ASME QNDE 2023
Quantitative Nondestructive Evaluation

Resin Flow Monitoring Using Capacitive Sensors

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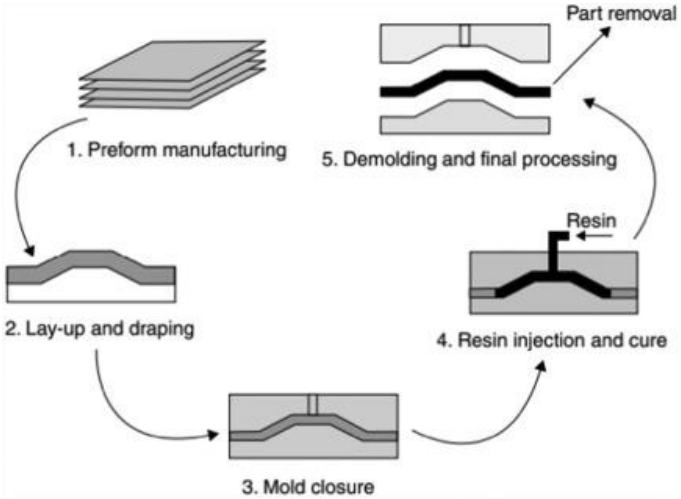
Outline

- Composite manufacturing process
- Out of autoclave vs autoclave process
- Motivation
- Capacitive sensing method
- Liquid flow experiments
- Impedance analysis of sensors on carbon fibre sheets
- Embedded sensors monitoring liquid flow
- Conclusion & future work

Composite manufacturing



- Widely used process in aerospace
- Dry fibre laid up in mold and placed in oven or autoclave
- Impregnation stage is most important as porosity and dry spots can occur
- This stage can be monitored to stop such anomalies or detect early signs of them

Out of autoclave vs autoclave

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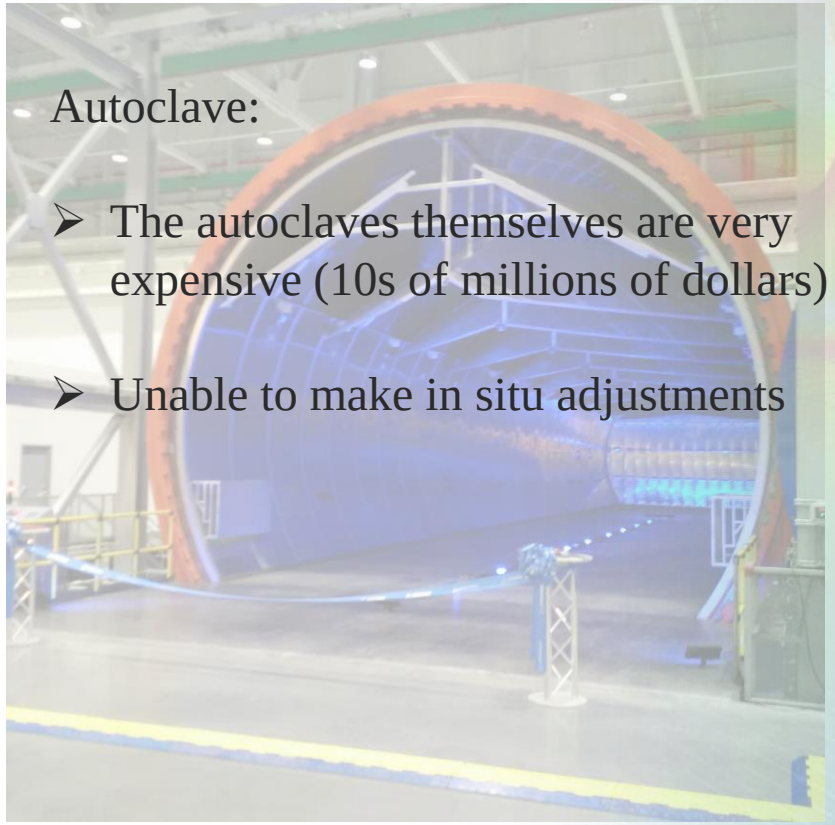
Out of autoclave:

- Cures at a lower temperature than autoclave
- Considerably cheaper as there is no autoclave involved
- Excellent structural performance – achieves the same quality as the autoclave process
- Not labour intensive



Autoclave:

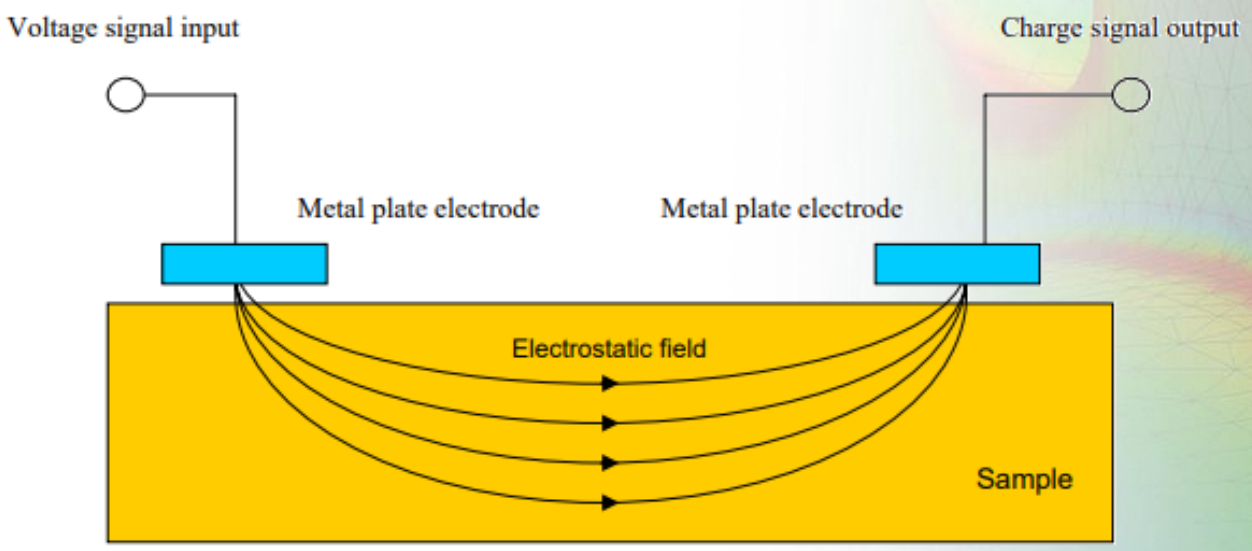
- The autoclaves themselves are very expensive (10s of millions of dollars)
- Unable to make in situ adjustments

Why capacitive sensing?

