Hybrid multiscale modelling to predict lightning damage on CFRP materials

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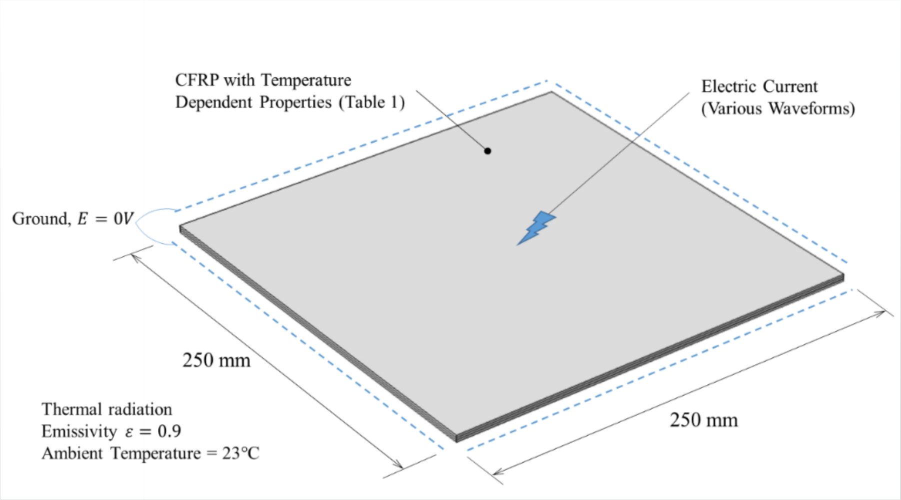
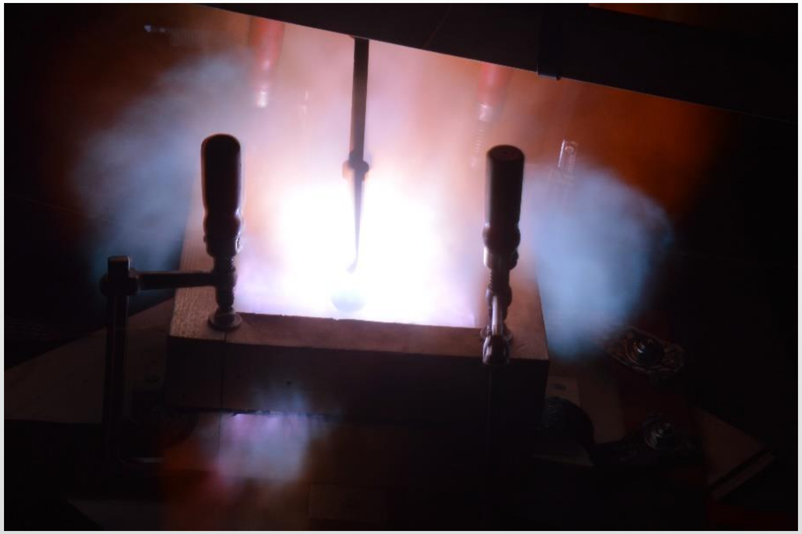
Introduction

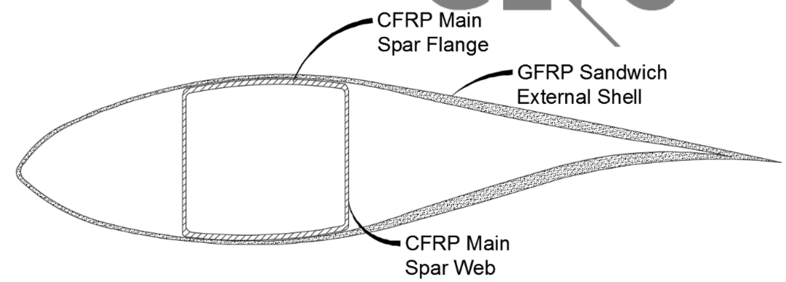
- The aims of this paper are:
  - Numerical model and experimental validation of lightning induced damage on CFRP materials
  - Determining the difference between resin damage and fiber damage based on heating.

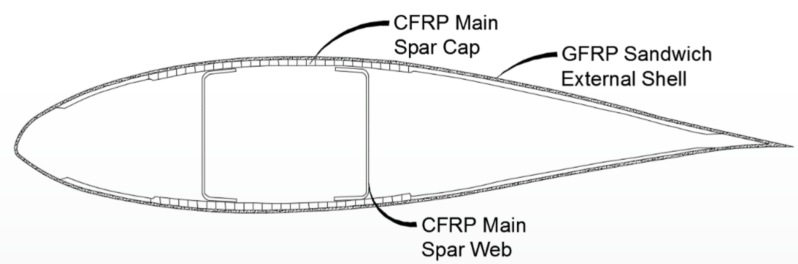




Introduction (CFRP Materials in Wind Turbine Blades)

- CFRPs provide a way to make longer wind turbine blades
- CFRP are increasingly used in wind turbine, aerospace, and automotive industry
- Anisotropic material properties. Particular issue with lightning





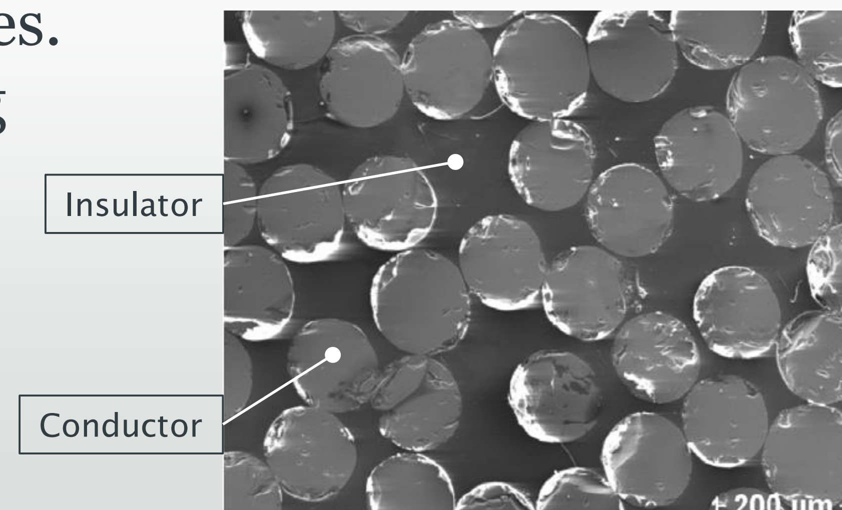


Image credit: researchgate.net/ Brauer, et al.

