STEVENS INSTITUTE of TECHNOLOGY
THE INNOVATION UNIVERSITY®

COMSOL CONFERENCE 2017 BOSTON

Remote Monitoring of Structures in composite material via embedded thermo-chemical sensors.

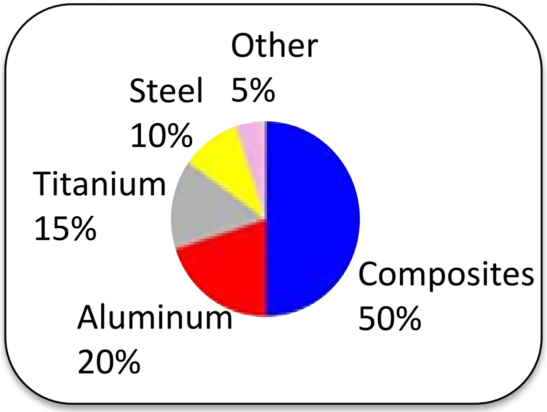
Behnoush Golchinfar

Marcus Rutner

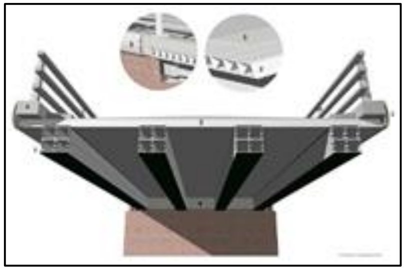
Dimitri Donskoy

Composite Material: Structural Material of the Future

- Carbon laminate
- Carbon Sandwich
- Fiberglass
- Aluminum
- Aluminum/steel/titanium pylons

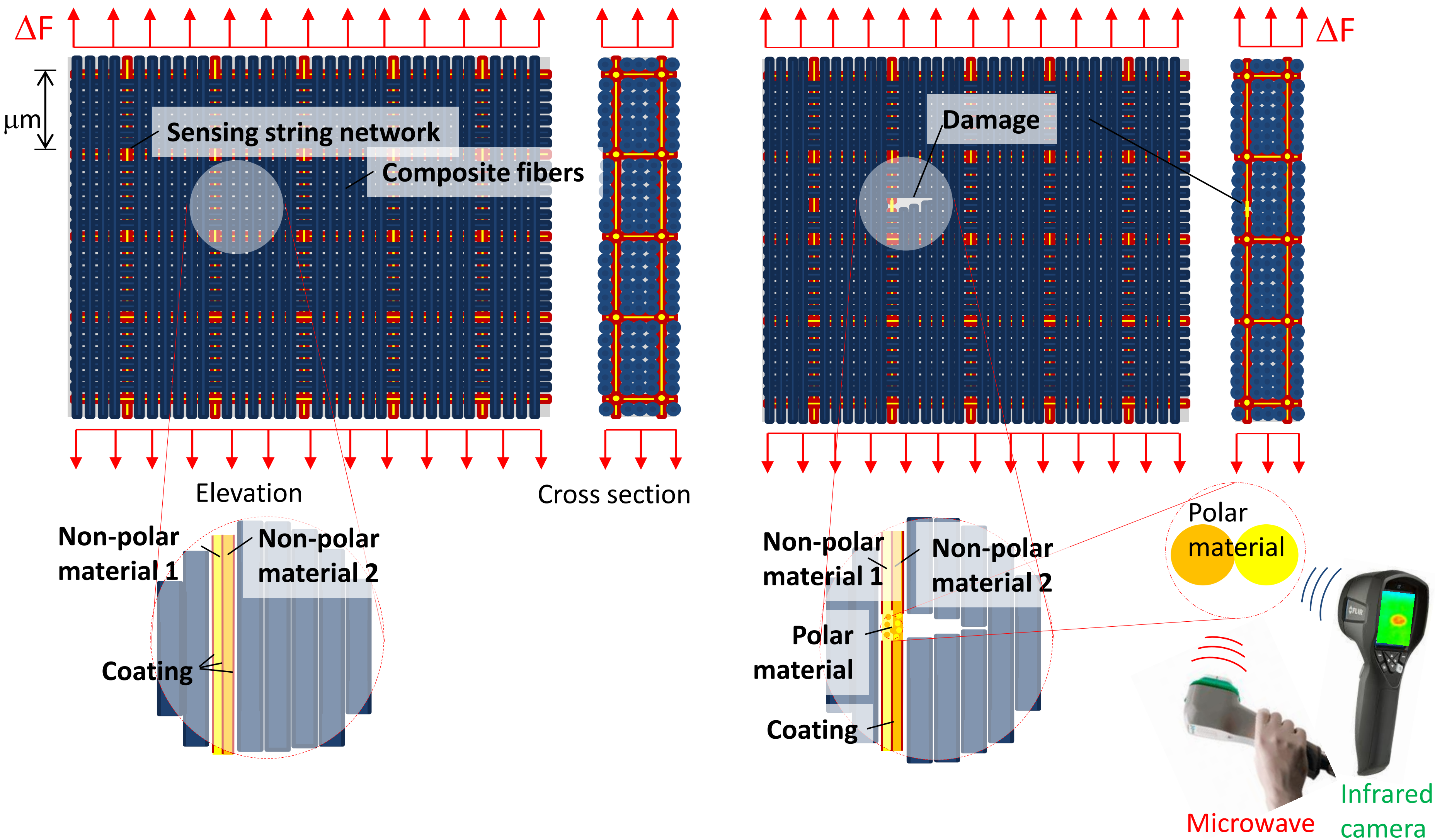


Boeing 787 Dreamliner

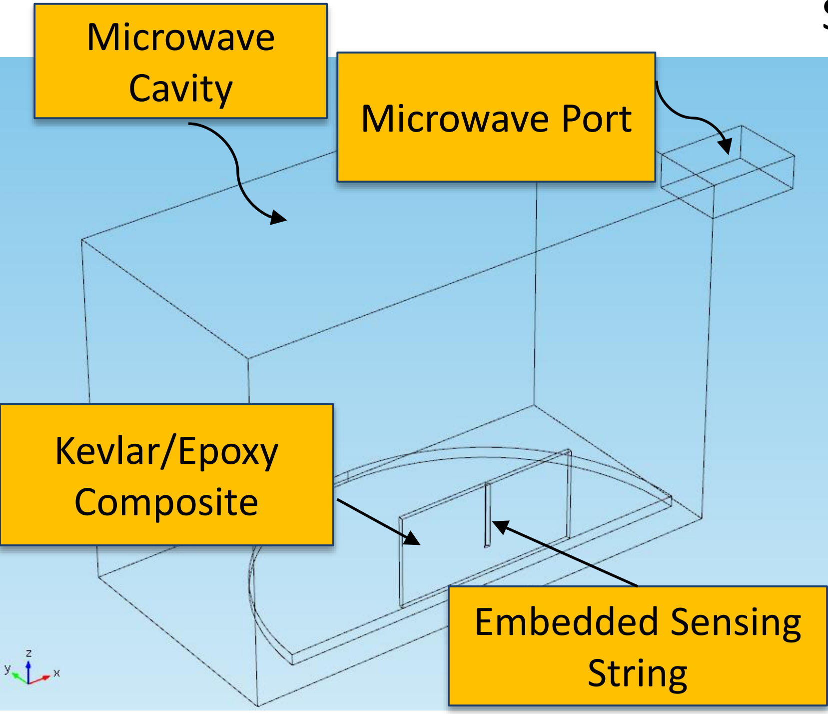


West Mill Bridge, England, 2002
(First Composite bridge in Europe)

