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Effects of Lightning on Pultruded Carbon Fiber Wind Blades

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Abstract. Modern wind turbine blades incur occasional damage from lighting strikes. In non-conductive glass laminates, lightning damage causes severe charring, and is often obvious from visual inspection. In conductive carbon laminates, lightning strikes do not always result in visible damage, and the impact on strength and fatigue resistance is uncertain. Thus, it is difficult to evaluate a carbon fiber wind blade suspected of receiving a lightning strike. This experimental study investigates the effect of electrical current running longitudinally through pultruded carbon fiber wind blade specimens. Testing simulated the worst 1% of lightning strike in terms of peak current, time to peak, and action integral, and the worst 50% of lightning strike in terms of charge transfer. Post-test, specimens were inspected using nondestructive inspection (NDI) methods and were then mechanically tested for ultimate tension and compression, and tension-tension fatigue. Results show that carbon fiber pultrusions withstand severe lightning currents with no visible or NDI-indicated damage. Preliminary structural tests show a decrease in ultimate compressive strength at the most severe lightning test case.

1. Introduction

Lightning is a prominent cause of blade failure. Occurrences and severity of lightning strike is expected to increase as wind turbine blade tip height continues to increase [1]. While lightning protection systems that run current to ground are common on modern-day turbines, failure of these systems does occur and can be problematic to the wind farm owner and operator. In non-conductive glass laminates, lightning damage causes severe charring, and is often obvious from visual inspection. In conductive carbon laminates, lightning strikes do not always result in visible damage, and the impact on strength and fatigue resistance is uncertain. Thus, it is difficult to evaluate a carbon fiber wind blade suspected of receiving a lightning strike.

Previous lightning impulse testing research has been completed on carbon fiber reinforced polymers (CFRP)s [2- 6] and aircraft composites [2, 5, 7- 9]. There has also been focus on attachment points of the leader [2, 5, 10]. Lastly, there are varying post-test methods that others have used, from strictly non-destructive investigation (NDI) methods to dynamic testing, micrographic inspection, compression, and shear testing [2, 5, 6, 8, 9]. The current work investigates the effect of current running longitudinally through pultruded carbon fiber wind blade specimens, rather than simulating a leader attachment. This assumes that lightning currents have entered the pultrusions and are being transferred between the fibers. Testing simulated the worst 1% of lightning strike in terms of peak current, time to peak, and action integral, and the worst 50% of lightning strike in terms of charge transfer [11]. After lightning testing,

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the specimens were inspected using ultrasonic, thermography, computed tomography technologies, and were mechanically tested for ultimate and transverse tension, and compression.

2. Objectives

The goal of this research is to determine the effects of lightning strikes on pultruded carbon fiber used in wind blades. Specifically, this study evaluates the impact on ultimate strength and fatigue resistance as a function of strike amperage and duration. If the impact is significant, can inspection equipment indicate the damage?

3. Methodology

3.1 Pre-Impulse Testing

Two types of pultruded carbon fiber specimens, vinylester (62% fiber volume fraction) and epoxy matrixed (65% fiber volume fraction), were used in this experiment. Specimens were 10.2cm wide by 19.7cm long by 0.05cm thick with fibers running longitudinally. Pre-test inspection of each specimen prior to lightning impulse testing included immersion and pulse echo ultrasonics, and thermography (Figure 1) at Sandia National Laboratories' Nondestructive Evaluation Lab. In immersion ultrasonics the specimen is submerged under water and a sound wave is sent and received from a transducer; any damage will reflect the sound back to the transducer sooner and that will be recorded in the scan. Immersion ultrasonics eliminate coupling problems between the specimen and transducer through submersion in water. MAUS pulse echo sends and receives data similarly to the immersion method with a single transducer sending and receiving data, however this is a fieldable technique and not submerged in water. A flash thermography setup was used consisting of two 5000 joule flash lamps that provide heat inside of a box. A camera then records images at 125 frames/second to create movies of heat transferring through the panel.

