provides the manufacturing specifications to fabricate carbon fiber reinforced plastic (CFRP) test panels, including finish, grounding configuration, and acceptable methods for pretest nondestructive inspection (NDI) and posttest destructive inspection. The test operations guidance elaborates on the provisions contained in SAE ARP5416 to address inconsistencies in the generation of damage protection performance data, so as to provide for maximum achievable correlation across capable lab facilities. In addition, the guidance details a direct effects test bed design to aid in quantification of the multi-physical phenomena surrounding a lightning direct attachment supporting validation data requirements for the development of predictive computational modeling. The lightning test bed is designed to accommodate a repeatable installation procedure to secure the test panel and eliminate test installation uncertainty. It also facilitates a means to capture the electrical waveform parameters in 2 dimensions, along with the mechanical displacement and thermal heating parameters which occur during lightning attachment.

Following guidance defined in the universal common practice LSP test documents, protected and unprotected CFRP panels were evaluated at 20, 40 and 100KAmps. This report presents analyzed data demonstrating the scientific usefulness of the common practice approach. Descriptions of the common practice CFRP test articles, LSP test bed fixture, and monitoring techniques to capture the electrical, mechanical and thermal parameters during lightning attachment are presented here. Two methods of measuring the electrical currents were evaluated, inductive current probes and a newly developed fiber-optic sensor. Two mechanical displacement methods were also examined, optical laser measurement sensors and a digital imaging correlation camera system. Recommendations are provided to help users implement the common practice test approach and obtain LSP test characterizations comparable across data sets.

## ACRONYMS

| | |
|---|---|
| AEST | Atmospheric Environment Safety Technologies |
| CFRP | Carbon Fiber Reinforced Plastic |
| CRES | Corrosion resistant steel |
| DN | Drawing Note |
| ECF | Expanded Copper Foil |
| FAA | Federal Aviation Administration |
| IR | Infra Red |
| KA | Kilo Amps |
| LSP | Lightning Strike Protection |
| NCAMP | National Center for Advanced Materials Performance |
| NIAR | National Institute for Aviation Research |
| NDE | Nondestructive evaluation |
| NMS | NCAMP Material Specification |
| NPS | NCAMP Process Specification |
| OML | Outer Mold Line (smooth Tool Side of Lay-up, this side is painted, and is also the side to be directly exposed to simulated lightning currents) |
| SAE | Society of Automotive Engineers |
| SURF | Surfacer |

## INTRODUCTION

NASA's work in advanced aeronautics includes growing interest in environmentally responsive aircraft, one component of which involves the use of composite materials to significantly reduce weight, and hence fuel consumption. The aircraft industry shares this interest and is utilizing more composite materials in each new generation of aircraft being manufactured for general aviation, business jet and jumbo jet aircraft applications. Boeing's 787 aircraft is just one example of the growing use of composites being incorporated in the construction of the next generation fleet.

With the increased use of composite materials in aircraft construction, new technical challenges arise. Composite skinned aircraft are far more vulnerable to lightning strikes than their aluminum skinned predecessors. Without proper lightning strike protection, the carbon fiber/epoxy composites can be significantly damaged, particularly at the entry and exit points of the strike. Approaches have been developed to protect the composite structures from lightning direct effects to reduce damage to acceptable levels by using conductive foils or meshes in the outer layer of the composite system (ref 1).

To ensure adequate lightning protection measures are implemented, direct effect lightning tests are mandated for aircraft certification following provisions contained in ARP5416. However, differences in the preparation of composite test articles as well as variability in test procedures & practices between independent LSP studies have made it difficult to compare and contrast performance differences between different LSP data sets. These inconsistencies limit the value of supplied data and prevent direct correlation between different LSP data sets.

A Universal Common Practice Guide to Conduct Lightning Energy Transfer Characterizations has been developed by Boeing Research & Technology under NASA contract #NNL10AA05B and demonstrated by NASA and to facilitate consistency in future carbon composite lightning strike protection evaluations and provide the means to obtain performance correlations across data sets. The Universal Common Practice documents specify the processes required to manufacture (DOC-128694), inspect (DOC-12865), test (DOC-128696) and conduct post-strike damage assessments (DOC-128697) to compare LSP performance metrics on composite substrate test panels. It is recognized that many factors besides lightning damage protection are involved in the selection of appropriate LSP for a particular CFRP system (e.g., cost, weight, corrosion resistance, shielding effectiveness, etc). The Universal Common Practice documents strive primarily to address the uniformity of test methods.

