

# Porosity Assessment in Resin-Infused CFRP Laminates Through Ultrasound and Infrared Thermography

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# Porosity in composites

Porosity in CFRP is defined as the presence of voids or air pockets within the resin matrix or between fiber layers.

The presence of voids within the composite matrix compromises:

- mechanical properties;
- durability;
- long-term performance.



- even a porosity level of 2% can reduce the compressive strength of CFRP laminates by up to 15% [1];
- the interlaminar shear strength may drop by more than 20%;
- significant reduction in fatigue life as void content increases.

Void content can reach up to **5%** in poorly controlled resin infusion processes [2], far exceeding acceptable industrial thresholds, which are typically **below 1%** for aerospace-grade parts.

[1] R. Rhead and P. Withers, "Effects of porosity on the compressive strength of CFRP laminates," *Comp. Science and Technology*, 66(3), 2006.

[2] J. Soutis, "Carbon fiber reinforced plastics in aircraft construction," *Materials Science and Engineering: A*, 412, 2005.

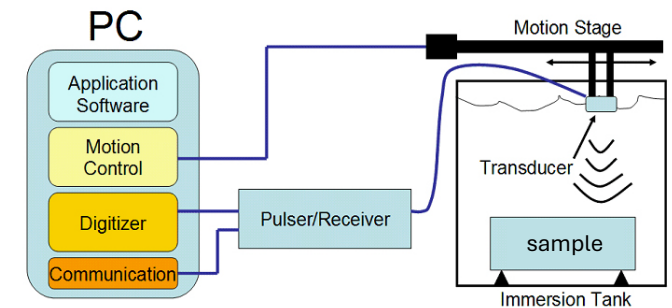
# Porosity in composites

**Challenge:** estimating the amount of porosity in composite laminates

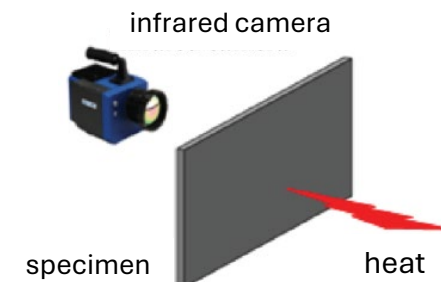
Conventional methods such as microscopy and destructive sectioning, although accurate, are **impractical for large-scale industrial applications** due to their invasive nature.

Two key non-destructive evaluation (**NDE**) methods for porosity assessment are investigated:

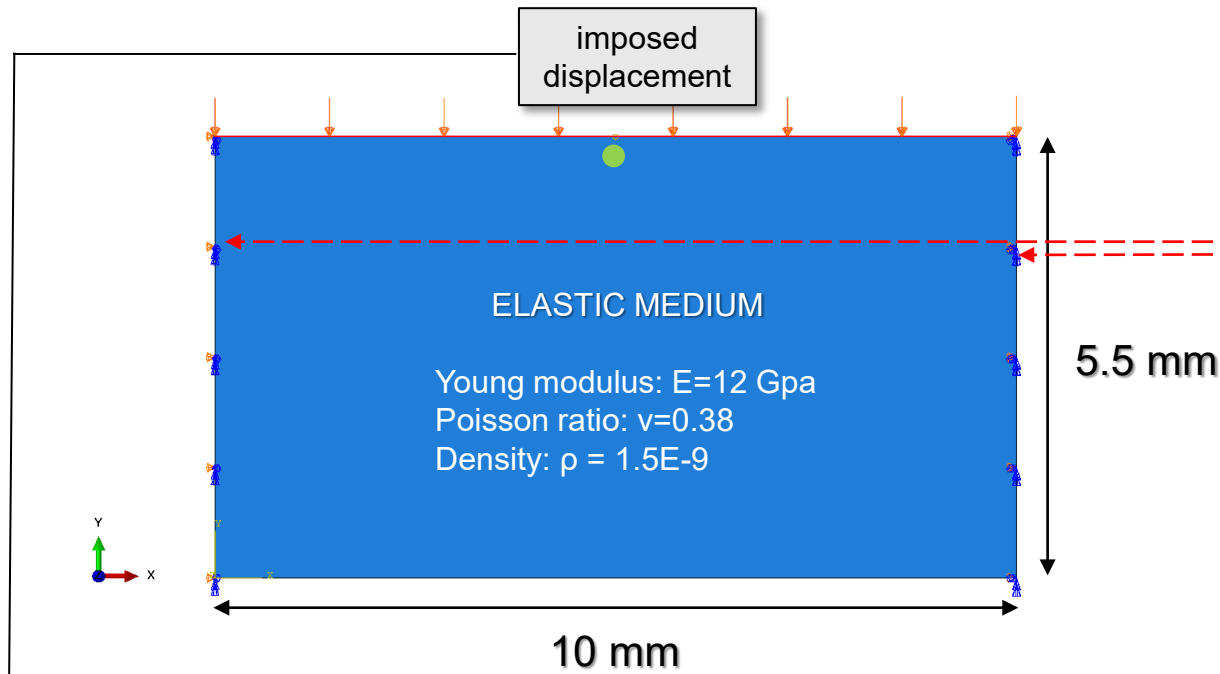
- ultrasonic testing (**UT**) → Immersion Ultrasonic Testing



- infrared thermography (**IRT**) → Pulsed Thermography

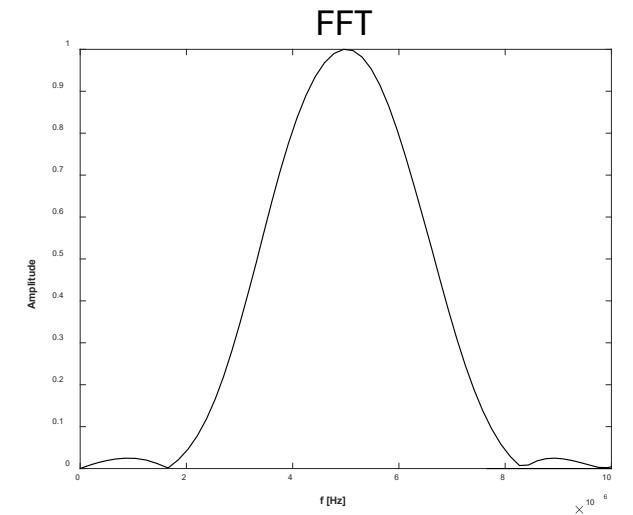
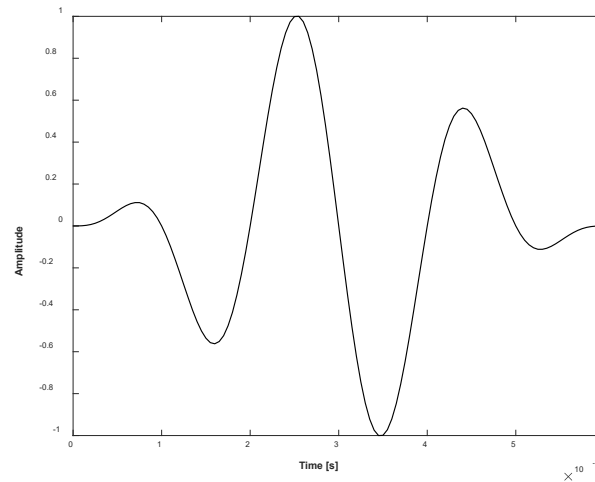