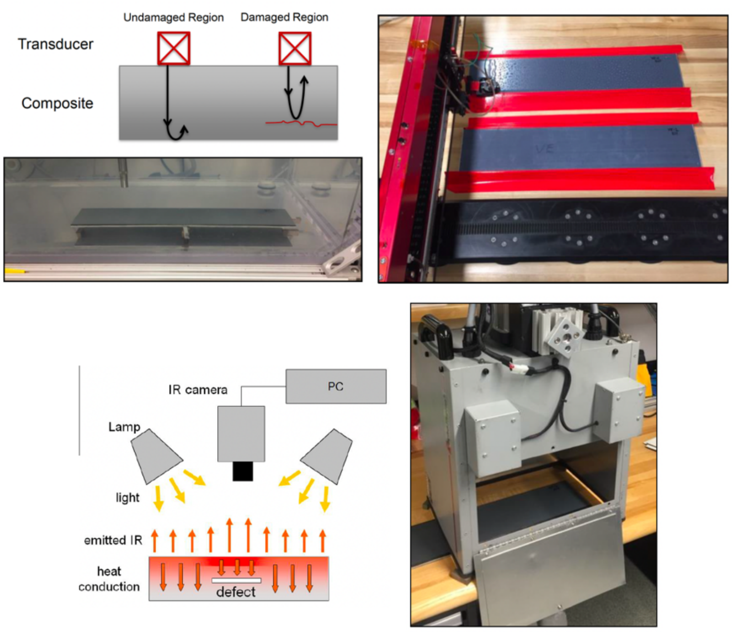

Figure 1: NDI methods: immersion ultrasonics (top left), MAUS pulse echo (top right), thermography (bottom).

3.2 Lightning Impulse Testing

Prior to testing, specimens were cut in half longitudinally. Testing setups were enclosed in environmental chambers for possible specimen explosion that could lead to asbestos-like hazards.

Lightning impulse testing was applied at 30 and 200kA peak-current, with current flow in the direction of carbon fiber alignment (right to left, Figure 2) and current measured by a current viewing transformer (CVT). Energy deposition in each specimen is characterized by the action integral, which is the time integral of the current-squared, in units of Joules/Ohm. The time-integral of the current gives the charge transfer across the specimen, in units of Coulombs. Representative plots of these characteristics can be found in Figure 3.

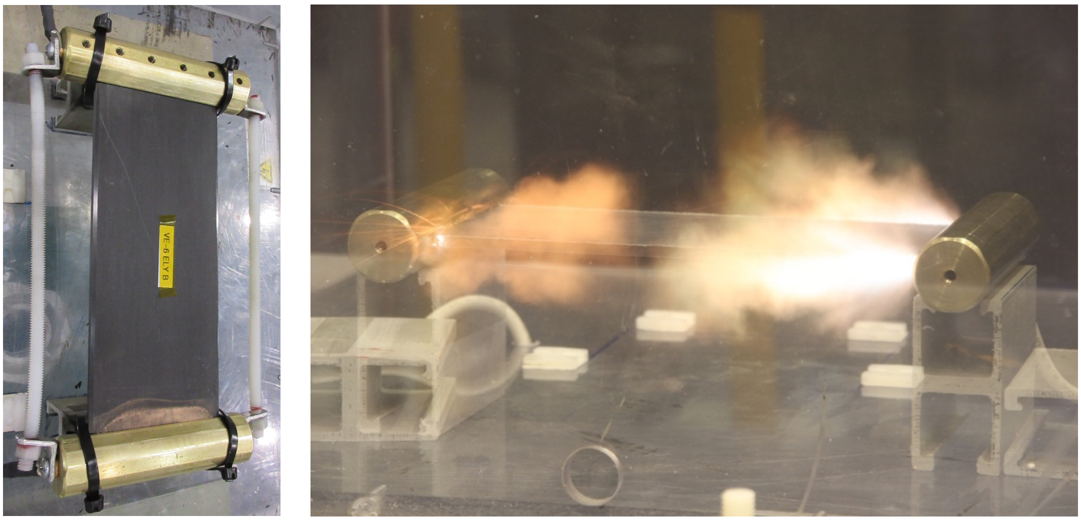

Figure 2: Lightning impulse testing fixture with specimen (left) and real-time test photo (right).