## LSP COMPOSITE SUBSTRATE MANUFACTURING PROCESSING GUIDE

Manufacturing procedures to fabricate protected and unprotected Carbon Fiber Reinforced Plastic (CFRP) test panel configurations that can be employed for the purposes of evaluating the protection capabilities of lightning strike protection materials are documented in NASA DOC-128694 (ref 2). The composite test panels are intended to provide consistent behavior in their response to simulated lightning strikes at pre-defined levels when tested by a capable vendor according to a test procedure written to enable consistent results. It is expected that commercial vendors of existing and emerging LSP materials and concepts would use the behavior of this protected configuration as a baseline performance standard which they would try to meet or exceed.

The unprotected configuration consists of a cured CFRP laminate stack up of tape (Hexcel HexPly 8552/AS4) and fabric (Hexcel HexPly 8552 / A193-PW, 3K-70-PW) prepregs, coated with a typical aerospace primer (0.5-1.5 mils thick) and paint (4-6 mils thick) finishing scheme. The finished panels are attached to aluminum grounding bars intended to draw electrical current from the lightning attachment point to the panel edges and thus to ground. The protected configuration contains a top LSP layer made up of Cytec Surfacemaster 905C Composite Surfacing Film above Dexmet 3CU7-100FA expanded copper foil and is included in the laminate stack up prior to cure. The laminates are to be designed per common aerospace industry practices (balanced, symmetric and sequence). The typical lightning strike panel will be quasi-isotropic in nature with a fabric ply on each side of the laminate. The laminate stack is defined as follows; 16 ply tape with 2 ply fabric (as follows):[(0/90F)/45/90/-45/0/45/90/-45/0/0/-45/90/45/0/-45/90/45/(0/90F)].

The panels have countersunk fastening with 2 inch spacing. Each panel is fastened to four independent aluminum ground bars. Common steel or CRES fasteners are used to provide a conductive path from the panel to the frame and eventually into the test equipment ground. Figure 1 shows a test panel with ground bars attached.

Figure 1. Photograph of CFRP Test Panel

## LSP COMPOSITE SUBSTRATE NDE ASSESSMENT

To ensure manufacturing quality control of the CFRP tests panels, the panels must undergo nondestructive evaluation testing to quantify their pretest condition. NASA DOC-128695 defines an appropriate pre-test inspection of the panel to ensure integrity of post-strike test results (ref 3). This reference guidance states the cured panels will be examined with a through transmission ultrasonic (TTU) 'C' scan inspection at 5 mHz. An ultrasonic indication (flaw) is an area with ultrasonic attenuation that is at least 6dB larger than the attenuation of the adjacent areas without flaws or defects. An ultrasonic "defect" is an indication greater than 0.50 inch in diameter. Multiple indications are allowed, up to three (3) per panel, as long as they are at least 1.00 inch apart. Any deviations are noted in the test data report. Figure 2 shows a typical TTU image of a CFRP test panel.

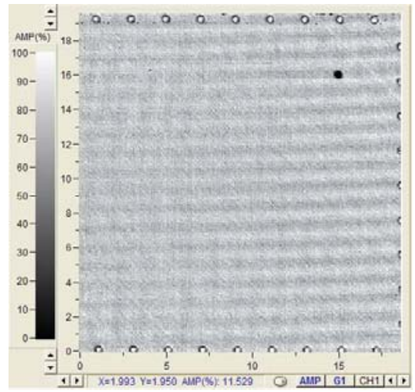


Figure 2. Typical TTU Image of CFRP Test Panel

## LSP COMPOSITE SUBSTRATE LIGHTNING TEST OPERATIONS MANAUL

Procedures to conduct lightning direct effects tests to provide a common baseline for correlation and comparison between LSP datasets are specified in NASA DOC-128696 (ref 4). This guidance defines the test setup and procedures to conduct direct effect lightning testing on CFRP test panels following provisions contained in ARP5416. The guidance in this document define test current waveform component D at 100 KA, 40 KA and 20 KA be combined with components B & C into a continuous lightning discharge. The 100 KA waveform is a D-bank waveform of 100,000 amps in conjunction with component B & C follow-on waveforms. The 40 KA and 20 KA test current waveforms are similar but at the reduced Component D peak current level. The specific pulse durations, action integral and charge transfer of the waveform components are mandated in ARP5416.

A test bed is used to secure the test article in a fixed position during test and constructed to minimize fixture-induced motion during the application of test current. The lightning test waveform will be injected into the test article by a jet diverting probe and initiator wire. Current from each of the ground bars as well as total current will be measured by current sensors. Additional test bed specifications will be discussed later in this paper. Figure 3 shows a CRFP test panel installed in the test bed. Kapton covers are used over the clamps to prevent attachment to the clamps.