- Compared to other methods such as ultrasonic testing and eddy current, it is inexpensive
  - PCBs are low cost to manufacture compared to the expensive probes used in UT and ECT
- Non- contact so sensors won't wear away
- Not unsafe compared to methods like radiography where there is exposure to radiation
- No training required to carry out this method
- Can be used to inspect a wide variety of materials (dielectric and non-dielectric)
  - Compared to eddy current which can only be used in conductive materials

Co-planar Capacitive Sensing

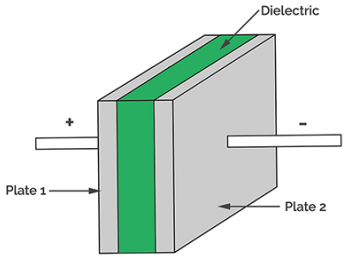
- Two electrodes are used
- Involves generating and passing an electrostatic field through a material
- One electrode drives the electric field and the other receives
- Resin flow will affect the resulting capacitance of the sensors because of the change in relative permittivity (from air to resin)
- A steady increase in capacitance when resin passes over the driving sensor before levelling out



Capacitor equation

- The equation for a capacitor is as follows:

$$C = \frac{\varepsilon A}{d} \quad (1)$$

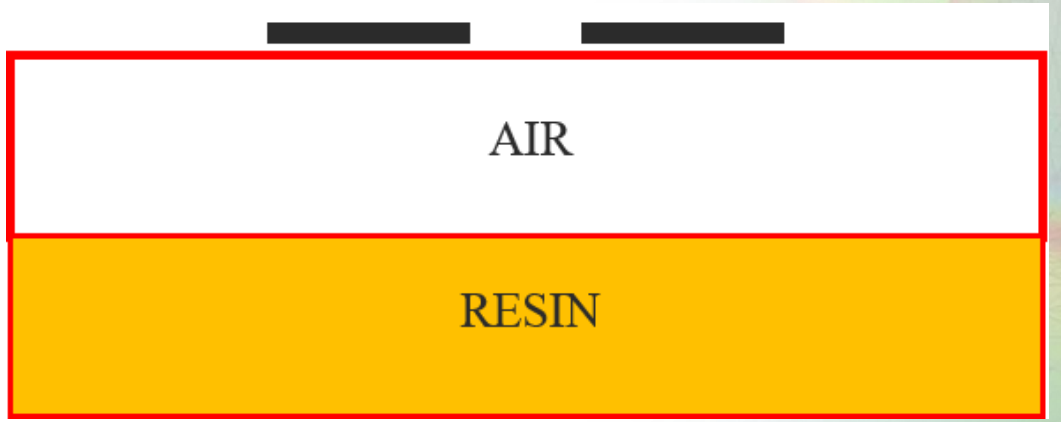


[2] - https://www.gadgetronicx.com/capacitor-working-tutorial-applications-circuits/

- C – capacitance, A – area of electrodes, d – separation distance between plates & ε - permittivity of the dielectric material
- All variables play a role in measuring the capacitance between the sensors
- The most important is the permittivity because this variable can change throughout the inspection process when trying to detect defects
- Relative permittivity of water – 80.1
- Relative permittivity of resin – 3.6

Co-planar sensing motivation

- Industrial needs from SPIRIT AeroSystems require single side inspection/monitoring
- Resin injected from the bottom of the mold and flowing transversally
- Capacitive sensors embedded in wing cover and placed on top of the mold
- Porosity, dry spot and other anomalies could occur so in-process inspection is required



Electrode size and spacing

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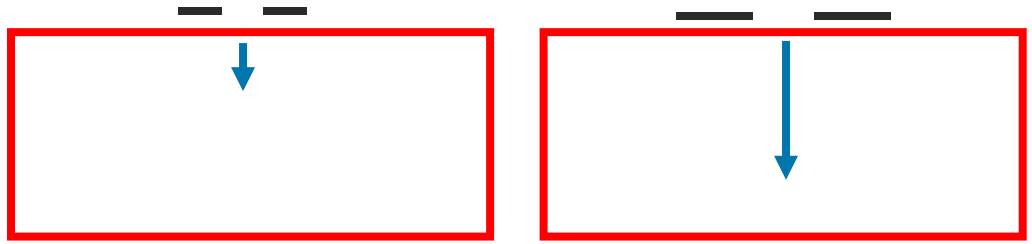
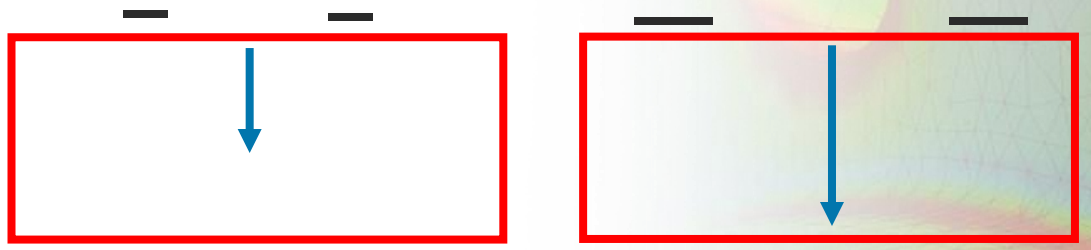
Size



- Electrode size impacts the penetration depth of the signal, the bigger the electrode, the greater the penetration depth
- The amplitude of the signal gets larger as the electrode size increases

Spacing



- Electrode spacing impacts the penetration depth of the signal, the greater the separation, the greater the penetration depth
- The drawback is that the amplitude of the signal gets smaller as the separation increases