Detection of Micro Cracks

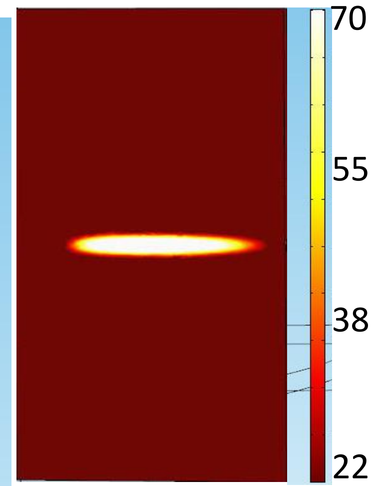


Macro Scale Simulation & Validation



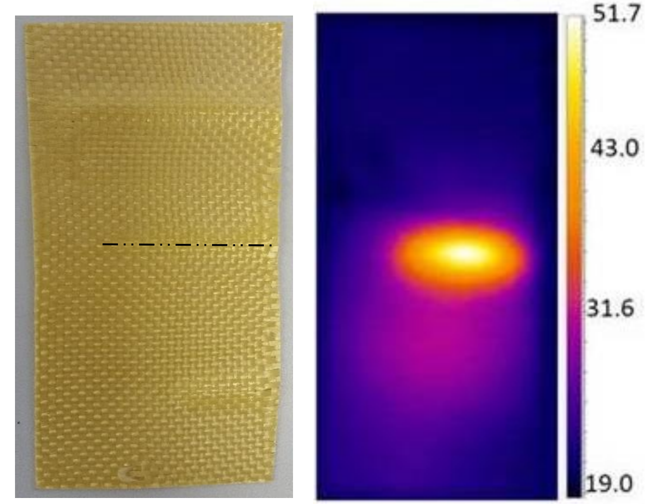
Microwave simulation-Geometry

Simulation Result

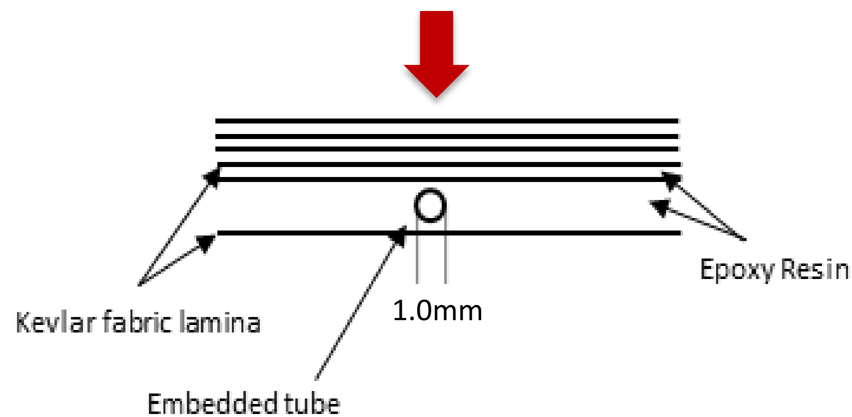


Max T=67.8°C

Experimental Tests



Microwave and IR Scanning from this side



COMSOL MULTIPHYSICS :
ELECTROMAGNETIC HEATING GOVERNING PHYSICS

RF Module & Heat Transfer

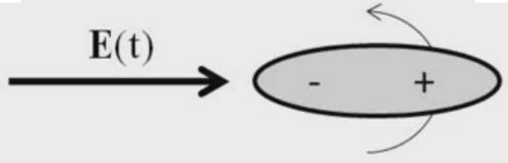
1 Maxwell`s Equations

$$\nabla \times \left(\mu_r^{-1} \nabla \times \mathbf{E}\right) - k_0^2 \left(\varepsilon_r - j\sigma / \omega\varepsilon_0\right) \mathbf{E} = \mathbf{0}$$

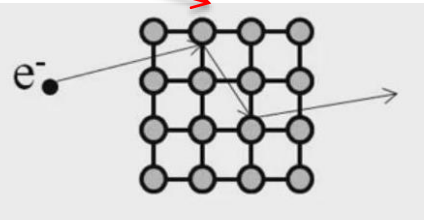
$$\mu_r = \mu_r' - j\mu_r''$$

Magnetic Permeability

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$$



Dielectric



Conduction Current Losses

2 Electromagnetic Losses

$$Q_{Hdipole} = \frac{1}{2} \omega \mu_r'' H \cdot H^*$$

$$Q_{Edipole} = \frac{1}{2} \omega \varepsilon_r'' E \cdot E^*$$

$$Q_{cond} = \frac{1}{2} \sigma E \cdot E^*$$

3 Heat Equation

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q$$

Negligible

$$\theta \sim \frac{\partial T}{\partial t} \rightarrow \int_0^T \frac{\partial T}{\partial t} = \int_0^T Q$$