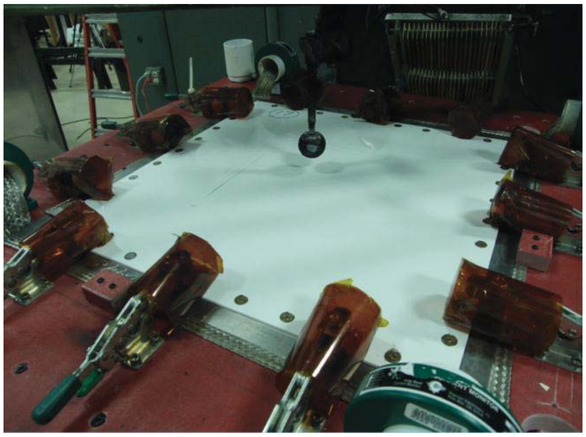

Figure 3. CFRP Panel installed in Test Bed.

## LSP COMPOSITE SUBSTRATE DESTRUCTIVE EVALUTAION TEST ASSESSMENT MANUAL

NASA DOC-128697 defines the post-test non-destructive and destructive evaluations of CFRP test panels for the purpose of evaluating the protection capabilities of LSP materials (ref 5). This guidance defines pulse echo ultrasonic testing to be performed to determine the extent of non-visible damage in the post-strike CFRP test panel. Pulse echo testing should be performed on both sides of the panel. It uses a single transducer that transmits and receives longitudinal waves in the range of 0.5 to 20 MHz. An ultrasonic indication (flaw) is an area with ultrasonic attenuation that is at least 6dB larger than the attenuation of the adjacent areas without flaws or defects. Delaminations in composites are also exhibited as acoustic signal returns at depth levels less than the full thickness of a laminate.

Destructive assessment involves taper sanding of the damaged area of the panel to determine how deep the actual damage is since pulse-echo ultrasound techniques have difficulty finding damage regions laying deeper into a laminate than damaged regions laying closer to the surface contacting the ultrasonic transducer. Figure 4 shows a CFRP panel after the destructive assessment had been performed.

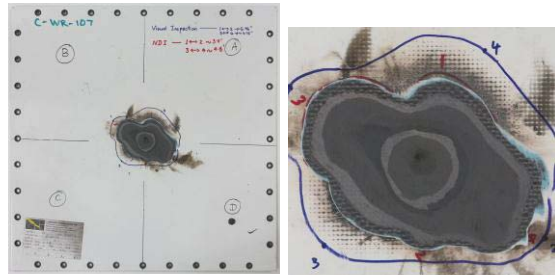

Figure 4. Photo of CFRP Panel after Taper Sanding.

## LSP COMPOSITE SUBSTRATE TEST BED DESIGN

The final reference guidance belonging to the Universal Common Practice Guide to Conduct Lightning Energy Transfer Characterizations is the LSP Composite Substrate Test Bed Design, NASA DOC-128698. This document describes a method to acquire real time monitoring of mechanical, thermal, and electrical parameters during plasma flashover arcing events (ref 6). Specifications are provided to safely monitor electrical current, temperature, and mechanical shock with adequate detection thresholds to support high fidelity modeling of composite structures for direct effect lightning damage assessments.

This approach is necessarily subjective, but the general approach taken has been to design a test bed that provides features for testing and modeling which are as good as or better than any methods established in leading laboratories today. The instrumentation recommended was selected based on practicality and affordability for an ongoing lightning test operation. The procedures and specifications in the referenced document will enable a high degree of correlation of results between testers.

The test bed fixture design allows leeway in construction provided the resulting structure has comparable rigidity and capability. The test panel is secured in position by toggle clamps which apply pressure to the panel’s ground bars and ensures solid contact to the 4 grounding straps. Four Pearson 4418 Current Probes are used to monitor the electrical current on the 4 grounding straps. The test bed design allows all four edges of the test panel to be independently sensed and provides a means to study current propagation for asymmetric LSP designs. Figure 5 shows a picture of the test bed assembly at Lightning Technologies Incorporated (LTI).

Figure 5. Test Bed installed at LTI.

A FLIR Systems SC645 IR camera is mounted 48" directly below the test panel to capture back side temperatures. Thermal data can be used to quantify energy deposition on test panels to identify attachment location and propagation direction and provide validation data for damage computation modeling. The SC645 camera has adequate thermal range, speed and remote operation making it ideally suited to monitor back side temperatures.

