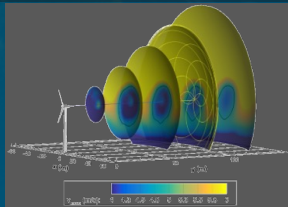




Effects of Lightning on Pultruded Carbon Fiber Wind Blades



PRESENTED BY

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Motivation

Problem: Determine effect of lightning damage on pultruded carbon fiber laminates.

Ability of inspection equipment to find damage

- Fiberglass vs. Carbon Fiber



Methodology

Vinylester (62% FVF)

Epoxy-matrixed (65% FVF)

Pre-Test Inspection

- Immersion Ultrasonics (UT), Pulse Echo UT, Thermography

Lightning Impulse Testing

Post-Test Inspection

- Immersion UT, Pulse Echo UT, Thermography, Computed Tomography

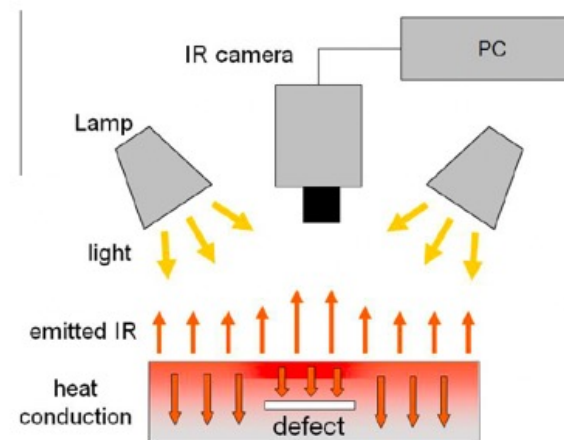
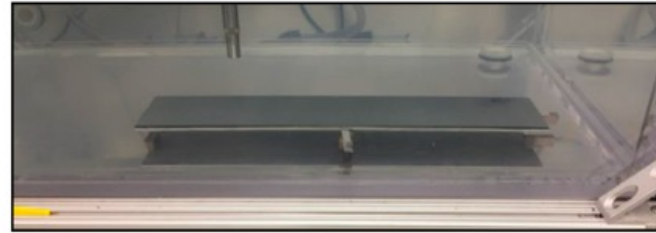
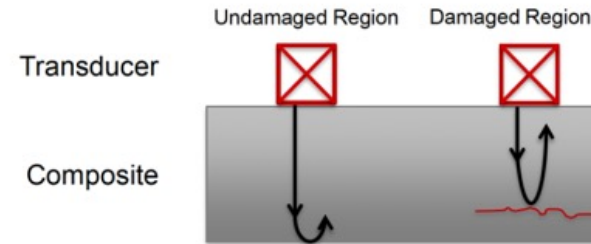
Post-Test Structural Testing



Immersion UT (top left)

Pulse Echo UT (top right)

Thermography (bottom)