$$T = a.Q.\Delta t$$

$Q \sim E^2$ 1

$T \sim E \rightarrow \Delta T = Q.\Delta t$ 2

$\Delta T \sim E^2.t$

Exposure

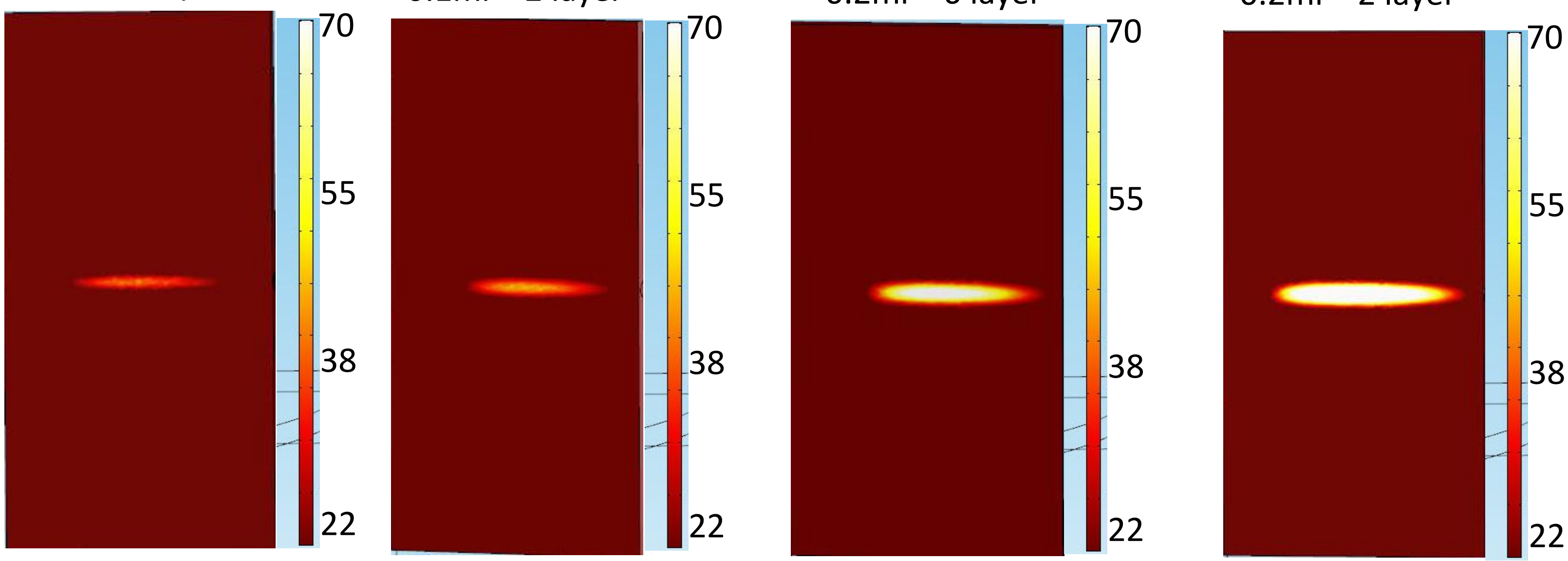
Challenges in first Simulations

Challenge of finding electrical and thermal properties of composite

	Kevlar/Epoxy	**Water**
Density [kg/m^3]	1450	1000
Thermal Conductance [W/(m × K)]	0.65	0.6
Heat Capacity at Constant Pressure [J/(kg×K)]	1420	4181.8
Relative Dielectric Permittivity	$4 - 0.12j$	80.36-9.36j
Electric Conductivity [S/m]	0.8×10^{-3}	0.025

Simulation Results

0.1ml – 6 layer | 0.1ml – 2 layer | 0.2ml – 6 layer | 0.2ml – 2 layer

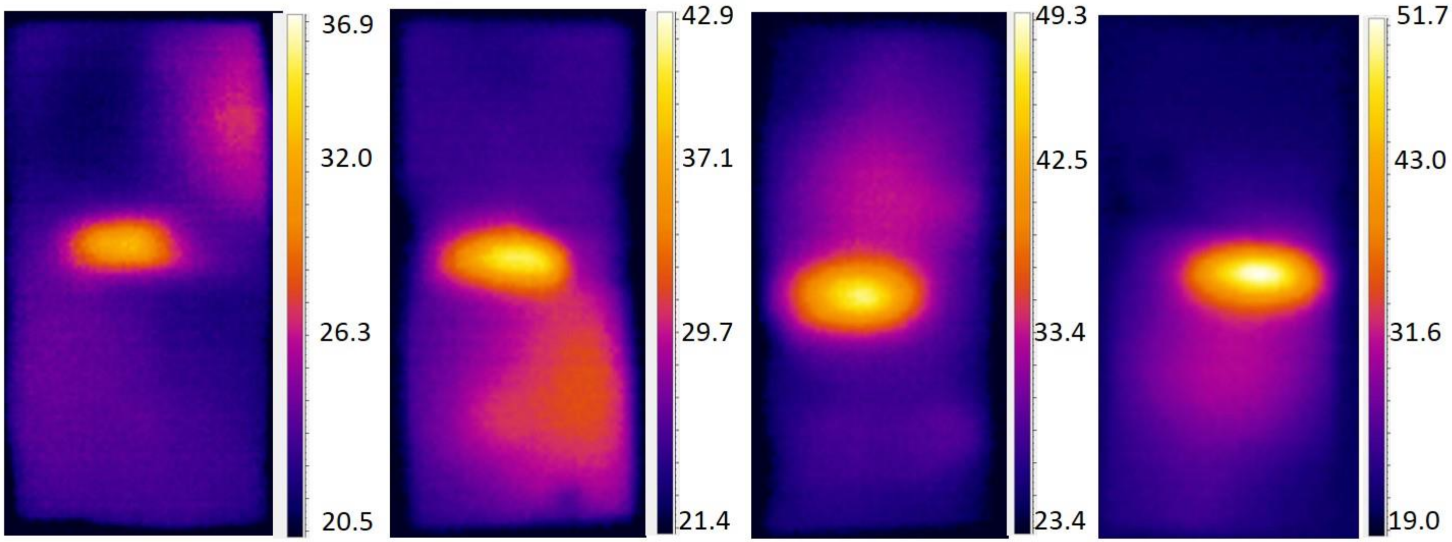


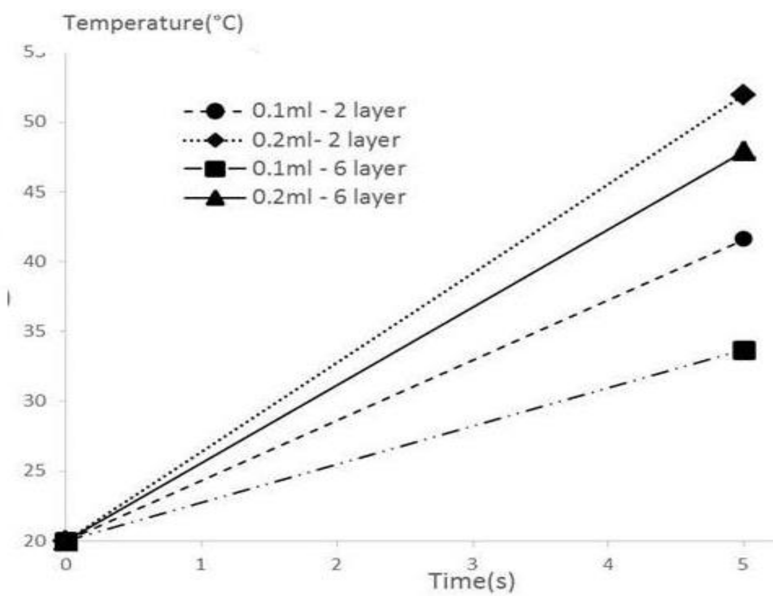
Max T=51.9°C | Max T=55.4°C | Max T=67.3°C | Max T=67.8°C

- Thermal signal on surface of Kevlar/epoxy matrix composite specimen when exposed to 2.45GHz Microwave.
- Variation of polar material volume and composite layup.