Mechanical displacement of the panel deflection is monitored using Keyence LK-G507 laser displacement sensors mounted 28" beneath the panel. A band pass Optical Filter (Keyence part OP-87110) is also required to eliminate lightning flash interference on the optical detector. This sensor has adequate sampling speed and range resolution to capture the peak deflection and sense lower-order vibrations. The test bed design specifies up to 3 displacement sensors to allow displacement measurements from multiple locations if desired. Figure 6 shows the IR camera and laser displacement sensors mounted in the test bed.

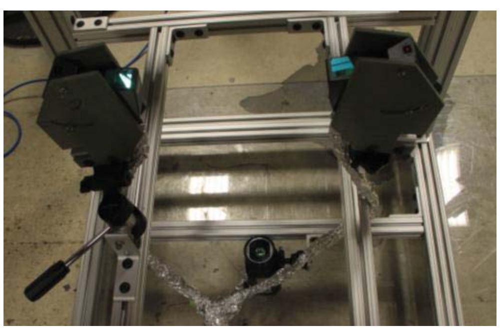

Figure 6. IR camera and laser displacement sensors mounted in the test bed

## LIGHTNING TEST RESULTS

The procedures defined in the Universal Common Practice Guide to Conduct Lightning Energy Transfer Characterizations were demonstrated in two lightning direct effect tests at the National Technical Systems' (NTS) Lightning Technologies (LTI) facility in Pittsfield, MA. Baseline lightning test assesments were obtained for protected and unprotected CFRP test panels in September, 2012 and again in July, 2013. The lightning test bed was succesfully implemented and caputred the electrcial, mechanical and thermal damage mechanism parameters during lightning strike attachment to the CFRP test panels.

The CFRP panels tested were manufactured in accordance to guidance in NASA DOC-128694 by Cessna Aircraft Company under a NASA contract in March 2012. Cessna further conducted pretest NDE assessment according to NASA DOC-128695 to ensure the test panels were within design specifications. These NASA documents were effective in providing Cessna the detailed specifications necessary to quote, manufacture and qualify the CFRP test panels without additional clarification. Cessna suggested a paint thickness of around 10 mils would better represent actual aircraft paint installations.

The protected and unprotected baseline CFRP panels were subjected to Component D waveform at 20, 40 & 100 KA peak currents with follow on Components B & C in a continuous lightning discharge in compliance with ARP5416 following test procedures in NASA DOC-128696. A minimum of 3 test panels were evaluated for each configuration and test condition during the September 2012 lightning test. In July 2013, 3 additional protected and 3 unprotected panels were retested at 100KA peak current.

## ELECTRICAL

The electrical current on the 4 edges of the test panel were independently monitored during the lightning test. 4 Pearson 4418 Current Probes were used to monitor the electrical ground current off the edges of the CFRP panel. The 4 ground straps were installed with equal length and kept as short as possible. A quarter inch thick Aluminum calibration test plate was struck repeatedly as a test case to measure current at the 4 edges to ensure no significant bias was observed. For this isotropic calibration test panel it is expected each ground strap would receive approximately 25% of the total current. Table 1 presents the peak current data measured on the 4 Pearson probes identified as Coil 1 thru Coil 4 for the July 2013 lightning test for 3 repeated strikes to the Aluminum calibration test plate and 3 protected and 3 unprotected CFRP panels struck at around 100KA.

The test data show the electrical current on each of the 4 ground straps is within about 5% of being equally distributed at peak current. Further investigation is needed to determine if adjustments to the length of individual ground straps could reduce the level of bias from the measurement or replacing the used braided copper ground strap with new straps would eliminate the bias. The Pearson probes were within calibration specifications. The CRFP test panel data show similar bias as the Aluminum calibration plate with coil 3 typically measuring higher and coils 1 and 4 typically measuring lower. These results are believed to have not impacted this study, but future evaluations of asymmetrical LSP concepts would require improved measurement fidelity. Figure 6 presents the electrical current measured at the 4 sides of a baseline protected CFRP panel at 100KA.

| Test Panel | Peak I (KA) | Coil 1 | Coil 2 | Coil 3 | Coil 4 |
|---|---|---|---|---|---|
| Al. Plate | 100 | 20.8 | 24.4 | 35.2 | 20.2 |
| Al. Plate | 100 | 21.6 | 24.4 | 35.2 | 20.2 |
| Al. Plate | 100 | 21.6 | 24.4 | 35.2 | 20.6 |
| Unprotected | 100 | 20.6 | 24.4 | 33.6 | 19.8 |
| Unprotected | 100 | 20.4 | 27.4 | 30.6 | 16.8 |
| Unprotected | 100 | 20.2 | 24.6 | 33.4 | 19.2 |
| Protected | 100 | 21.6 | 25.2 | 34.0 | 19.6 |
| Protected | 100 | 22.4 | 24.8 | 35.2 | 19.8 |
| Protected | 100 | 20.2 | 26.6 | 33.0 | 18.4 |

Table 1. Pearson Probe Current Data collected July 2013.