# Modeling



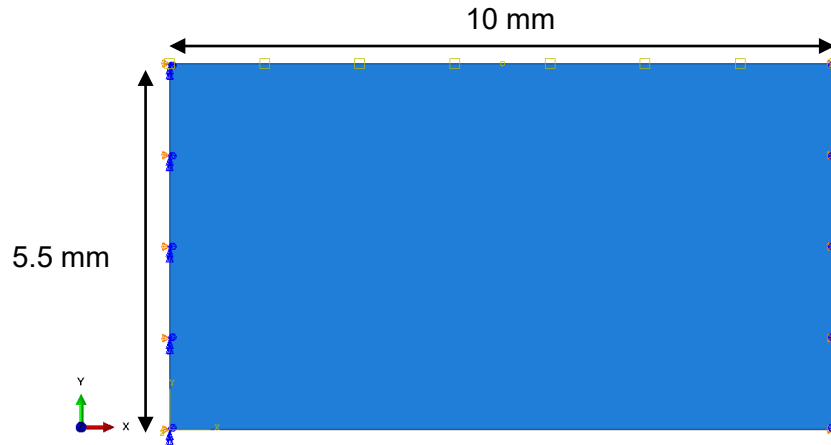
**symmetry boundary conditions** perpendicular to the direction of wave propagation to avoid diffraction effect: **plane wave condition** is assumed.

time variation law  
three cycle Hanning-windowed  
tone-burst signal  
with 5 MHz central frequency



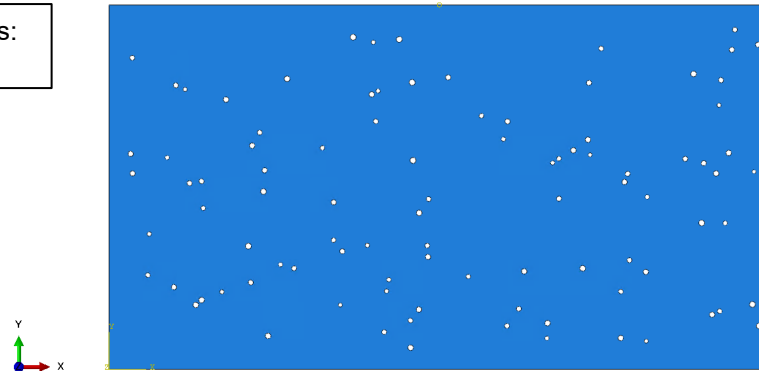
# Modeling

pore modeling:  MATLAB® →  python™ →  ABAQUS  
Abaqus Scripting Interface



**MODEL 1**  
no porosity

Pore diameters:  
0.1, 0.085 mm



**MODEL 2**  
low porosity

## Pore modeling:

- First, a MATLAB-based script generates pore shapes and sizes and checks if there are overlaps among pores.
- Afterwards, a Python-based script, is employed to embed pores into the finite element model.

## Absorption modeling:

Rayleigh damping model assumes the damping of the material as a function of the mass (M) and the stiffness matrix (K):

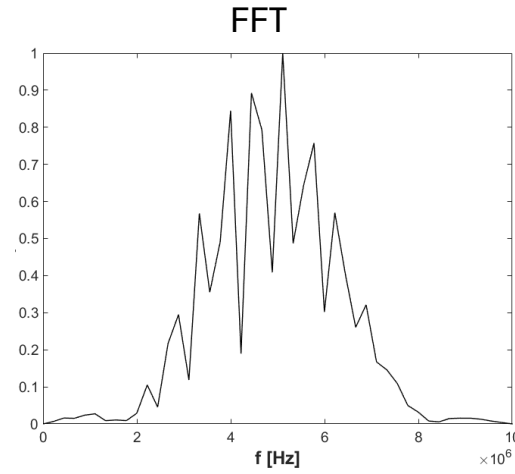
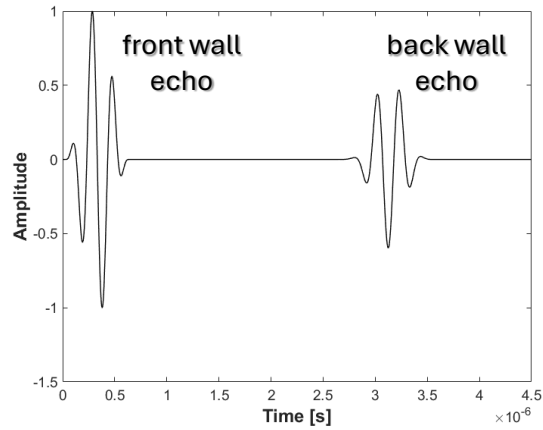
$$C = \alpha M + K \beta$$

At higher frequencies ( $f > 1$  kHz) the *mass proportional damping factor*  $\alpha$  has less effect than the *stiffness matrix proportional damping factor*  $\beta$  and thus, it is neglected. It is assumed  $\beta = 2$  ns

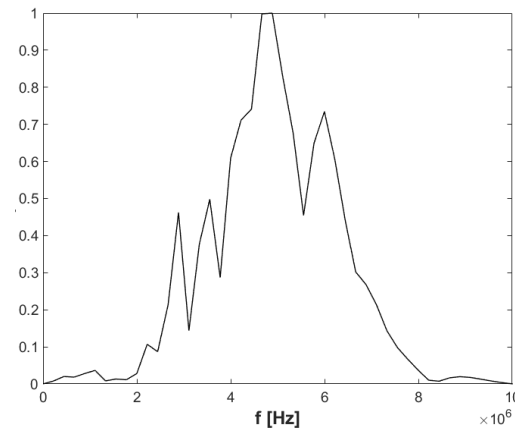
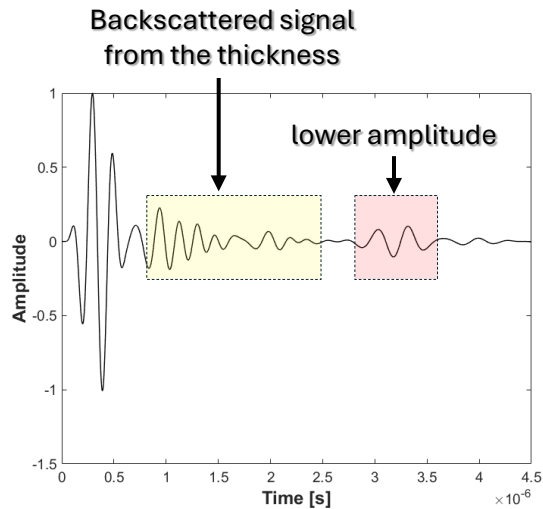
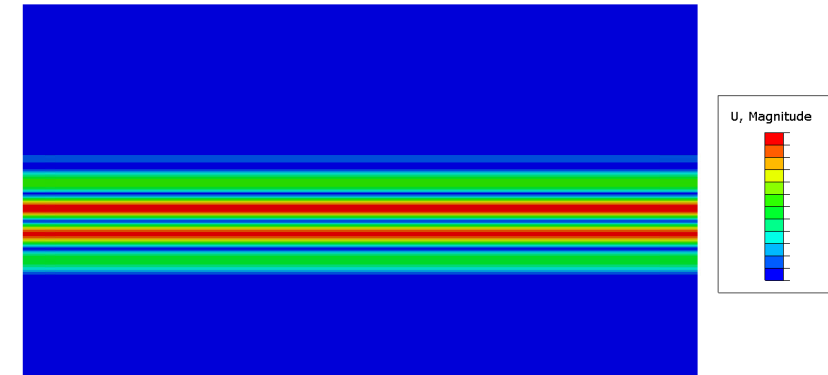
Both scattering from pores and absorption contribute to the total amount of attenuation.