Introduction (Lightning in CFRP Materials)

- Lightning injects electrical currents into CFRP materials on wind turbines in two scenarios

- These situations cause serious damage up to detachment of the tip of a blade

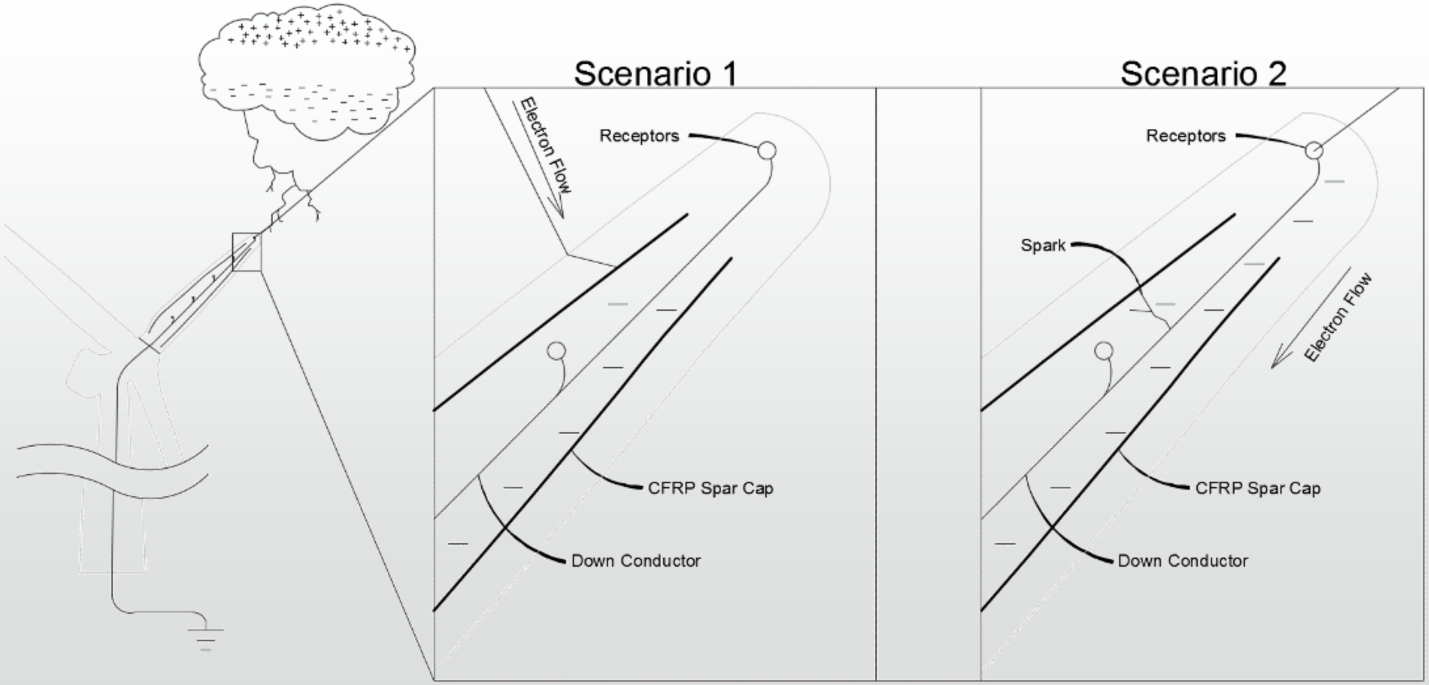


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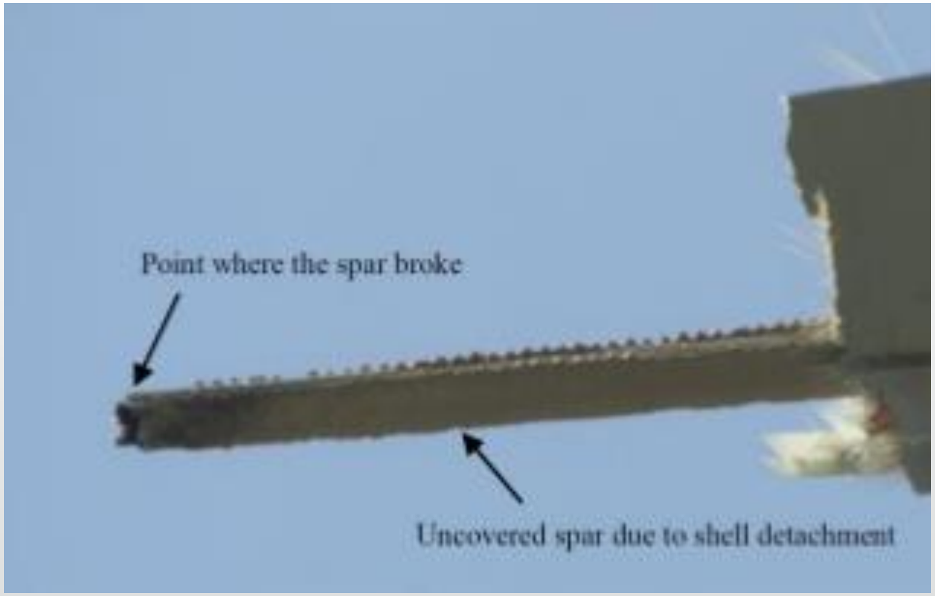
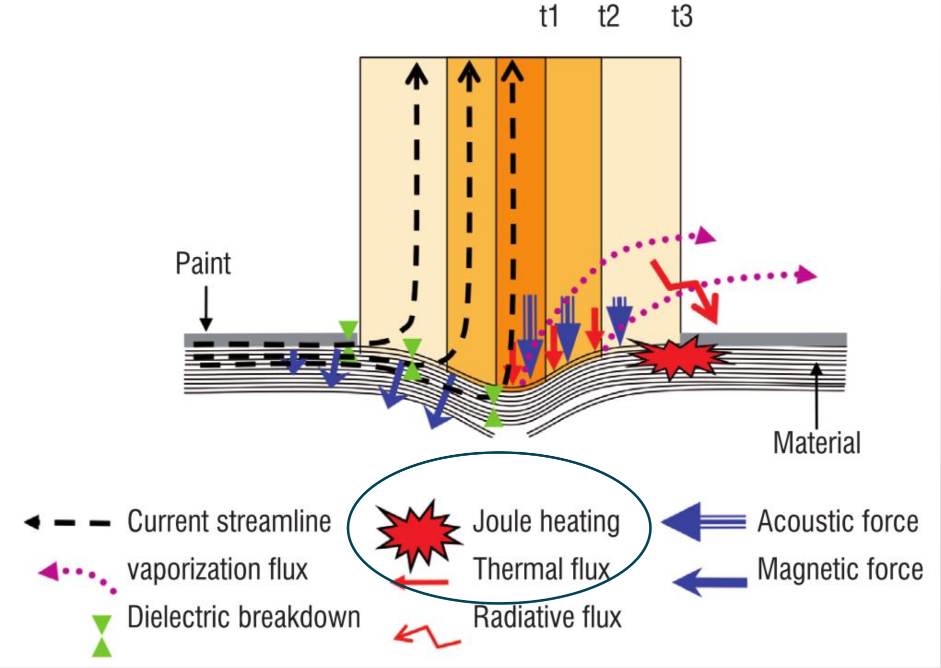
Image credit: http://betterplan.squarespace.com