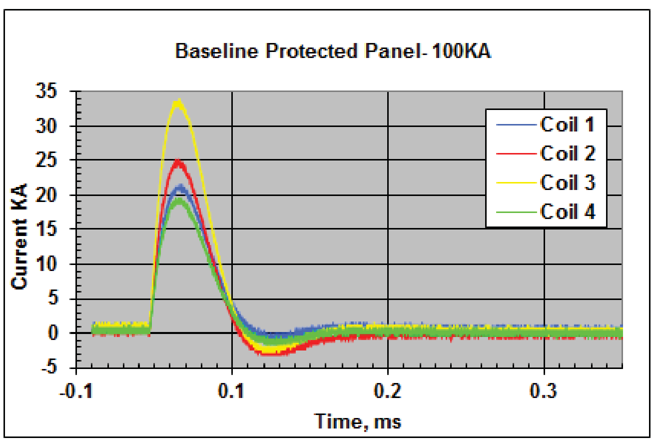


Figure 6. Current waveform at 100KA measured on the 4 edges of the protected baseline CFRP panel.

A NASA Langley developed 1310nm-Based Fiber-Optic Sensor was also used to record lightning currents at LTI in September 2012.(ref 7) The system performed well and showed great potential utilization in laboratory settings. Test labs typically use multiple sensors to capture A or D with B & C combined waveform components. The Faraday sensor can capture the full waveform. Test labs also typically will not allow measurement of the incident lightning current before it goes thru the jet diverter for safety reasons. A Faraday sensor could safely monitor input current for purposes of scientific study. The Faraday sensor is a promising new instrument for measuring currents in lightning labs.

## MECHANCIAL

Two Keyence LK-G507 laser displacement sensors were used to measure the peak deflection at the center of the panel. A band pass Optical Filter (Keyence part OP-87110) were needed to eliminate interference from the lightning flash. White spray paint was applied to the back side of the panels to compensate for the reduction in received laser power due to the optical filter. The sensors were placed 28” from the back surface of the panel and 13.1 degrees off normal to prevent the sensors from blocking the IR camera view. The data is adjusted to compensate for the off normal measurement. The sensor was sampled at 100 microseconds. A fiber optic link was used to connect the laptop computer outside the test area with the Keyence controller inside the test facility to manually trigger data collection. The cables between the Keyence sensors and Keyence controller were wrapped in metal foil to prevent electromagnetic interference from the lightning strike. The controller buffers 65536 data points with each trigger. Approximately 6.5 seconds of data is collected for each strike. Automated triggering would ensure more reliable data collection from the Keyence sensors.

Table 2 shows selective peak deflections at 100KA for the Aluminum plate, and protected and unprotected CFRP panels. The data presented show the unprotected CFRP panels have about 1 mm higher deflection than protected panels. The Aluminum plate has a higher deflection with paint than without paint. This type of qualitative data enables a more thorough analysis of LSP solutions to minimize damage caused by mechanical force from the lightning induced shock wave.

A time profile of mechanical displacement versus time is presented in Figure 7 for an Aluminum plate with paint, unprotected and protected CFRP test panels at 100 KA. The data shows a typical damped sinusoidal response from the lightning impact on the test panel.

In addition to the Keyence sensors, a Digital Image Correlation (DIC) system was used to acquire full field displacements on the back surface during the lightning strike tests in September 2012. The DIC technique uses a pair of digital high speed cameras (Phantom V7.3, fitted with Schneider Optics Xenon-Emerald 2.8/28mm lens) to record images of the panels back surface. The back surface was spray painted with a white finish and a stamped on black speckle pattern. Correlation software (manufactured by Correlated Solutions Inc., VIC 3D 2010) is used to determine the displacements of the surface based on the motion of the speckle pattern. The cameras were mounted on the floor approximately 50 inches away from the back of the panel and operated at 650 frames per sec with a resolution of 800 x 600 pixels. The DIC system worked well and provided valuable validation data to computational damage modeling researchers.

| Test Panel | Peak I (KA) | Sensor 1 Peak Deflection (mm) | Sensor 2 Peak Deflection (mm) |
|---|---|---|---|
| Al. Plate | 100 | 0.56 | 0.44 |
| Al. Plate | 100 | 0.57 | 0.62 |
| Al. Plate with Paint | 100 | 1.15 | 1.04 |
| Unprotected | 100 | 3.78 | 3.77 |
| Unprotected | 100 | 3.72 | 3.76 |
| Protected | 100 | 2.35 | 2.63 |
| Protected | 100 | 2.86 | 2.82 |

Table 2. Mechanical Displacement Measured at Center of Test Panel.

