THE SIMULATED LIGHTNING STRIKE INVESTIGATION ON NOVEL HYBRID LAMINATES COMPRISING ELECTRICAL CONDUCTIVE MATRIX

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Content

- Introduction to the aircraft lightning strike damage and protection
- Polyaniline-based all-polymeric conductive resin
- Hybrid laminate for lightning strike protection
- Summary and future plan

Introduction to the aircraft lightning strike damage and protection

Aircraft lightning strike damage

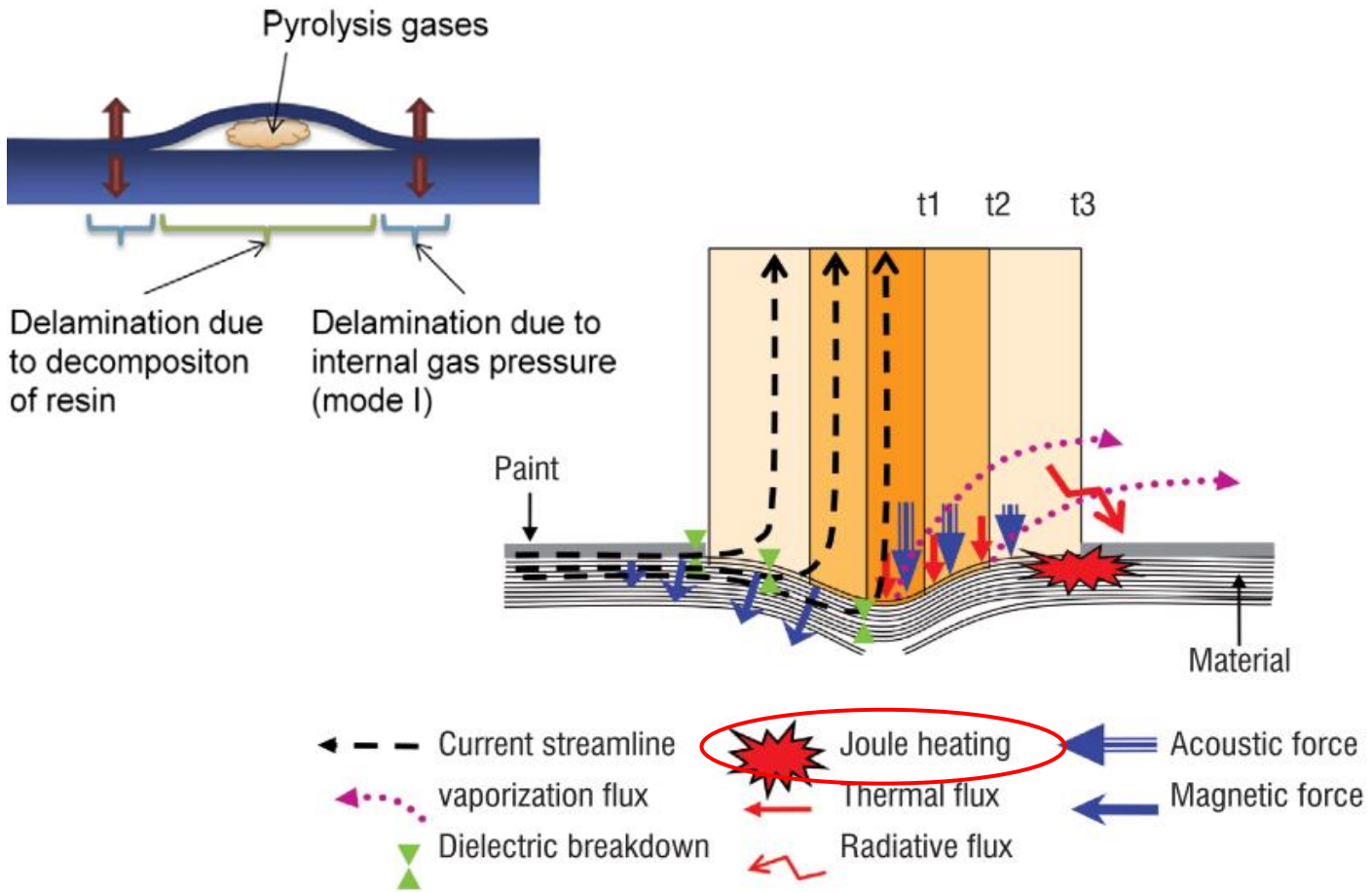


Illustration of the various direct and indirect effects at the lightning attachment point[1][2]

Damage on aircraft by lightning strike

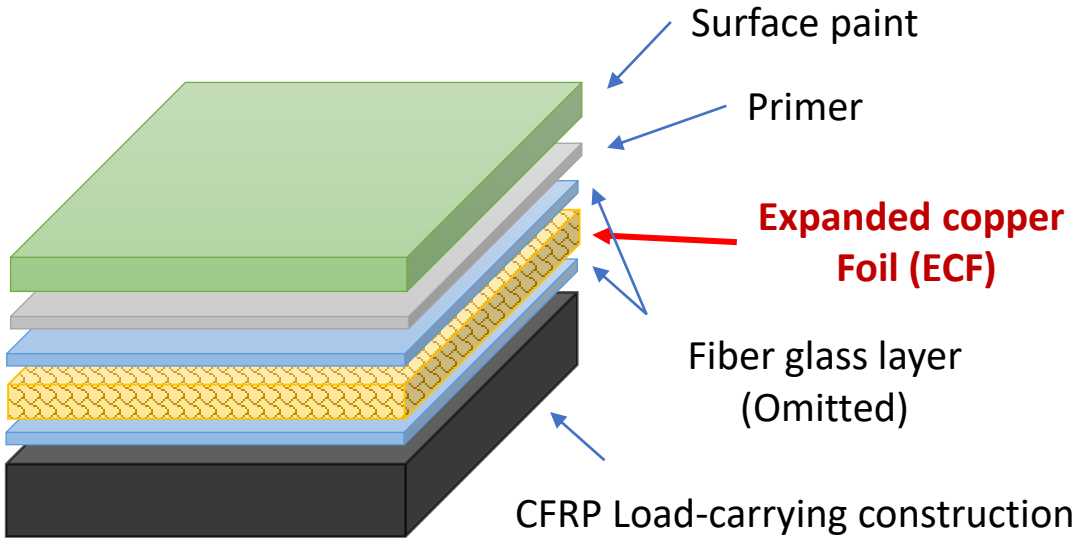
CF/Epoxy laminate strike by simulated lightning

[1] L. Chemartin, et al., "Direct Effects of Lightning on Aircraft Structure : Analysis of the Thermal , Electrical and Mechanical Constraints," *J. Aerosp. Lab*, no. 5, pp. 1–15, 2012.

[2] T. Ogasawara, et al., Coupled thermal-electrical analysis for carbon fiber/epoxy composites exposed to simulated lightning current, Compos. Part A Appl. Sci. Manuf. 41 (2010) 973–981.