# Numerical Results: pore effect

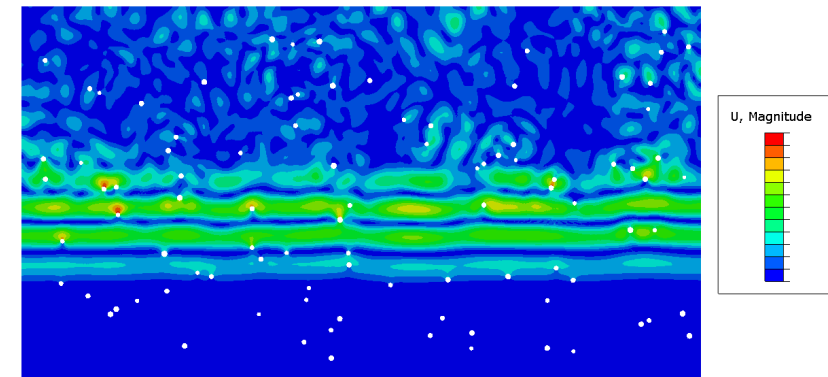
dynamic explicit analysis with fixed time increment  $1 \cdot 10^{-10}$  s



homogeneous material without pores



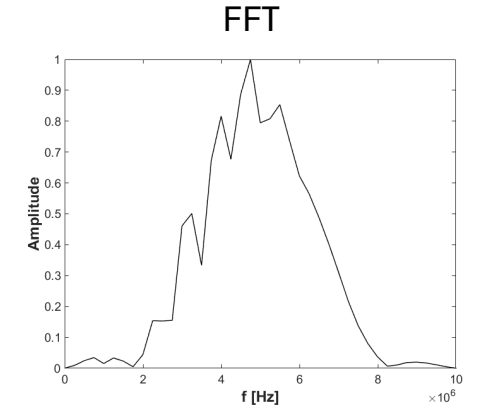
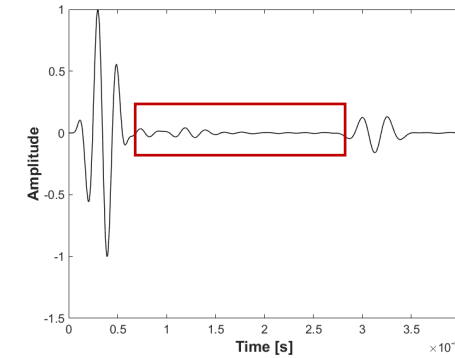
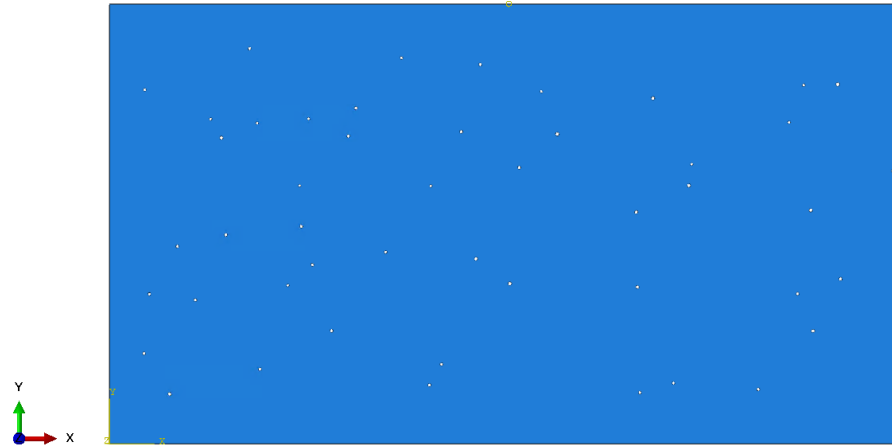
homogeneous material with pores



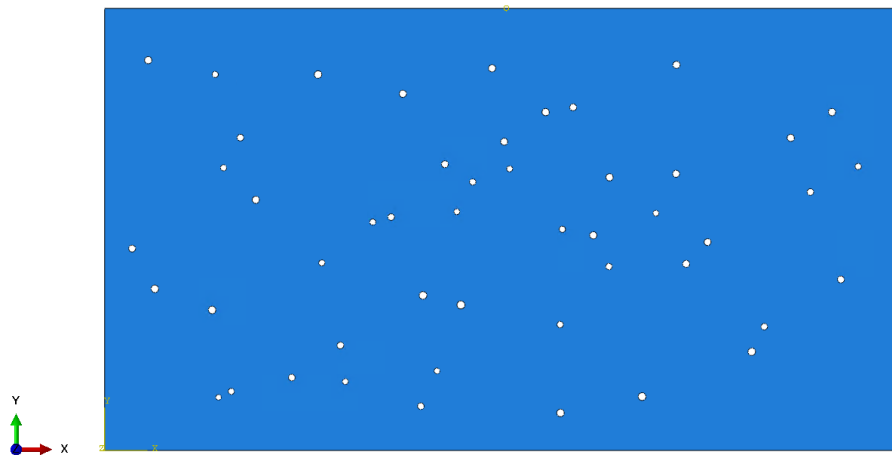
As the porosity increases the back wall echo shows variation in amplitude

# Numerical Results: pore size effect

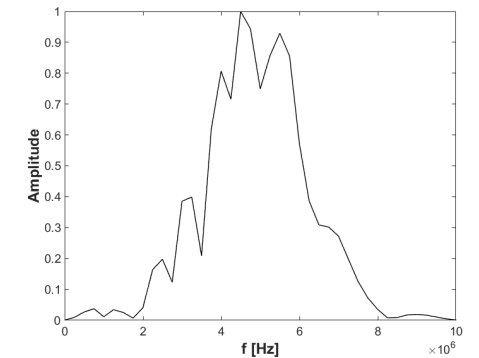
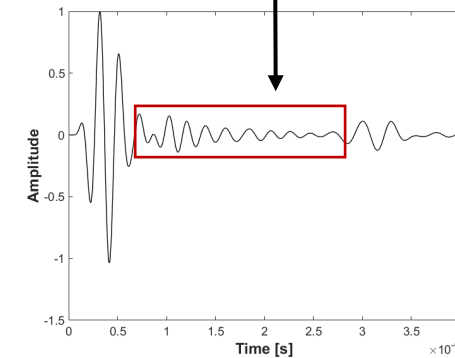
small pores