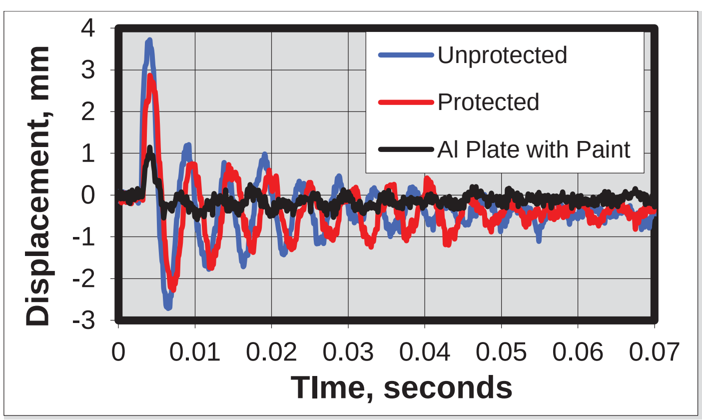


Figure 7. Displacement versus Time Plot of Aluminum Plate with Paint, Unprotected and Protected CFRP Test Panels at 100 KA.

**THERMAL**

A FLIR Systems SC645 IR camera was used to capture the temperature on the backside of the test panel during lightning strike. The camera acquired 30 seconds of data at 25Hz for each acquisition. This was adequate to capture the peak temperatures on the back side of the panel. The camera was mounted 48” directly below the test panel to capture back side temperatures. The IR camera was manually triggered with a fiber optic link connecting the camera to a laptop computer outside the test area. The camera power cable and Ethernet cable going to the fiber optic link were covered with metal foil to prevent upset. Automated triggering for the IR camera would ensure more reliable data collection.

IR cameras can accurately measure calibrated temperatures if the thermal emissivity of the measured object is known. Even though IR data was acquired during the two test series, the back side emissivity of the test panels were not measured and true calibrated temperatures have not been established on this test data. The back side emissivity varied between test panels and relative temperature values could not reliably be established. Some panels had white paint on the back side to ensure the Keyence sensors operated correctly with the optical filters and others had white paint with black speckles to support the digital image correlation testing. The rest had no paint on the back side. It is recommended that guidance be included in the Universal Common Practice to specify an appropriate white coating of known emissivity to be applied to the back side of the test panels to eliminate the need for additional testing to acquire calibrated temperatures.

**DAMAGE ASSESSMENT**

Damage assessments were conducted on the struck CFRP panels in accordance to guidance in NASA DOC-128697 by the National Institute for Aviation Research (NIAR) at Withita State University under a NASA contract in May 2013. The NASA document was sufficient to enable NIAR to quote the task and perform the damage assessment without additional clarification. Table 3 presents a summary of the nondestructive damage assessment showing the pulse echo (PE) damage depth measurement and Through Transmission Ultrasound (TTU) damaged area measurements for protected and unprotected CFRP panels at 20, 40 and 100 KA strike currents. The data shows a fairly wide variation in damage depth and damage area within the same test configuration and current level and appears to have an inverse relationship between damage depth and damage area.

Comparisons of like panels at the same current level typically show deeper damage has a smaller damage area. Additional test panels are needed to increase the statistical data set to improve confidence in this data.

| Test Panel | Peak I (KA) | Maximum Damage Depth per PE (in) | Damage Area per TTU (in2) |
|---|---|---|---|
| Unprotected | 20 | 0.028 | 4.552 |
| Unprotected | 20 | 0.083 | 5.978 |
| Unprotected | 20 | 0.026 | 9.491 |
| Unprotected | 40 | 0.054 | 4.831 |
| Unprotected | 40 | 0.045 | 4.43 |
| Unprotected | 40 | 0.036 | 7.855 |
| Unprotected | 100 | 0.048 | 8.35 |
| Unprotected | 100 | 0.06 | 10.707 |
| Unprotected | 100 | 0.055 | 9.771 |
| Protected | 20 | 0.05 | 3.244 |
| Protected | 20 | 0.035 | 7.345 |
| Protected | 20 | 0.038 | 2.558 |
| Protected | 40 | 0.04 | 6.5 |
| Protected | 40 | 0.038 | 4.895 |
| Protected | 40 | 0.04 | 1.326 |
| Protected | 100 | 0.031 | 6.688 |
| Protected | 100 | 0.05 | 5.145 |
| Protected | 100 | 0.042 | 6.091 |