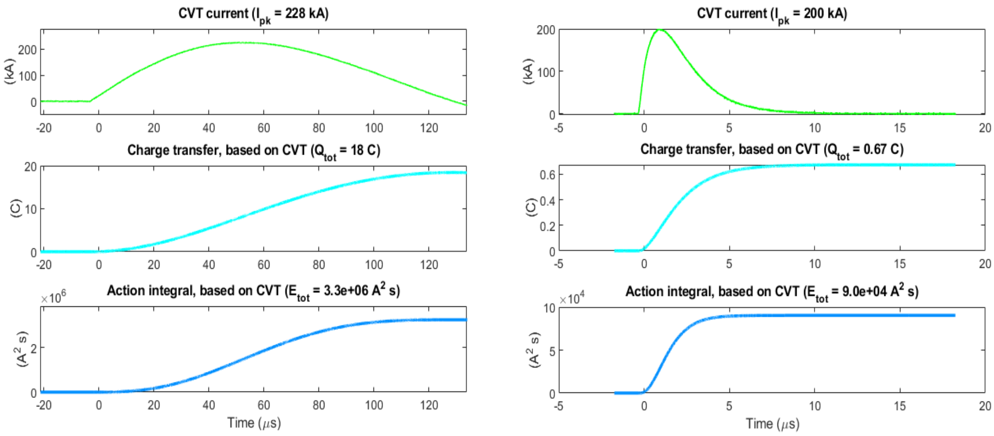

Figure 3: 30-microsecond rise time pulser (left), and 1-microsecond rise-time pulser (right) at around 200kA current.

Two pulser setups were used (with each peak-current level) including a 22kV, 30-microsecond rise-time pulser (Figure 2, 3) which allows for a maximum of ~20 Coulombs charge transfer across the specimen and more than 3×10^6 Joules/Ohm energy deposition in the specimen. A faster 200kV, 1-microsecond rise-time pulser (Figure 3) allows for a lower maximum of about 1 Coulomb charge transfer and about 10^5 Joules/Ohm energy transfer but represents the "worst" 1% of lightning transients. The 200kV, 1 microsecond rise-time pulser requires the high voltage components to be submerged in oil to prevent unwanted arcing (Figure 4). Together, the two pulsers cover the worst 1% of lightning strike in terms of peak current, time to peak, and action integral, and the worst 50% of lightning strike in terms of charge transfer [11]. Two pulsers and two current levels resulted in a total of 4 test cases

(Figure 5) applied to each matrix type specimen: 1-microsecond rise-time, 30kA peak current; 1-microsecond, 200kA; 30-microsecond, 30kA; and 30-microsecond, 200kA with 3 specimens per test case.

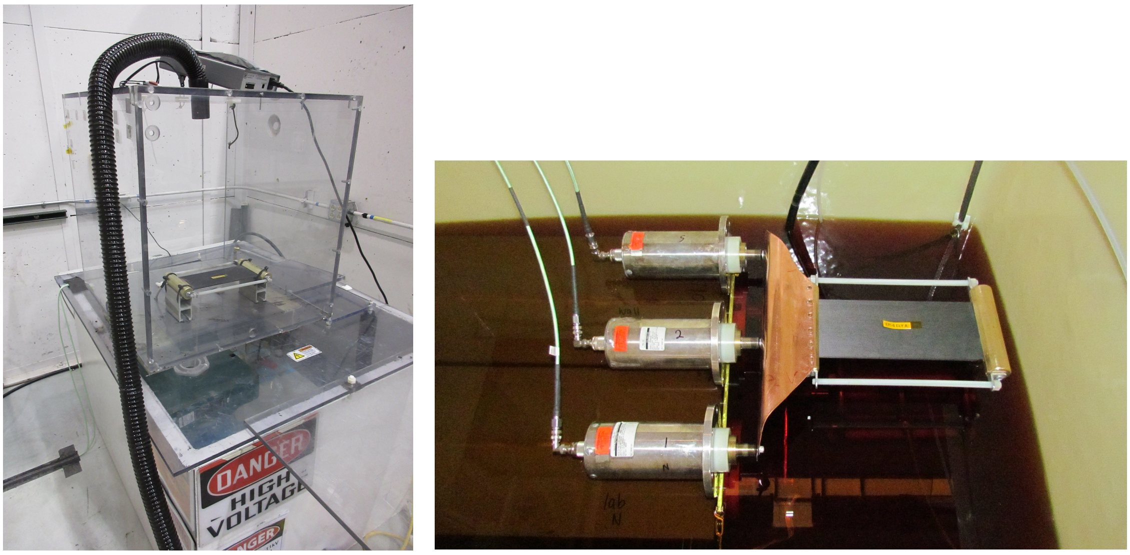

Figure 4: 22kV, 30-microsecond rise-time pulser (left), 200kV, 1-microsecond rise-time pulser (right).

