domminio

Digital method for improved manufacturing of next-generation multifunctional airframe parts

Multiscale Modeling of Composites: **Towards AI assisted virtual testing of composites**

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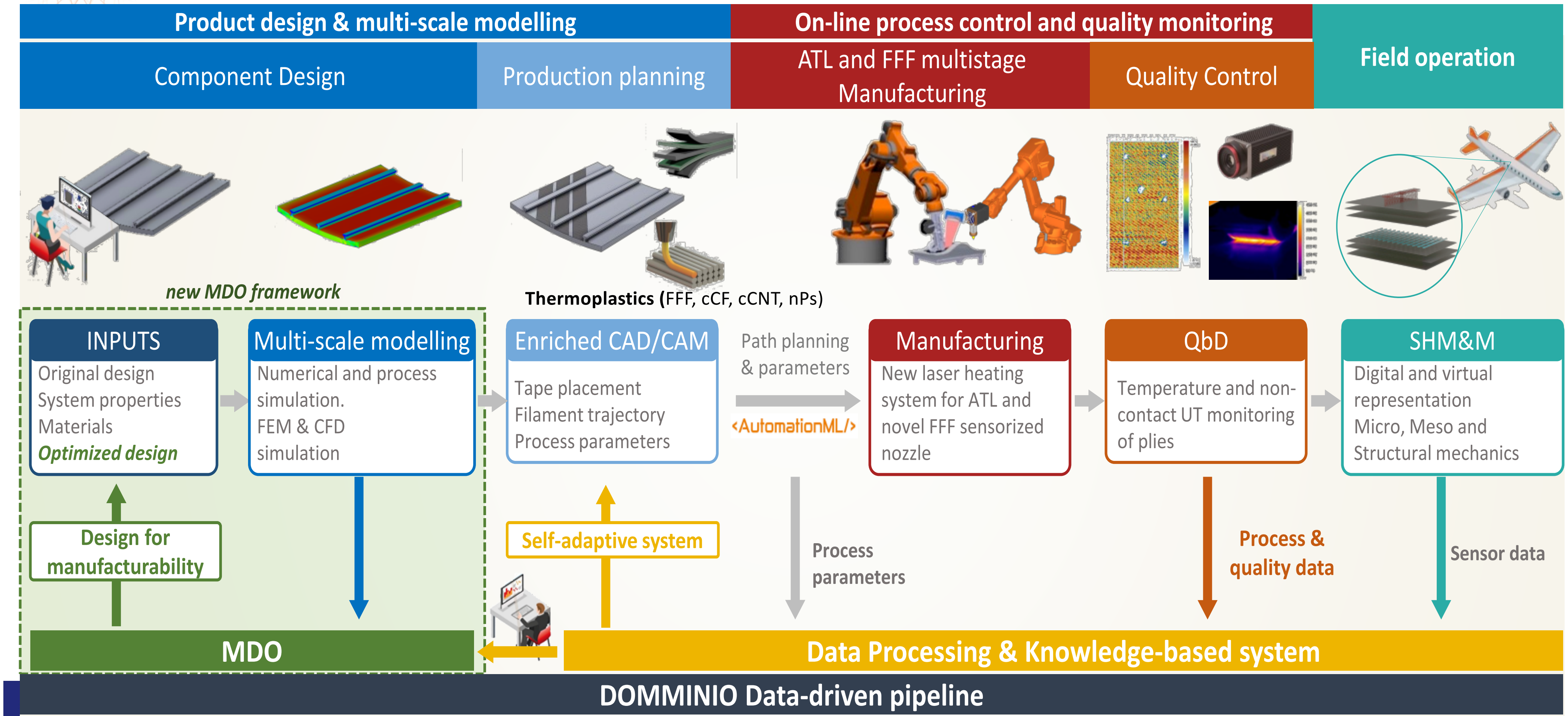
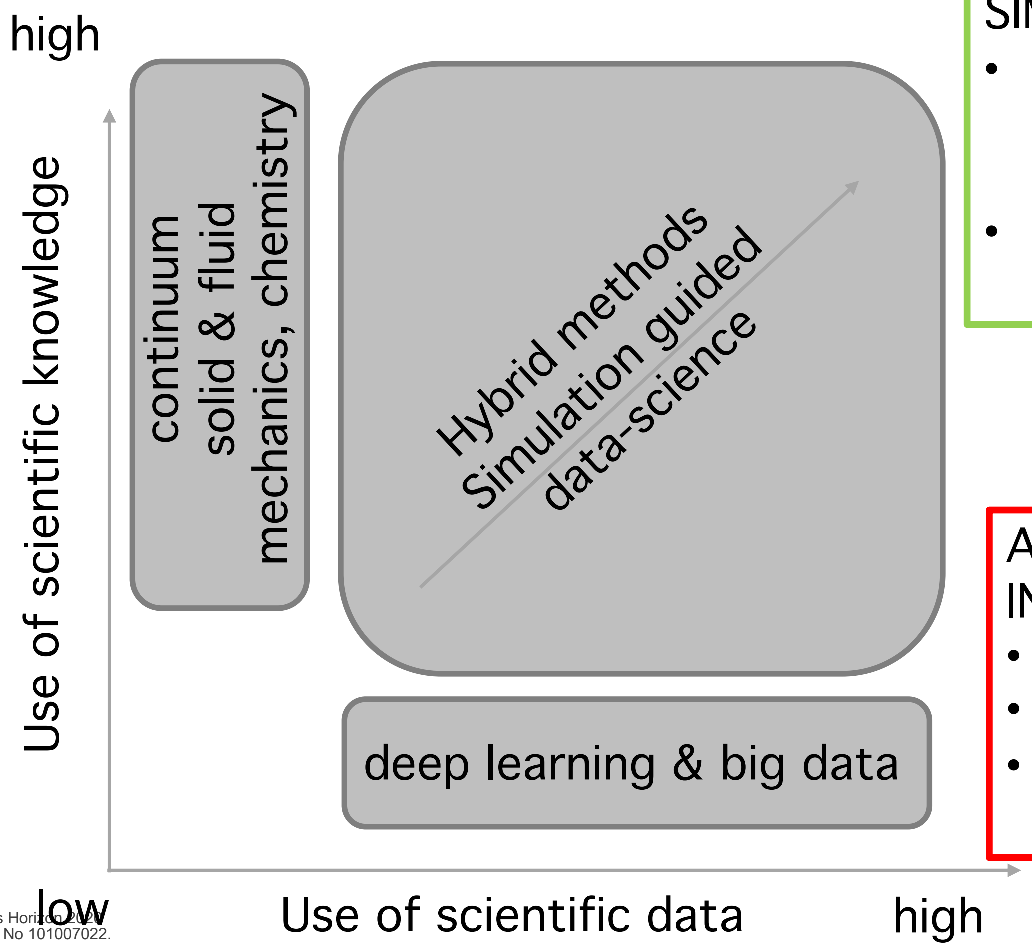
CM3
Barcelona, Spain, 22-24 November 2021