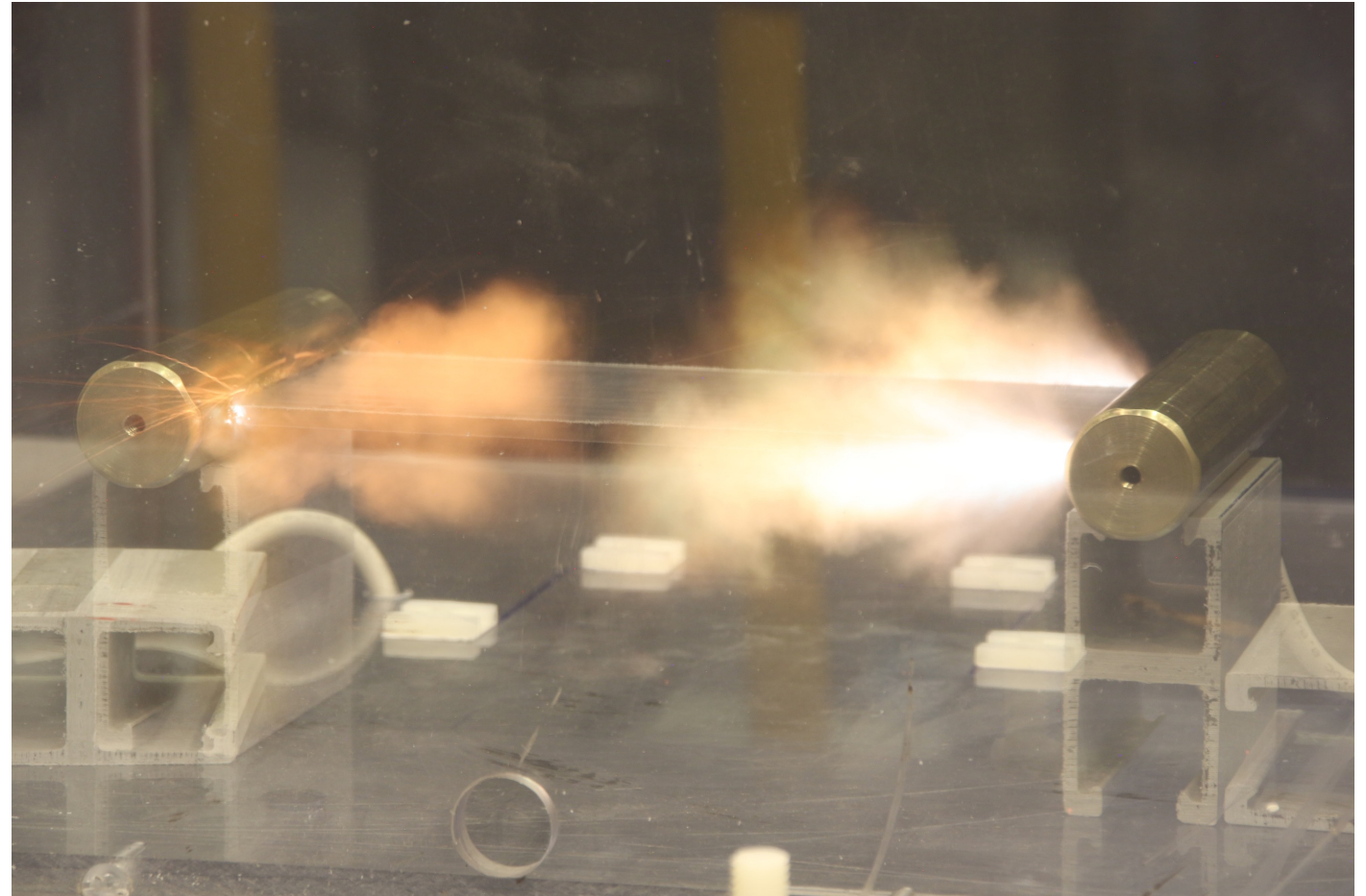
5 Lightning Impulse Testing

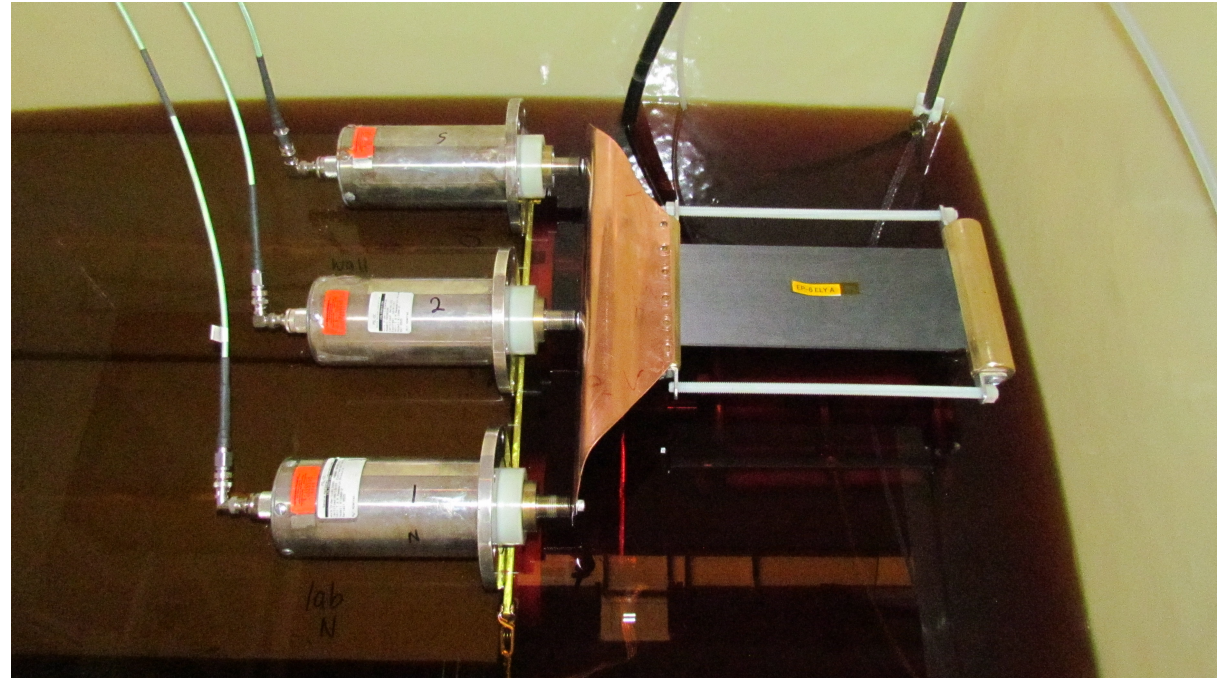
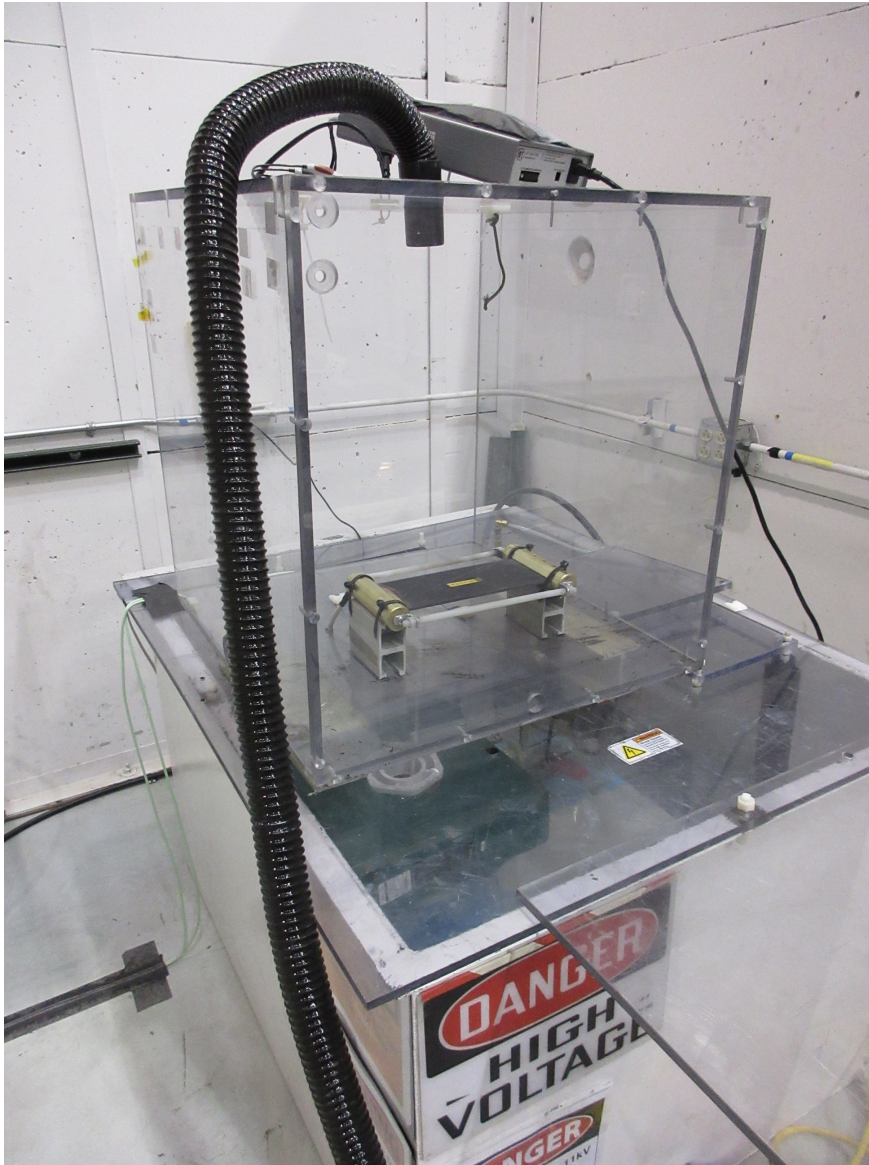


Pulsers: (200kV) 1 microsecond
(22kV) 30 microsecond

Peak Currents: 30kA, 200kA

Average 50% and worst 1%





(22kV) 30 microsecond rise-time pulser (left)

(200kV) 1 microsecond rise-time pulser (top right)