Experimental Results

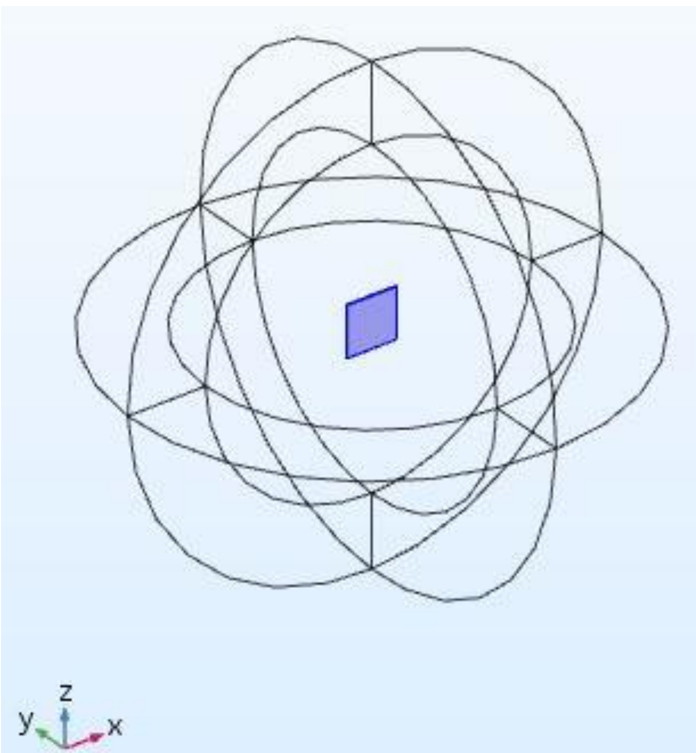
0.1ml – 6 layer | 0.1ml – 2 layer | 0.2ml – 6 layer | 0.2ml – 2 layer