OVERVIEW



Product design & multi-scale modelling
On-line process control and quality monitoring
Component Design
Production planning
ATL and FFF multistage Manufacturing
Quality Control
Field operation
new MDO framework
Thermoplastics (FFF, cCF, cCNT, nPs)
INPUTS
Original design
System properties
Materials
Optimized design
Multi-scale modelling
Numerical and process simulation.
FEM & CFD simulation
Enriched CAD/CAM
Tape placement
Filament trajectory
Process parameters
Path planning & parameters
<AutomationML/>
Manufacturing
New laser heating system for ATL and novel FFF sensorized nozzle
QbD
Temperature and non-contact UT monitoring of plies
SHM&M
Digital and virtual representation
Micro, Meso and Structural mechanics
Design for manufacturability
Self-adaptive system
Process parameters
Process & quality data
Sensor data
MDO
Data Processing & Knowledge-based system
DOMMINIO Data-driven pipeline

VIRTUAL TESTING
- Physically-based ✓
- Time consuming ✗
- On-the-fly ✗



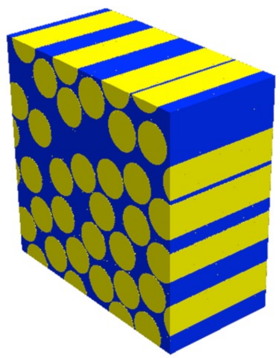
SIMULATION GUIDED AI
- Trustworthy AI (physically-constrained)
- Reduce of tests for data-sets

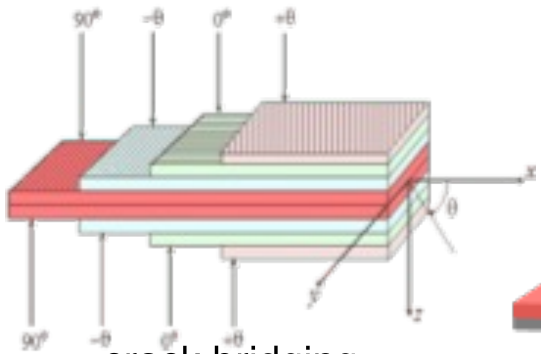
ARTIFICIAL INTELLIGENCE
- Hidden patterns ✓
- Black-box ✗
- Experimental trials are expensive ✗

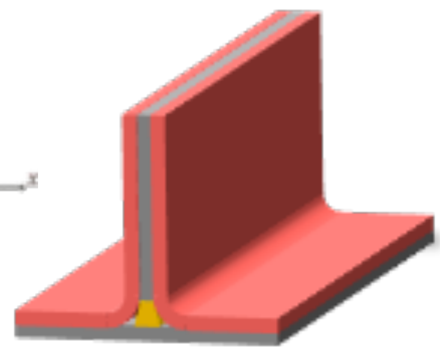
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101007022.

- Fiber-reinforced composites present a simple -but efficient- hierarchical structure that leads to tough materials from brittle constituents.

dominant length scale	fiber diameter ≈ 10 μm	ply thickness 150-300 μm	laminate thickness 2-20 mm







	matrix shear yielding interface decohesion	crack bridging fiber pull-out fiber kinking interply decohesion	buckling crushing

- Understanding the fracture behavior requires a multiscale approach for characterization and modeling to account for the interaction between length scales.

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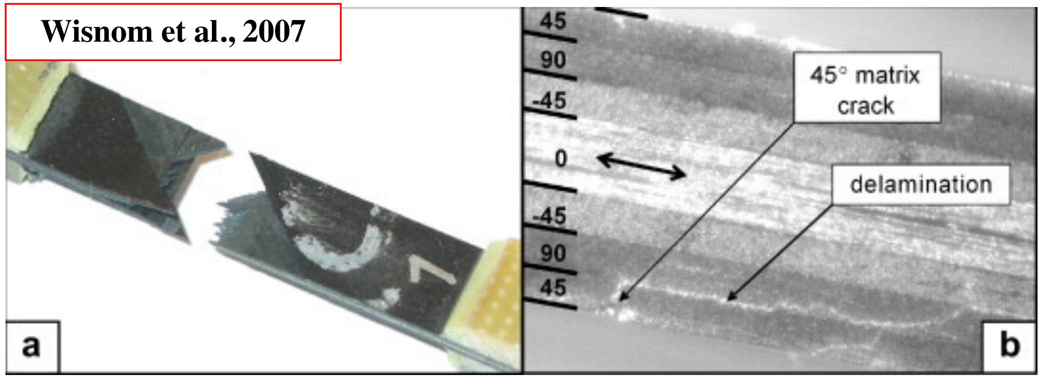
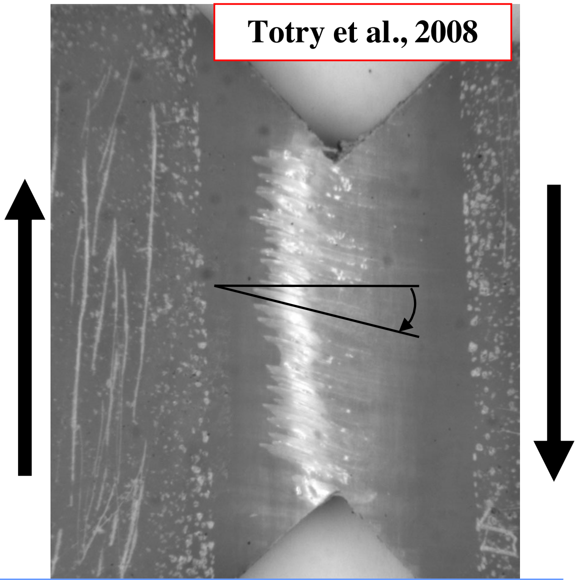
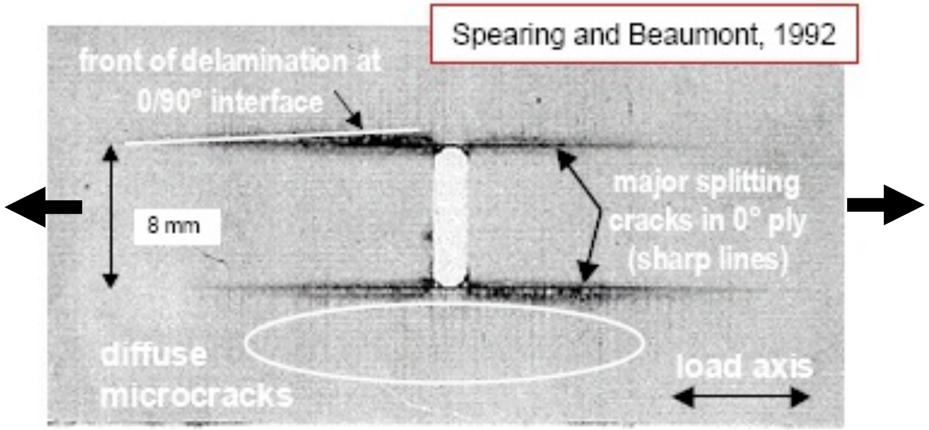
Intralaminar failure (fiber failure, matrix cracking, interface decohesion)





Non linearity (geometry and material)



Interlaminar failure (delamination)