large pores



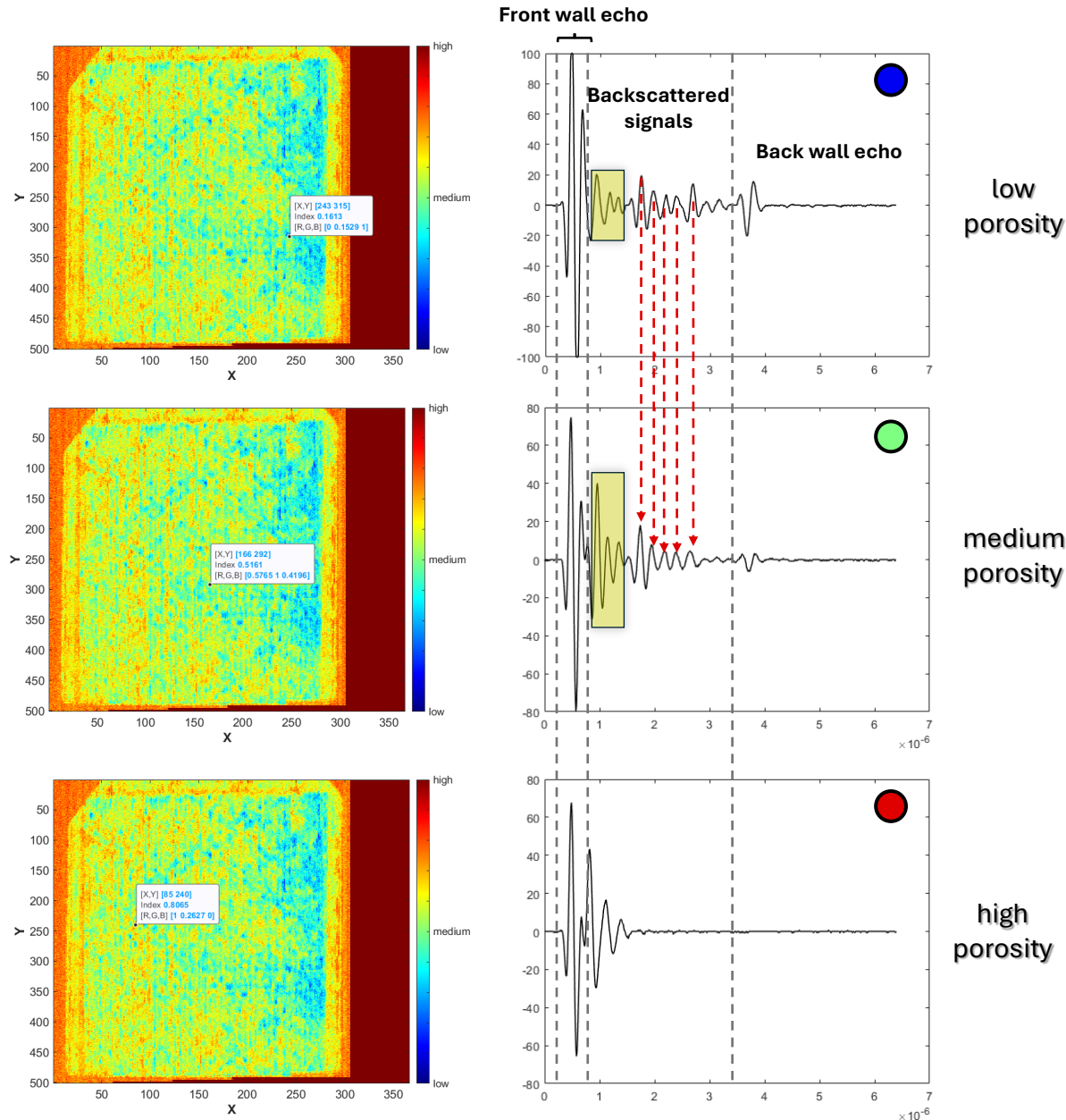
Backscattered signal intensification



Same number of pores, larger size: the variation in the amplitude of the back wall echo is negligible, while the greater amplitude of the backscattered signals from the thickness is evident

# Previous findings

C-SCAN shows the amplitude of the back wall echo



As porosity increases, it is mainly the **amplitude of the back wall echo** that varies and not so much the intensity of the backscattered signals

# Manufacturing

## Material:

- 2 layers of fibers  $-45^{\circ}/+45^{\circ}$ , 1200 GSM (grams per square meter), 48k (the reinforcing fibers are aligned in a unidirectional way and held together by stitching, rather than being woven into a fabric)
- IN2 Epoxy Infusion Resin (low viscosity)

## Laminate:

**40 cm × 40 cm × 2.75 mm** in symmetric configuration.

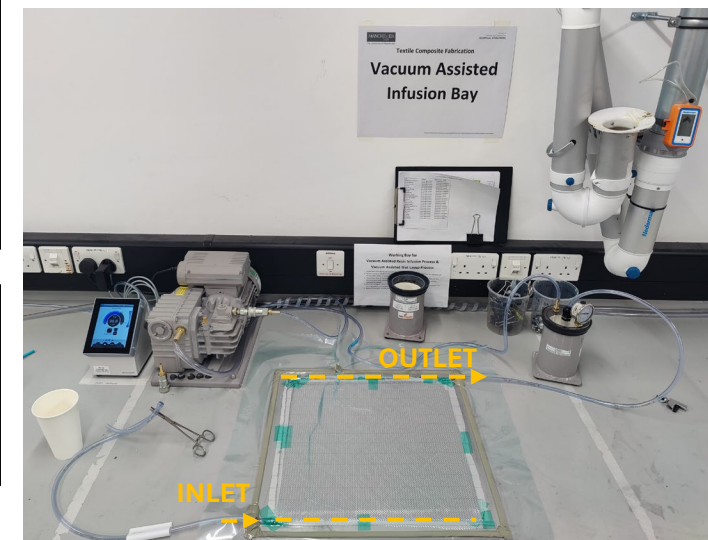


## Manufacturing process:

- Vacuum Assisted Resin Transfer Molding (**VARTM**)
- resin and hardener (10:3)
- **degassing time of 30 minutes** to reduce entrapped air bubbles
- cure at room temperature for 24 hours
- post-cure the panel in an oven at  $60^{\circ}\text{C}$  for 6 hours

## Test articles:

- Laminate with low porosity
- Laminate with medium porosity (vacuum pressure 50 mbar)



# Ultrasonic Testing



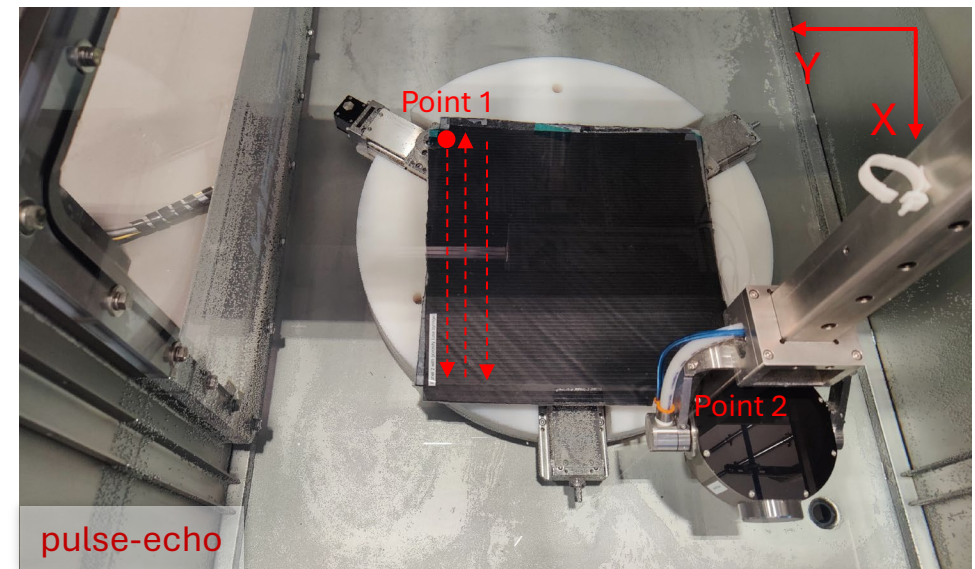
## TecSCAN TS-3000 - 6 Axis Immersion Scanner