Table 3. Nondestructive Damage Assessment Summary

Table 4 presents the averaged damage depth and damage area from data in Table 3 for each test scenario. The unprotected panels clearly have deeper damage over a larger area than protected panels at the same current level. However, comparisons between the same panel configurations at different current levels does not show a meaningful trend as one would expect and suggests additional test data are needed to improve statistical confidence.

| Test Panel | Peak I (KA) | Average Damage Depth per PE (in) | Average Damage Area per TTU (in2) |
|---|---|---|---|
| Unprotected | 20 | 0.056 | 6.67 |
| Unprotected | 40 | 0.045 | 5.7 |
| Unprotected | 100 | 0.054 | 9.61 |
| Protected | 20 | 0.041 | 4.38 |
| Protected | 40 | 0.039 | 4.24 |
| Protected | 100 | 0.041 | 5.97 |

Table 4. Averaged Nondestructive Damage Assessment

Through Transmission Ultrasound was not the NDE technique defined in the Universal Common Practice to quantify the extent of damage area. NASA DOC-128697 states pulse echo ultrasonic testing should be performed to both sides of the panel to determine the extent or boundary of non-visible damage in the CFRP test panel. NIAR provided additional data using TTU analysis to complement the PE measurements even though PE measurements provided satisfactorily test results. Figure 8 shows a TTU scan of a damaged CFRP panel next to its photograph.

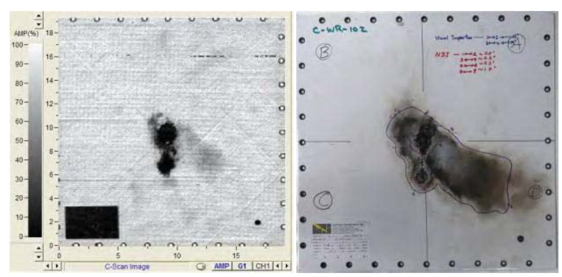


Figure 8  TTU scan of Damage CRFP (left), Photograph of Same Panel (right)

Destructive damage assessments were also conducted by NIAR after the nondestructive evaluations were performed on the 18 CFRP test panels. Destructive assessment procedures involve taper sanding the CFRP panel to remove all damage to determine the remaining residual thickness. Four measurements were made at the deepest damage locations. Table 5 presents the remaining thickness of undamaged composite from the four measurement readings of the destructive damage assessment.  Table 6 shows destructive damage assessment data for the protected panels. The data trends are shown to be similar to the PE damage depth measurements shown in Table 3. Additional test panels are needed to improve the statistical data set to develop higher confidence in these values.

| Peak I (KA) | Panel Thickness (in) | Calculated Minimum residual thickness (In) | Reading #1 | Reading #2 | Reading #3 | Reading #4 |
|---|---|---|---|---|---|---|
| 20 | 0.137 | 0.109 | 0.035 | 0.035 | 0.035 | 0.035 |
| 20 | 0.138 | 0.055 | 0.07 | 0.067 | 0.061 | 0.066 |
| 20 | 0.136 | 0.11 | 0.031 | 0.026 | 0.025 | 0.027 |
| 40 | 0.137 | 0.092 | 0.064 | 0.064 | 0.065 | 0.064 |
| 40 | 0.138 | 0.102 | 0.042 | 0.046 | 0.045 | 0.044 |
| 40 | 0.135 | 0.081 | 0.061 | 0.066 | 0.066 | 0.064 |
| 100 | 0.136 | 0.088 | 0.054 | 0.053 | 0.058 | 0.055 |
| 100 | 0.136 | 0.076 | 0.06 | 0.059 | 0.059 | 0.06 |
| 100 | 0.138 | 0.083 | 0.06 | 0.059 | 0.053 | 0.057 |