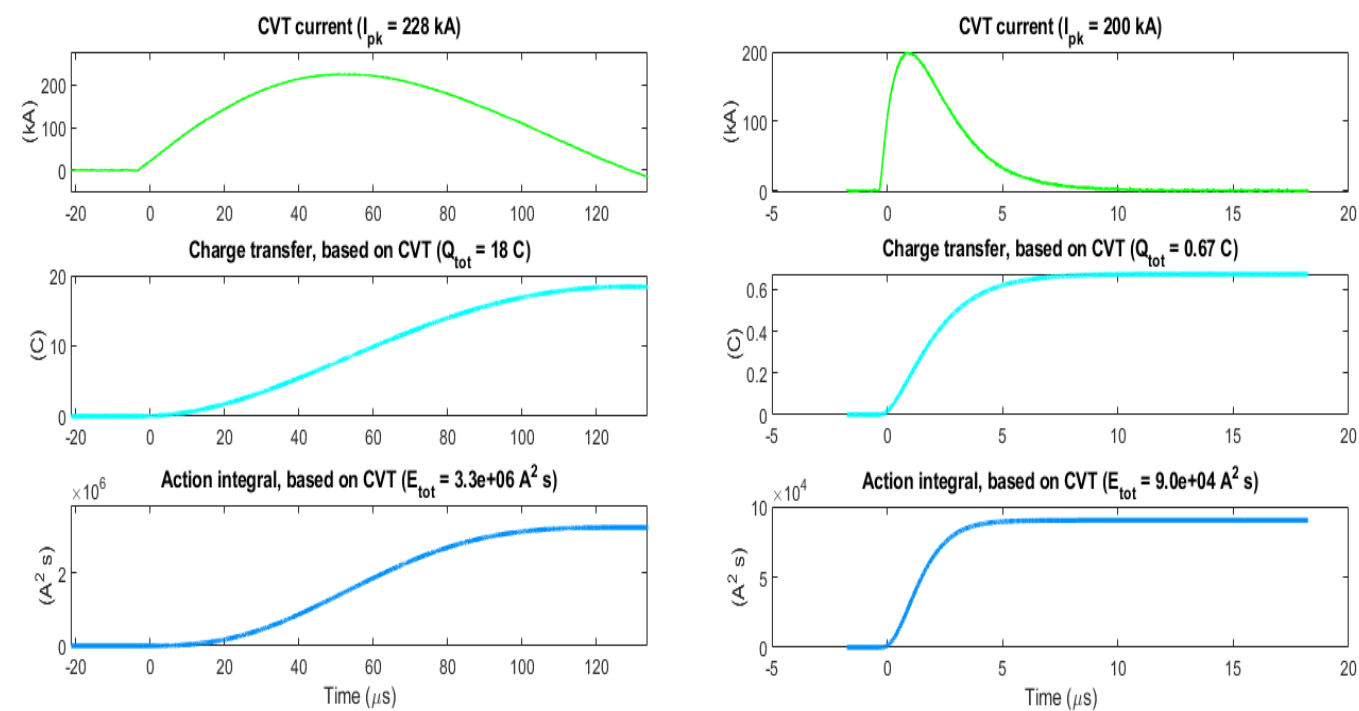
7 Lightning Impulse Testing



	30 kA peak current			200 kA peak current		
1-μs pulser	<u>RETURN STROKE PARAMETERS</u> ¹			<u>RETURN STROKE PARAMETERS</u> ¹		
		1%	50%		1%	50%
	a. Peak Current (kA)	200	30	a. Peak Current (kA)	200	30
	b. Time to Peak (μs)	0.1-15	3	b. Time to Peak (μs)	0.1-15	3
	c. Max. Rate of Current Rise (kA/μs)	400	150	c. Max. Rate of Current Rise (kA/μs)	400	150
	d. Time to Decay to Half Peak (μs)	10-500	50	d. Time to Decay to Half Peak (μs)	10-500	50
	e. Amplitude of Continuing Current ² (A)	30-700	150	e. Amplitude of Continuing Current ² (A)	30-700	150
	f. Duration of Continuing Current (ms)	500	150	f. Duration of Continuing Current (ms)	500	150
	<u>FLASH PARAMETERS</u>			<u>FLASH PARAMETERS</u>		
	a. Number of Strokes	>20	4	a. Number of Strokes	>20	4
30-μs pulser	b. Interstroke Interval (ms)	10-500	60	b. Interstroke Interval (ms)	10-500	60
	c. Total Flash Duration (ms)	30-1000	180	c. Total Flash Duration (ms)	30-1000	180
	d. Total Charge Transfer (C)	350	15	d. Total Charge Transfer (C)	350	15
	e. Action Integral $[\int I^2 dt]$ (A ² s)	3x10 ⁶	5x10 ⁴	e. Action Integral $[\int I^2 dt]$ (A ² s)	3x10 ⁶	5x10 ⁴
	¹ The entire cloud-to-ground discharge may be comprised of multiple individual major current pulses. These are known as <u>return strokes</u> or, simply <u>strokes</u> .			¹ The entire cloud-to-ground discharge may be comprised of multiple individual major current pulses. These are known as <u>return strokes</u> or, simply <u>strokes</u> .		
	<u>RETURN STROKE PARAMETERS</u> ¹			<u>RETURN STROKE PARAMETERS</u> ¹		
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	d. Time to Decay to Half Peak (μs)	10-500	50	d. Time to Decay to Half Peak (μs)	10-500	50
	e. Amplitude of Continuing Current ² (A)	30-700	150	e. Amplitude of Continuing Current ² (A)	30-700	150
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	30 kA peak current	200 kA peak current
1-μs pulser	<p>50% lightning peak current 1% lightning time to peak</p> <p>Current = (Ch1 + Ch2 + Ch3) * Calibration Calibration = 4,000</p> <p>Test day: 5/25/2021 File no. 1 → VE-7A File no. 2 → VE-8A File no. 3 → EP-9A File no. 4 → VE-9A File no. 5 → EP-10A</p> <p>Test day: 5/26/2021 File no. 6 → EP-11A</p>	<p>1% lightning peak current 1% lightning time to peak 50% lightning action integral</p> <p>Current = (Ch1 + Ch2 + Ch3) * Calibration Calibration = 20,000</p> <p>Test day: 5/4/2021 File no. 0 → EP-5A</p> <p>Test day: 5/5/2021 File no. 1 → VE-5A File no. 2 → EP-6A File no. 3 → VE-6A File no. 4 → EP-7A File no. 5 → EP-8A</p> <p>Test day: 5/26/2021 File no. 8 → VE-10A</p>
30-μs pulser	<p>50% lightning peak current 50% lightning action integral</p> <p>Current = Ch3 * Calibration Calibration = 50,000</p> <p>Test day: 5/20/2021 File no. 0 → VE-6B File no. 1 → EP-7B File no. 2 → VE-7B File no. 3 → EP-9B File no. 4 → VE-10B File no. 5 → EP-10B</p>	<p>1% lightning peak current 50% lightning charge transfer 1% lightning action integral</p> <p>Current = Ch3 * Calibration Calibration = 50,000</p> <p>Test day: 5/13/2021 File no. 0 → EP-5B File no. 1 → VE-5B File no. 2 → EP-6B File no. 3 → VE-8B File no. 4 → EP-8B File no. 5 → VE-9B</p>