Co-planar sensors

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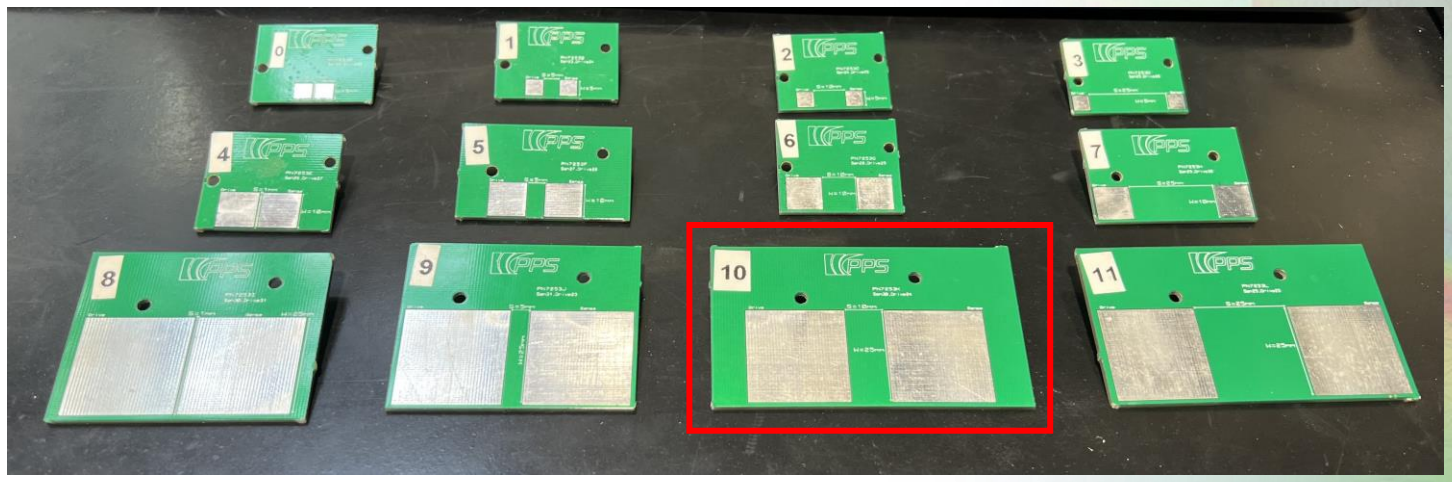
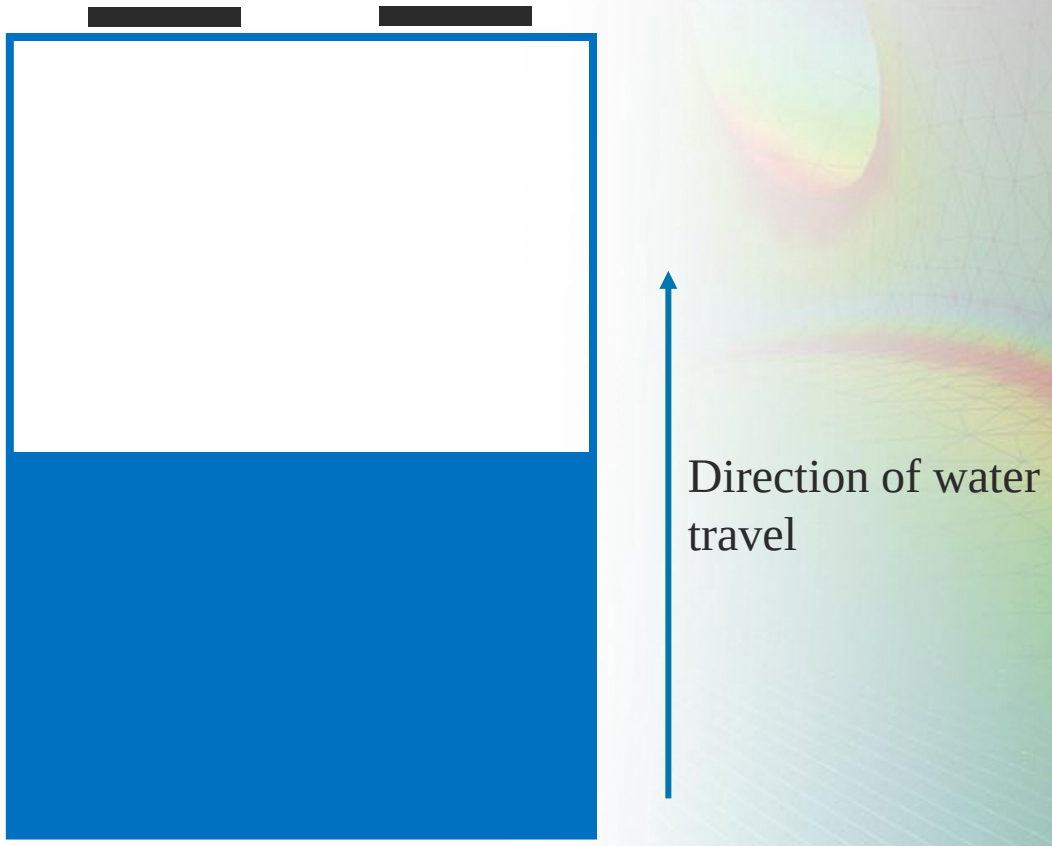
Sensor	Size (mm)	Separation (mm)
0	5x5	1
1	5x5	5
2	5x5	10
3	5x5	25
4	10x10	1
5	10x10	5
6	10x10	10
7	10x10	25
8	25x25	1
9	25x25	5
10	25x25	10
11	25x25	25



- Sensors were acquired from Pressure Profile Systems (PPS)
- 3 sizes, 4 separation distances

Transversal Method

- Water rises from bottom up
- Water poured in until the sensor detects the water rising
- Container used was a beaker of height 140mm, sensor fixed across top of beaker
- Sensor 10 used
  - 25x25mm, separation 10mm