1-µs pulser — 30 kA peak current

RETURN STROKE PARAMETERS[1]	1%	50%
a. Peak Current (kA)	200	30
b.Time to Peak (µs)	0.1-15	3
c. Max. Rate of Current Rise (kA/µs)	400	150
d.Time to Decay to Half Peak (µs)	10-500	50
e. Amplitude of Continuing Current[2] (A)	30-700	150
f. Duration of Continuing Current (ms)	500	150
FLASH PARAMETERS		
a. Number of Strokes	>20	4
b. Interstroke Interval (ms)	10-500	60
c. Total Flash Duration (ms)	30-1000	180
d. Total Charge Transfer (C)	350	15
e. Action Integral [$\int I^2 dt$] (A^2s)	$3x10^6$	$5x10^4$

[1]The entire cloud-to-ground discharge may be comprised of multiple individual major current pulses. These are known as return strokes or, simply strokes.

1-µs pulser — 200 kA peak current

RETURN STROKE PARAMETERS[1]	1%	50%
a. Peak Current (kA)	200	30
b.Time to Peak (µs)	0.1-15	3
c. Max. Rate of Current Rise (kA/µs)	400	150
d.Time to Decay to Half Peak (µs)	10-500	50
e. Amplitude of Continuing Current[2] (A)	30-700	150
f. Duration of Continuing Current (ms)	500	150
FLASH PARAMETERS		
a. Number of Strokes	>20	4
b. Interstroke Interval (ms)	10-500	60
c. Total Flash Duration (ms)	30-1000	180
d. Total Charge Transfer (C)	350	15
e. Action Integral [$\int I^2 dt$] (A^2s)	$3x10^6$	$5x10^4$

[1]The entire cloud-to-ground discharge may be comprised of multiple individual major current pulses. These are known as return strokes or, simply strokes.

30-µs pulser — 30 kA peak current

RETURN STROKE PARAMETERS[1]	1%	50%
a. Peak Current (kA)	200	30
b.Time to Peak (µs)	0.1-15	3
c. Max. Rate of Current Rise (kA/µs)	400	150
d.Time to Decay to Half Peak (µs)	10-500	50
e. Amplitude of Continuing Current[2] (A)	30-700	150
f. Duration of Continuing Current (ms)	500	150
FLASH PARAMETERS		
a. Number of Strokes	>20	4
b. Interstroke Interval (ms)	10-500	60
c. Total Flash Duration (ms)	30-1000	180
d. Total Charge Transfer (C)	350	15
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30-µs pulser — 200 kA peak current

RETURN STROKE PARAMETERS[1]	1%	50%
a. Peak Current (kA)	200	30
b.Time to Peak (µs)	0.1-15	3
c. Max. Rate of Current Rise (kA/µs)	400	150
d.Time to Decay to Half Peak (µs)	10-500	50
e. Amplitude of Continuing Current[2] (A)	30-700	150
f. Duration of Continuing Current (ms)	500	150
FLASH PARAMETERS		
a. Number of Strokes	>20	4
b. Interstroke Interval (ms)	10-500	60
c. Total Flash Duration (ms)	30-1000	180
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[1]The entire cloud-to-ground discharge may be comprised of multiple individual major current pulses. These are known as return strokes or, simply strokes.

Figure 5: Selections for test plan based on work by Uman, et al., 2010 [11].

3.3 Post-Test Nondestructive Inspection
Post-impulse testing specimens were returned to the Nondestructive Evaluation Lab for inspection using immersion and MAUS Pulse Echo ultrasonics, thermography, and computed tomography (CT) to see if damage was detectable.

3.4 Post-Test Structural Testing
Post-impulse test specimens and two control specimens were sent to Montana State University's Composites lab for structural testing. Specimen plates were divided for longitudinal tensile, transverse tension, compression, and fatigue testing (Figure 6). A total of 5 specimens per test case and matrix type were subjected to longitudinal tensile, and transverse tensile testing; and 6 specimens per test case and matrix type were subjected to compression testing. Transverse tests were performed to specifically test for possible damage in the non-conductive matrix. An Instron 8562, 100kN capacity frame was used for compression testing following ASTM D6641 [12], while an Instron 8802, 250kN capacity frame was used for tensile testing following ASTM D3039 [13].