- X Y Z Axes driven by servo motor
- Automated Gimbal / Gimbal manipulator
- Automated Turn Table

Stainless-Steel tank (1.5 m X 0.9 m X 0.9 m deep)

Trasducer: 5 MHz immersion probe

Scanning step: 1 mm

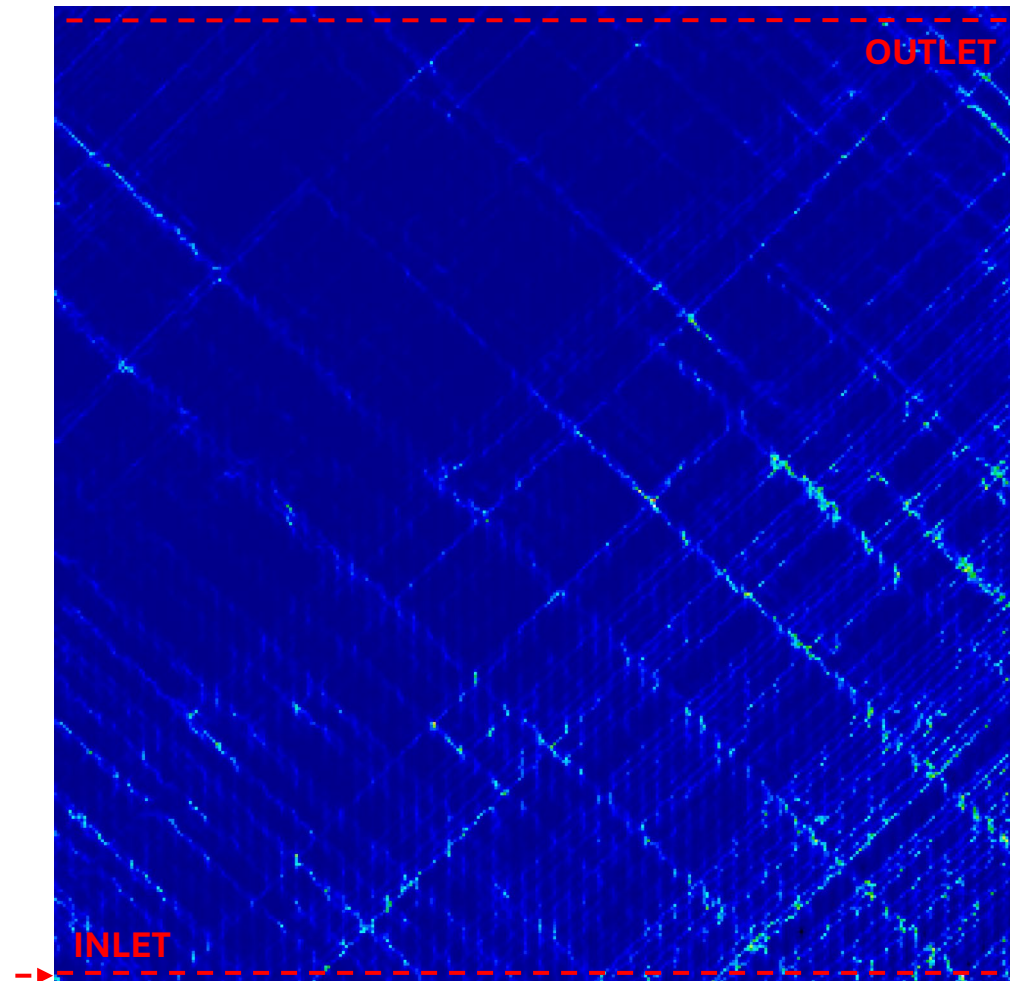


The **rectangular scan** performs the inspection of an area defined by two axes and two points