Numerical Simulations

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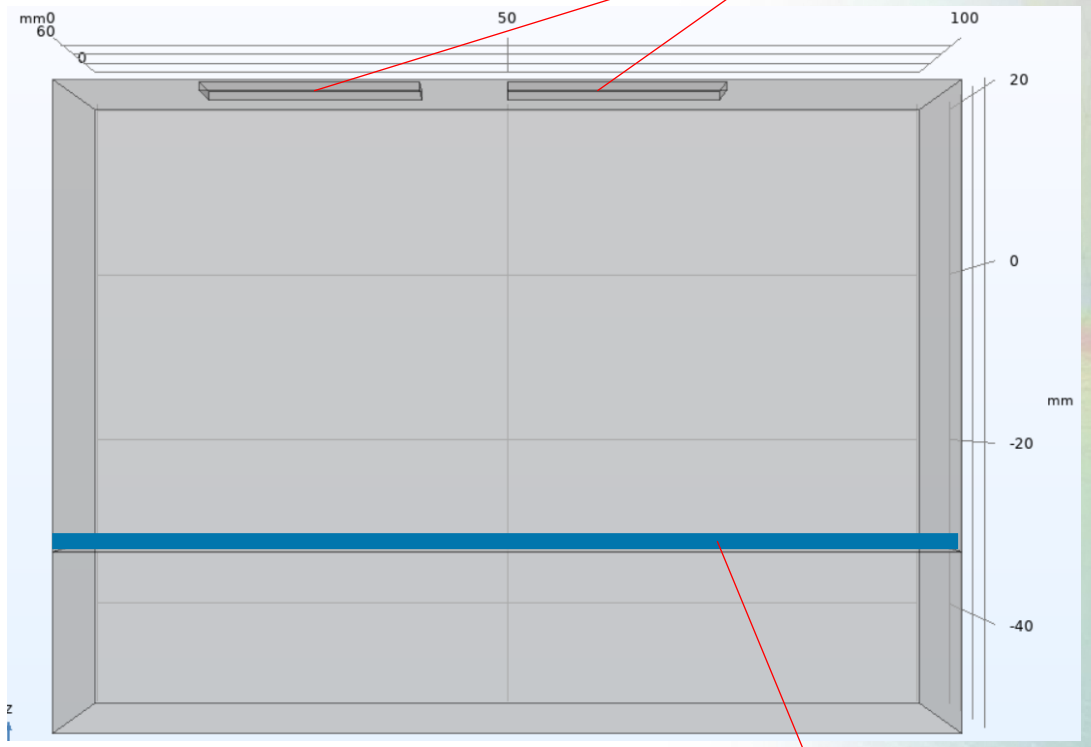
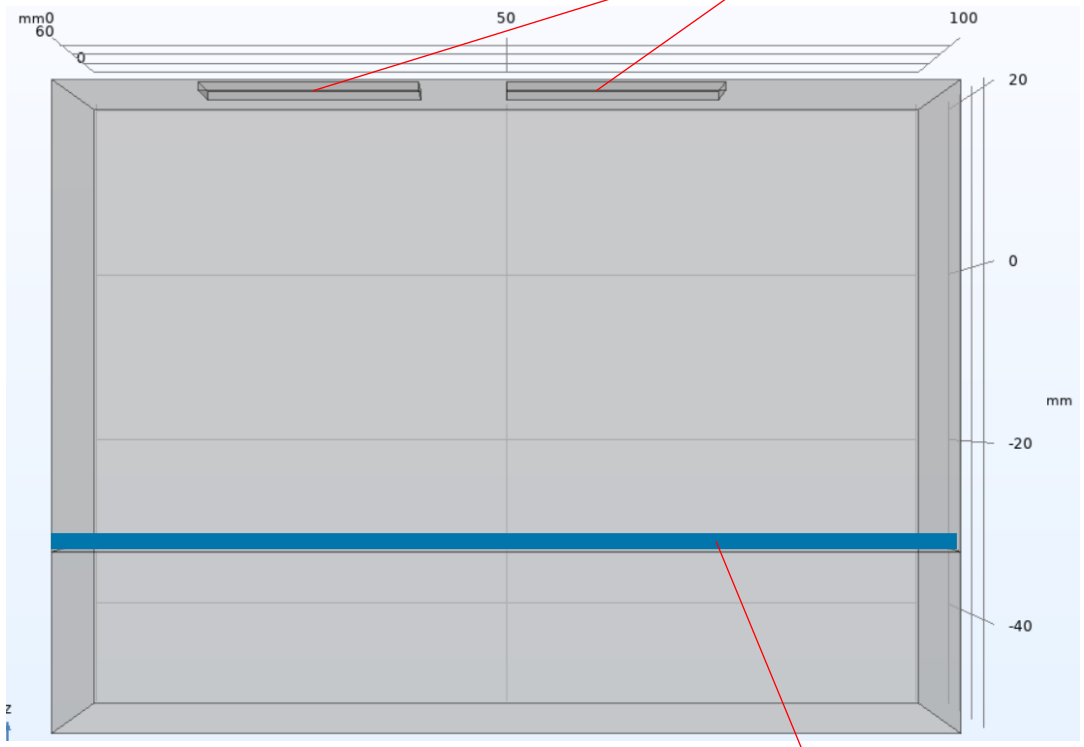
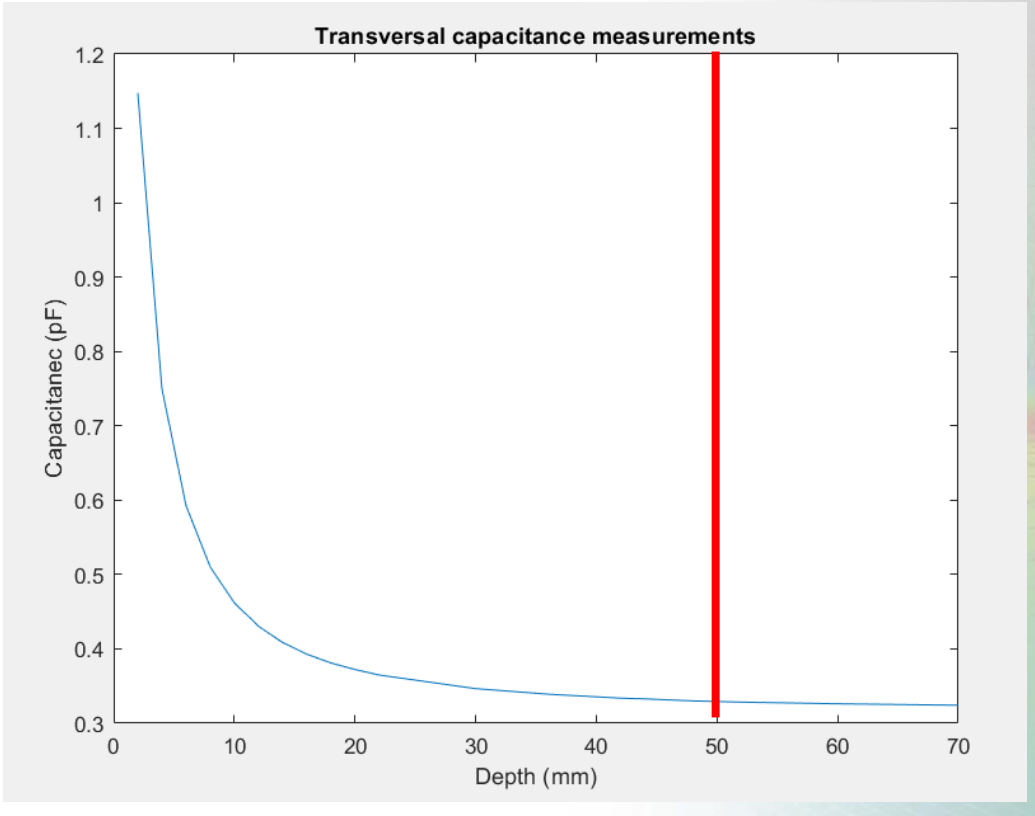
- This numerical model is validated for the initial vertical flow experiment
- The model was run for varying water levels (blue line)
- The model shows changing capacitance values for varying water levels
- Terminal capacitance helps determine the penetration depth of the sensor (water only)