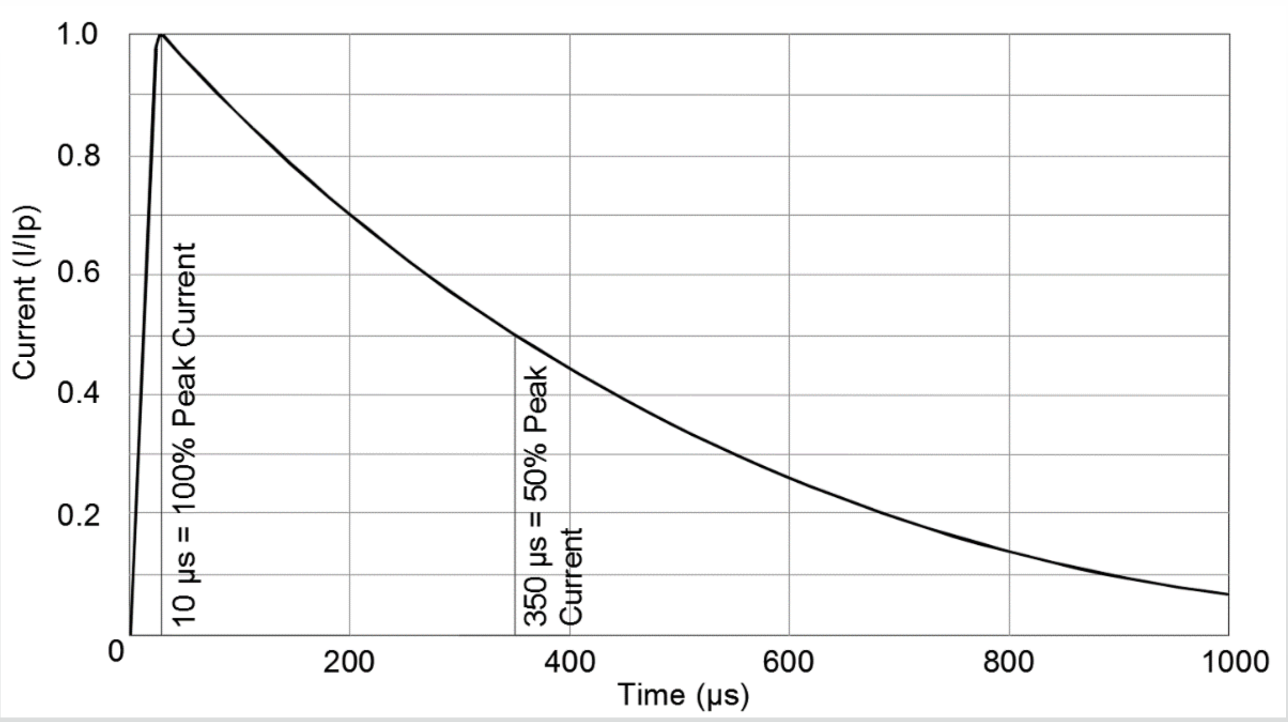
Introduction (Lightning in CFRP Materials)

- The physics of a lightning strike on a CFRP material involves complex interactions
- However, thermal damage is the leading cause of damage



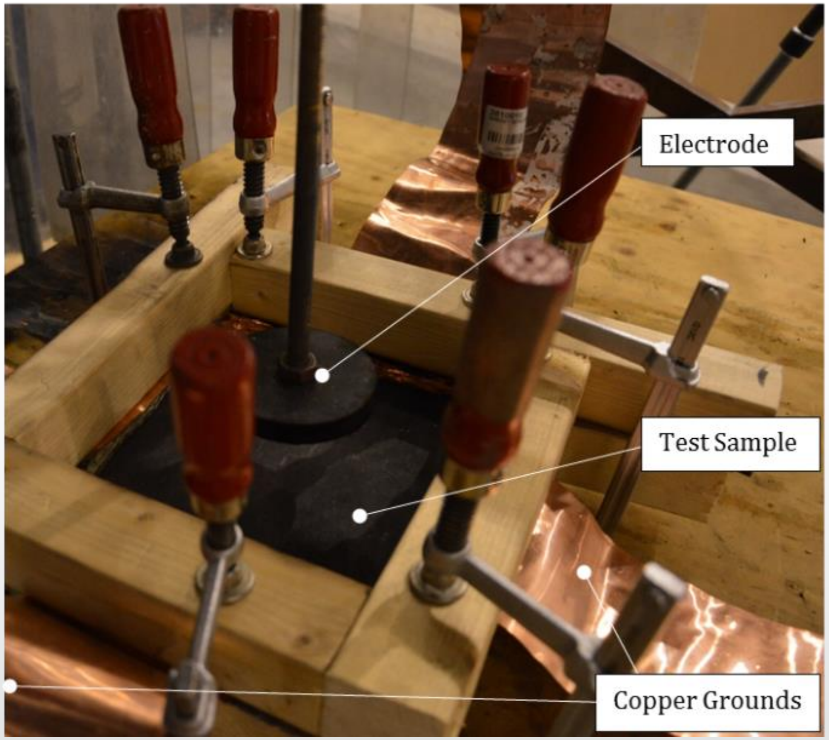
Introduction (Lightning in CFRP Materials)

- IEC-61400-24 lightning protection standard calls for a level 1 lightning strike to be:
  - 200 kA; 10MJ/Ohm should be used.
  - 10/350μs