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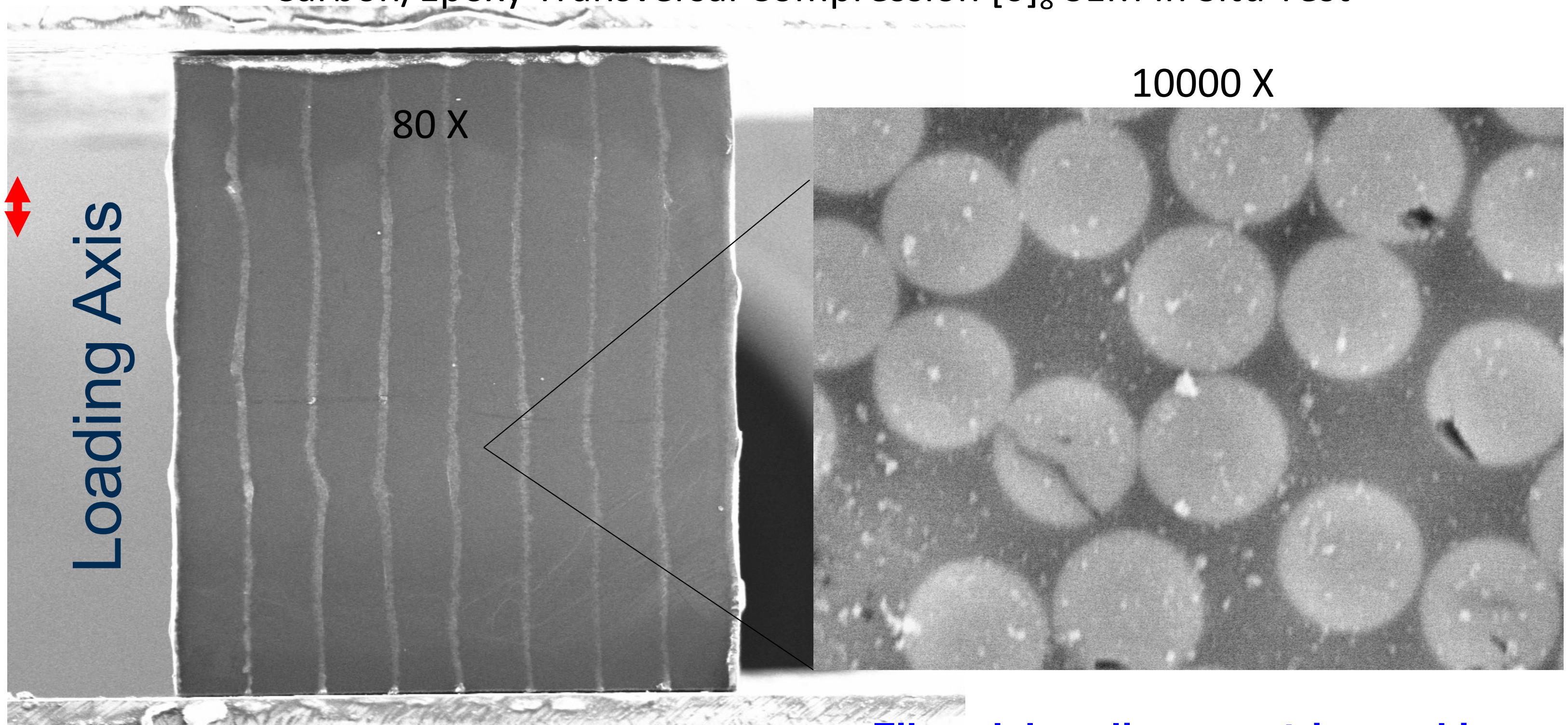
Damage triggered at the microscale

Carbon/Epoxy Transversal Compression $[0]_8$ SEM In Situ Test



Plastic shear banding and failure → **Fiber debonding + matrix cracking**

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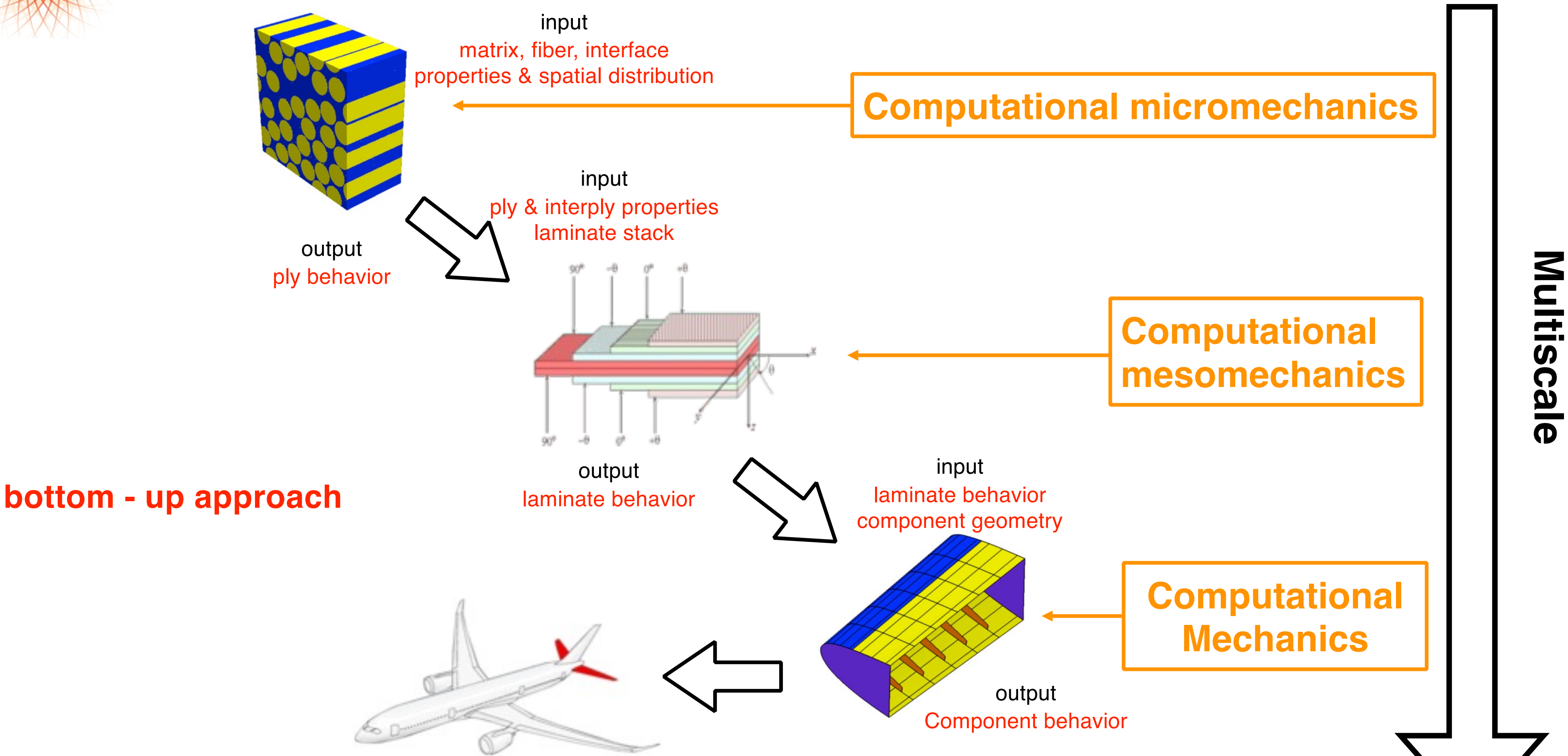
MULTISCALE SIMULATION STRATEGY