Numerical Simulation

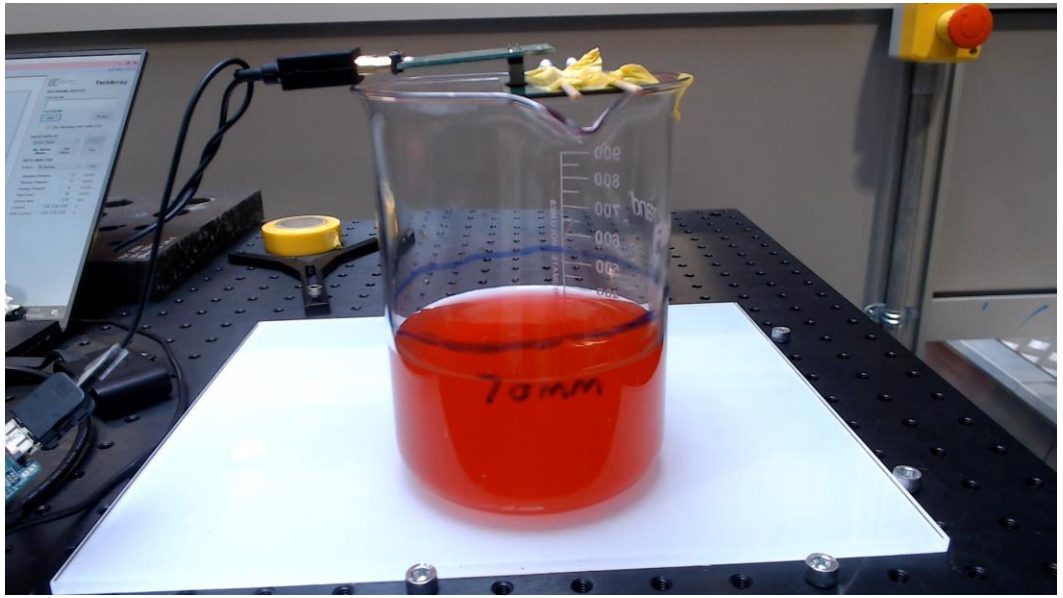


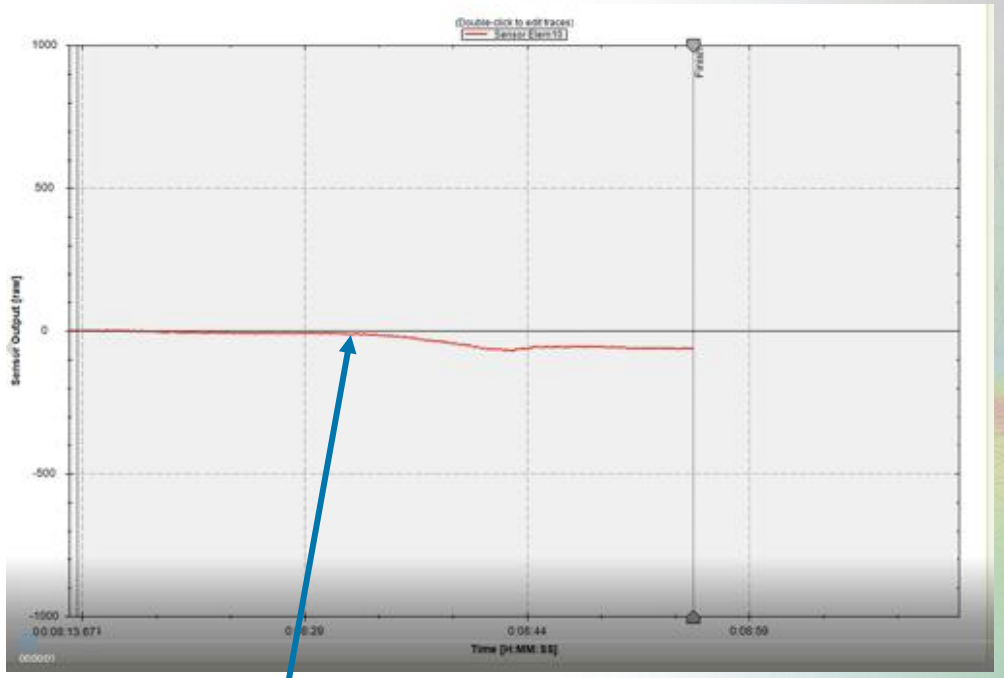


Capacitance stabilises, beginning at 50-60mm then levelling around 70mm

Distance from electrode (mm)

Transversal flow results

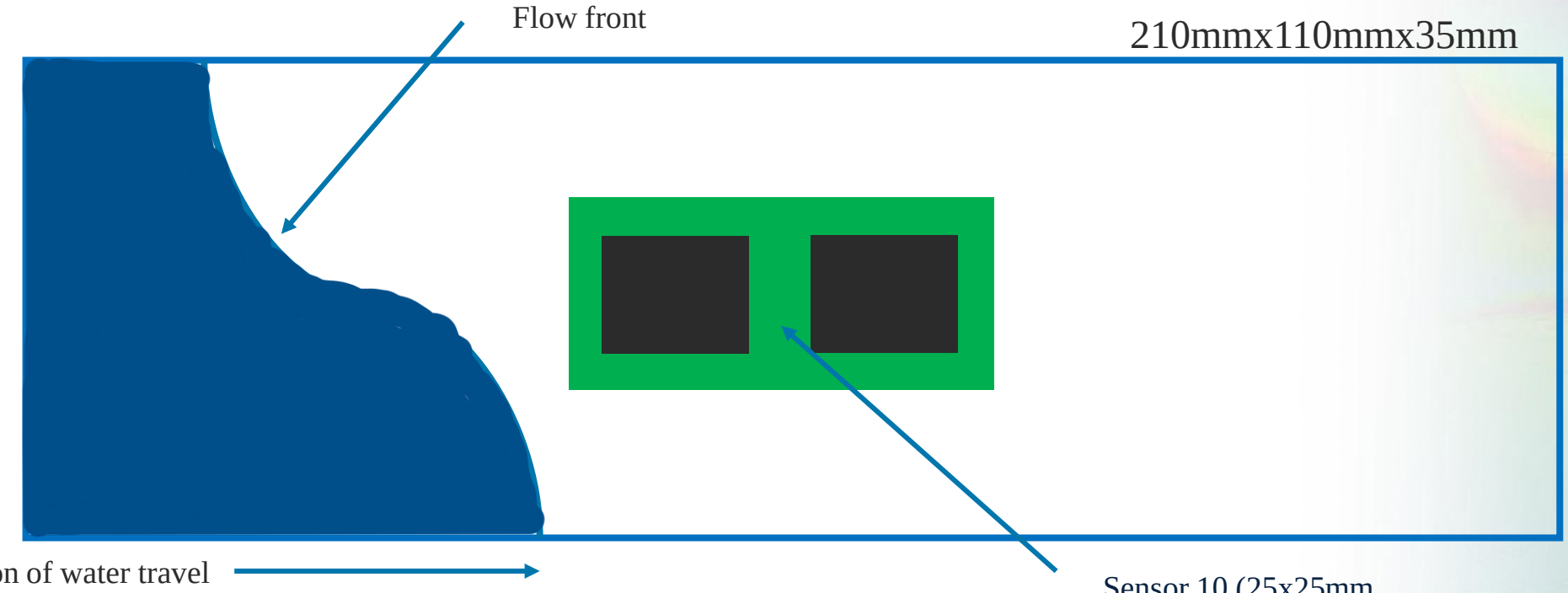




- Sensitive to transversal flow
- Flow detected at a depth around 70mm
  - Validated with COMSOL model