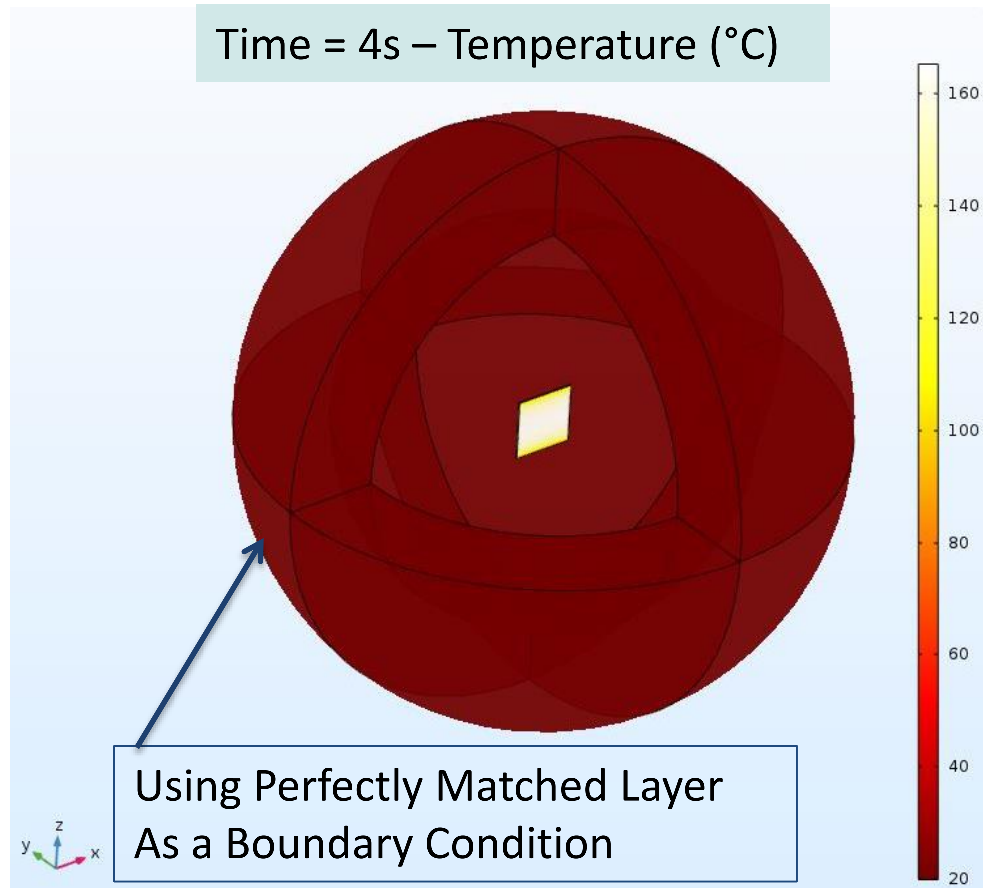




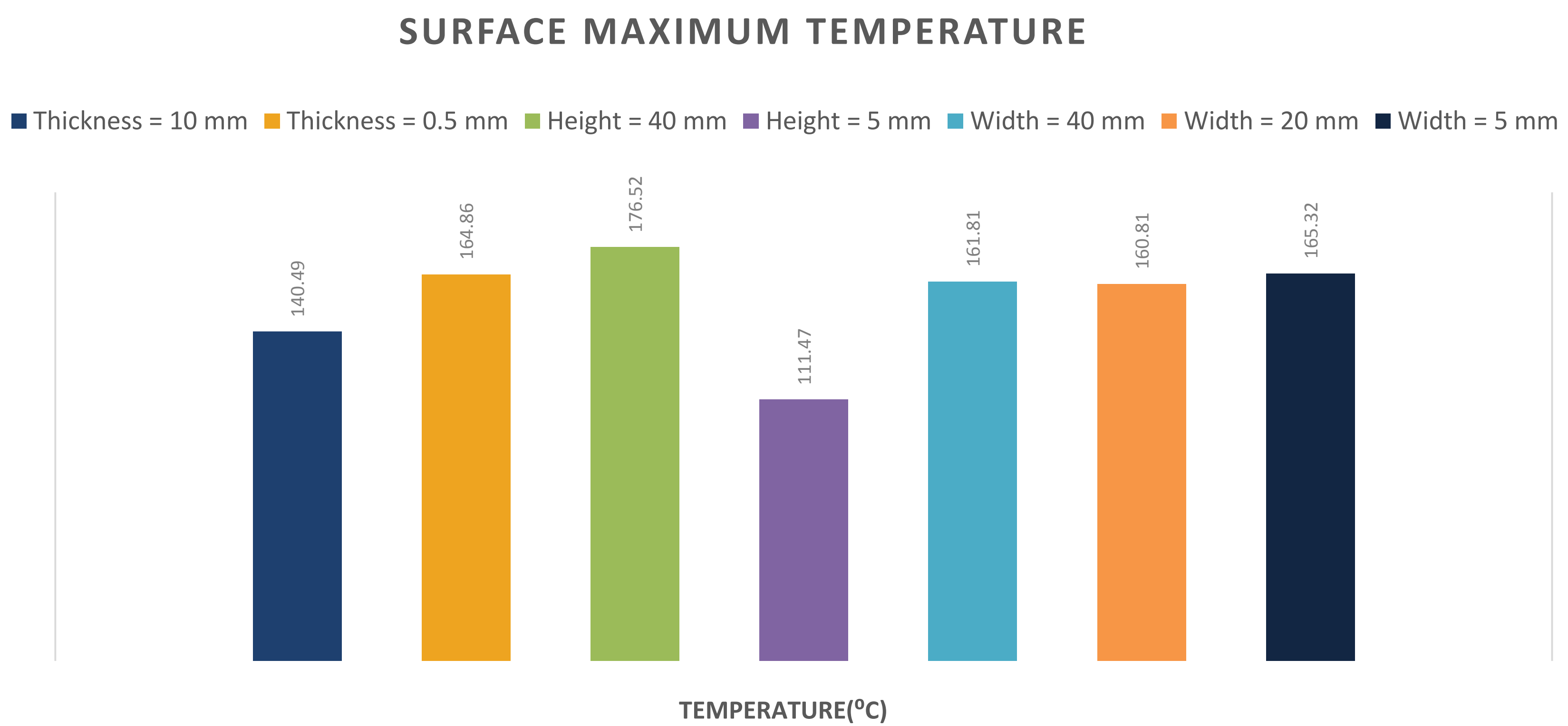
Parametric Study on Kevlar Composite Patch