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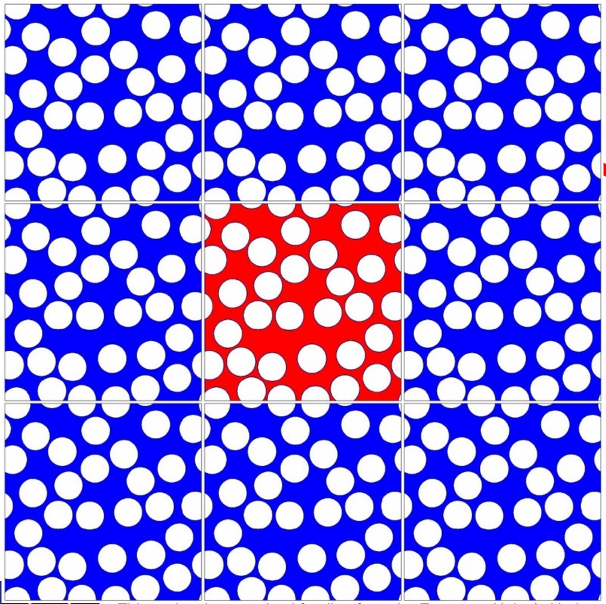
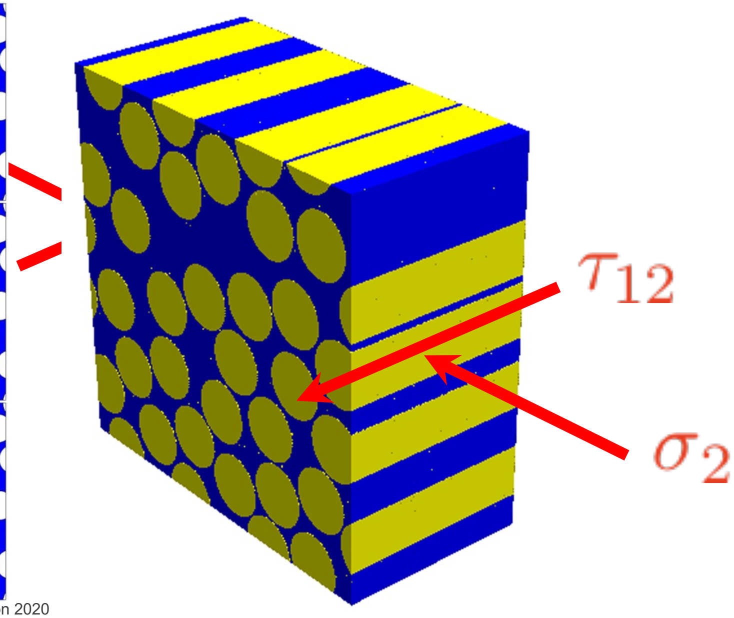
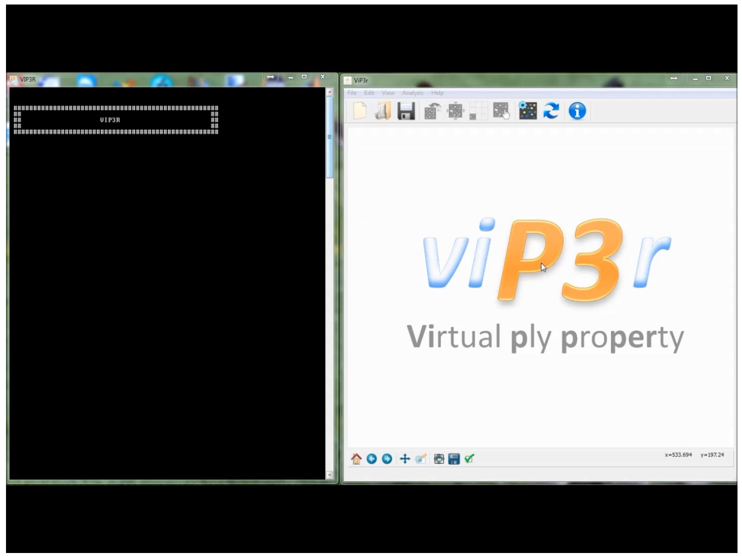
- Fiber centers are generated randomly and sequentially to reach target volume fraction in a square RVE. A periodic microstructure is formed by an indefinite translation of the RVE.
- A 3D parallelepiped containing a random and homogeneous dispersion of fibers is obtained by extruding the 2D RVE along the fiber axis.
- Periodic boundary conditions are imposed between opposite faces of the RVE (jig-saw puzzle)







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FIBER MODEL

Fibers behave as elastic solids: transverse isotropic (carbon fibers) and isotropic (glass fibers)

Interface decohesion is accounted for using a cohesive crack model

INTERFACE MODEL

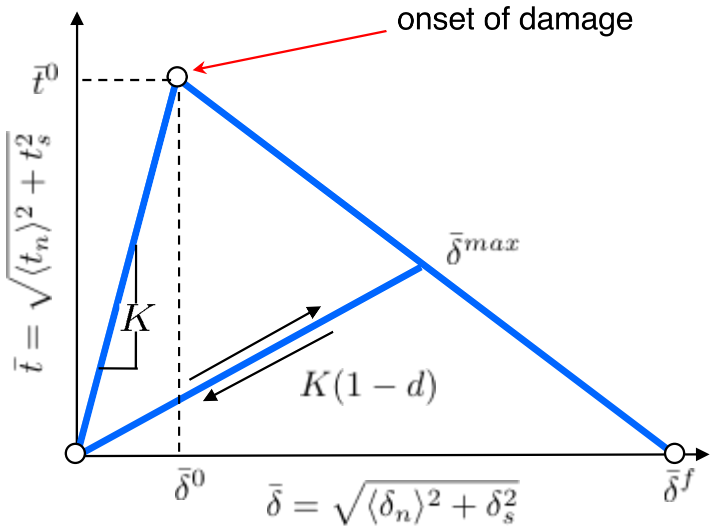
- Onset of damage $max\left\{\frac{\langle t_n\rangle}{N}, \frac{t_s}{S}\right\} = 1$
- Traction-separation law

$$\begin{aligned} t_n &= (1-d)K\delta_n \quad \text{if} \quad \delta_n > 0 \\ t_n &= K\delta_n \quad \text{if} \quad \delta_n \leq 0 \\ t_s &= (1-d)K\delta_s \end{aligned}$$

- Evolution of the damage parameter

$$d = \frac{\bar{\delta}^f(\bar{\delta}^{max} - \bar{\delta}^0)}{\bar{\delta}^{max}(\bar{\delta}^f - \bar{\delta}^0)}$$