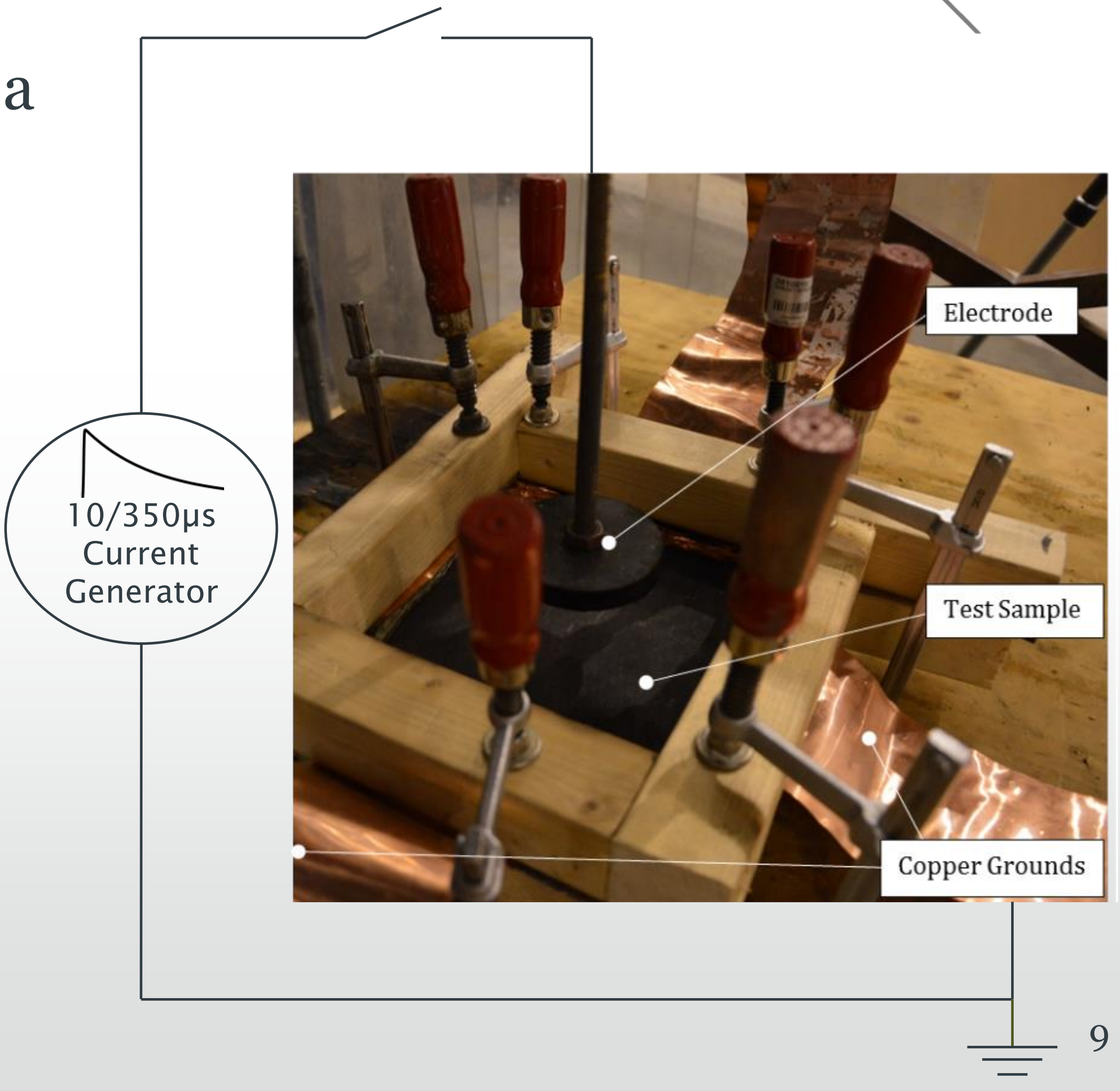
Experimental Method

- Carbon fiber epoxy composite system
- Five ply unidirectional layup ($[0]_5$)
- The dimensions of the samples 250mm wide x 250mm long x 4.5mm thick



Experimental Method

- Testing was done on a CFRP sample with a current generator which had a 20 mm spark gap to inject current
- The 10/350μs waveform was used:
  - 30 kA
  - 60 kA