Lightning strike protection (LSP)

➢ **Commercial LSP design: Metal mesh, metal foil**



Key parameter of ECF: Area density

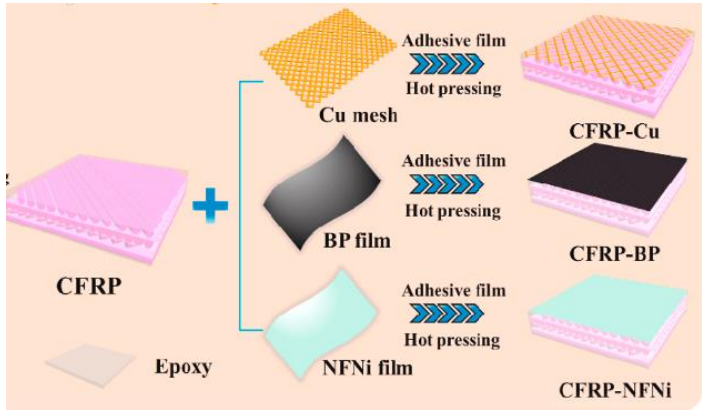
grams per square meter (gsm)

Lighter weight, higher protection efficiency

<u>Better fuel efficiency, longer range</u>

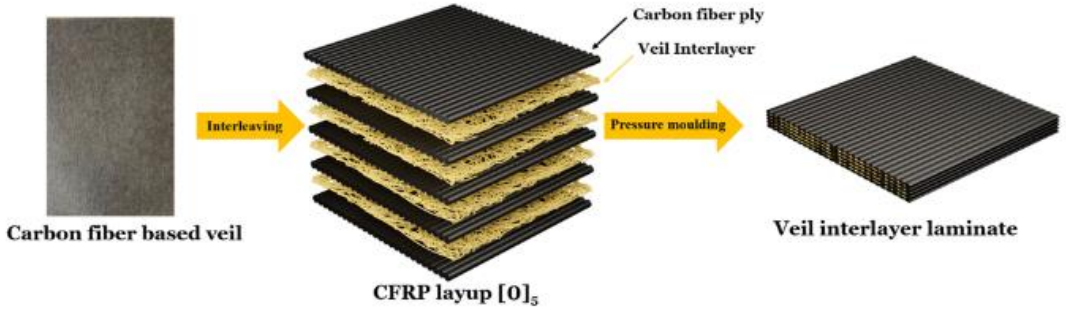
➢ **Innovative LSP design :**

High conductive LSP layer (Surface conductivity)



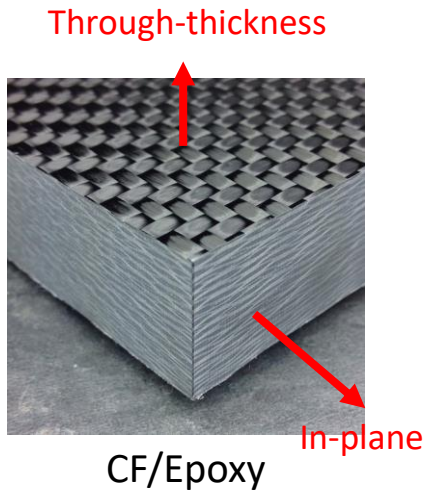
Zhu, H., Fu, K., Yang, B., & Li, Y. (2021). Nickel-coated nylon sandwich film for combination of lightning strike protection and electromagnetic interference shielding of CFRP composite. *Composites Science and Technology*, *207*(August 2020), 108675. https://doi.org/10.1016/j.compscitech.2021.108675

High conductive interleave (through-thickness conductivity)



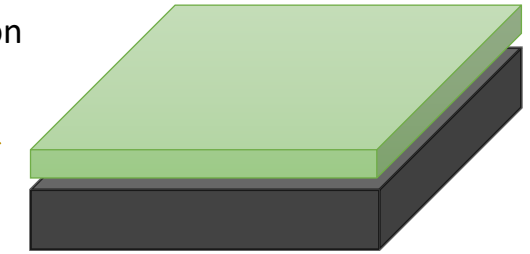
Waqas, M., Robert, C., Arif, U., Radacsi, N., Ray, D., & Koutsos, V. (2022). Improving the through-thickness electrical conductivity of carbon fiber reinforced polymer composites using interleaving conducting veils. *Journal of Applied Polymer Science*, *139*(43). https://doi.org/10.1002/app.53060

Conductive Matrix and ICPs

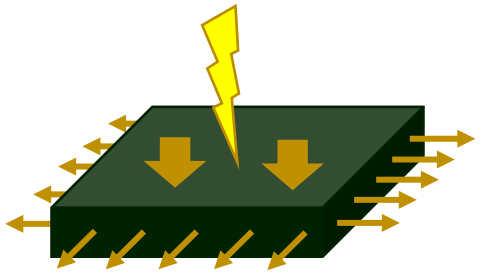


Conductive Modification

Surface layer
(fiberglass, primer, paint etc.)

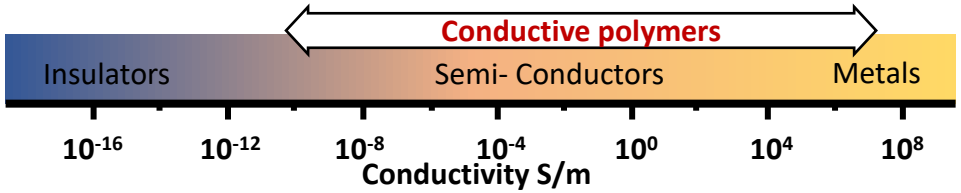


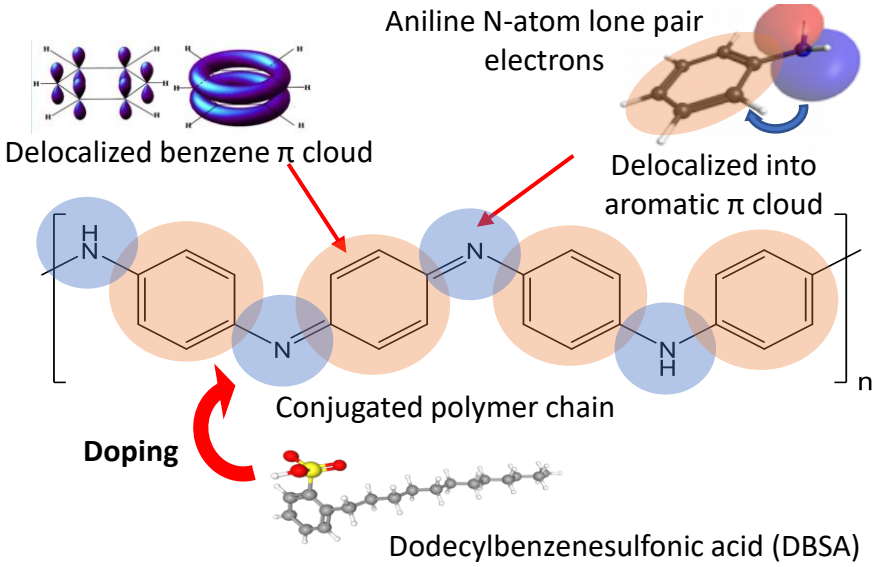
CF/Conductive matrix



Advantage:
High strength
Low weight
Cost-efficient matrix
Etc.
Disadvantage:
Flammable
Insulated (through-thickness)

Intrinsically Conductive Polymers (ICPs) Resin





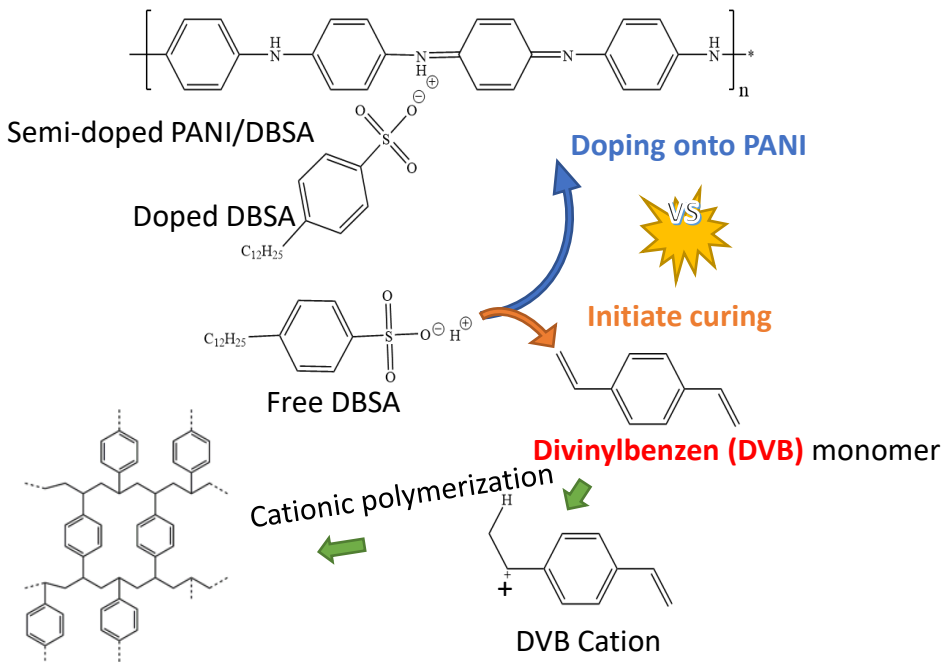
Structure and doping of Polyaniline (PANI)