Expose composite to Plane wave



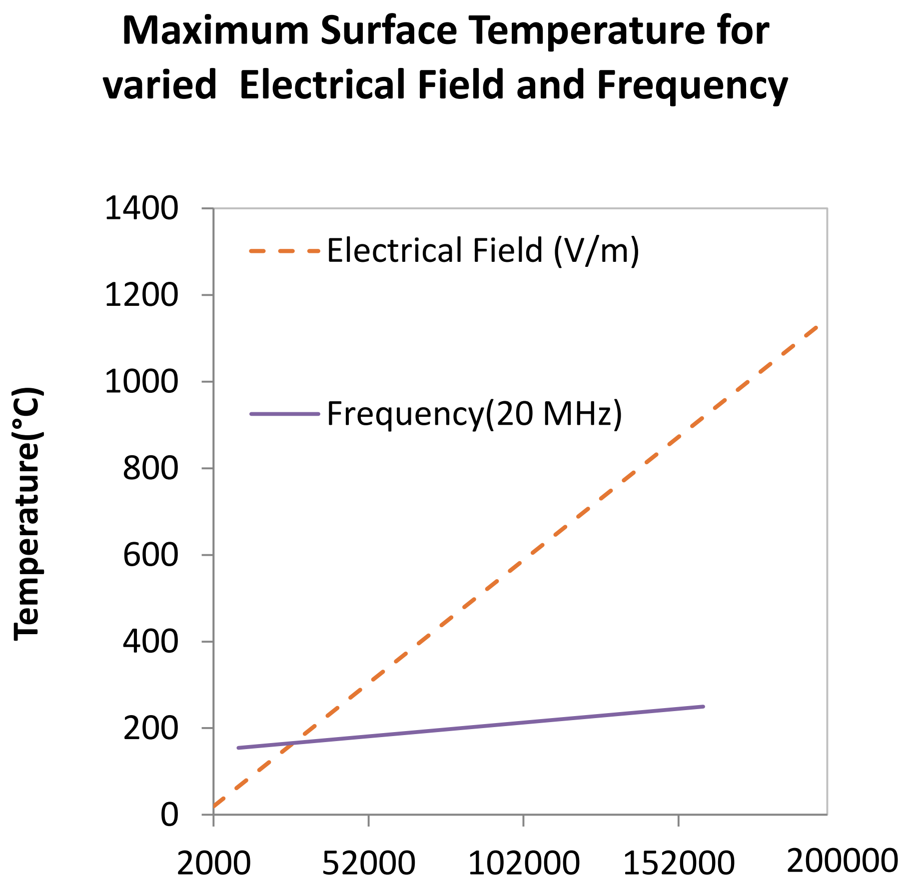


Parametric Study: Composite without water inside-Geometry Effect

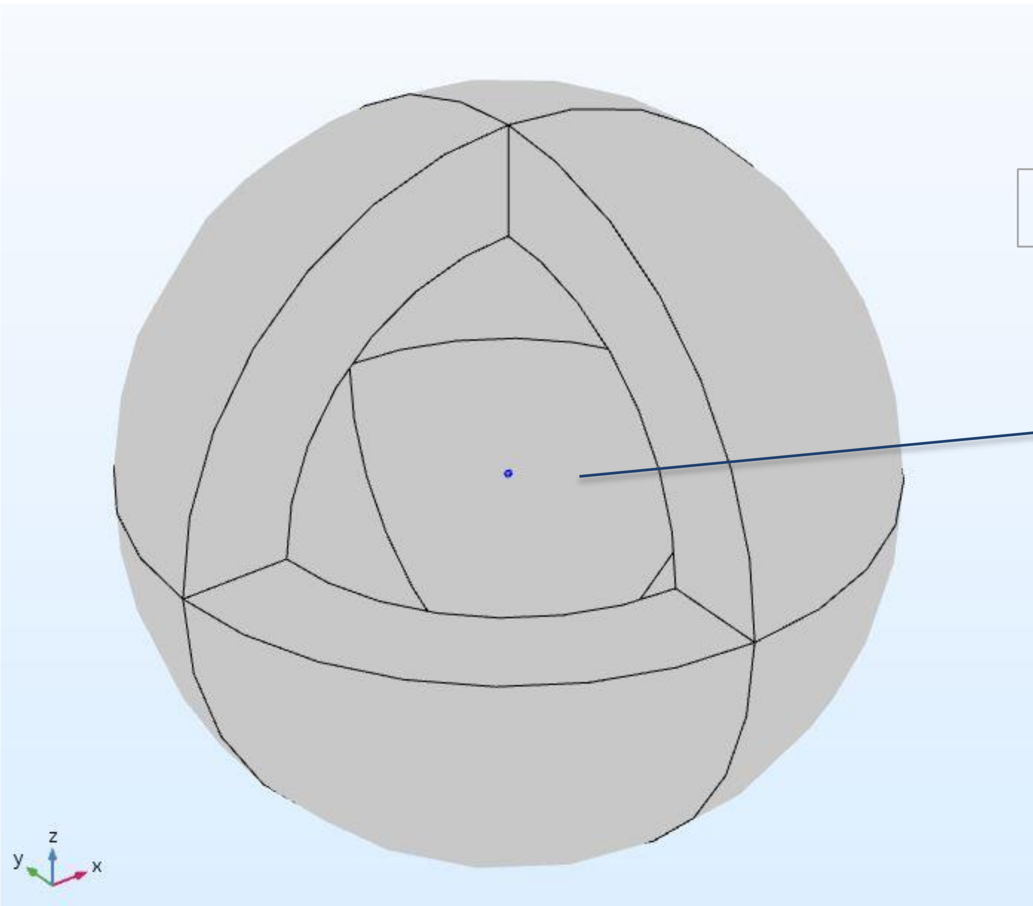


No consistent change has been observed by changing shape in the maximum surface temperature, more investigation has to be done

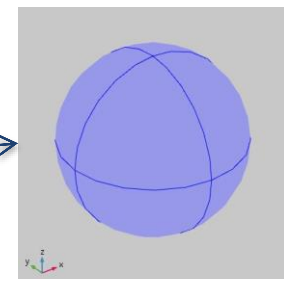
Results from Parametric Study in Composite Patch