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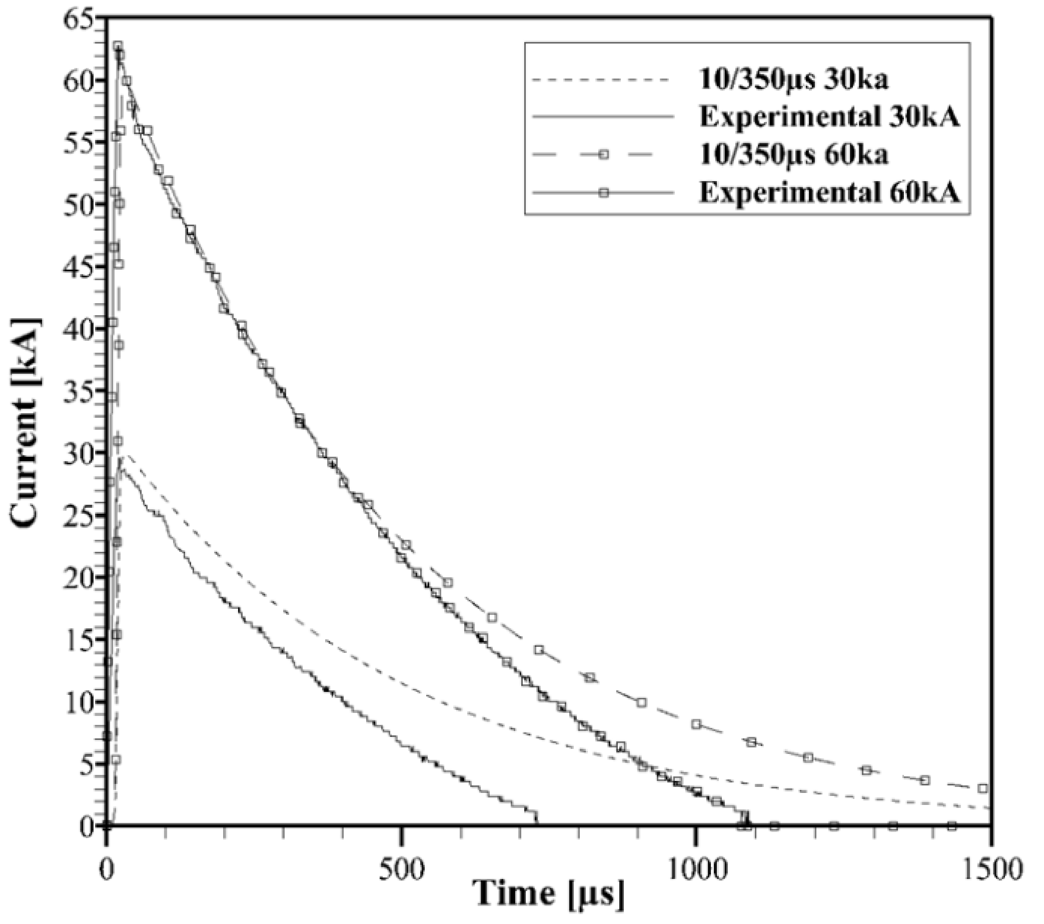
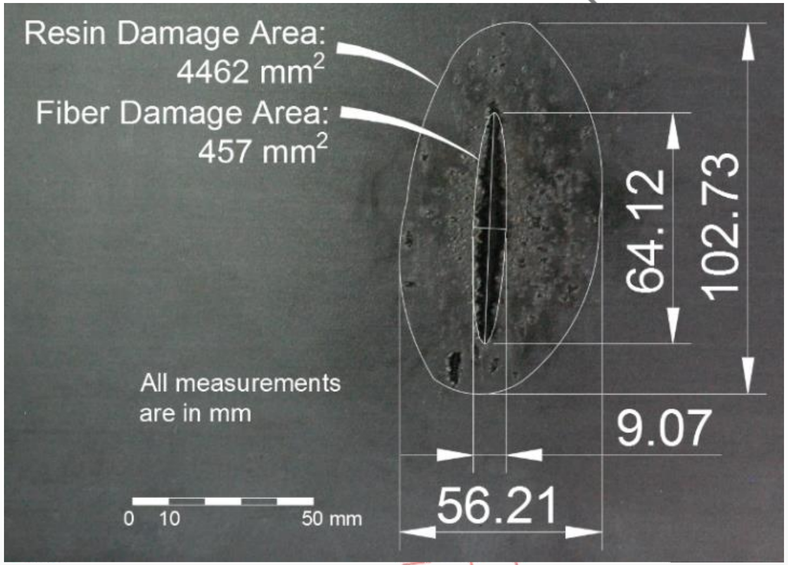
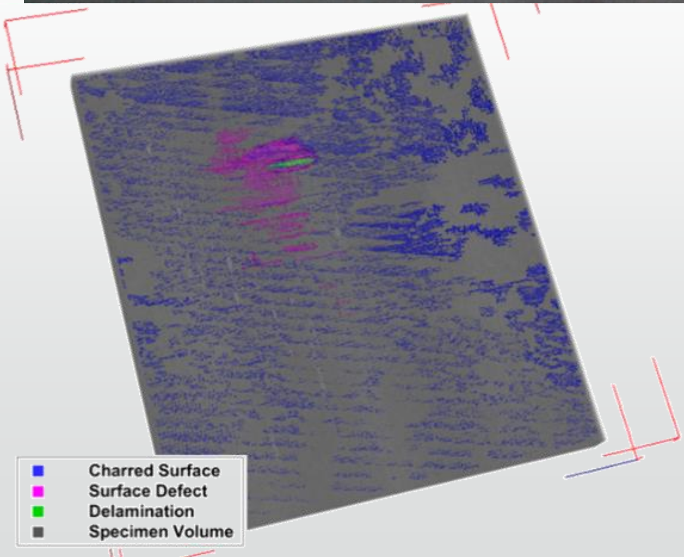


Experimental Results

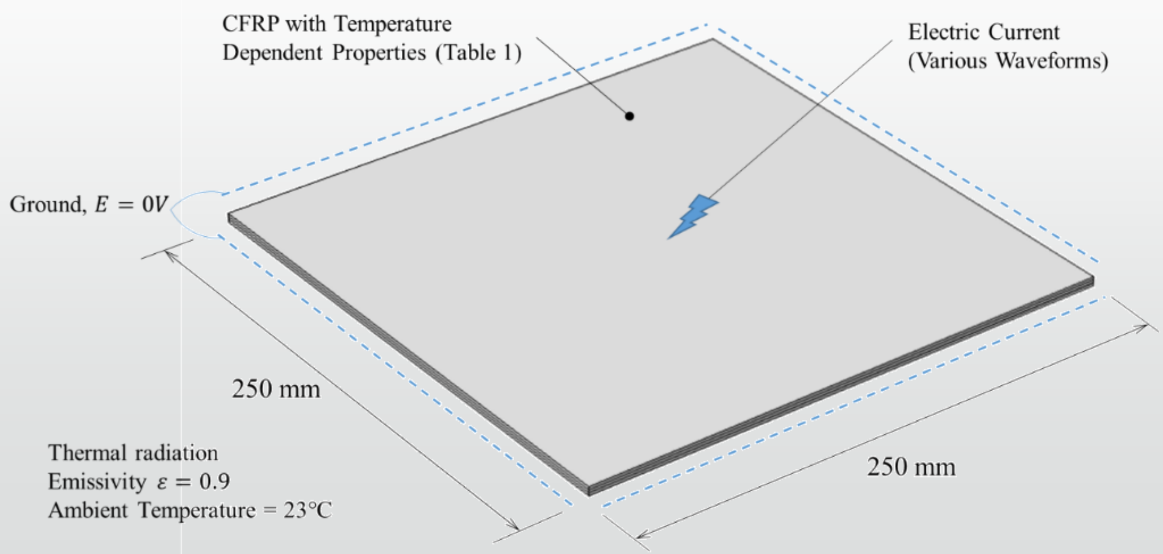
- Visual indications of fiber and resin damage from the surface.
- Computed Tomography (CT) inspections were done on the samples to get in depth analysis of damage.