- **Merit of PANI:**
  High conductivity, Easy synthesis, Eco-friendly, Environment friendly;
- **Demerit of doped PANI**
  No mechanical strength, Poor processability;

Polyaniline-based conductive resin and CF/PANI

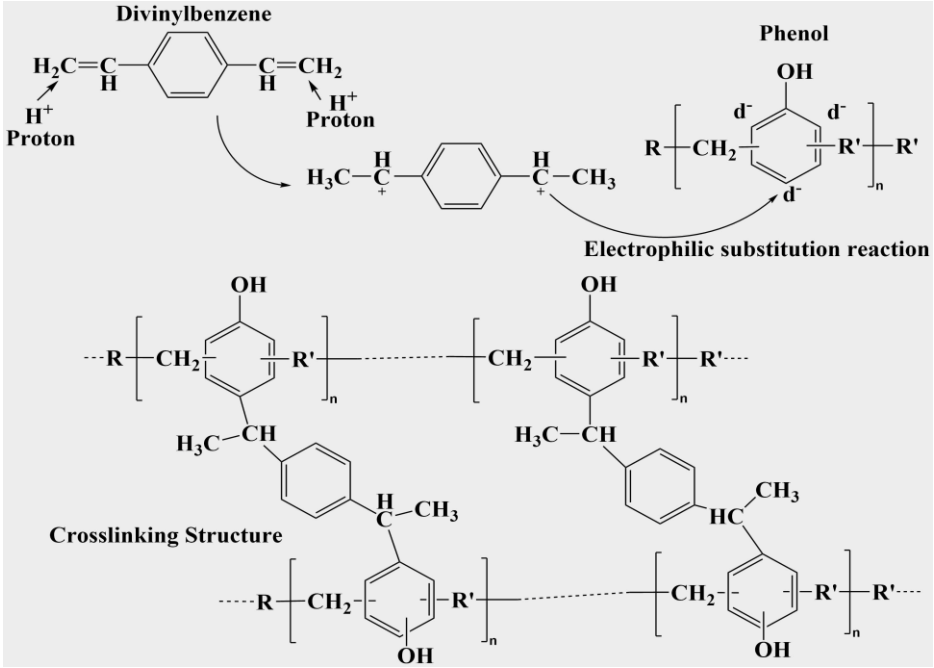
Polyaniline-based all-polymeric conductive resin

New PANI-DBSA/Phenol-DVB **(PDPD)** resin system



Curing mechanism of PANI/DBSA/Divinylbenzene(DVB) resin system

New PANI-DBSA/Phenol-DVB **(PDPD)** resin system



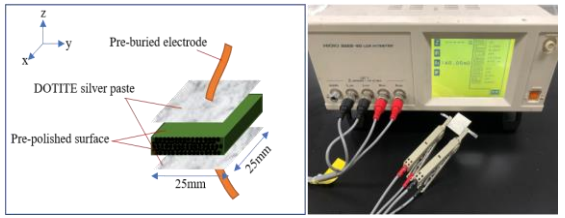
The curing mechanism of phenol-DVB in the presence of protonic acid.

	Epoxy	PDD (50wt%DVB)	PDD (70wt% DVB)	PDPD-28	PDPD-35
PANI content (wt%)	0	15	9	9	9
DC Conductivity (S/cm)	$<10^{-13}$	0.27	0.07	0.32	0.4
Flexural Modulus (GPa)	3.4-4.5	1.2	1.79	2.43	2.73
Flexural Stress (MPa)	75-120	18.1	26.7	55.92	65.24

V. Kumar, **T. Yokozeki**, T. Goto, and T. Takahashi, "Mechanical and electrical properties of PANI-based conductive thermosetting composites," J. Reinf. Plast. Compos., vol. 34, no. 16, pp. 1298–1305, 2015.

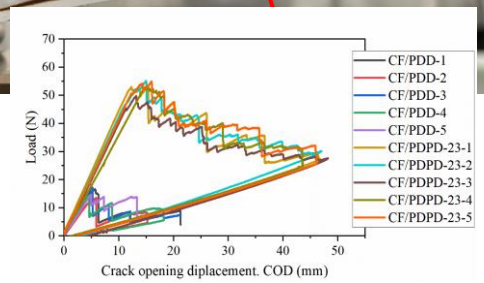
V. Kumar, Y. Zhou, G. Shambharkar, V. Kunc, and **T. Yokozeki**, "Reduced de-doping and enhanced electrical conductivity of polyaniline filled phenol-divinylbenzene composite for potential lightning strike protection application," Synth. Met., vol. 249, no. January, pp. 81–89, 2019.