- Interface fracture energy $G_F = \frac{1}{2}\bar{t}^0\bar{\delta}^f$



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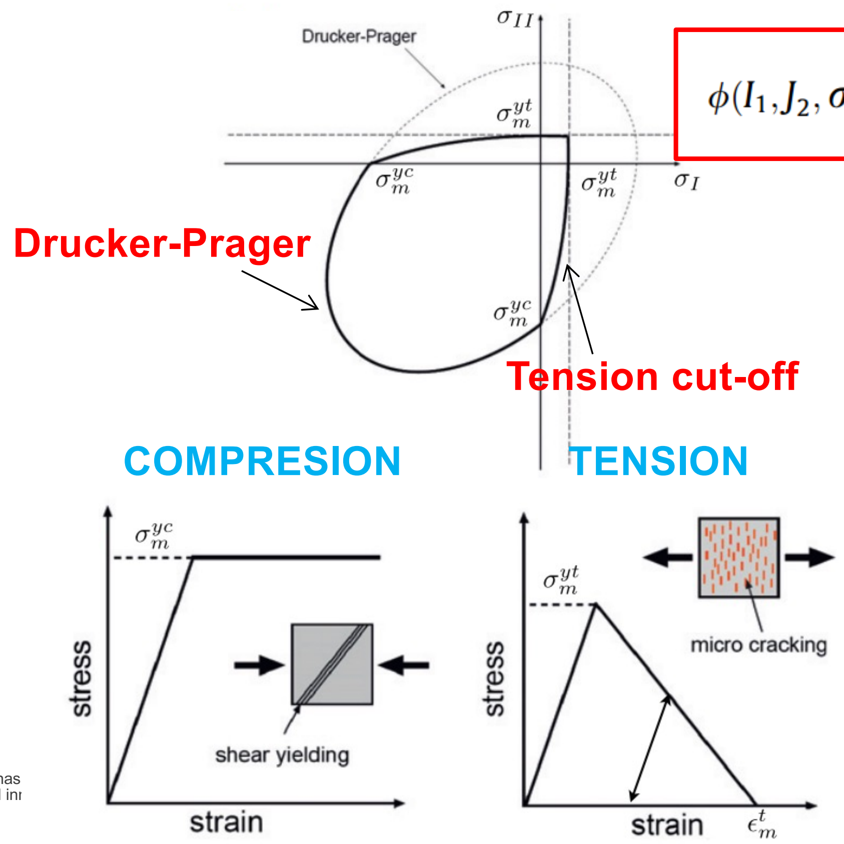
MATRIX MODEL

The epoxy matrix followed a modification of Drucker-Prager plasticity (Lubliner) to account for brittle fracture in tension and shear yielding



$$\phi(I_1, J_2, \sigma_I, \beta, \alpha) = \frac{1}{1-\alpha}\left(\sqrt{\frac{3J_2}{2}} + \frac{I_1}{3}\alpha + \beta\langle\sigma_I\rangle\right) - \sigma_m^{yc} = 0$$

- α •Pressure sensitivity
- σ_m^{yc} •Compression yield stress
- σ_m^{yt} •Tension cut-off

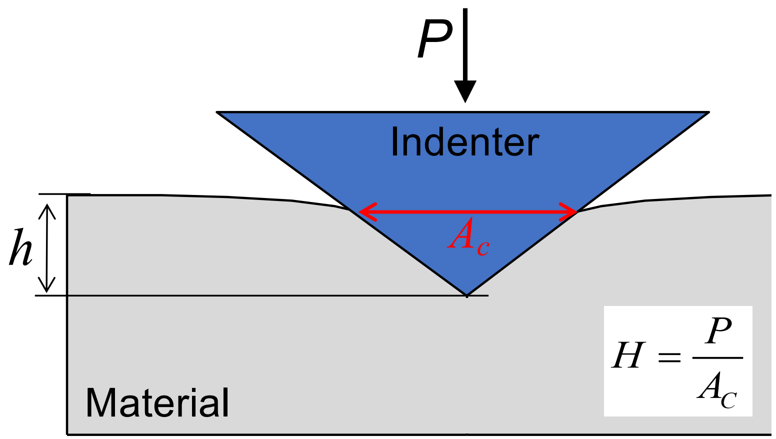
$$\beta = \frac{\sigma_m^{yc}}{\sigma_m^{yt}}(1-\alpha) - (1+\alpha)$$

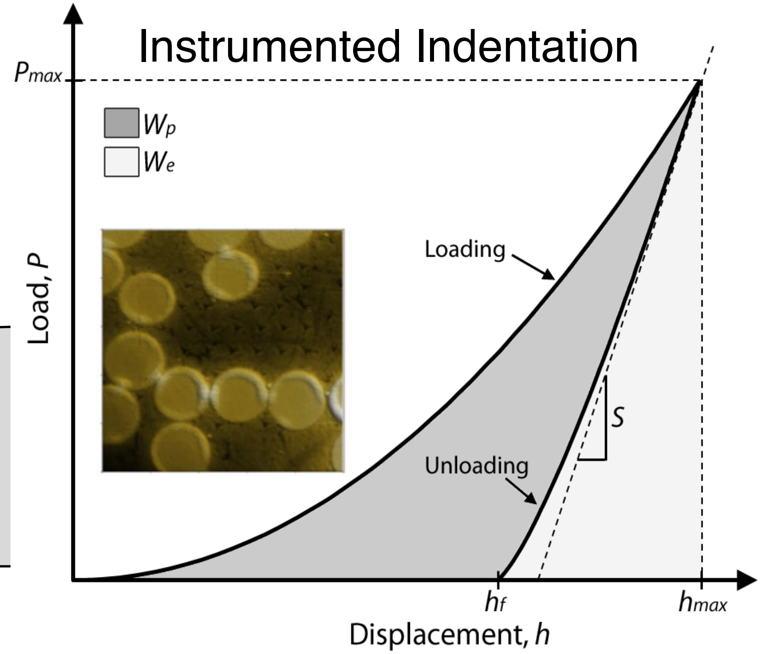
- G_m^f • Fracture energy for softening

This project has
research and in

MATRIX/FIBER INTERFACE PROPERTIES

MATRIX PROPERTIES





- Load P vs. depth h of the indenter is monitored
- Hardness H is dependent on the yield strength σ_m^{yc}
- Real and apparent contact areas differences (pile-up and sink-in)
- FEM detailed model of indentation in pressure dependent materials
- Drucker Prager solids σ_m^{yc} and α