Numerical Method

- Joule heating model
  - COMSOL 5.3 finite element mulitphysics was used to calculate the Joule heating equations and the pyrolysis.
  - 10/350μs waveforms were analytically inputted through the Heidler equation [1]



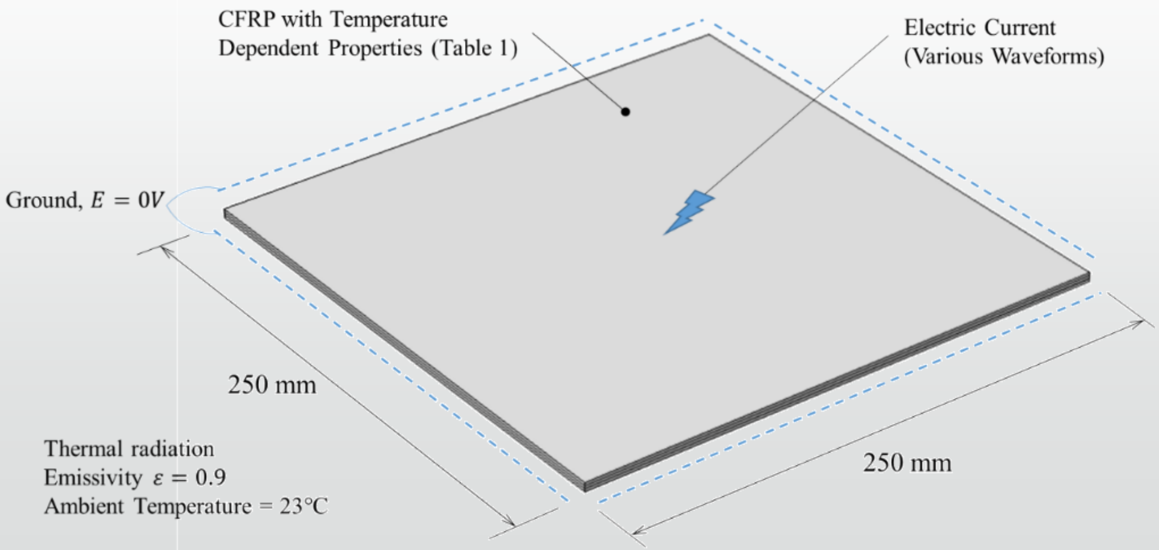
Numerical Method

- Joule heating formulation had slight modification to ensure fiber fractions were accounted correctly in the heat equations.

- Similar approach to Xu [2]

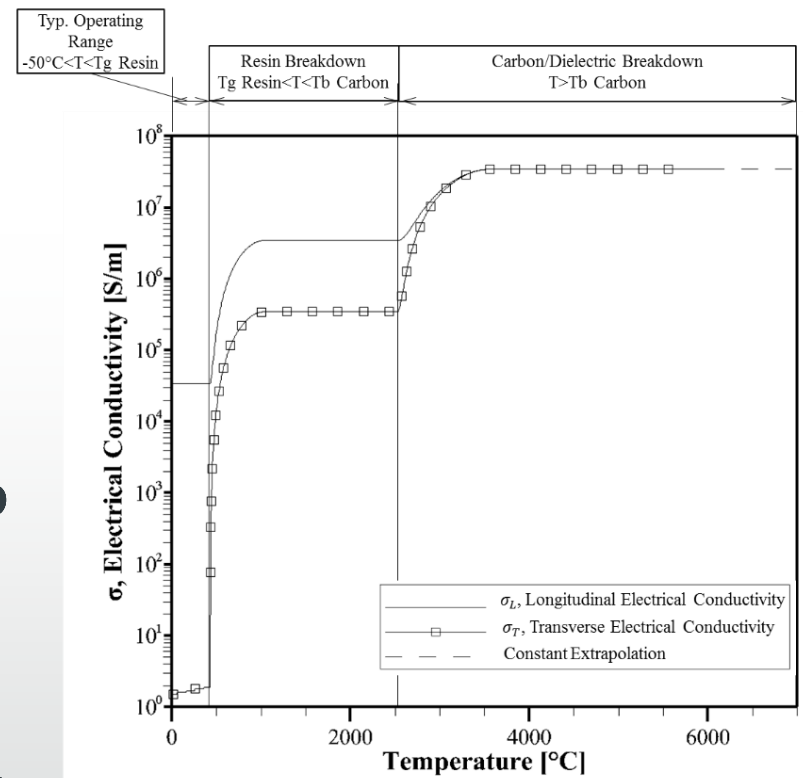
Heat Capacity

$$\rho\left(\phi_f C_f + \phi_M C_M + \phi_g C_g\right)\frac{\partial T}{\partial t} + \nabla \cdot q = Q$$



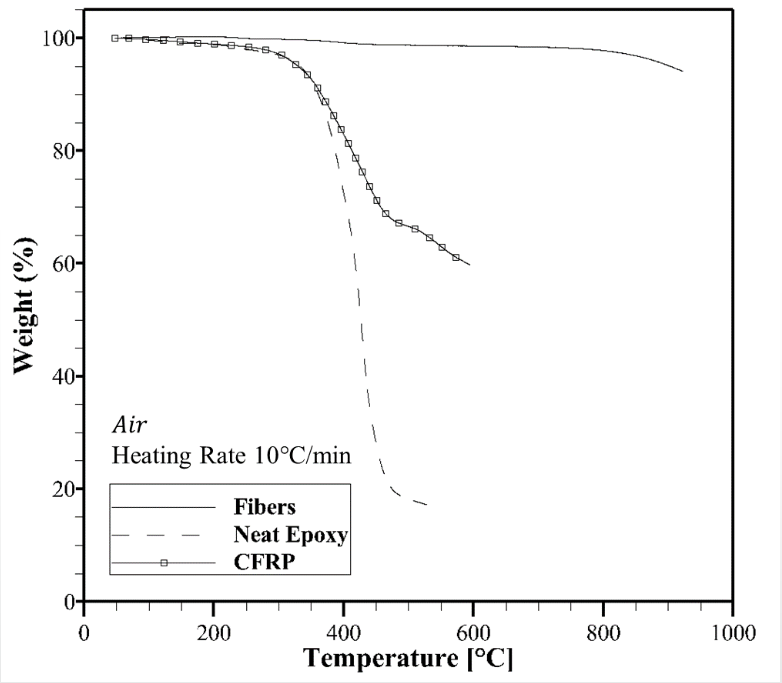
Numerical Method

- Temperature dependent material properties were used.
  - Three zones:
    - “Typical operating range” (0° C to 60° C): Normal CFRP material properties
    - “Resin Breakdown” (60° C to 3000° C): Carbon fiber properties
    - “Dielectric Breakdown” (>3000° C): High magnitude electrical conductivity to dissipate energy