Table 5. Destructive Evaluation Residual Thickness Measurements for Unprotected CRP Test Panel

| Peak I (KA) | Panel Thickness (in) | Calculated Minimum residual thickness (In) | Reading #1 | Reading #2 | Reading #3 | Reading #4 |
|---|---|---|---|---|---|---|
| 20 | 0.145 | 0.095 | 0.039 | 0.028 | 0.029 | 0.032 |
| 20 | 0.144 | 0.109 | 0.021 | 0.024 | 0.022 | 0.022 |
| 20 | 0.141 | 0.103 | 0.02 | 0.02 | 0.018 | 0.019 |
| 40 | 0.142 | 0.102 | 0.031 | 0.021 | 0.024 | 0.025 |
| 40 | 0.143 | 0.103 | 0.042 | 0.042 | 0.041 | 0.042 |
| 40 | 0.143 | 0.105 | 0.022 | 0.026 | 0.027 | 0.025 |
| 100 | 0.144 | 0.113 | 0.014 | 0.008 | 0.016 | 0.013 |
| 100 | 0.143 | 0.093 | 0.047 | 0.031 | 0.033 | 0.037 |
| 100 | 0.143 | 0.101 | 0.032 | 0.034 | 0.036 | 0.034 |

Table 6. Destructive Evaluation Residual Thickness Measurements for Protected CRP Test Panel

## CONSLUSIONS

A Universal Common Practice Guide to Conduct Lightning Energy Transfer Characterizations has been developed by Boeing Research & Technology under NASA contract #NNL10AA05B and demonstrated by NASA to facilitate consistency in future carbon composite lightning strike protection evaluations and provide the means to obtain performance correlations across data sets. The Universal Common Practice documents specify the processes required to manufacture (DOC-128694), inspect (DOC-12865), test (DOC-128696) and conduct post-strike damage assessments (DOC-128697) to compare LSP performance metrics on composite substrate test panels. The guidance also includes the LSP Composite Substrate Test Bed Design, NASA DOC-128698. This document describes a method to acquire real time monitoring of mechanical, thermal, and electrical parameters during plasma flashover arcing events. Specifications are provided to safely monitor electrical current, temperature, and mechanical shock with adequate detection thresholds to support high fidelity modeling of composite structures for direct effect lightning damage assessments.

The procedures defined in the Universal Common Practice Guide were demonstrated by NASA in two lightning direct effect tests conducted at the National Technical Systems' (NTS) Lightning Technologies (LTI) facility in Pittsfield, MA in September 2012 and July 2013. The CFRP test panels were manufacutred by Cessna Aircraft Company under a NASA contract in March 2012. Cessna was able to quote, manufacture and qualify the CFRP test panels without additional clarification beyond the guidance documents.

The protected and unprotected baseline CFRP test panels were subjected to Component D waveform at 20, 40 & 100 KA peak currents with follow on Components B & C in a continuous lightning discharge in compliance with ARP5416. The electrical current on the 4 edges of the test panel were independently monitored during the lightning test. 4 Pearson 4418 Current Probes were used to monitor the electrical ground current off the edges of the CFRP panel. The test data showed the electrical current on each of the 4 ground straps was within about 5% of being equally distributed at peak current. Further investigation is needed to eliminate the bias from the grounding system to study asymmetrical LSP designs.

Two Keyence LK-G507 laser displacement sensors were used to measure the peak deflection at the center of the panel. A band pass Optical Filter (Keyence part OP-87110) was required to eliminate interference from the lightning flash. White spray paint was applied to the back side of the panels to compensate for the reduction in received laser power due to the optical filter. The mechanical test data showed the unprotected CFRP panels have about 1 mm higher deflection than protected panels at 100 KA and the Aluminum plate has a higher deflection with paint than without paint. Mechanical displacement data provides a means to quantify LSP solutions to minimize damage caused by mechanical force from the lightning induced shock wave.

A FLIR Systems SC645 IR camera was used to capture the temperature on the backside of the test panel during lightning strike. The back side emissivity of the test panels was not measured and true calibrated temperatures have not been established on this test data. It is recommended that guidance be included in the Universal Common Practice to specify an appropriate white coating of known emissivity to be applied to the back side of the test panels to eliminate the need for additional testing to acquire calibrated temperatures.

Damage assessments were conducted under a NASA contract in May 2013 by the National Institute for Aviation Research (NIAR) at Withita State University on the struck CFRP panels in accordance to guidnace in NASA DOC-128697. The NASA document was sufficient to enable NIAR to quote the task and perform the damage assessment without additional clarification.

The unprotected test panels showed deeper damage over a larger area than protected panels at the same current level. However, comparisons between the same panel configurations at different current levels did not show a meaningful trend as one would expect and suggests additional test data are needed to improve statistical confidence.

## REFERENCES

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