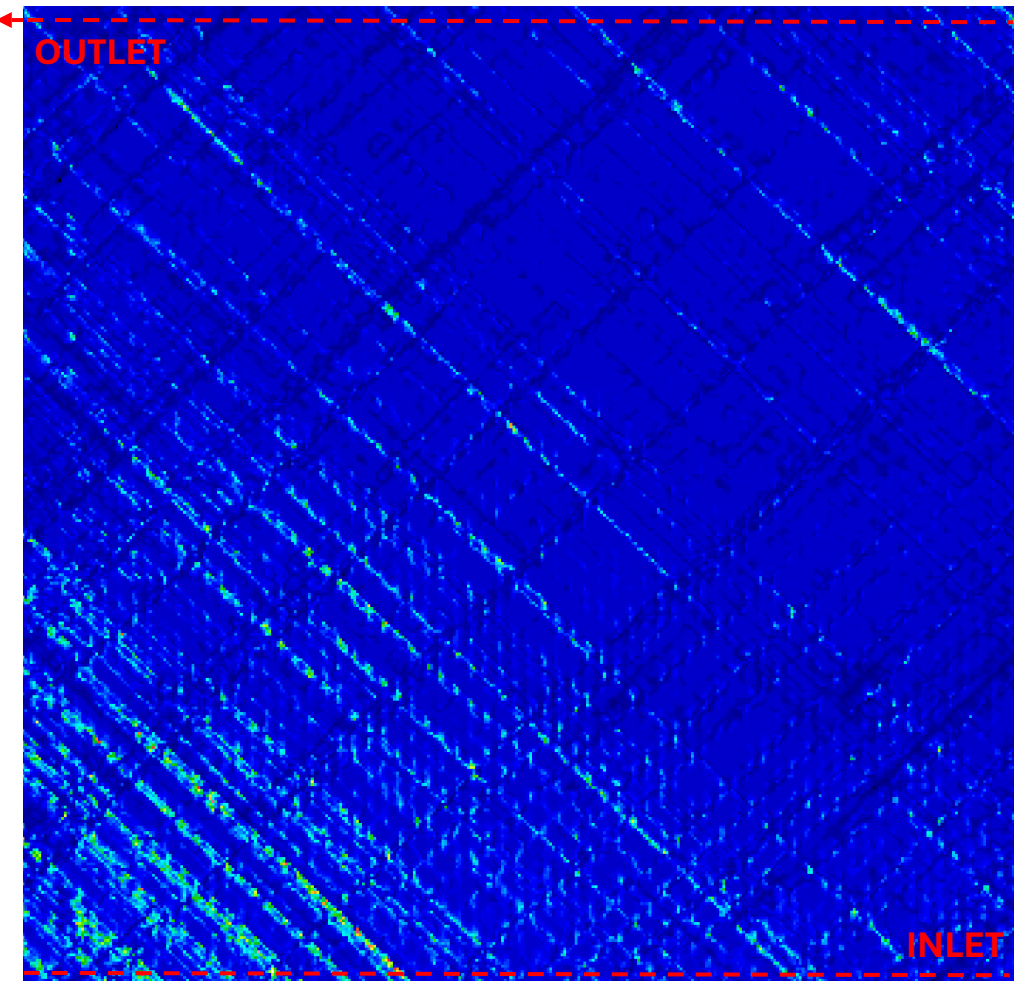
# Ultrasonic Testing: low porosity

C-Scan based on attenuation: amplitude drop between front and back wall echoes

rough surface (top layer in contact with separation layer) towards probe



smooth surface (bottom layer on metal plate) towards probe

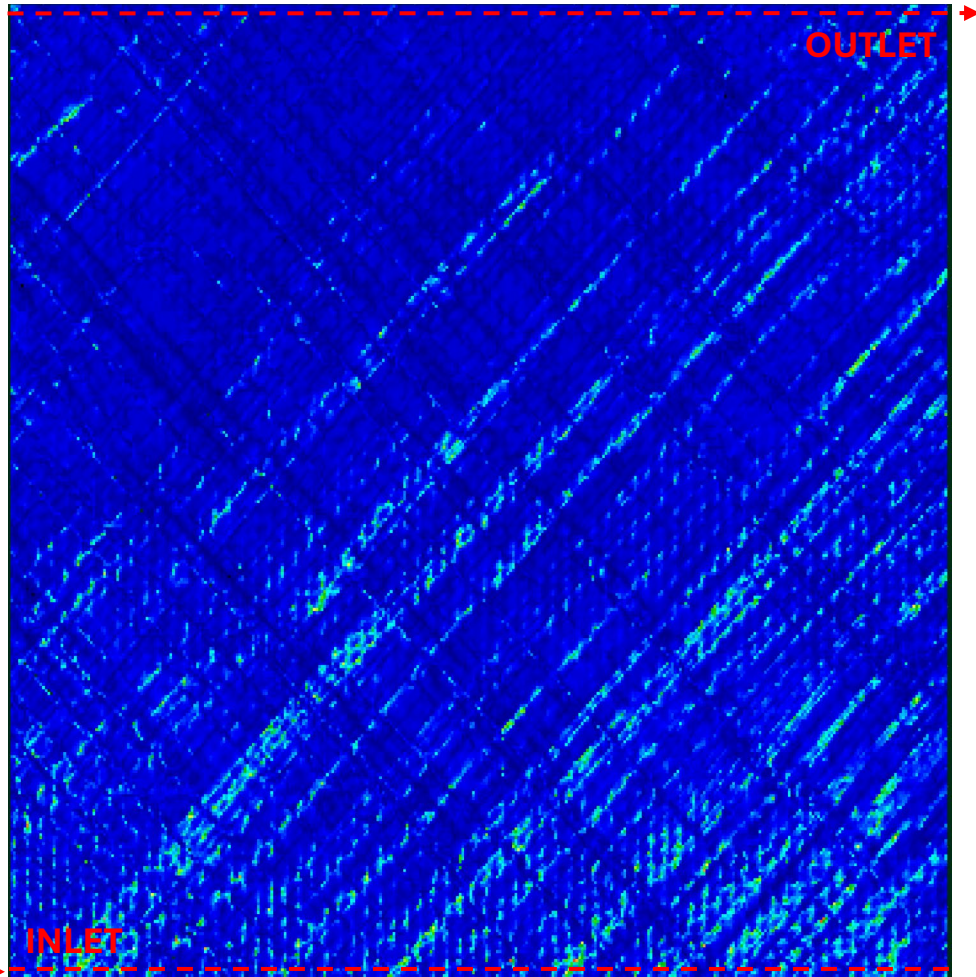


exponential color bar: darker areas → very low attenuation | lighter areas → very high attenuation

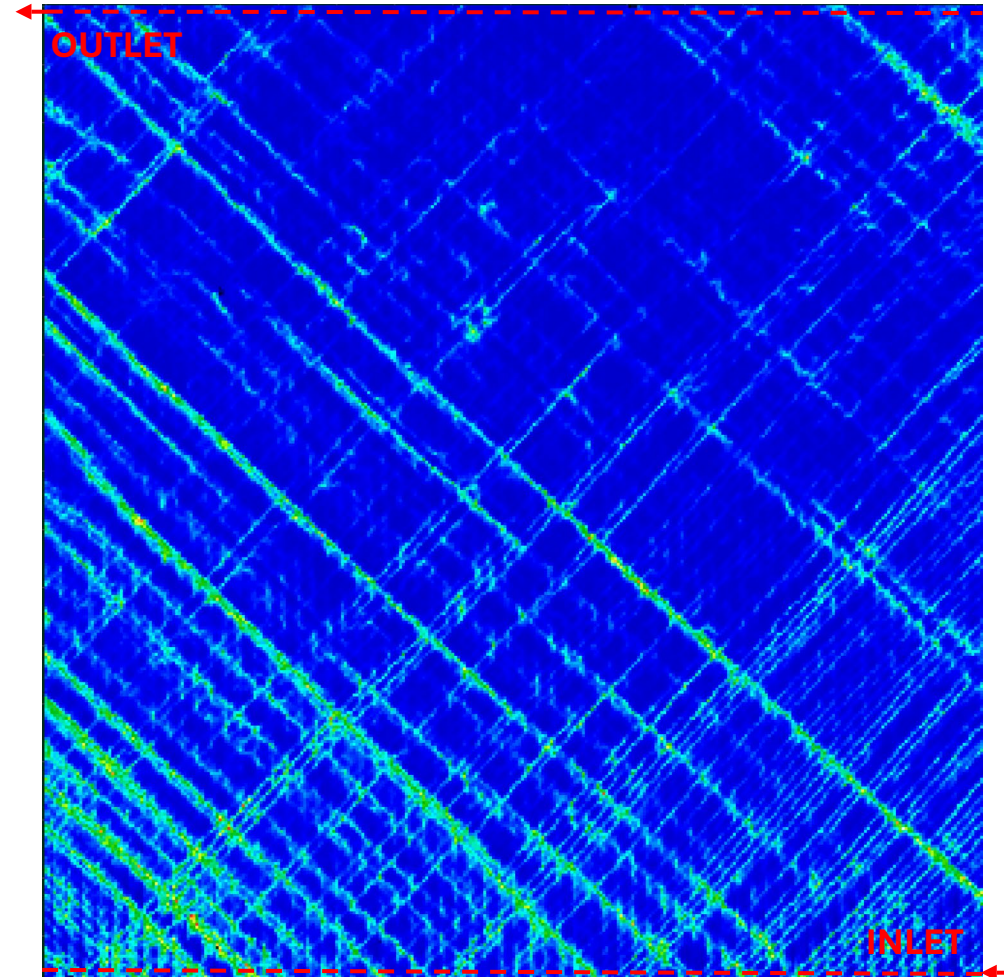
# Ultrasonic Testing: medium porosity (50 mbar)