Numerical Method

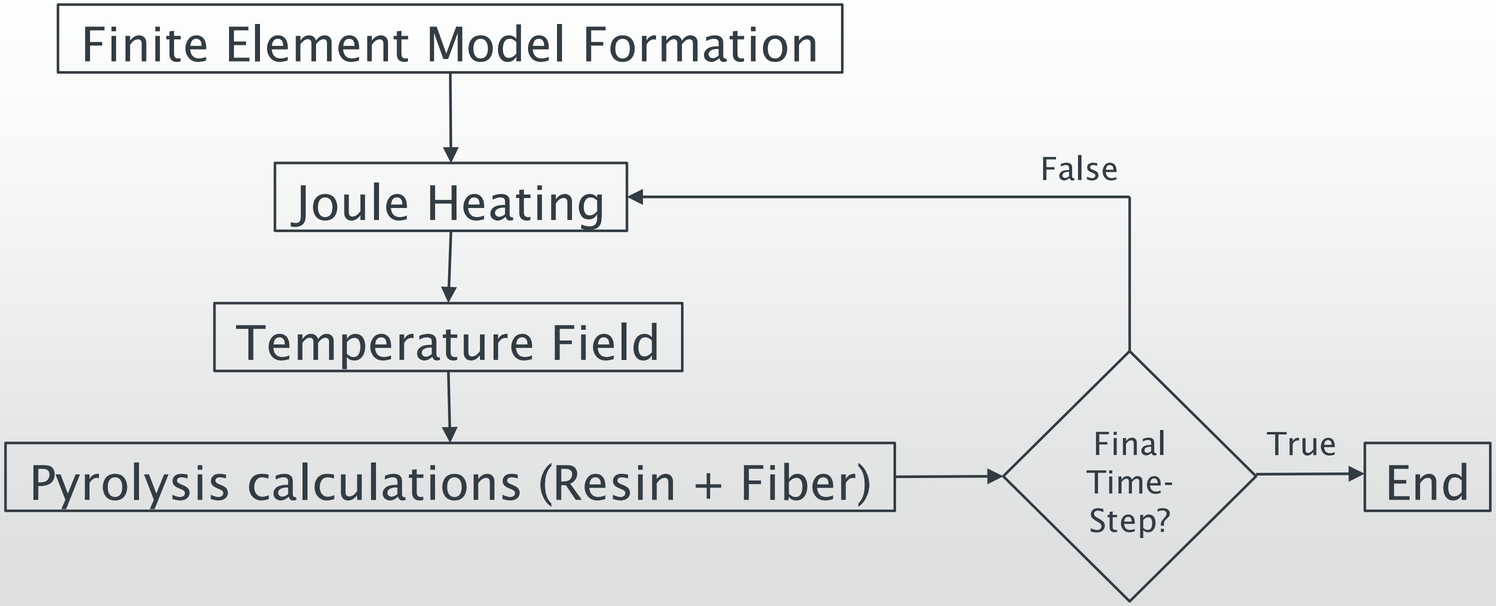
- Separating the fiber damage and matrix damage by pyrolysis equation:
  - $\frac{dC_f}{dt} = K_f(T)(1 - C)^n$
  - $\frac{dC_M}{dt} = K_M(T)(1 - C)^n$
  - where $K_i = A_i e^{-\frac{E_i}{RT}}\ for\ i = f, M$



Numerical Method

- The finite element model runs sequence of calculating the temperatures, then checking the pyrolysis through an Arrhenius equation

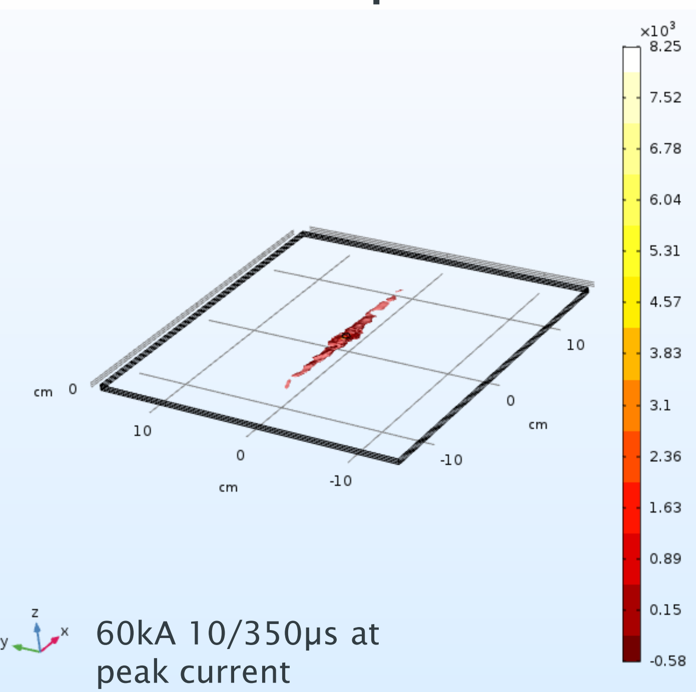
- Similar approach to Dong et. al. [3]