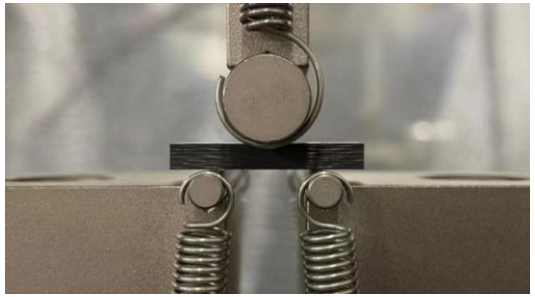
Properties of the CF/PANI composites



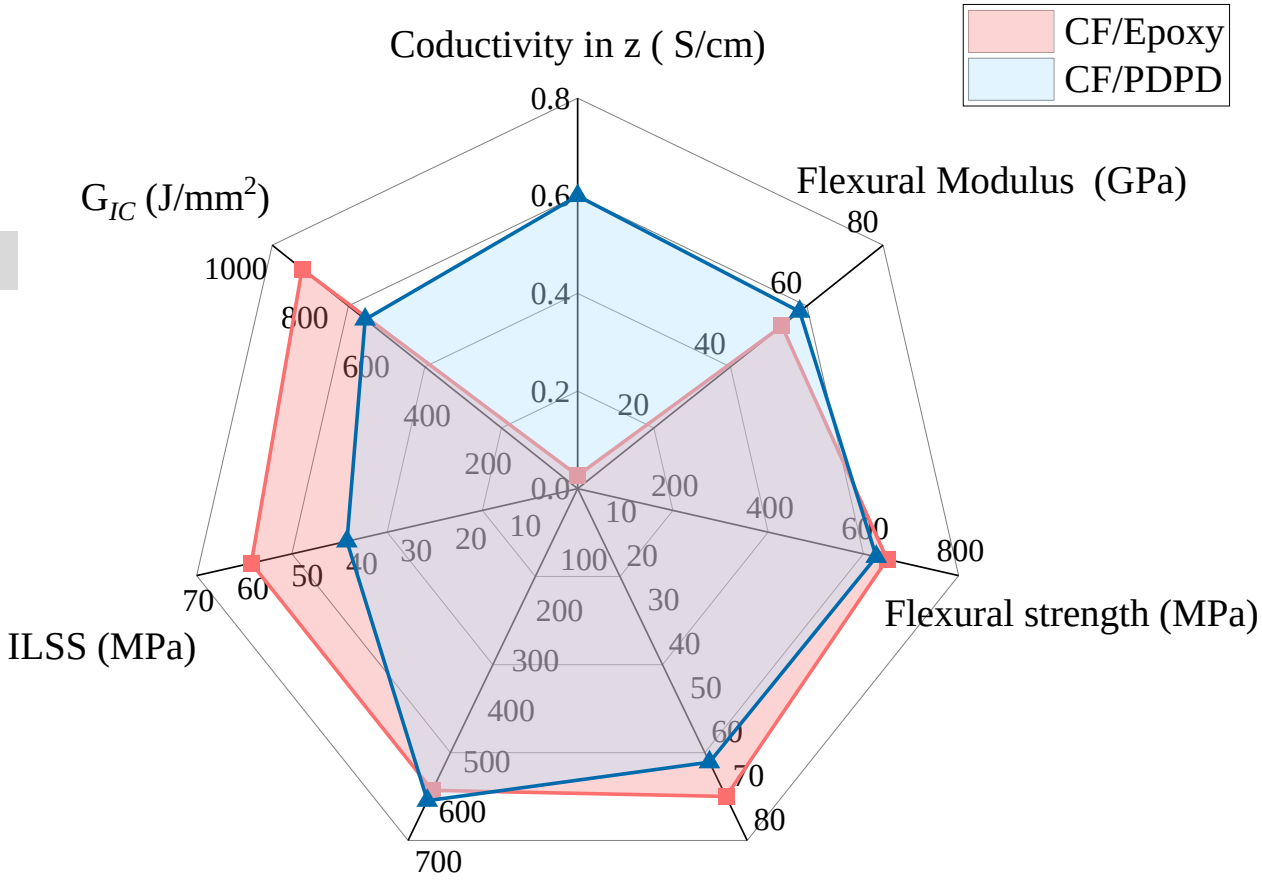
z-Conductivity test

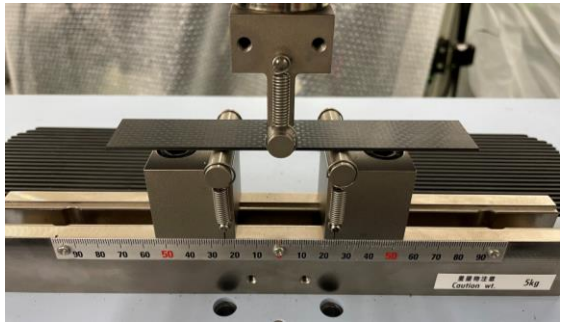
DCB test for fracture toughness



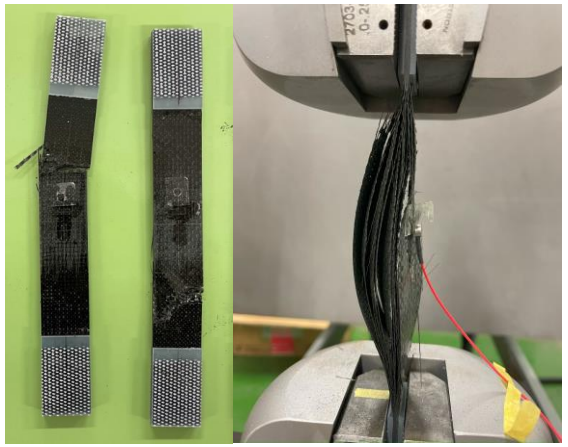


ILSS test



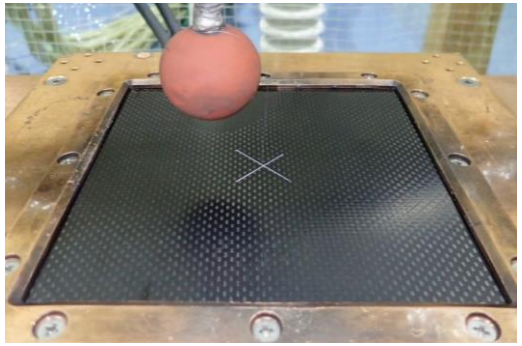


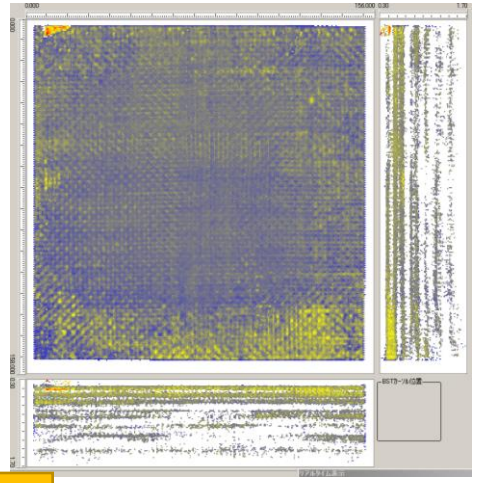
3-point bending test

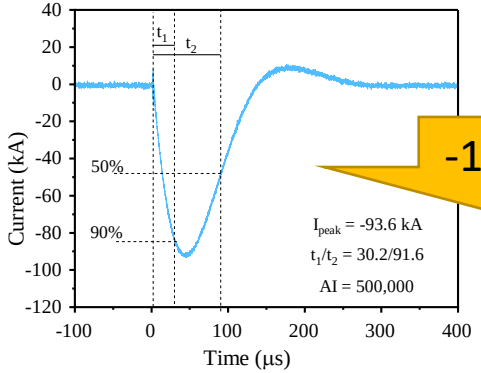


Uniaxial tensile test

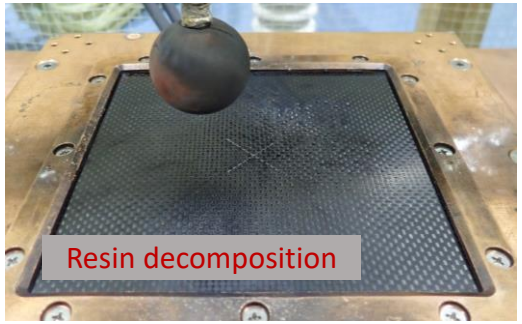
Previous result of CF/PANI lightning strike test