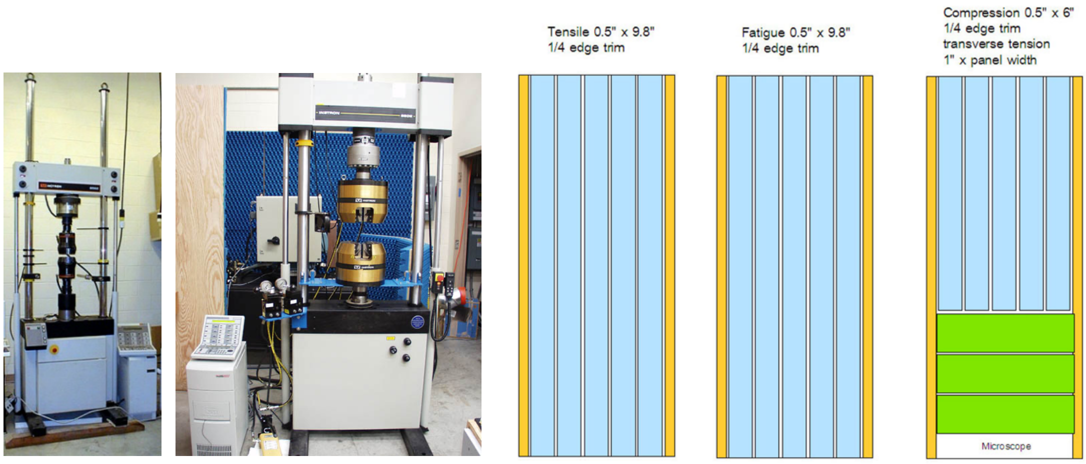


Figure 6: Instron 8562 (left), Instron 8802 (middle), sub-specimen division (right).

4. Results

4.1 Lightning Impulse Testing
All specimens survived testing with no large-scale visible damage. Infrared images show that lightning impulse testing at the 200kA peak current and the faster 1-microsecond rise-time pulser showed signs of edge or skin effects (Figure 7). More current flows along the long edges of the specimen than in the center, preferentially heating the edges to about twice the temperature of the center. In contrast, the 30-microsecond pulser distributes current evenly through the specimen (i.e., uniform current density). Edge effects and how they scale to larger blades will be investigated in future work.

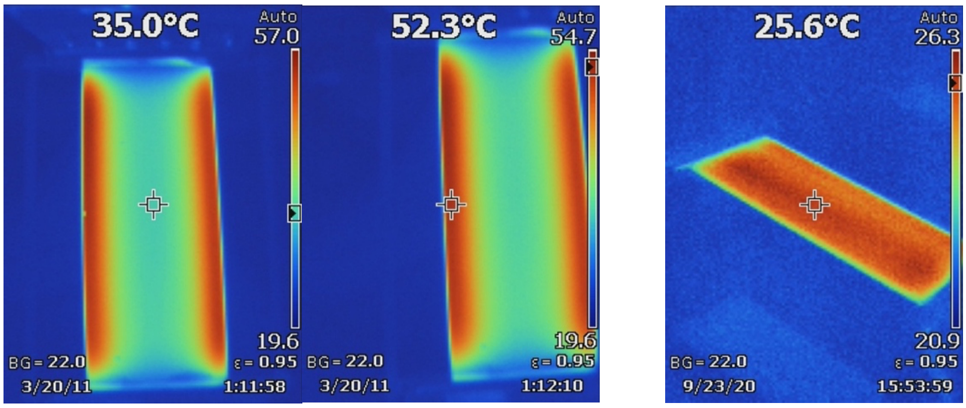


Figure 7: Infrared images showing edge/skin effects present in 200kA, 1-microsecond rise time tests (right, center) vs. uniform current density in the 30-microsecond rise time tests (right).

4.2 Post-Test Nondestructive Inspection

Damage found with post-test NDI methods appear to be located only on the surface of the specimens, with no internal damage evident (Figure 8). The test fixture contained a copper mesh to ensure even contact between the brass electrode and specimen; during testing, this mesh ignited which was the likely cause for the surface damage evident in the post-test NDI. Additionally, no evidence of damage was found in the CT imaging.