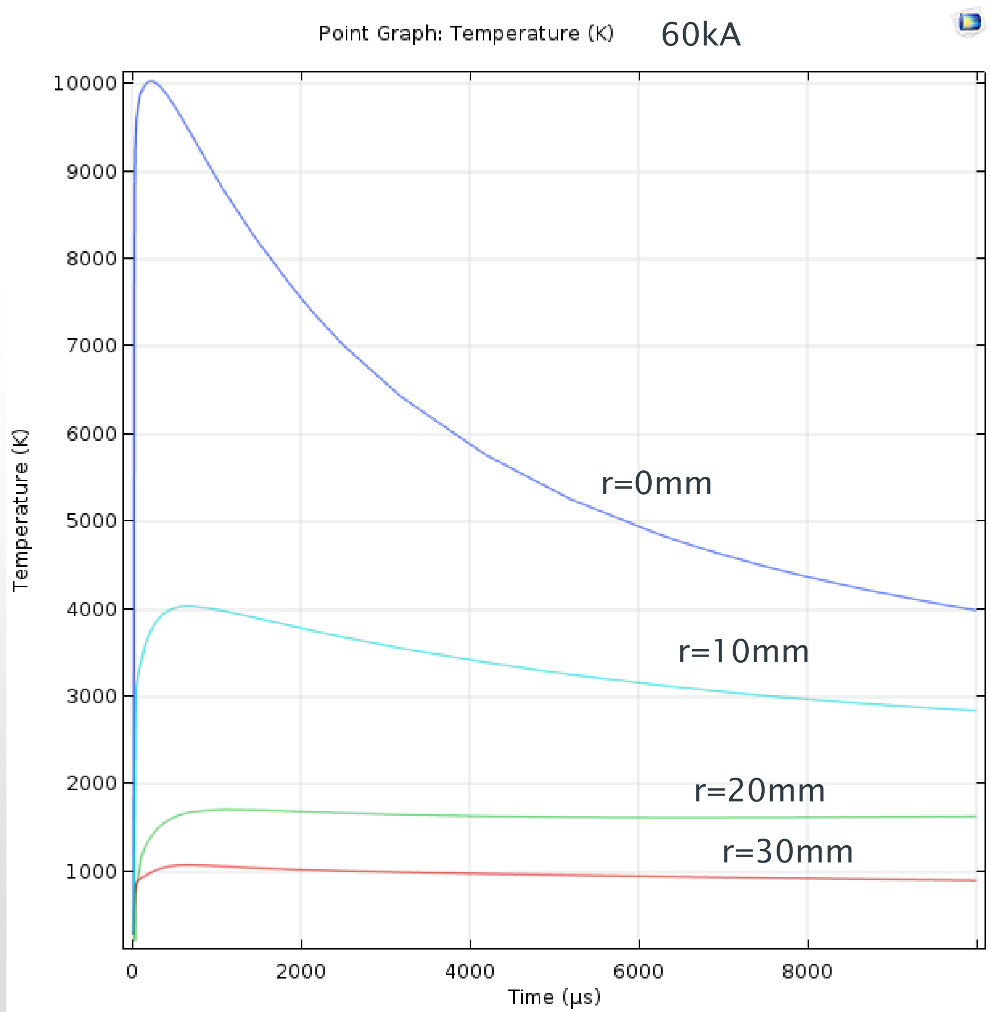


Numerical Results

- Temperature results show large magnitudes larger than resin, and carbon boiling point.

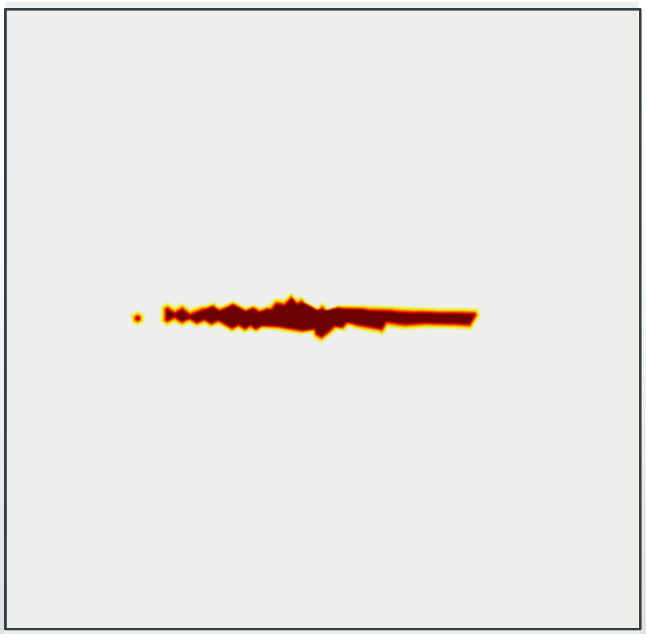
- Just outside of current source temperature are around 4000° C.



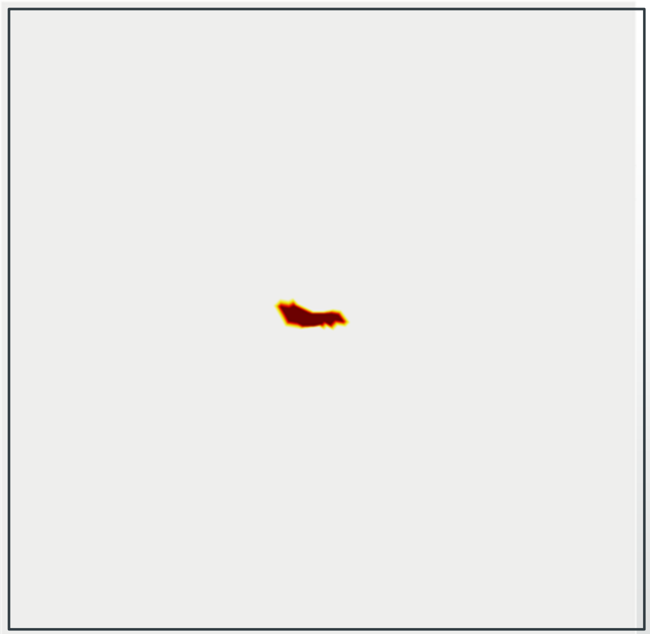


Numerical Results

- Numerical results showed that fiber and resin damage could be separated.



Resin Damage



Fiber Damage

■ = Damage section ☐ = Undamged section

Results (Numerical compared to Experimental)

- The comparison between the damage depth shows 14.6% difference
- The comparison of damage volume (resin and fiber) showed a 22.4% difference

Sample	Damage Depth			Resin Damage Volume			Fiber Damage Volume		
	Exp.	Num.	% Error	Exp.	Num.	% Error	Exp.	Num.	% Error
30 kA	0.834	0.741	11.2%	3721	3044	18.2%	381.1	324.3	14.9%
60 kA	0.978	0.836	14.6%	6372	4741	25.6%	817.7	634.5	22.4%

Conclusions

- Comparative study of lightning strike induced damage in CFRP panels
- Coupled thermal-electrical FE model implemented in the software tool COMSOL
- Material decomposition by pyrolysis described by the Arrhenius equation which separates resin and fiber.

Future Work

- Incorporating mechanism to predict delamination
- Using the result from this model into a structural model

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THANK YOU FOR YOUR ATTENTION

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References

[1] Heidler, F., and J. Cvetić. 2002. "A Class of Analytical Functions to Study the Lightning Effects Associated with the Current Front." European Transactions on Electrical Power 12(2): 141–50.

[2] Xu, Hebing, and Jun Hu. 2016. "Study of Polymer Matrix Degradation Behavior in CFRP Short Pulsed Laser Processing." Polymers 8(299): 1–14. http://www.mdpi.com/2073-4360/8/8/299.

[3] Dong, Qi, Yunli Guo, Xiaochen Sun, and Yuxi Jia. 2015. "Coupled Electrical-Thermal-Pyrolytic Analysis of Carbon Fiber/epoxy Composites Subjected to Lightning Strike." *Polymer (United Kingdom)* 56: 385–94. http://dx.doi.org/10.1016/j.polymer.2014.11.029.