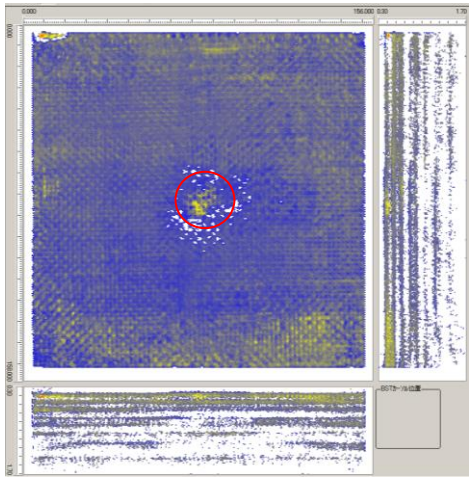




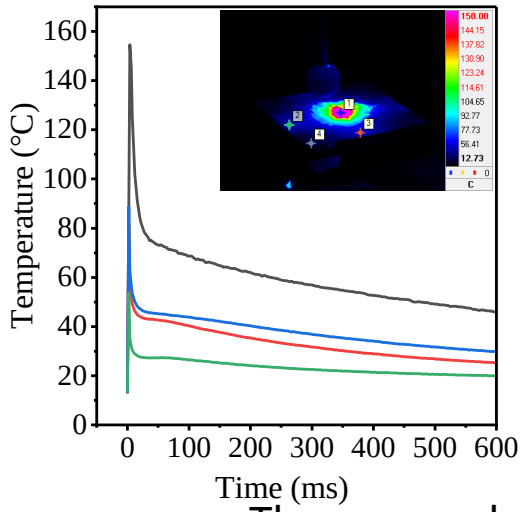


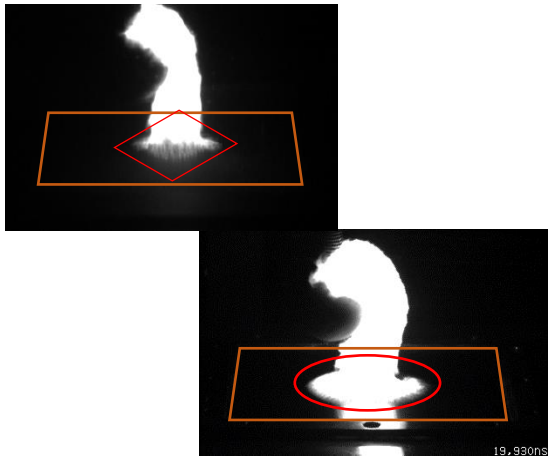
-100kA



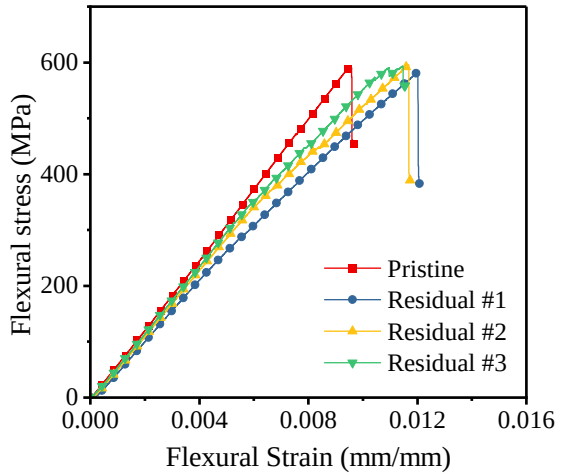


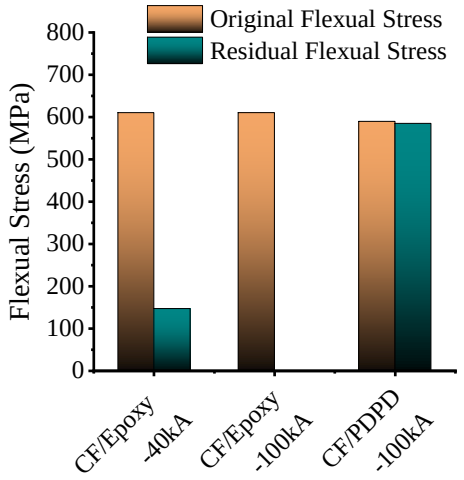
Minor visible damage





Thermography and High-speed camera

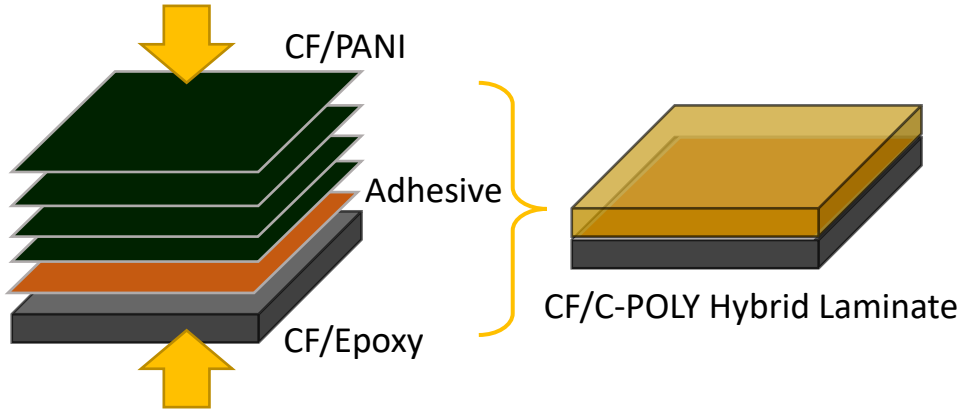


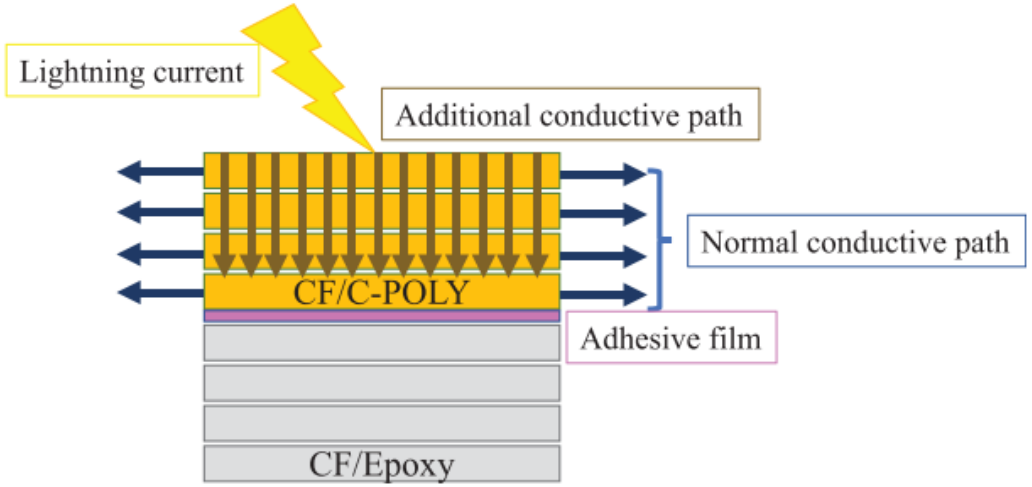


High residual mechanical properties

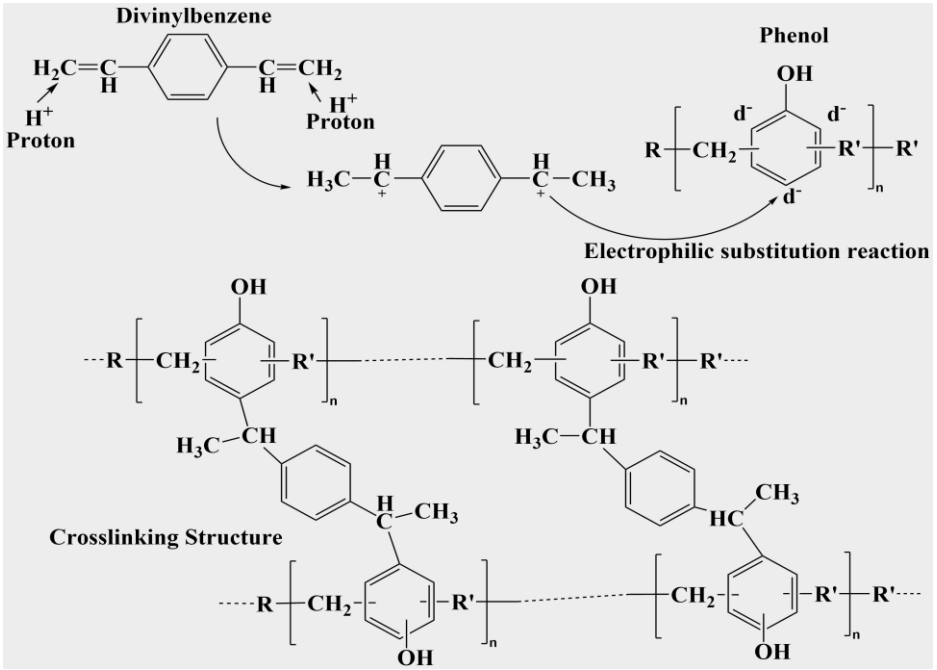
Hybrid laminate for lightning strike protection

Introduction of hybrid laminate for LSP





S. Manomaisantiphap, V. Kumar, T. Okada, and T. Yokozeki, "Electrically conductive carbon fiber layers as lightning strike protection for non-conductive epoxy-based CFRP substrate," J. Compos. Mater., vol. 54, no. 29, pp. 4547–4555, 2020.