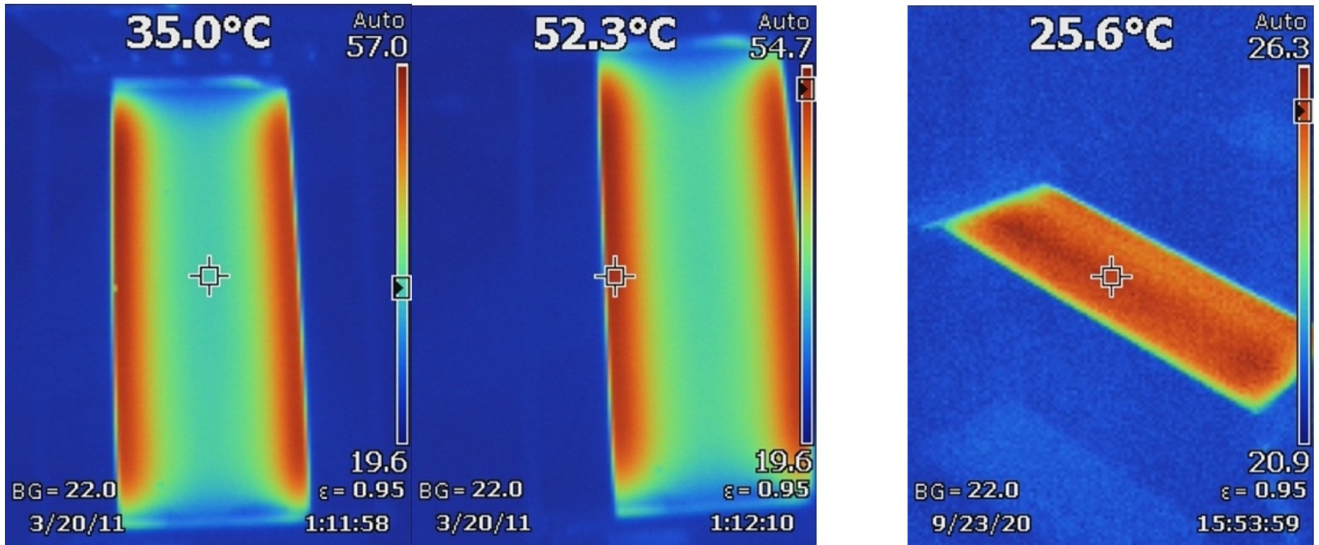
Current Viewing Transformer (CVT) (top plots)

Charge Transfer (middle plots)