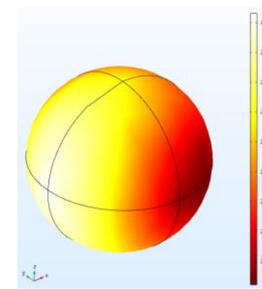
Parametric Study on Water Droplet



Droplet`s Geometry

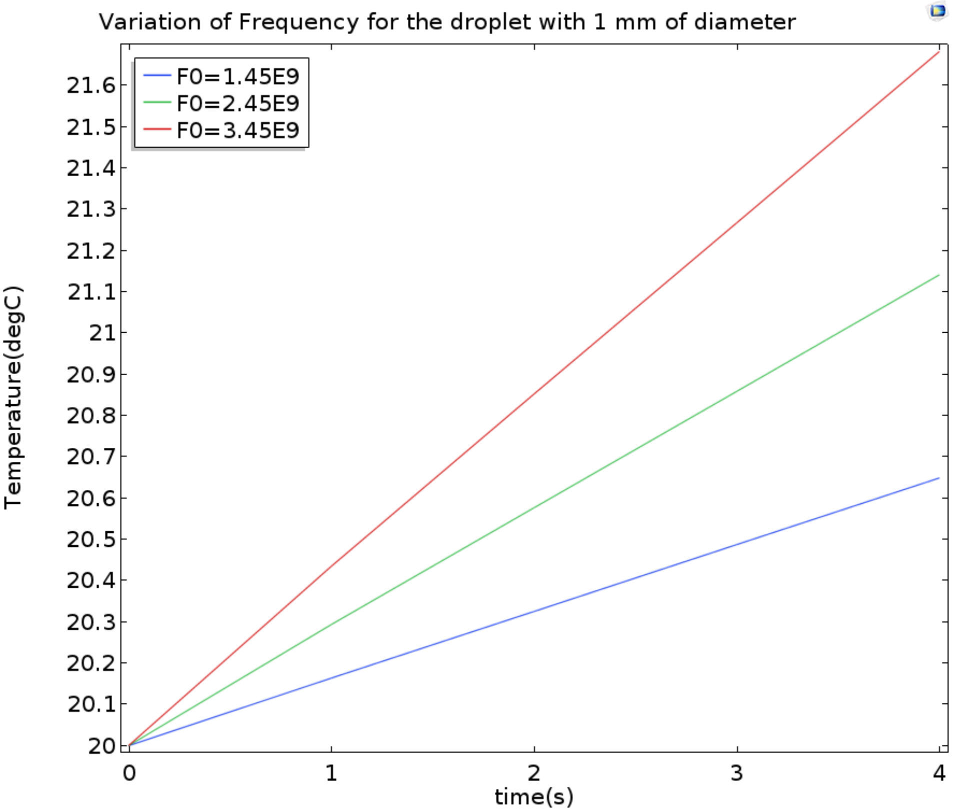


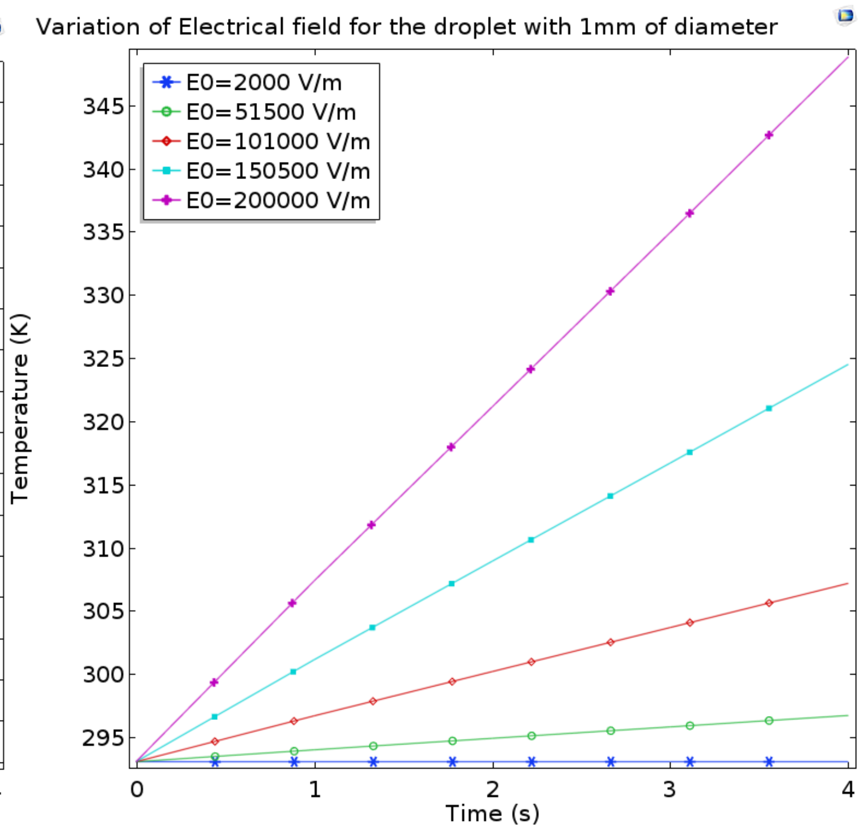
Temperature Plot



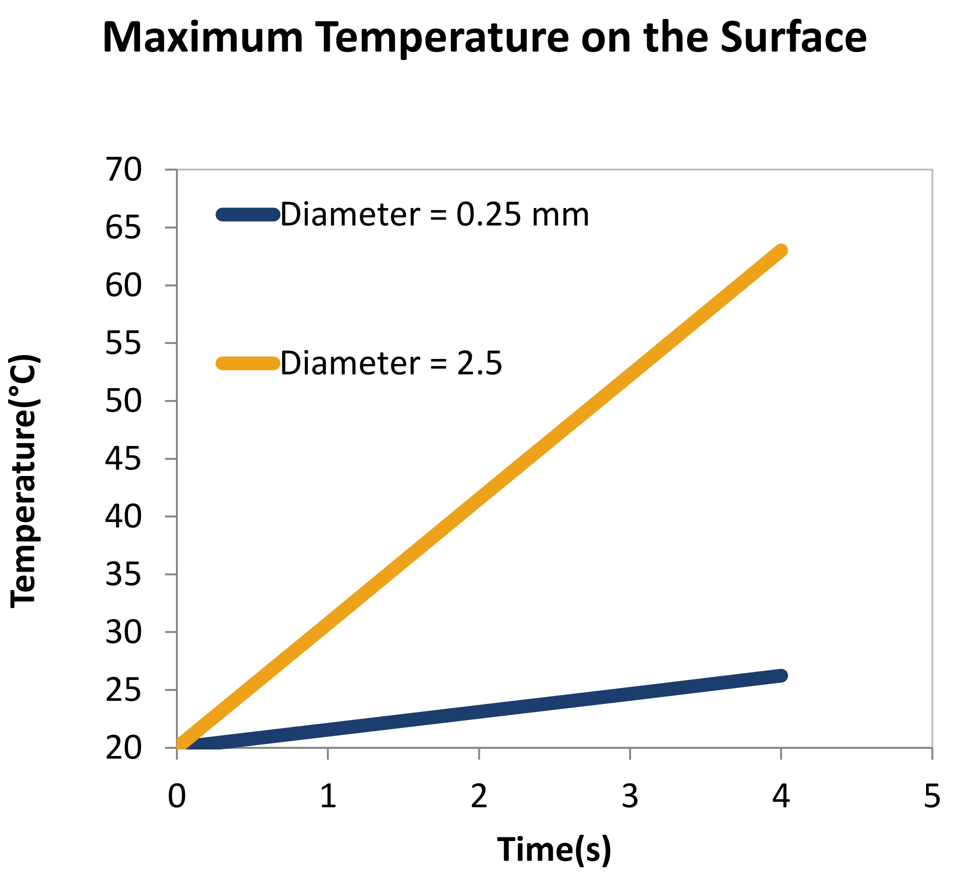
Parametric Study on Water Droplet`s result

Base Model Characteristics				
Droplet`s Diameter	Initial Temperature	Frequency	Electric Field Amplitude	Time of Exposure
1 mm	20°C	3.45 GHz	35000 V/m	4 s