Sensor detects water flow/rising

Horizontal Method



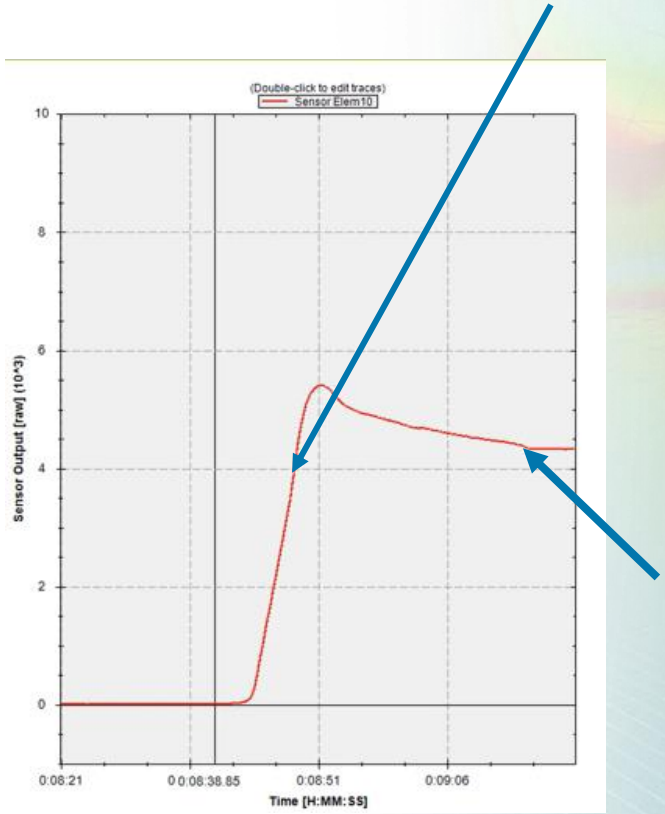
- The water is injected from one side and flows to the other
- Water is detected when the water passes over the driving electrode

Sensor 10 (25x25mm, separation – 10mm)
Software for sensor supplied by PPS (chameleon)

Horizontal flow results

- Horizontal flow detected
- Showing very good sensitivity

Steady rise – water flowing over driving sensor



Levelling out – water has passed over sensing electrode

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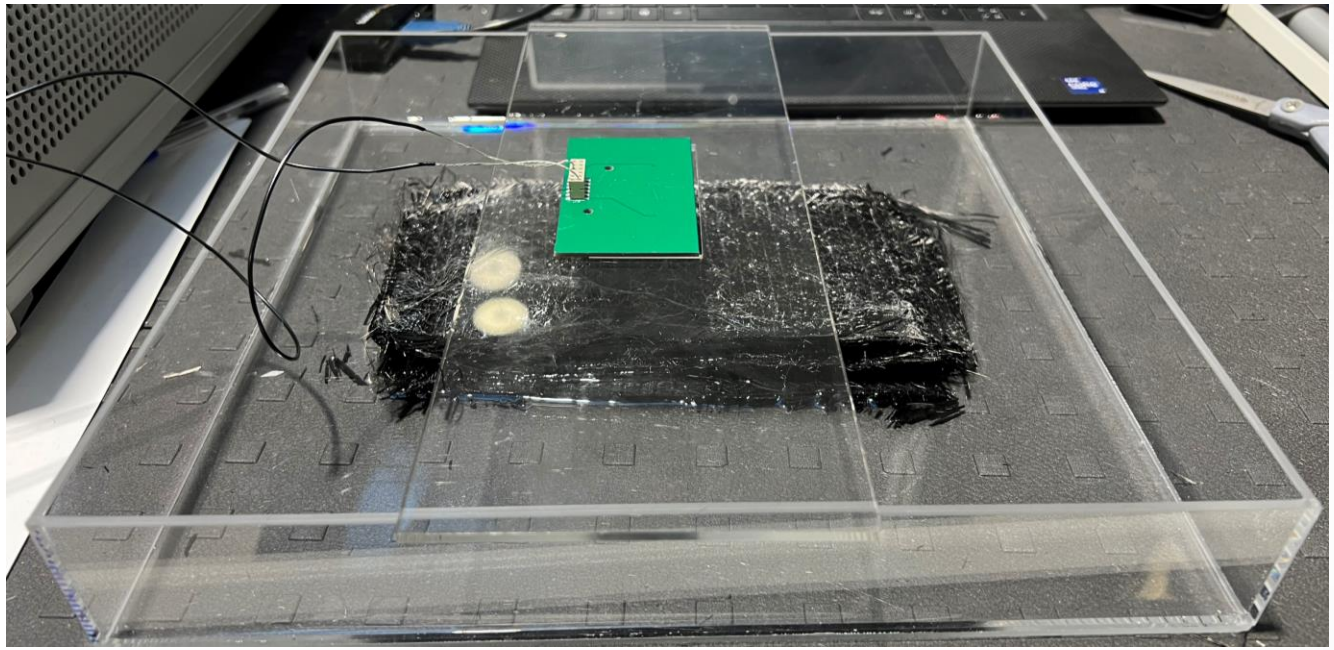
Transversal flow with carbon fibre sheets

Transversal flow with carbon fabrics



- 32 sheets of triaxial (0/45/135) non-crimp carbon fabric stacked in a chamber with total height of 30 mm
- Sensor number 10 (dimensions) placed at height of 32 mm
- Connected to impedance analyser Agilent 4395A
- Frequency swept from 10 kHz – 1 MHz and the resulting impedances plotted
- The sweep was carried out for different levels of water (5-10 mm with steps of 1 mm)