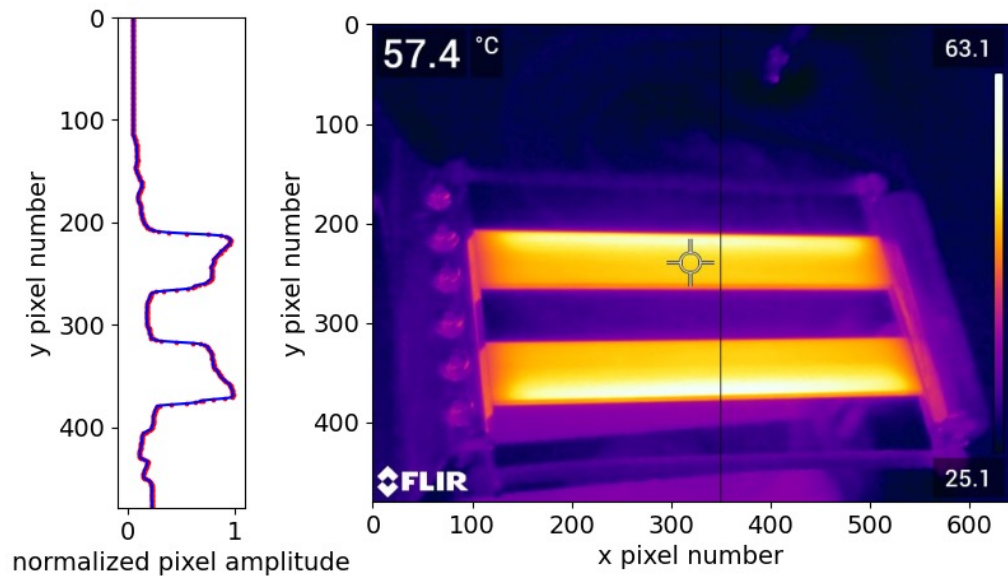
Action Integral (bottom plots)

- energy deposition

9 Investigation of Edge Effects



'2/3' test, 179.2 kA peak current

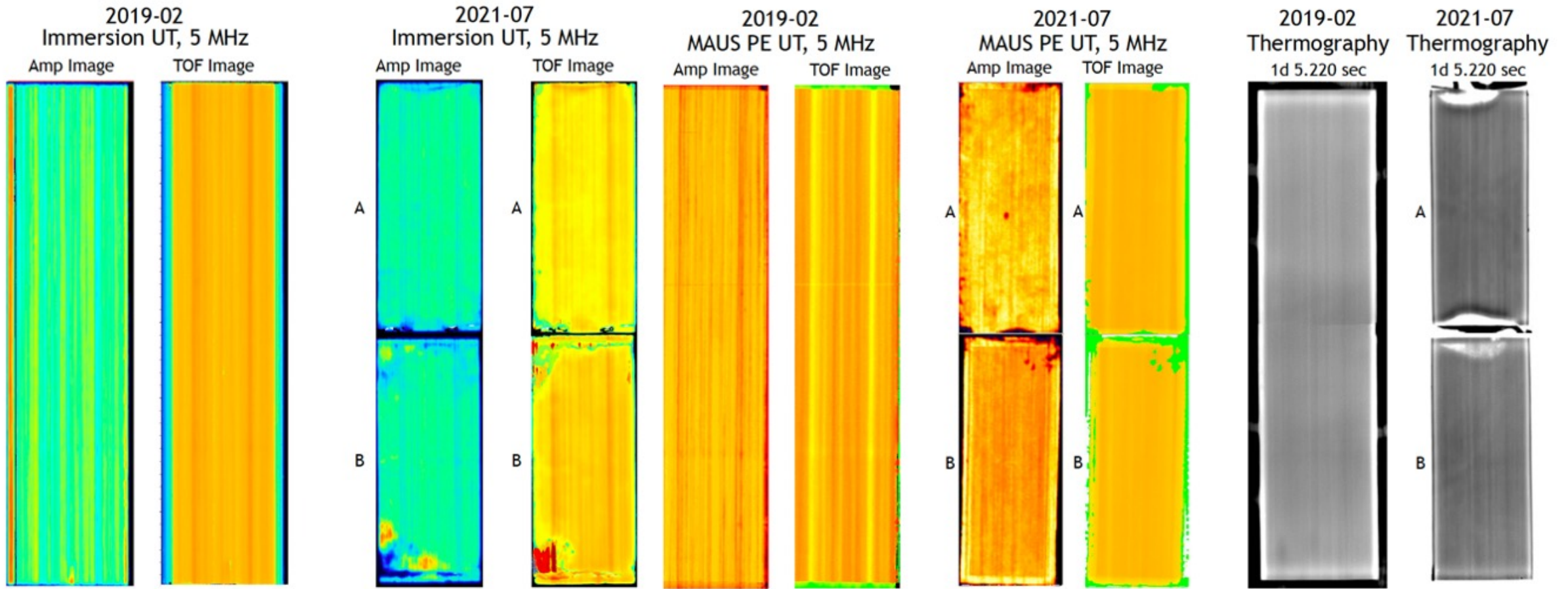


Infrared images

~200kA, 1microsecond rise time tests
(top right, top center)

30microsecond rise time test (top
right) uniform temperature.