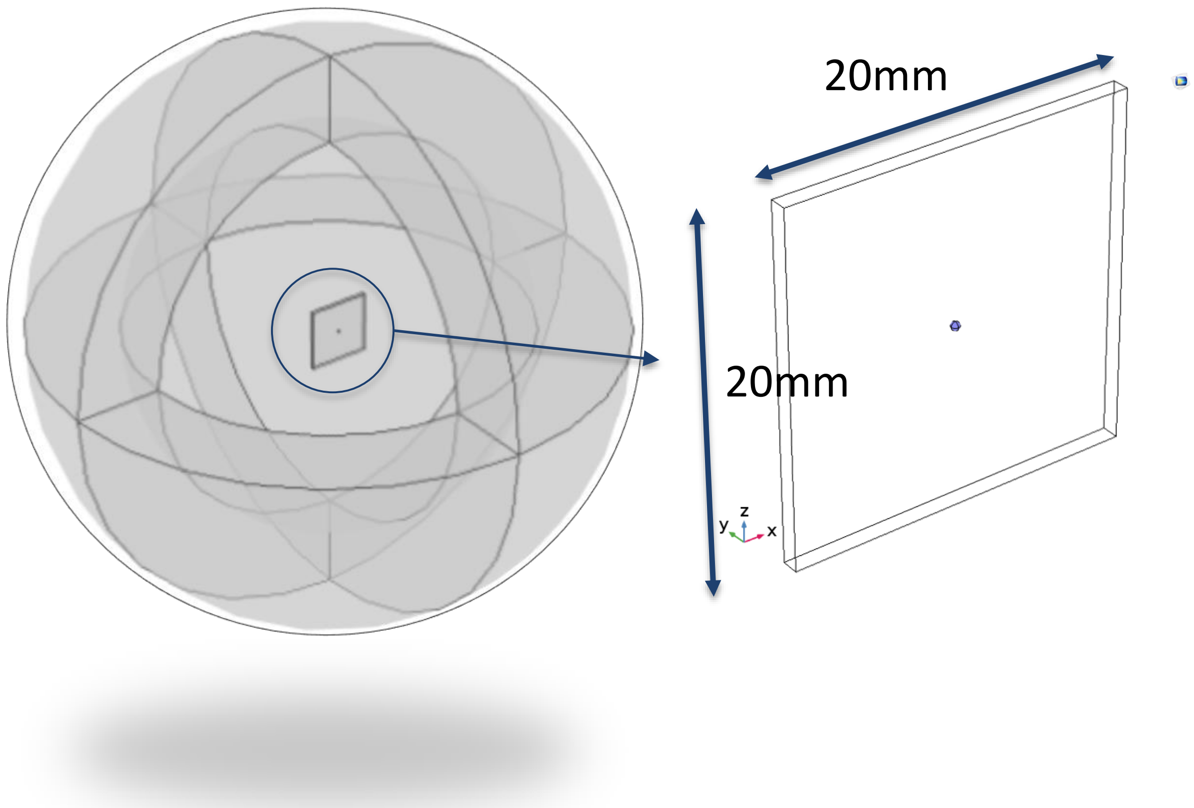




Results for The Water Droplet`s Parametric Study

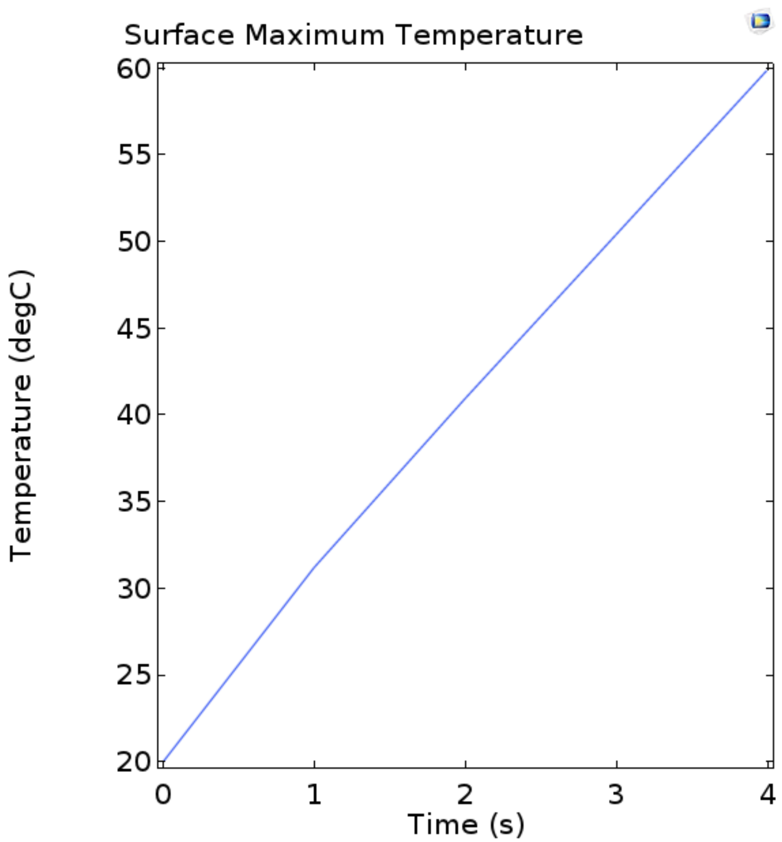


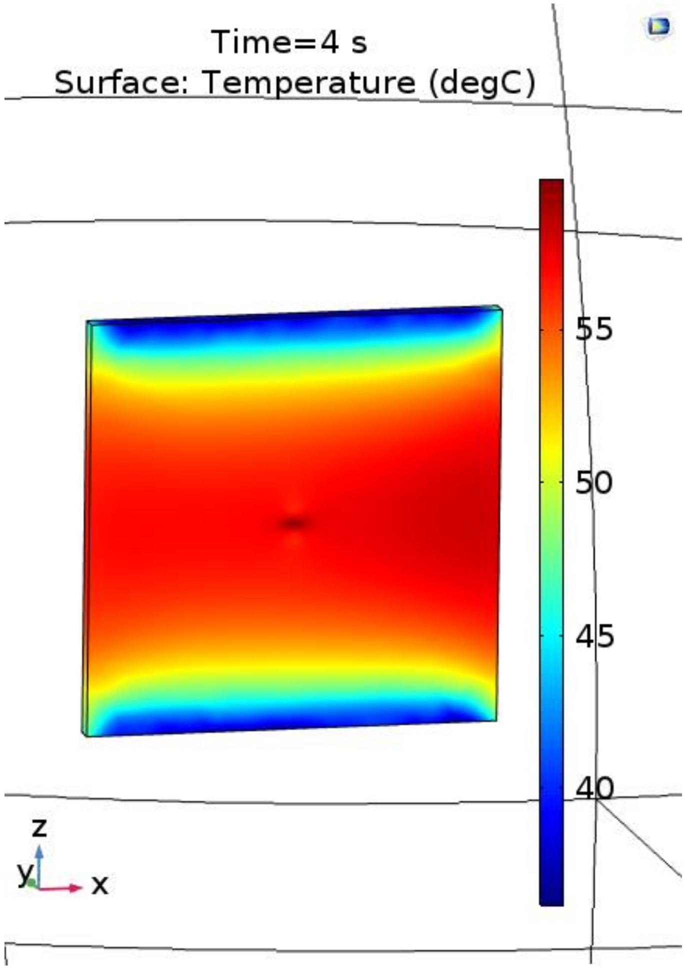
Parametric Study Composite with embedded water droplet



Droplet`s Volume	1.96e-4 ml
Composite Thickness	1 mm
Composite Material	Kevlar
Electrical Field	35000V/m
Frequency	3.45 GHz

Simulation Results- Composite with embedded water droplet





Summary

Two different types of simulation with RF and Heat Transfer modules has been conducted:

- Microwave oven example was used: Microwave heating of the kevlar specimen in Macro-scale

- PML was used with Plane wave radiation: composite patch and small droplets were exposed to plane wave.

Future plan:

Manufacturing a prototype of the composite containing micro-size water channels for validation.

THANK YOU

ANY
QUESTIONS?

18

Test Specimen

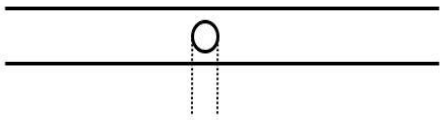
Kevlar fiber reinforced matrix composites with embedded sensing string

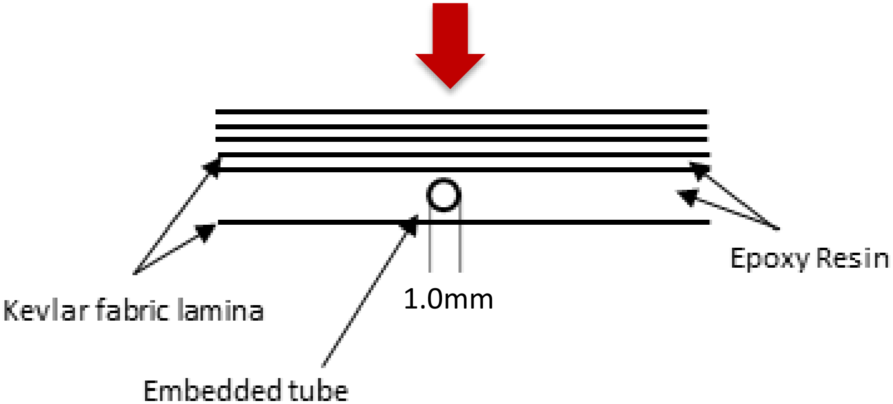
2-layer layup

6-layer layup

Microwave and IR Scanning from this side

Cross section:





- Coupling two different physics:

- Electromagnetic Heating $$P_v = 2\pi f \varepsilon_0 \varepsilon'' E^2$$
- Heat Transfer : $$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 \mathrm{T} + P_v$$

Experimental Test/ Results

- Injecting water as polar material in middle channel of the sample
- Heating up surface with microwave
- Visualizing surface temperature signal using infrared camera

Summary

- Novel SHM method coupling the mechanical, chemical and thermal domains
- Detection of internal defects in composites
- Large coverage, no power source required, in-situ real time detection and ease of interpretation
- Sensitivity studies → polar material quantity and composite layup
- Outlook:
  - Manufacturing of embedded sensing string network
  - Diagnostics and Prognostics supporting integrity monitoring