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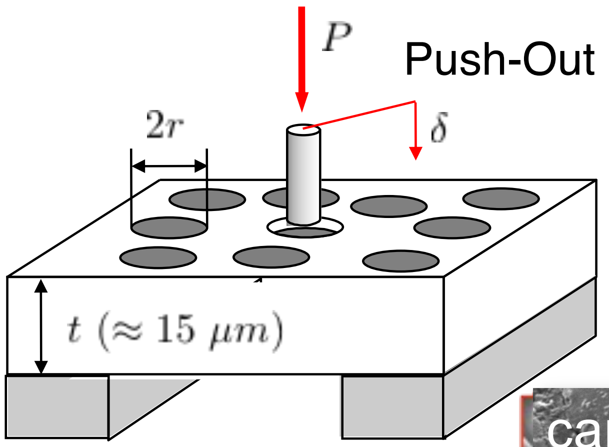
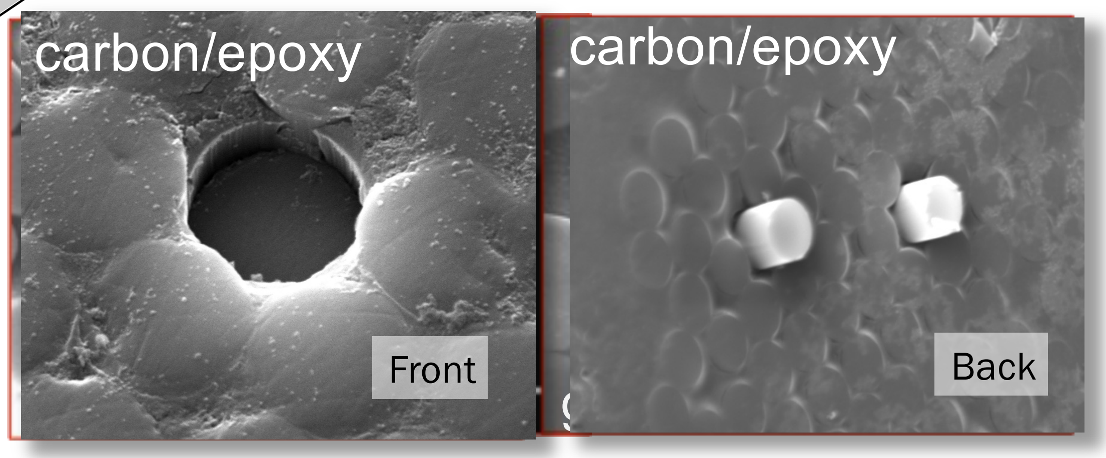
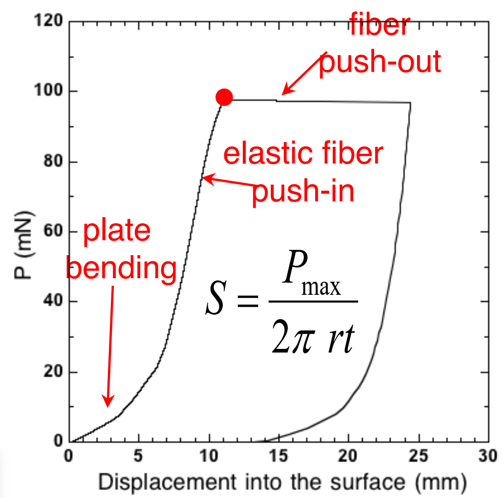
Push-Out on Polymer Matrix Composites







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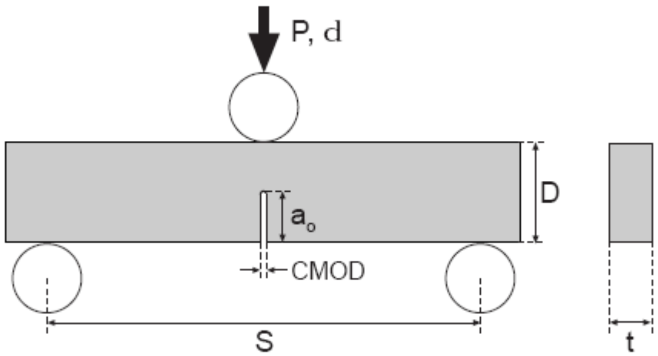
M. Rodríguez, J. M. Molina-Aldareguía, C. González, J. LLorca. A methodology to measure the interface shear strength by means of the fiber push-in test. Composites and Technology, 72, 11924-1932, 2012.

THREE POINT BENDING

- TPB notched specimens
- $a_0/D \approx 0.5$ for stable crack growth
- On-line detailed inspection of failure micromechanisms



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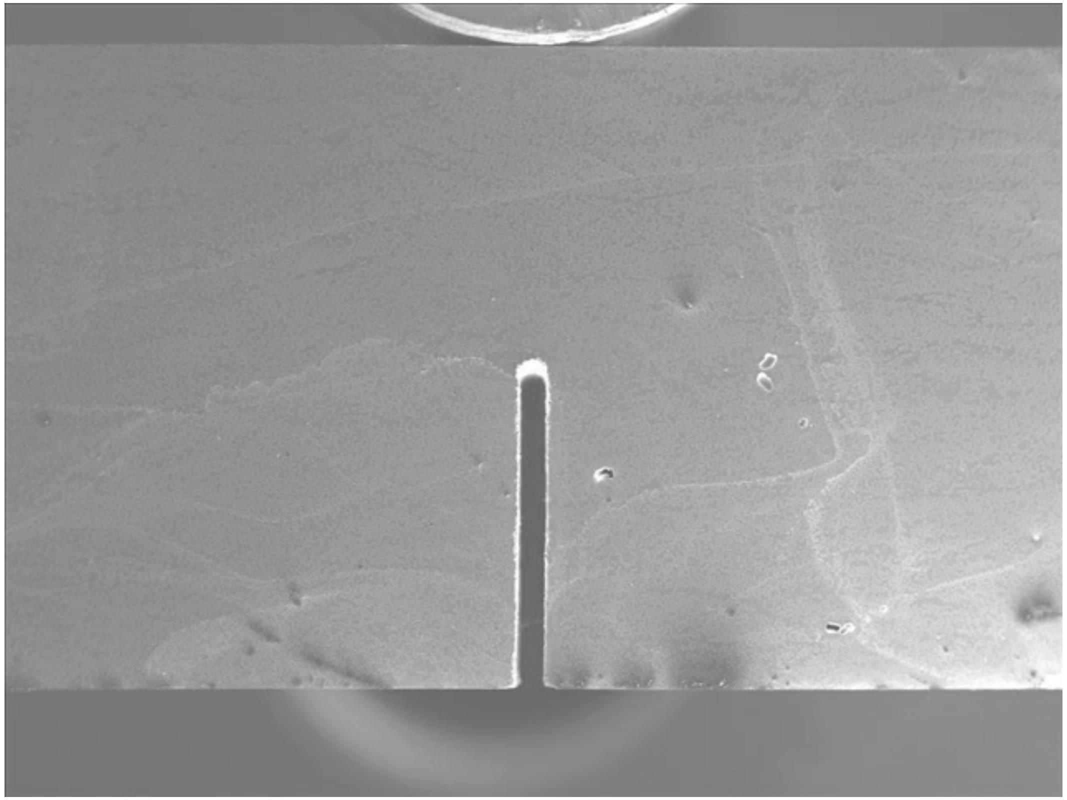
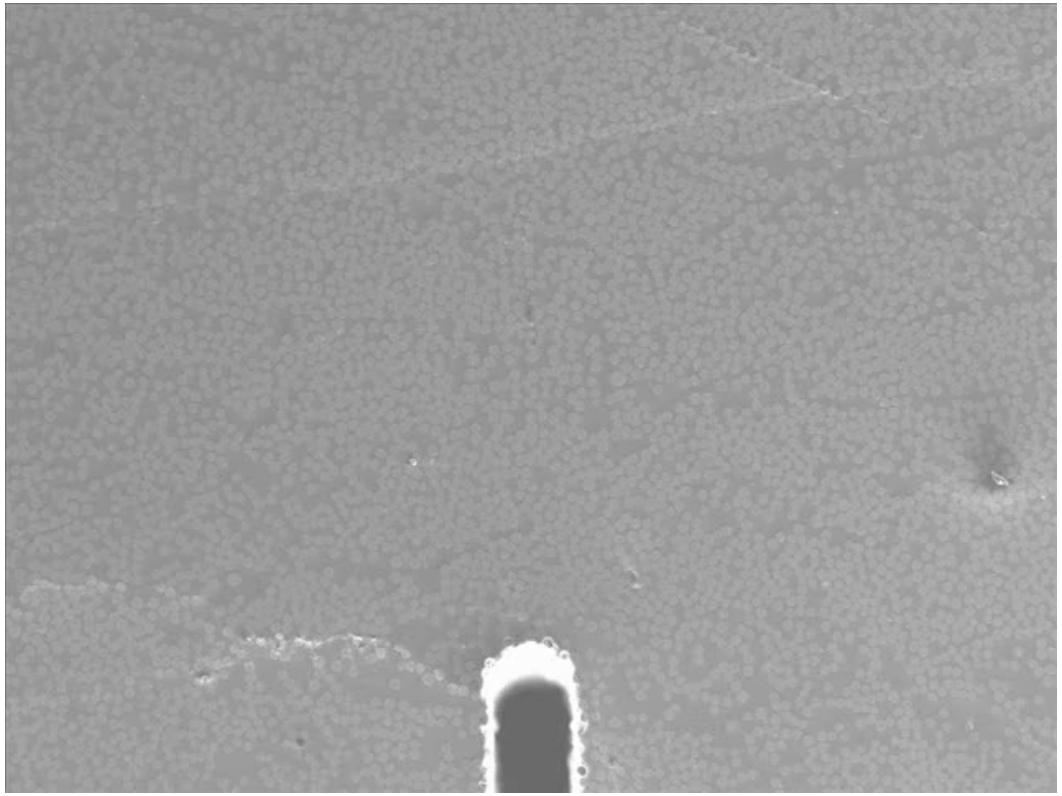
L. P. Canal, C. González, J. Segurado, J. LLorca.
Composites Science and Technology, 72,1223–1232, 2012.