The air bubbles remain trapped in the fiber tow

rough surface (top layer in contact with separation layer) towards probe

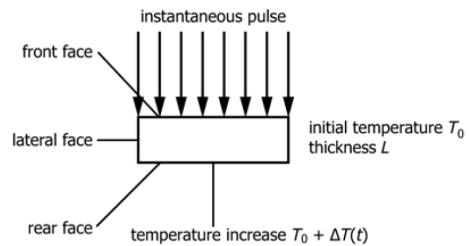


smooth surface (bottom layer on metal plate) towards probe

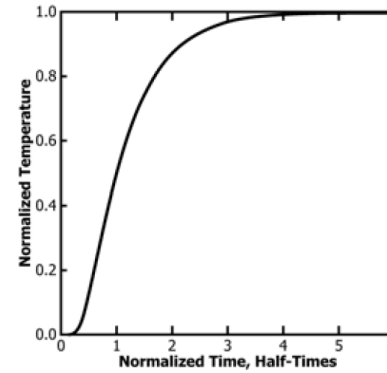


exponential color bar: darker areas → very low attenuation | lighter areas → very high attenuation

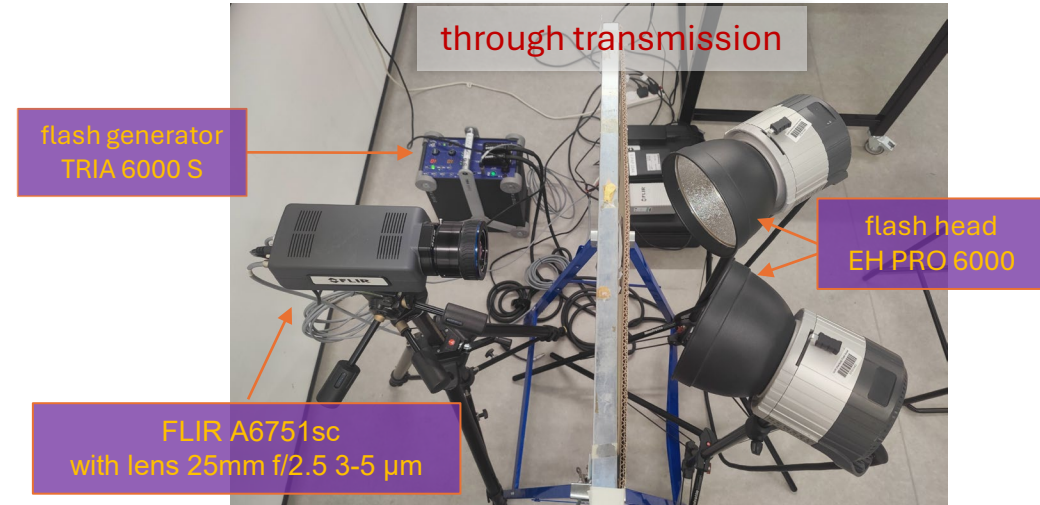
# Flash Method (ASTM E1461 – 13)



Schematic of the Flash Method



Characteristic Thermal Curve for the Flash Method



The flash method is used to measure values of thermal diffusivity,  $\alpha$ , of a wide range of solid materials.

Parker et al proposed a semi-empirical equation for thermal diffusivity expressed as:

$$\alpha_{0.5} = \frac{0.1388h^2}{t_{0.5}}$$

The mapping of the thermal diffusivity requires its calculation for each pixel.

Thermal diffusivity quantifies how quickly heat spreads through the material



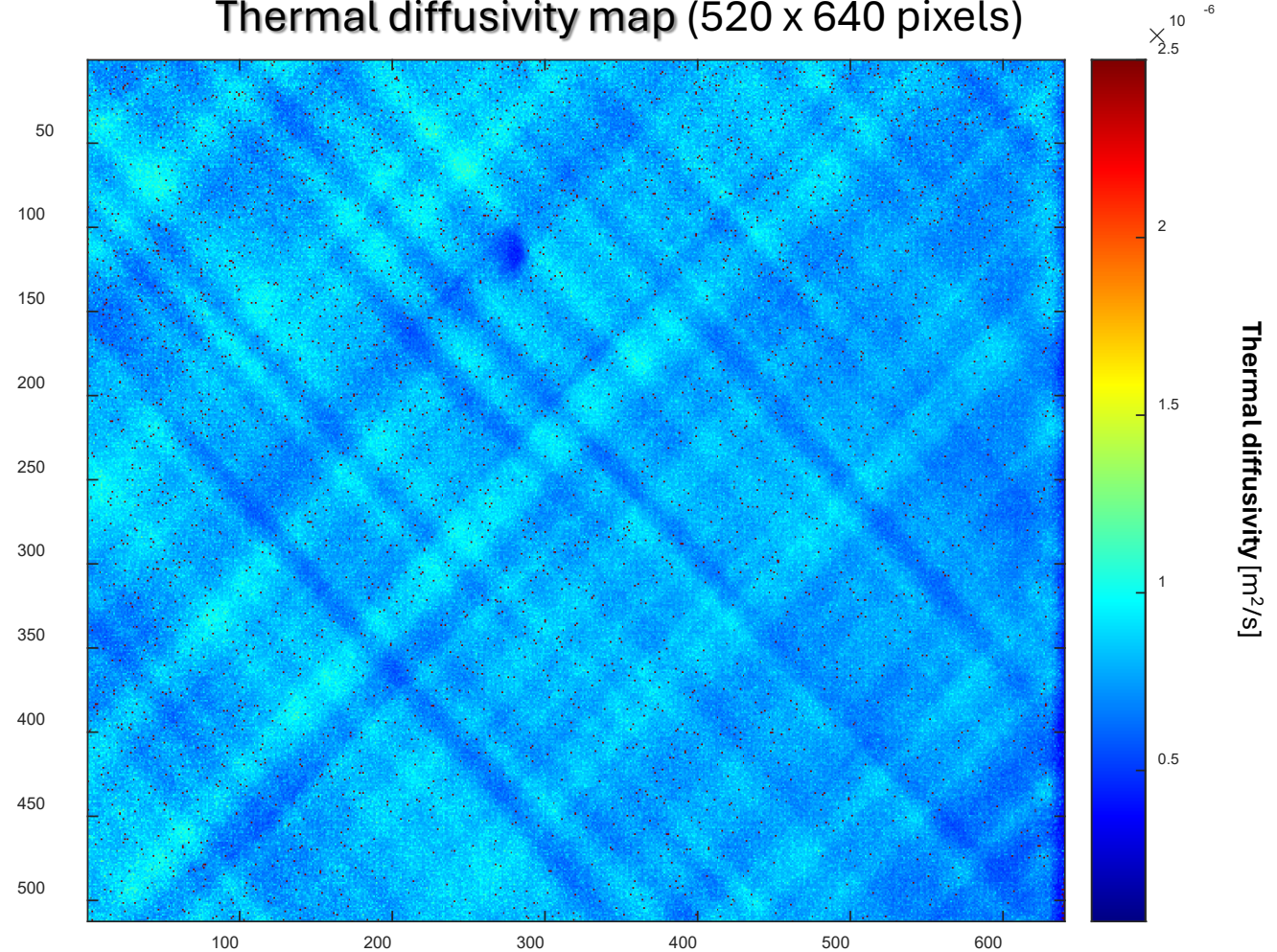
# Pulsed Thermography: medium porosity (50 mbar)