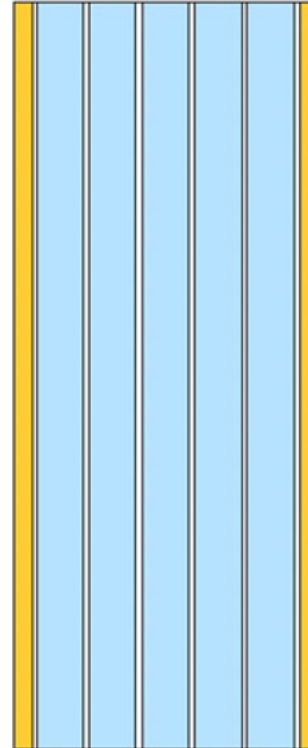
2/3 test, ~180kA, 1microsecond rise
time (bottom)



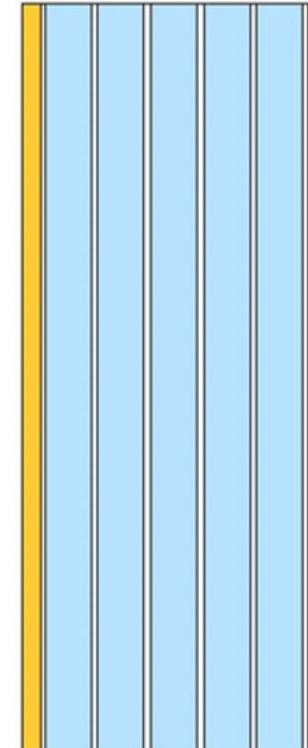
Immersion UT, Pulse Echo UT, Thermography, Computed Tomography (CT)



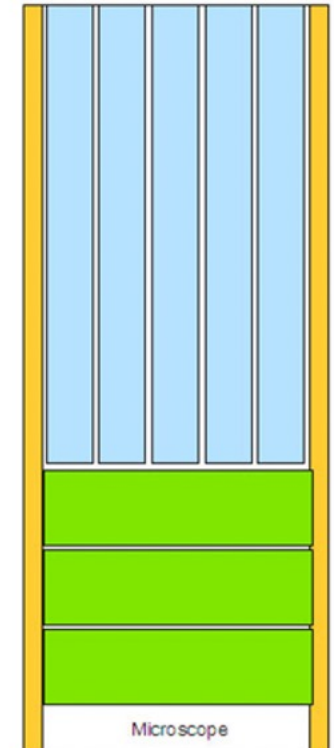
Tensile 0.5" x 9.8"
1/4 edge trim



Fatigue 0.5" x 9.8"
1/4 edge trim

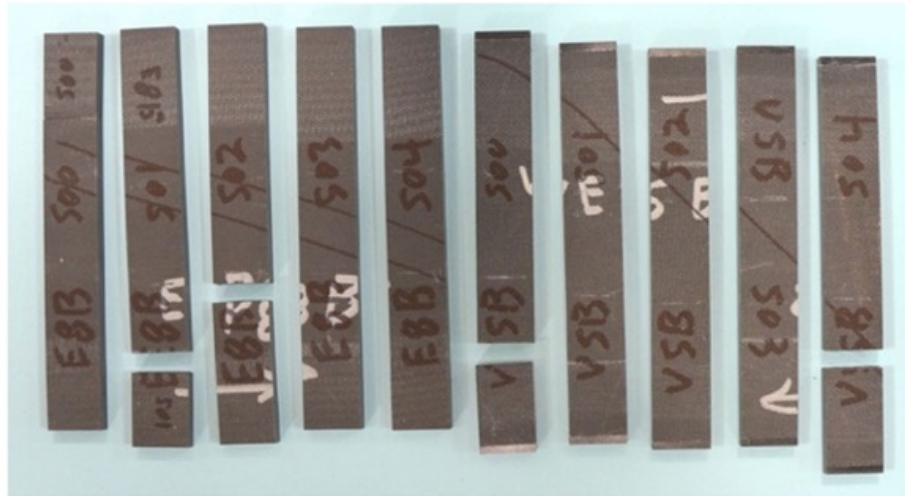


Compression 0.5" x 6"
1/4 edge trim
transverse tension
1" x panel width



MSU's structural load frames:

(L-R) Instron 8562 (100kN capacity) and
Instron 8802 (250kN capacity)