Phenol oligomer and DVB can be cured with a small amount of proton acid

	Epoxy	PDPD	Phenol-D
PANI content (wt%)	0	9	0
DC Conductivity (S/cm)	$<10^{-13}$	0.26	$<10^{-13}$
Flexural Modulus (GPa)	3.4-4.5	2.23	3.20
Flexural Stress (MPa)	75-120	55.92	129.3

Fabrication of the new hybrid laminate

PDtPD Conductive resin

T300 woven fabric

PDtPD prepreg

0.8 ~ 1 S/cm

CF/PDtPD

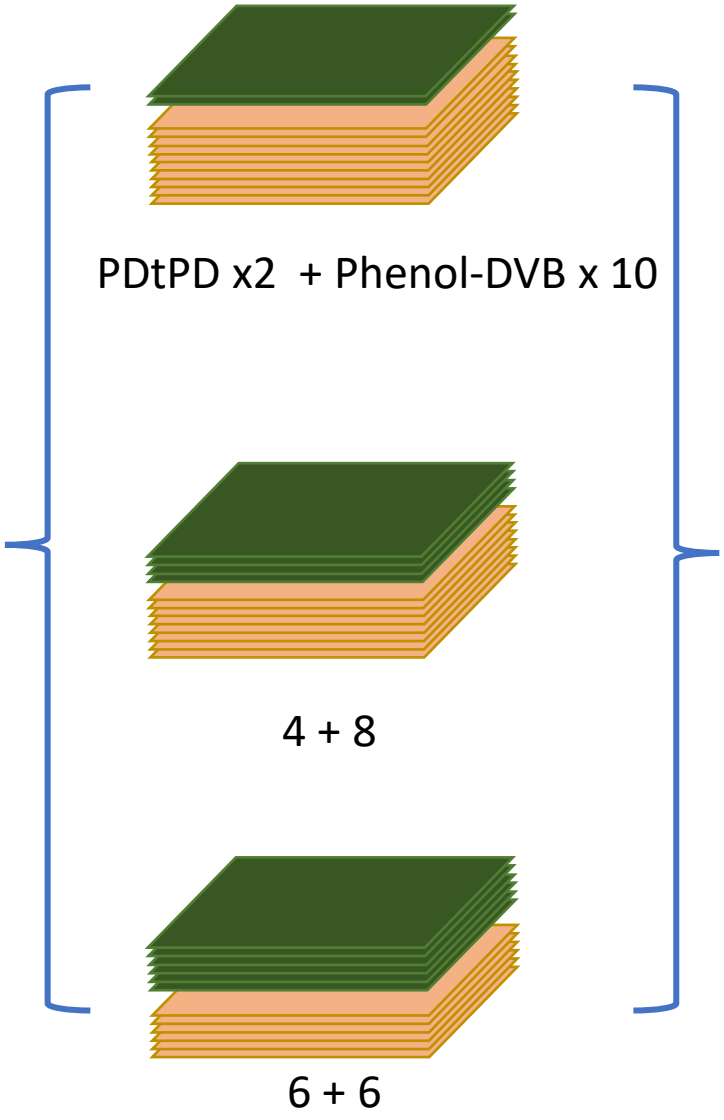
Pure Phenol-DVB resin

T300 woven fabric

Phenol-DVB prepreg

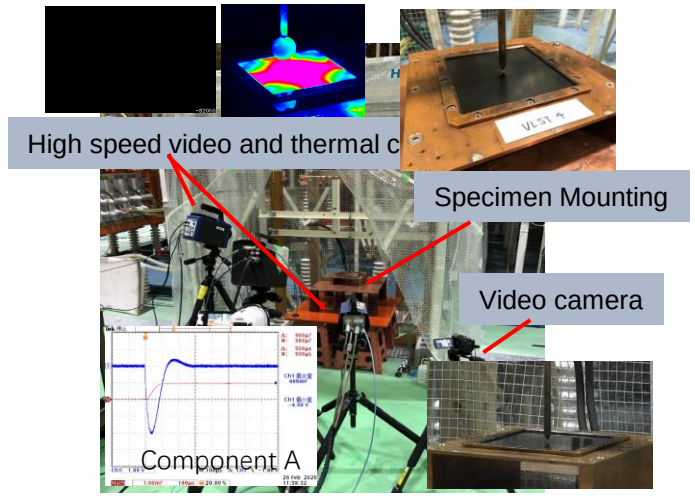
CF/Phenol-DVB

The curing profile applicable to both



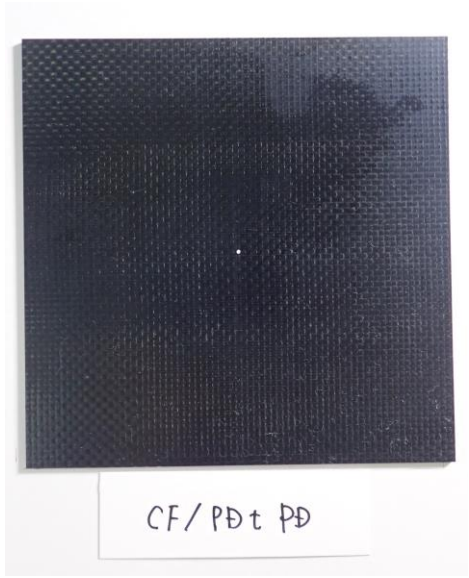
Stacking sequence of $[0/90]_{12}$

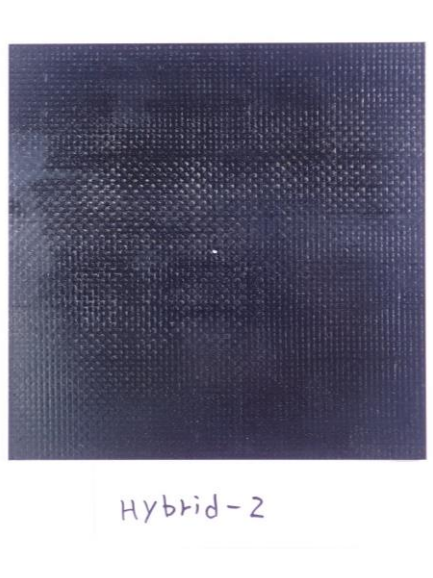
Hybrid -2
Hybrid -4
Hybrid -6

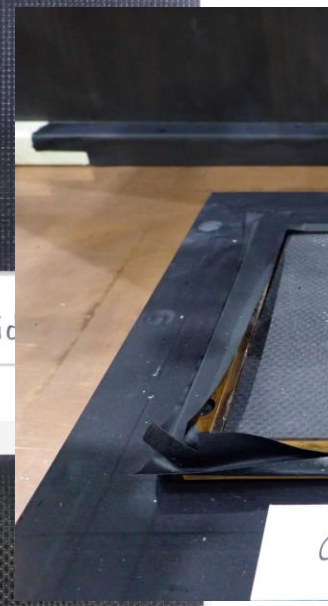


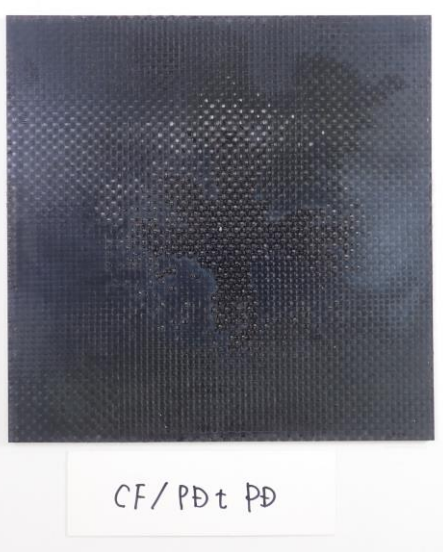
Simulated lightning strike test

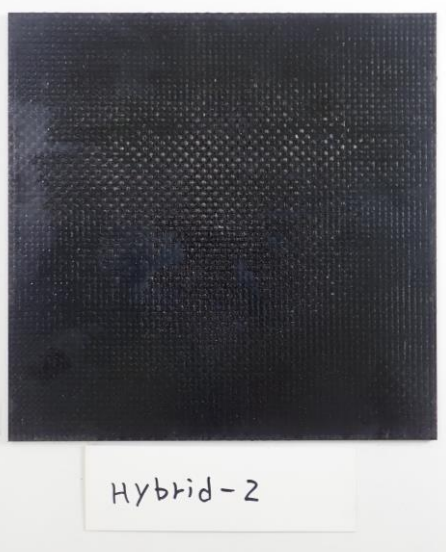
Visual damage inspection

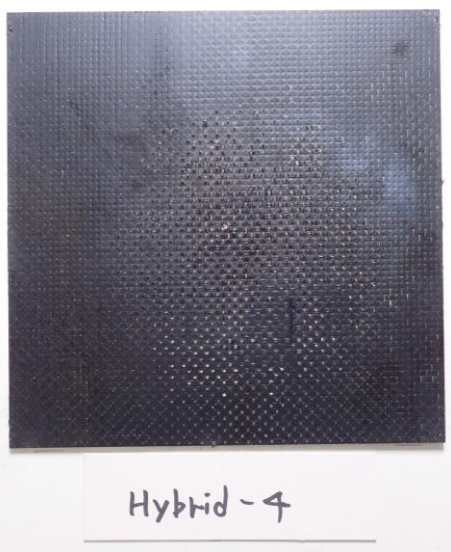




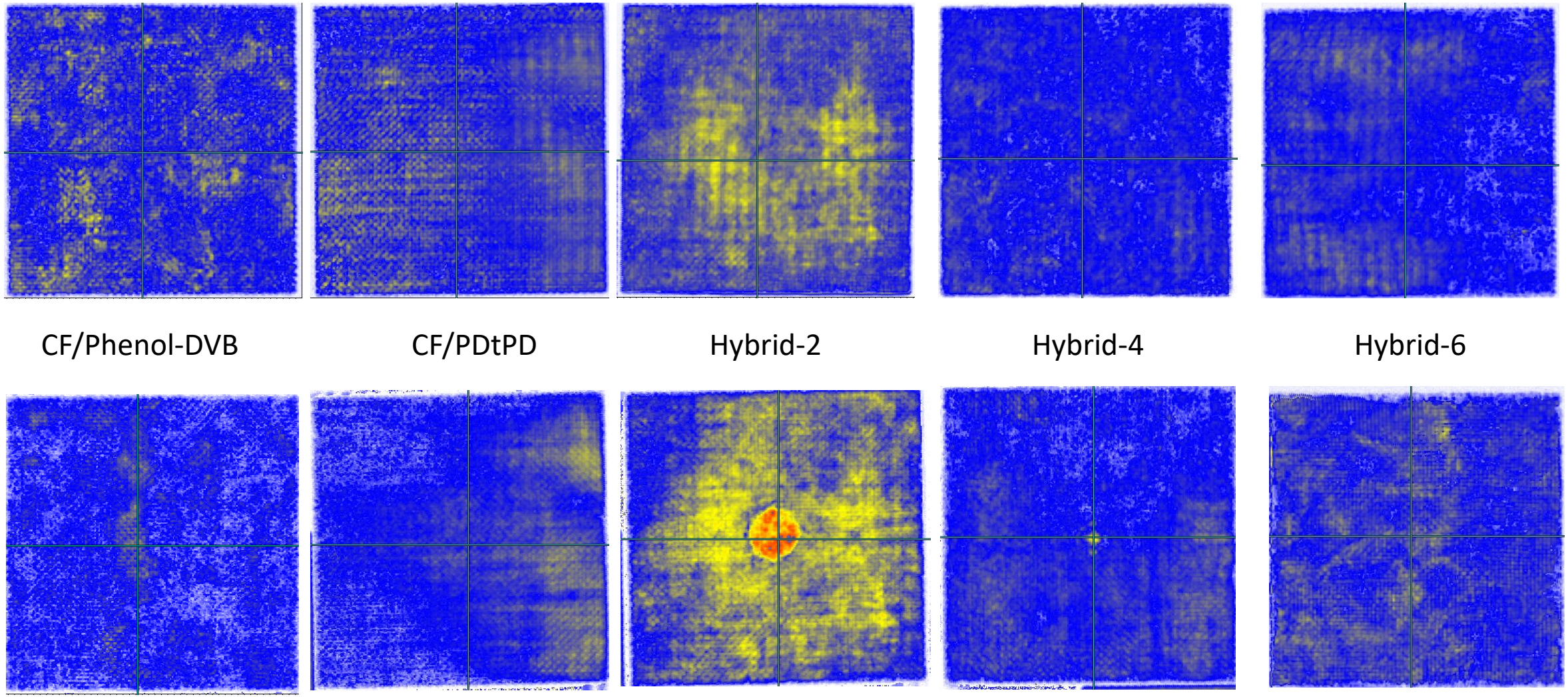