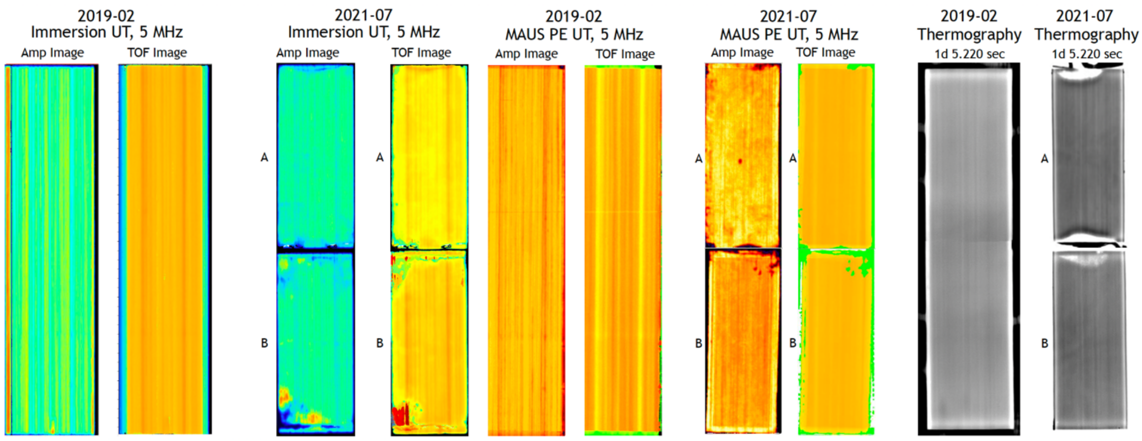


Figure 8: Pre and Post-test nondestructive inspection images: immersion, MAUS pulse echo, and thermography.

4.2 Post-test Structural Testing

Longitudinal tensile testing in thick carbon fiber pultrusions (greater than 2mm per ASTM D3039 [13]) is problematic due to grip pressures exceeding the low through thickness compressive strength which results in grip failures. All longitudinal tensile specimens failed in the grips and at lower stresses and strains (Figure 9). However, these results indicate no significant difference in elastic modulus, and ultimate tensile strength and strain between the different lightning impulse test cases. Future work will focus on thinner specimens.

Transverse tension specimens were limited, and due to the width of the original specimen, were shorter than acceptable per ASTM D3039 [13]. These specimens experienced typical failures primarily focused around the grip region. Fiber waviness may also be affecting test results, so transverse tension results are preliminary (Figure 10).

Compression specimens also show a high number of grip failures and localized crushing. However, compression results do appear to indicate a decreased ultimate compressive strength in the epoxy-matrixed specimens tested at the 30-microsecond, 200kA test case (Figure 10). This result is interesting because the test case represents the largest energy input into the specimen; a larger energy input results in a greater heating of the specimen. The 30-microsecond pulser is applying a roughly 30x longer duration current than the 1-microsecond pulser, with delayed cooling due to the slower decay back to 0 Amps (top green plots, Figure 3).

Tensile fatigue testing at R=0.1 was suspended due to premature failure caused by gripping forces exceeding the compressional strength through the thickness of the specimen. Thinner specimens will be tested in future work.