Impedance analysis results

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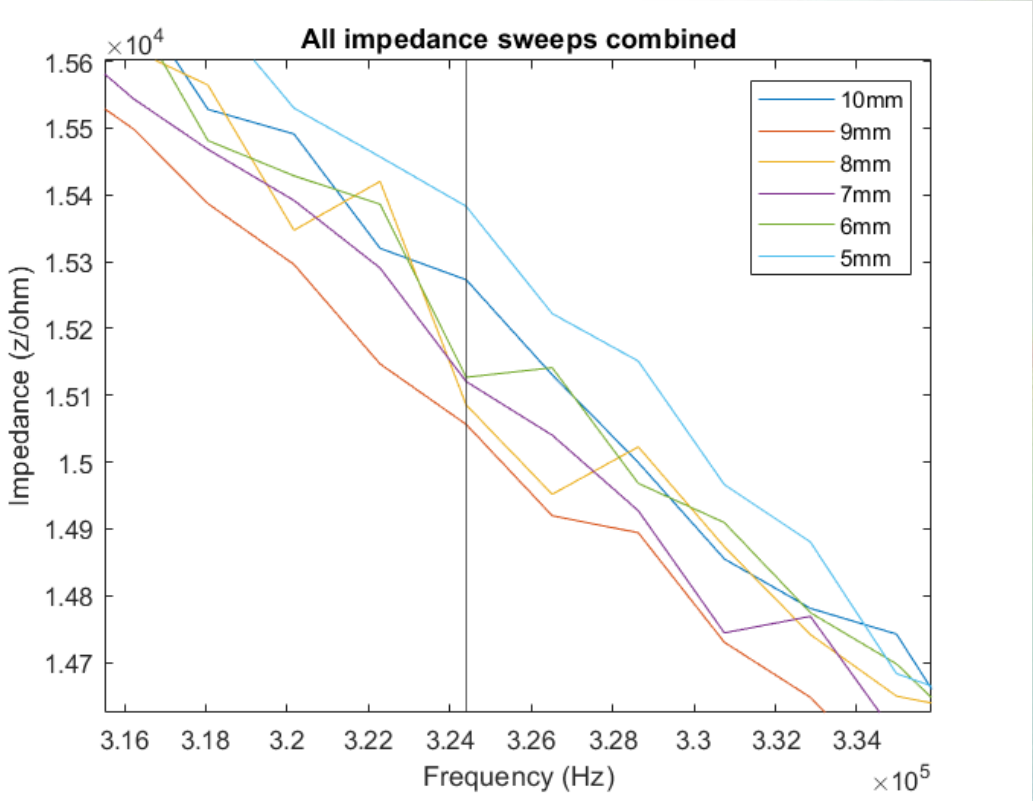
- **When water is 10mm away from sensor to 5mm away from sensor, there is no significant change in the output**
- No sensitivity was observed for water level when carbon fabrics are in the mold
- The presence of carbon fibre is to replicate a manufactured sample in a mold
- No sensitivity suggests the fabrics have a shielding effect on the electric field



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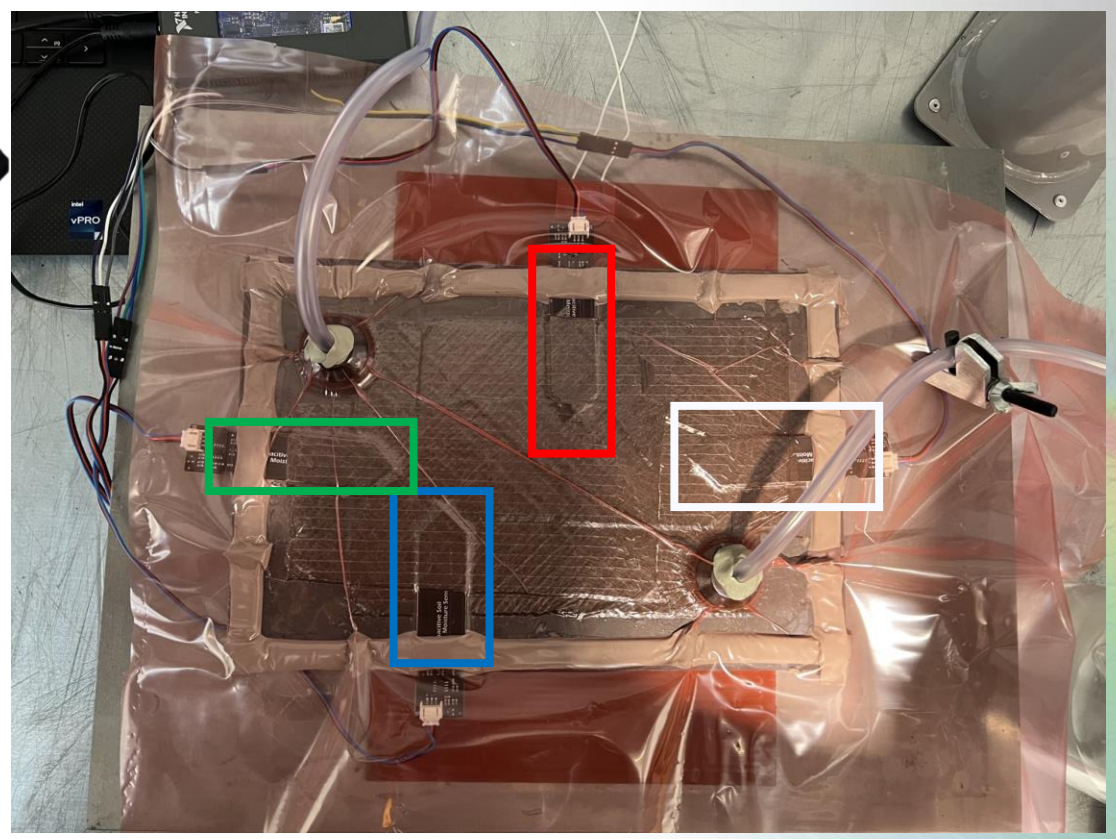
Embedded capacitive sensors for resin flow monitoring

Data acquisition through myRio



- Resin flow can be monitored at different locations on the sample
- 4 sensors spread across the carbon fabric
- Water used instead of resin