NOTCHED THREE POINT BENDING MODEL





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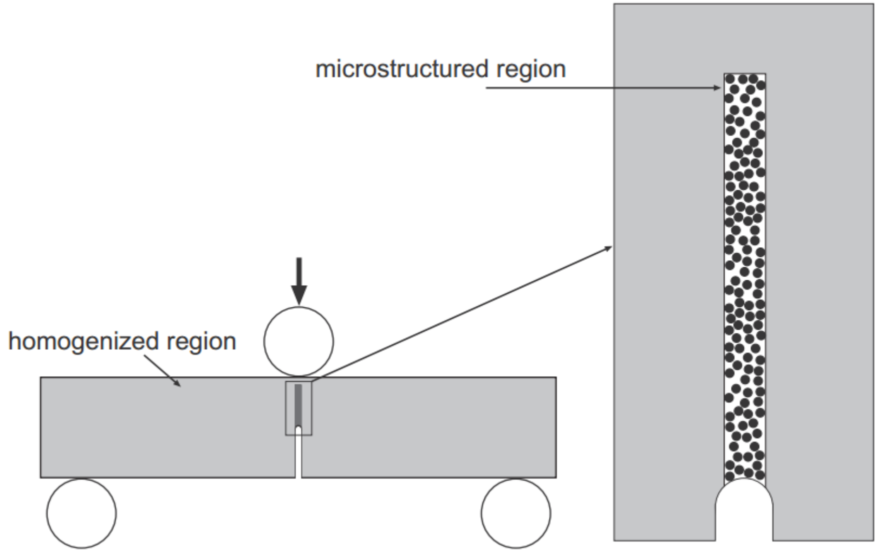
NOTCHED THREE POINT BENDING MODEL

- Simulations were carried out with Abaqus/standard under plane strain conditions within the framework of an embedded cell model.



- The elastic constants of the transversely isotropic homogenized composite were obtained from those of the matrix and fibers using Mori-Tanaka
- Discretization was carried out with quadratic triangles (CPE6M)
- Interfaces were discretized with linear triangles (COH2D)

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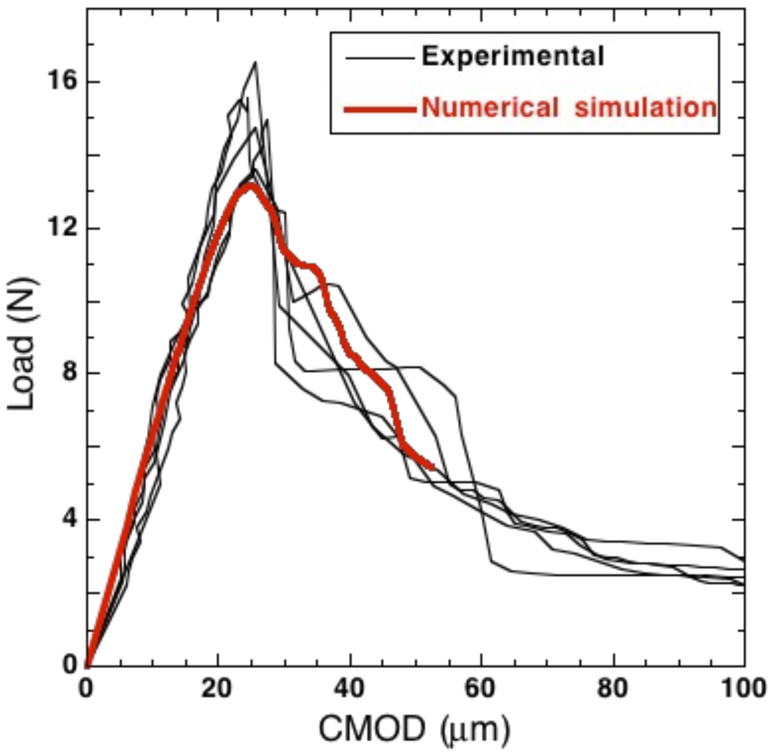
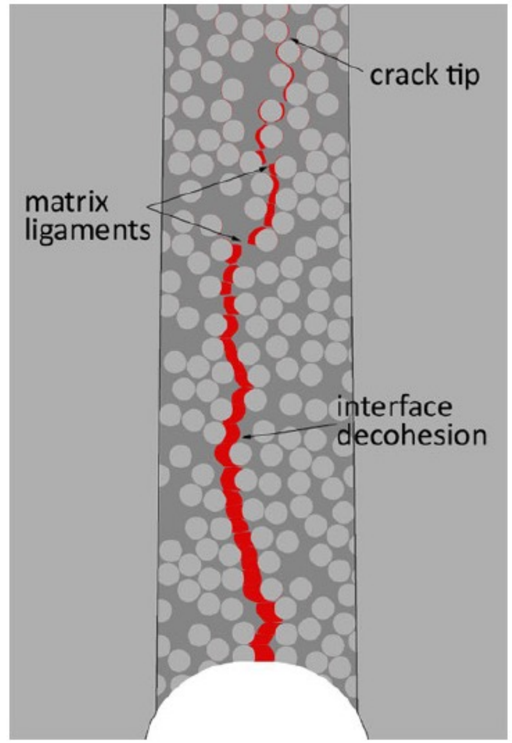
NOTCHED THREE POINT BENDING MODEL





- The numerical model is able to reproduce accurately the macroscopic P- CMOD curves as well as the microscopic failure mechanisms.