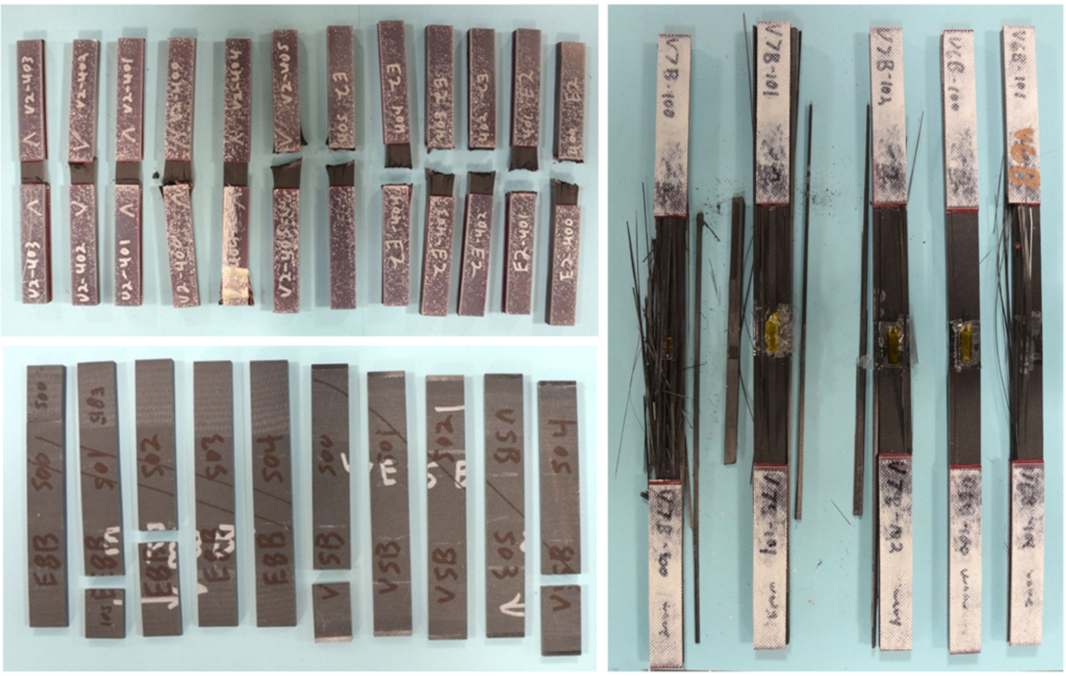
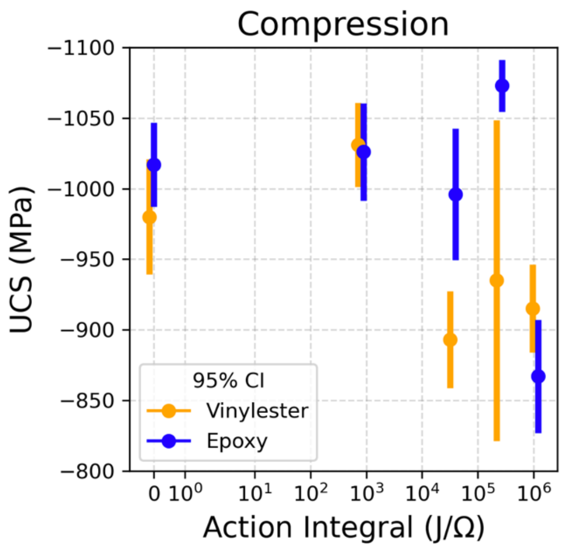


Figure 9: Post-Structural Testing Specimens: compression (top left), transverse tensile (bottom left), and longitudinal tension (right).



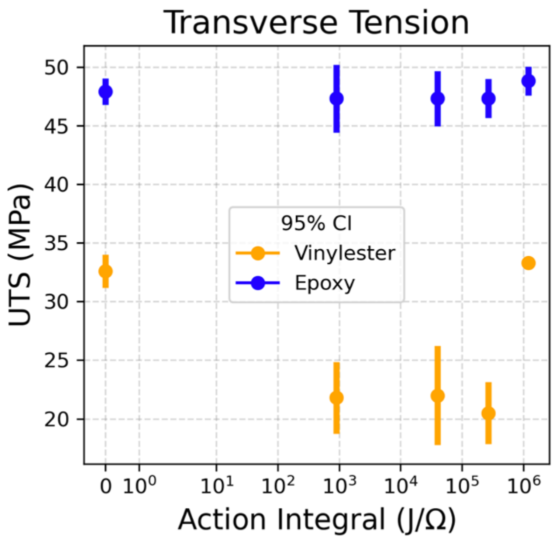


Figure 10: Strength vs. action integral (energy per unit resistance, with 95% CI) plots for compression testing (left), and transverse tension (right). Controls (no impulse testing) listed at 0 energy and largest energy input into specimen towards the right of the plot.

5. Conclusions

The high-current testing has shown that the carbon fiber pultrusions withstand severe lightning currents with no visible or NDI-indicated damage. High fidelity and field methods were used for these inspections, and if damage does exist, NDI methods were not capable of finding them. A decrease in compressive strength of the epoxy-matrixed specimens were noted for those in the highest energy test case of 200kA, 30-microsecond rise time. Post-test structural results are preliminary, and more investigation will be required. Additional results will provide guidance to wind farm owner/operators regarding inspection or repair that may be required when a pultruded carbon fiber wind blade is struck by lightning. Additionally, these results can be used by designers to ensure blades can continue to be operated safely in the event of a strike.

6. Future Work

Results of the edge/skin affects identified in the 1-microsecond rise time, 200kA test case will be investigated through modelling/testing in phase 2. Phase 2 lightning impulse testing will also focus on bonded specimens and multiple/return strikes. Lastly, post-test structural results indicate a need to test thinner specimens.

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