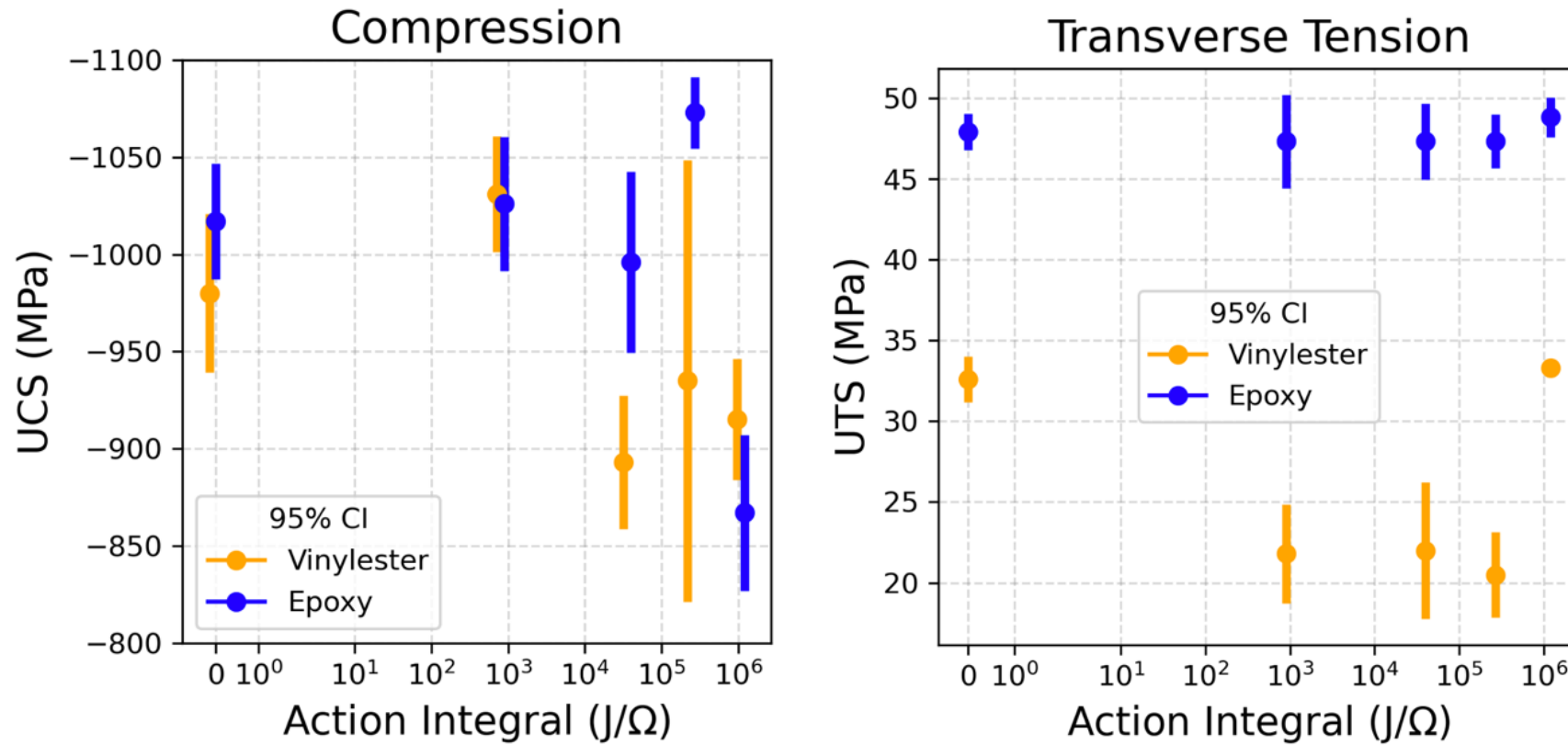


Compression (top left)

Transverse Tension (bottom left)

Longitudinal Tension (right)

Tensile Fatigue (in progress)



Strength vs action integral (energy per unit resistance, 95% CI)

Carbon fiber pultrusions withstand severe lightning currents, but with some ultimate strength degradation.

Preliminary results show that epoxy-matrixed specimens tests at 200 kA and a 30 microsecond rise-time had decreased compressive strength. Vinylester specimens also had decreased compressive strength at higher action integrals, but further testing is needed to confirm this conclusion.

Post-test structural results preliminary, more investigation required.

No recommendations can be made on NDI methods to be used for determining damage in a carbon fiber blade struck by lightning.



Repeat on thinner specimens for improved structural testing

Testing on adhered stacked plates

Multiple strike testing

Examine edge effects

Acknowledgments



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Ray Martinez – Sandia National Labs, High Current Facility

References can be found in paper: “Effects of Lightning on Pultruded Carbon Fiber Wind Blades”.

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