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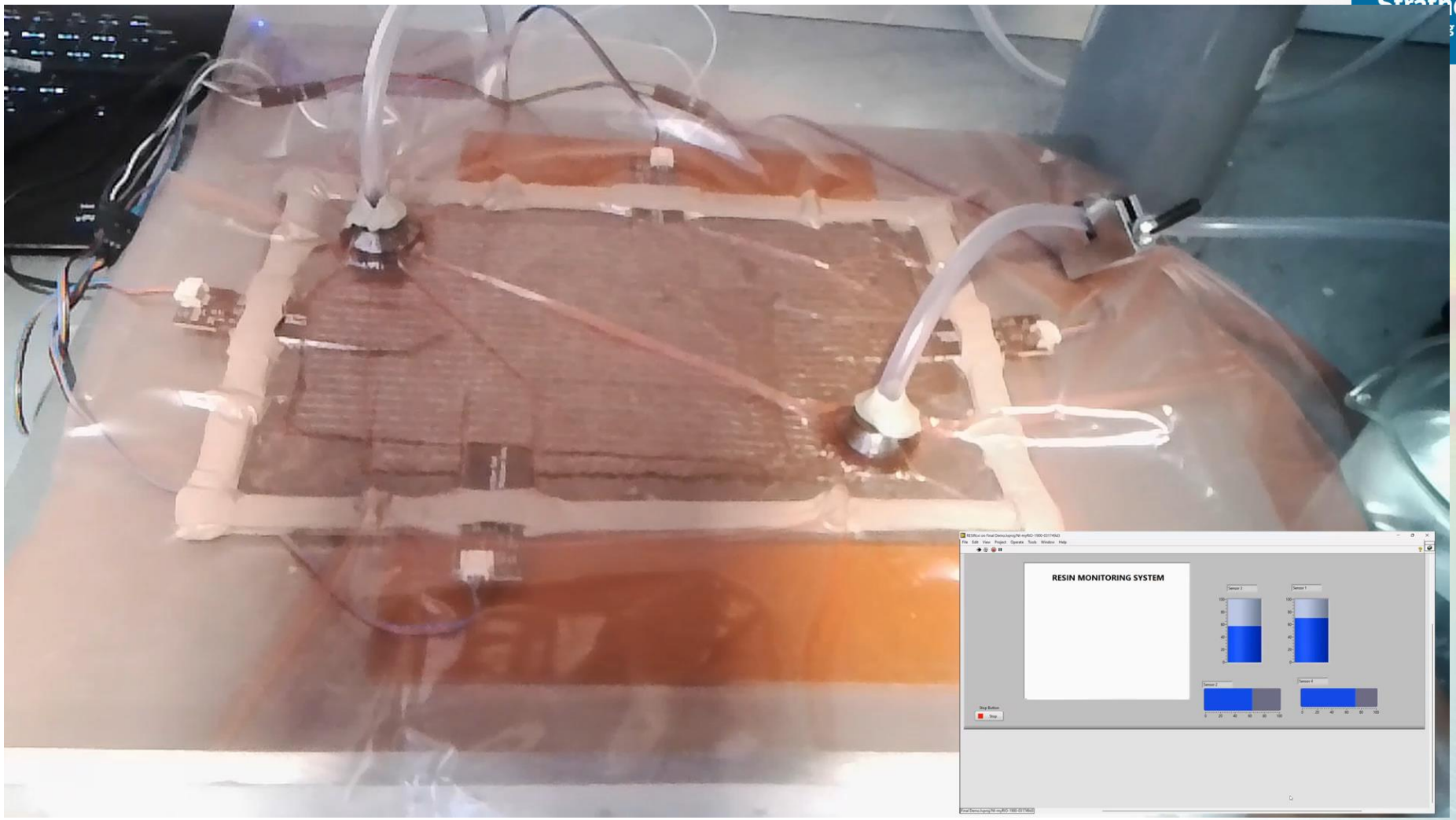

Conclusion

- Horizontal flow monitoring was successful with and without carbon fabrics
- Transversal flow monitoring was possible when the water reached 70mm from the sensor
- With carbon fabrics transversal flow could be monitored when the water level reached 2-4mm from the sensor
- Embedded sensors showed good sensitivity to water flow in vacuum bagging process

Future work:

- Look into sensors that are sensitive to flow outside the bag

Thank You

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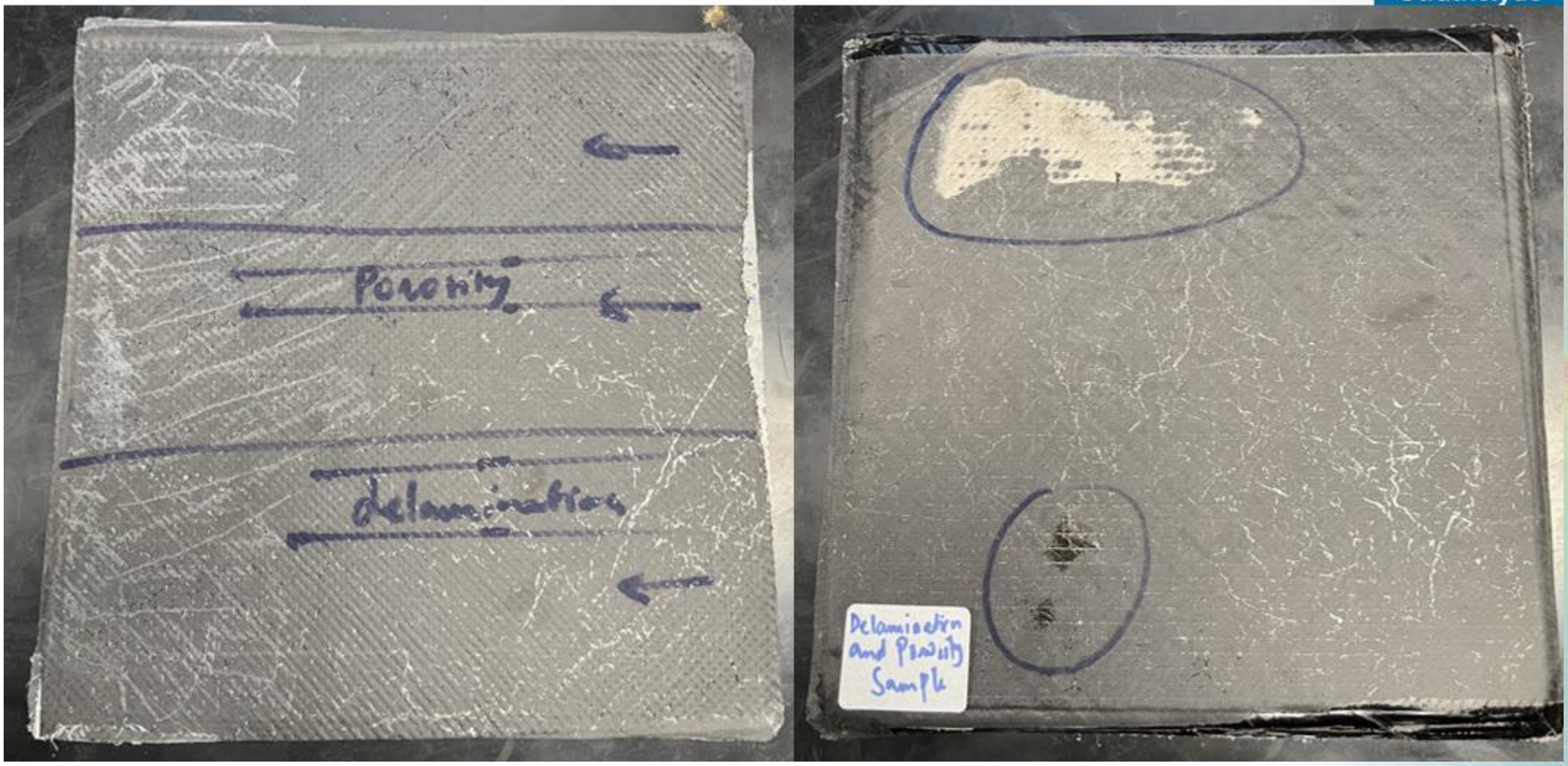
Porosity
Delamination
Delamination and Porosity Sample