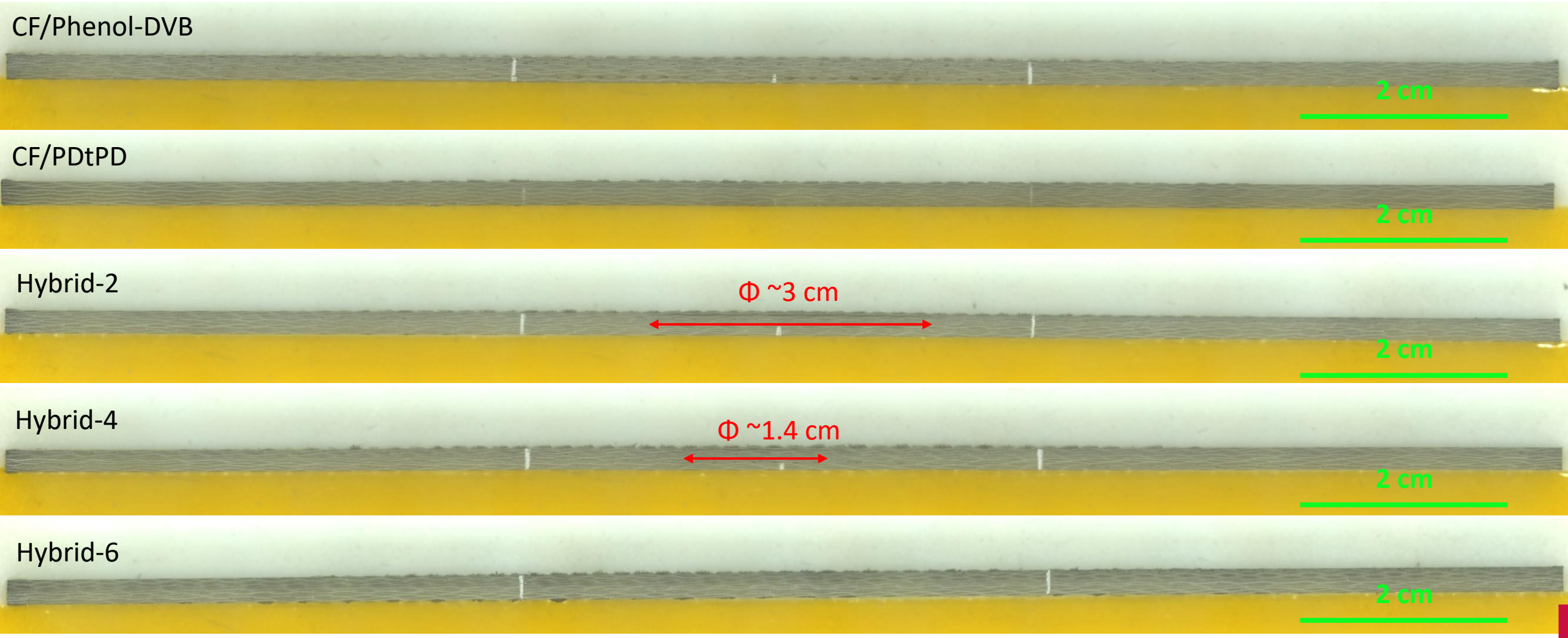




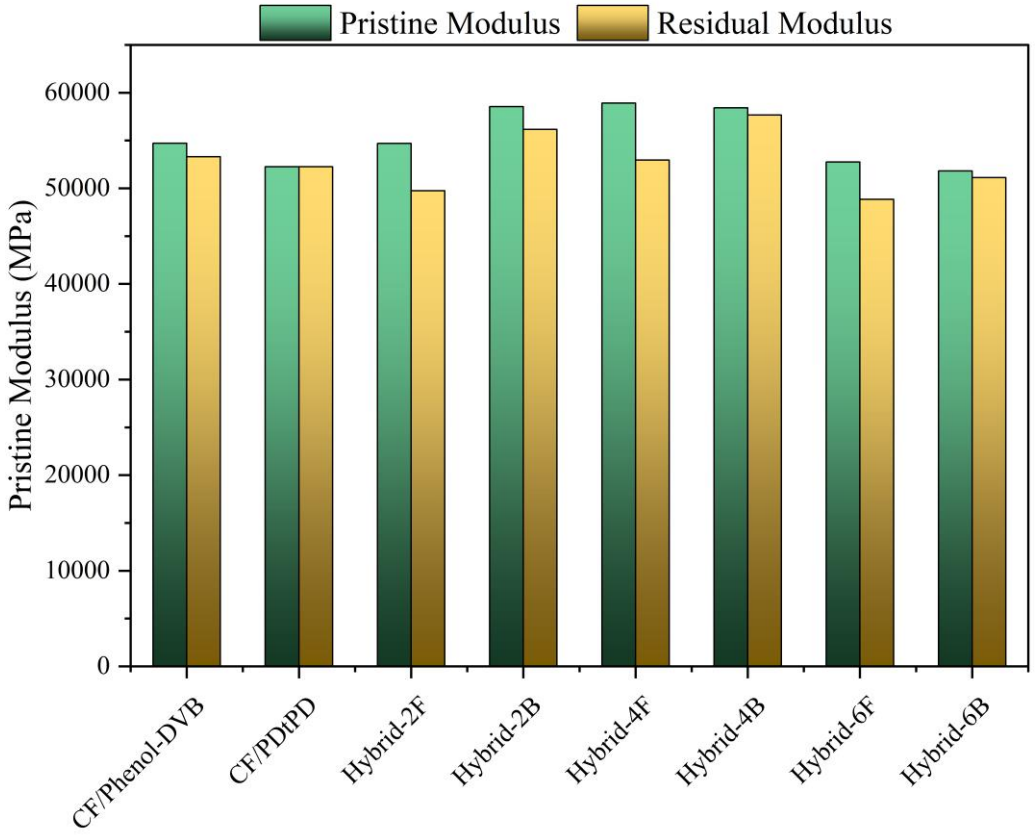
Ultrasonic damage inspection (C-scan)

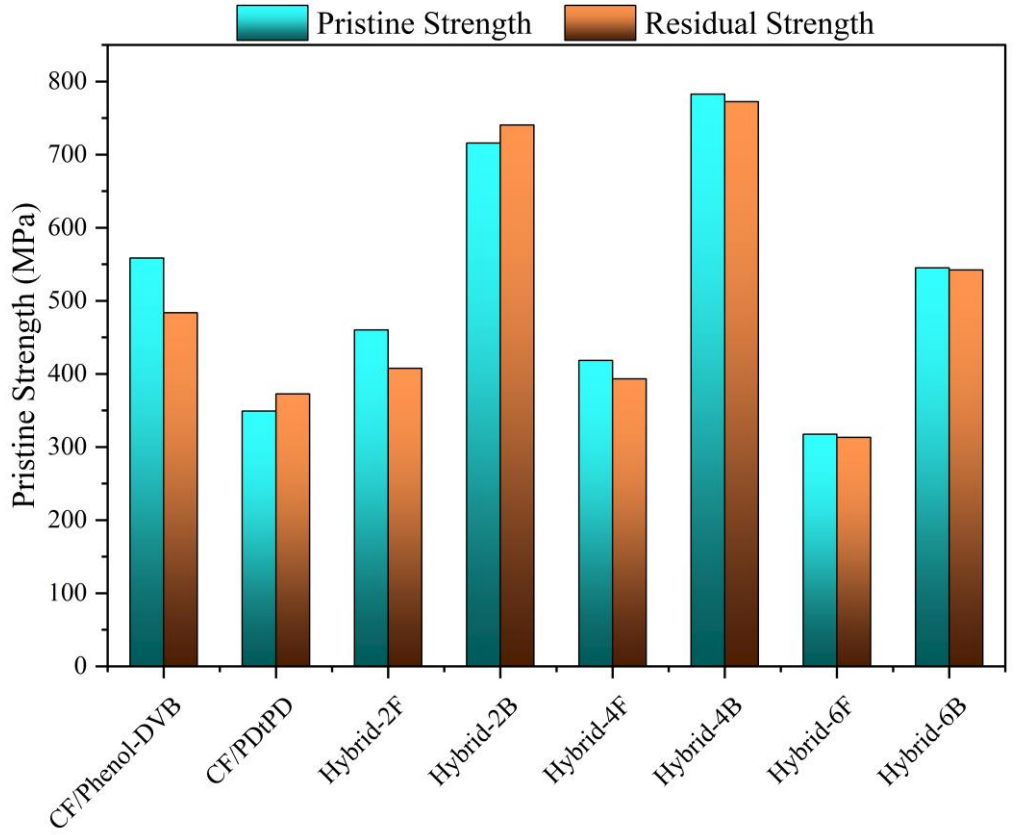


Cross-section image (center)



Residual mechanical properties





Residual mechanical properties of the control and hybrid laminates after the lightning strike test

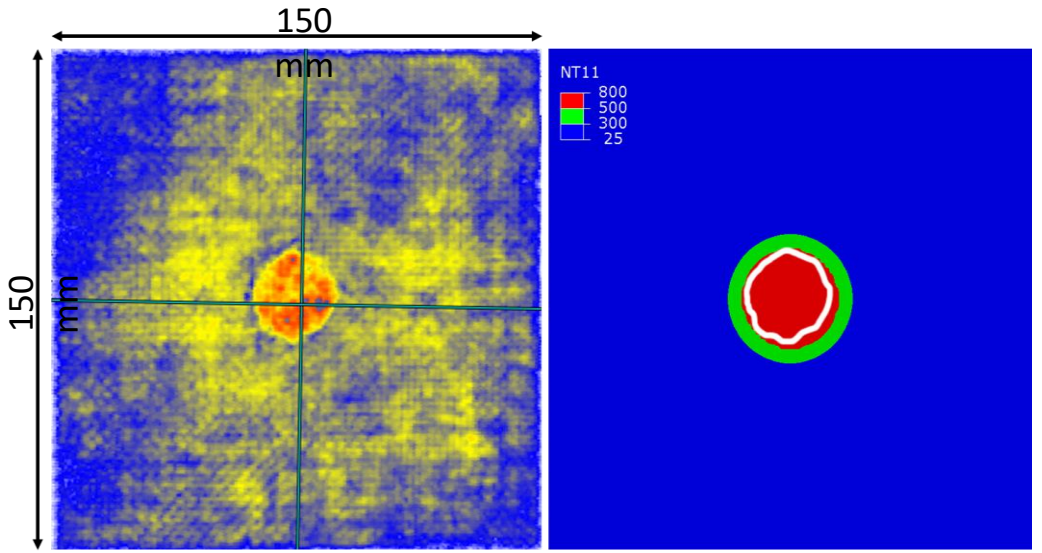
Summary and future plan

Summary

- A new hybrid laminate system with electrically conductive doped layers and load-carrying layers is designed and manufactured with a one-step curing process
- The artificial lightning strike test is performed on hybrid laminates with different hybrid combinations to observe the self-protection feature against the lightning strike
- The experimental results suggested the increasing number of doped layers comprising conductive resin matrix show better protection for the load-carrying layers against lightning strike damage
- Further verification is needed to provide more detailed discussion and conclusion

Future plan

- Optimize the manufacturing process for hybrid laminate
- Prepare more samples for further verification
- Thermal-electric modeling is being completed in ABAQUS and some preliminary results are available
- Further simulations will be completed to establish the number of doped plies required to minimize lightning damage



Top surface experimental NDI damage

Predicted top surface damage with experimental overlay

1 - Millen SLJ, Murphy A. Spatial and temporal Waveform A and B loading and material data for lightning strike simulations based on converged FE Meshes 2021.
2 - Foster P, Abdelal G, Murphy A. Understanding how arc attachment behaviour influences the prediction of composite specimen thermal loading during an artificial lightning strike test. Compos Struct 2018;192:671–83.
3 - Millen SLJ, Murphy A. Understanding the influence of test specimen boundary conditions on material failure resulting from artificial lightning strike. Eng Fail Anal 2020;114.

Thank you very much