Since air (or vacuum within a void) has a significantly lower thermal conductivity than constituents (resin or fiber), voids act as **thermal insulators**



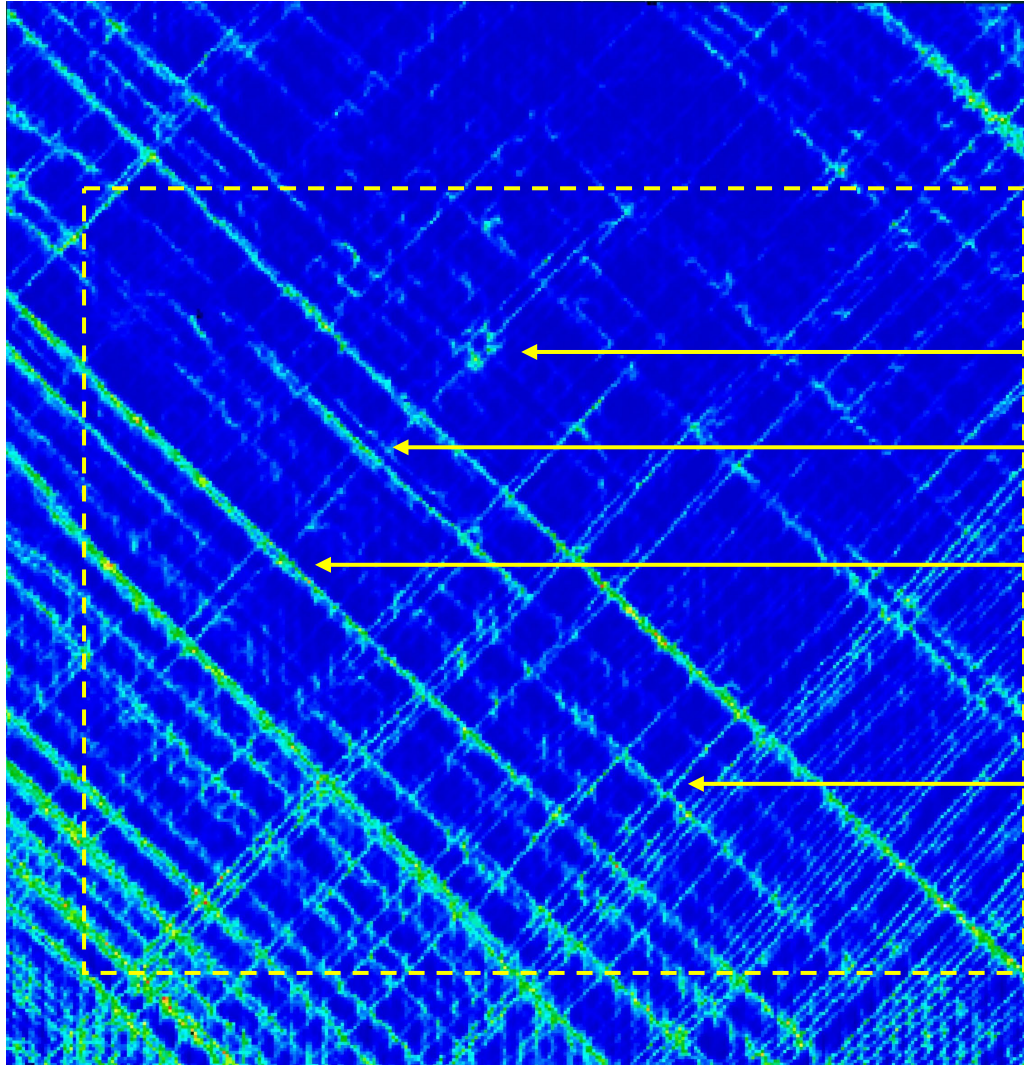
A **decrease in thermal diffusivity** can be correlated with **increased porosity** due to the insulating effect of voids

Thermal diffusivity map (520 x 640 pixels)



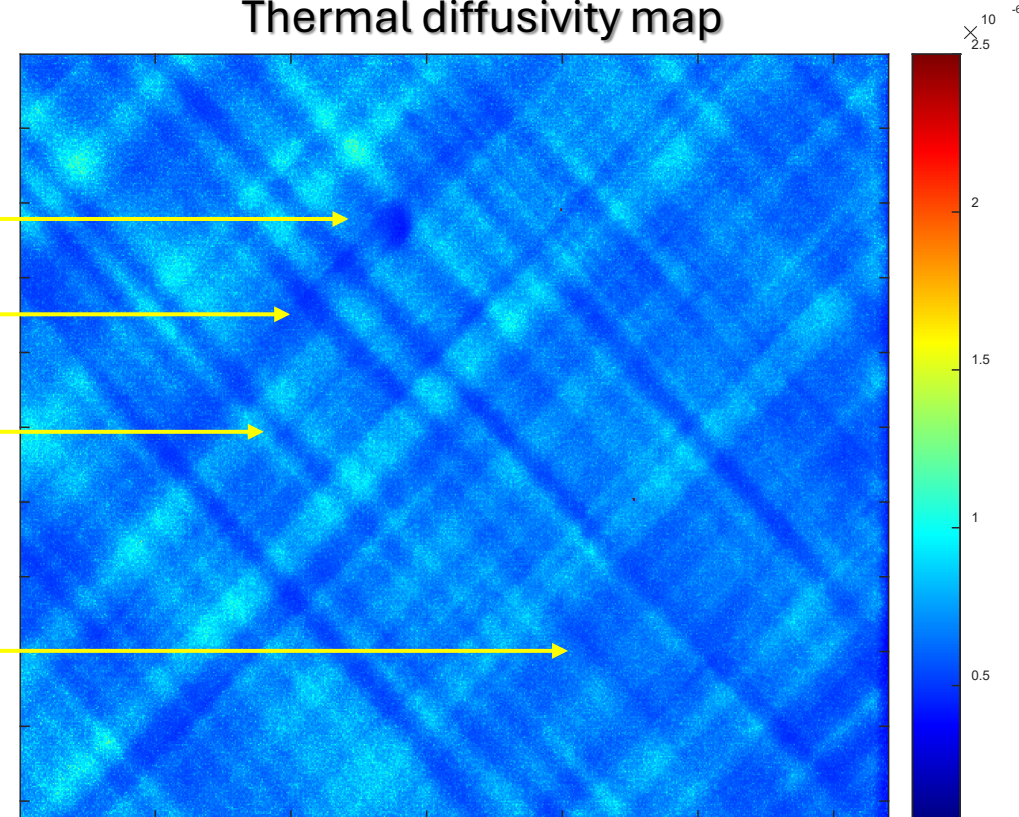
# Ultrasonic Testing vs Pulsed Thermography

Attenuation map



The heat propagates more slowly through region with higher porosity due to the decreased thermal diffusivity

Thermal diffusivity map



where the attenuation increases the thermal diffusivity drops and vice versa

# Future goals

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- Introducing controlled amount of air to estimate, through UT and PT, the amount of porosity
- Thermal diffusivity evaluation in reflection mode (*time domain*)
- Pulsed Phase Thermography in transmission and reflection mode (*frequency domain*)
- Ultrasonic Testing in through transmission mode

**Thank you for listening**