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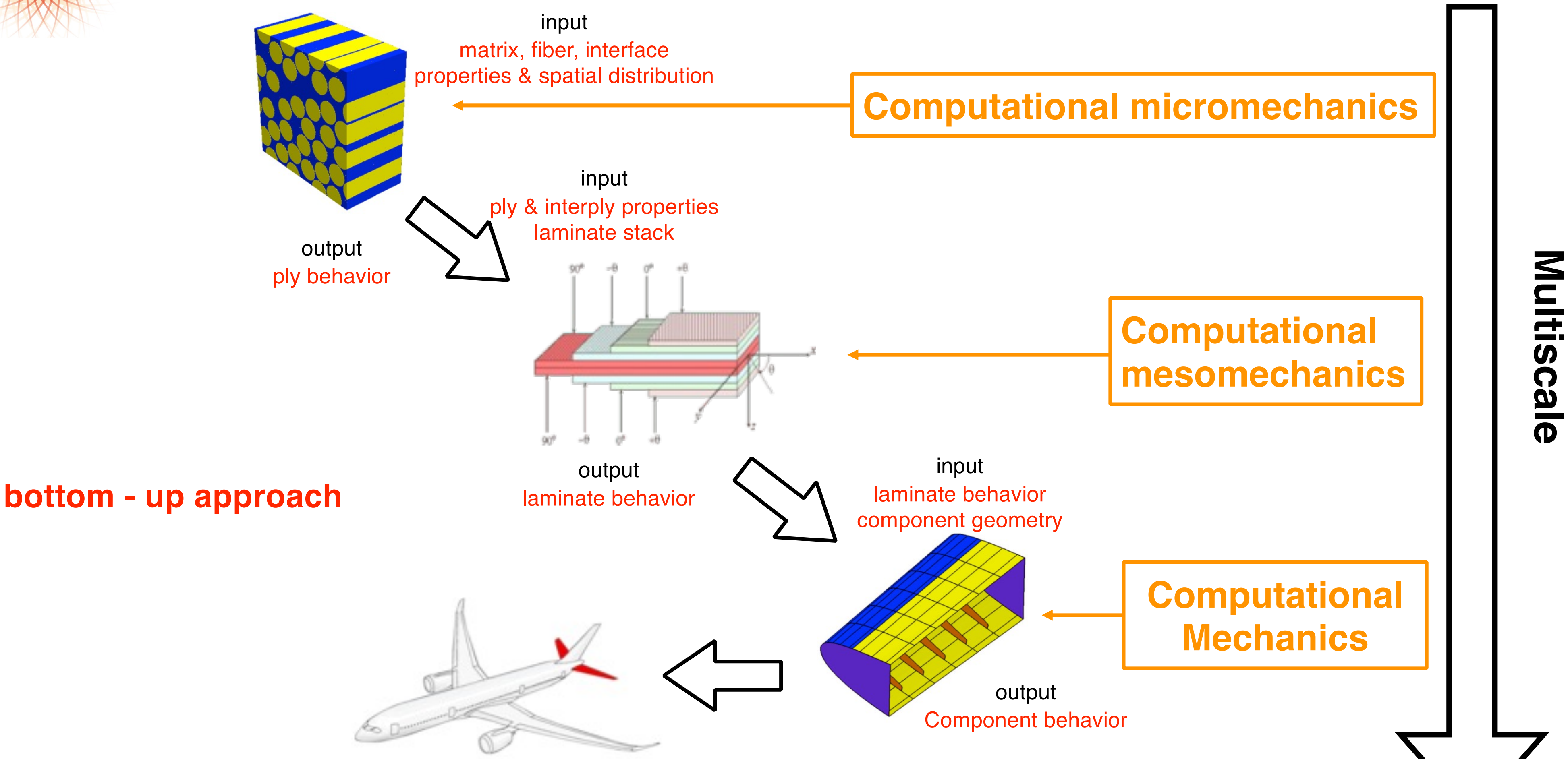
MULTISCALE SIMULATION STRATEGY



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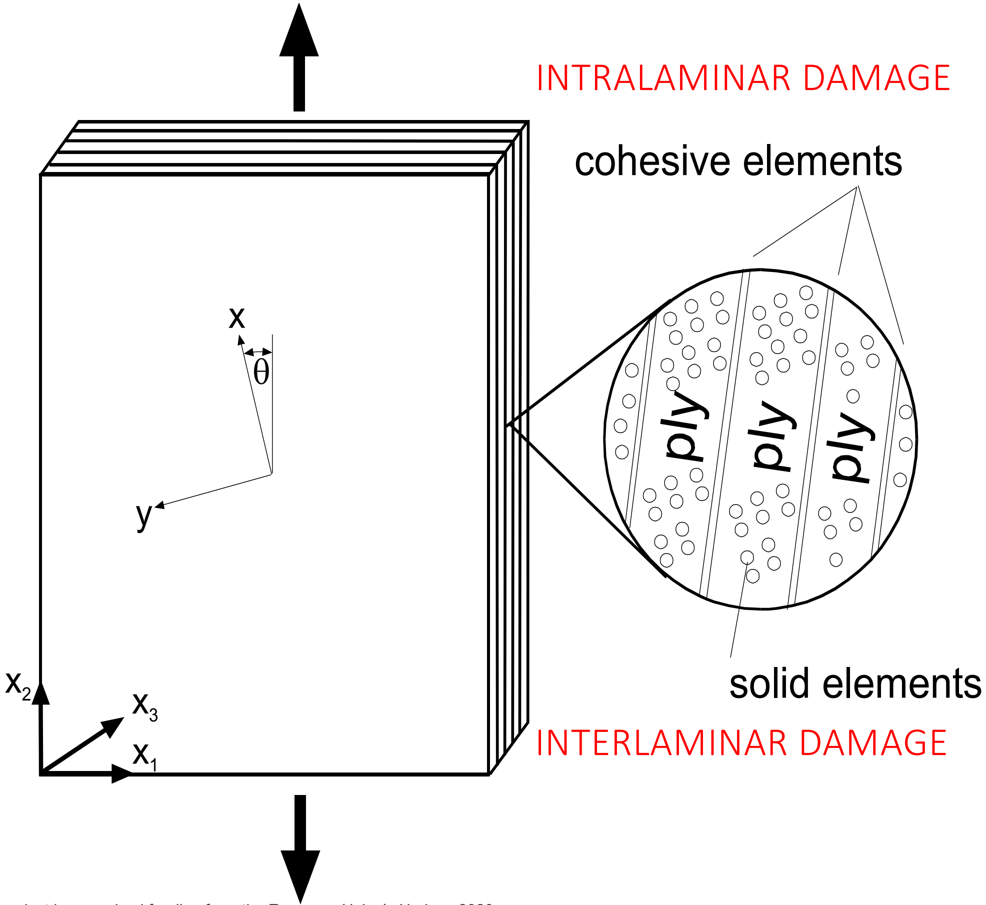
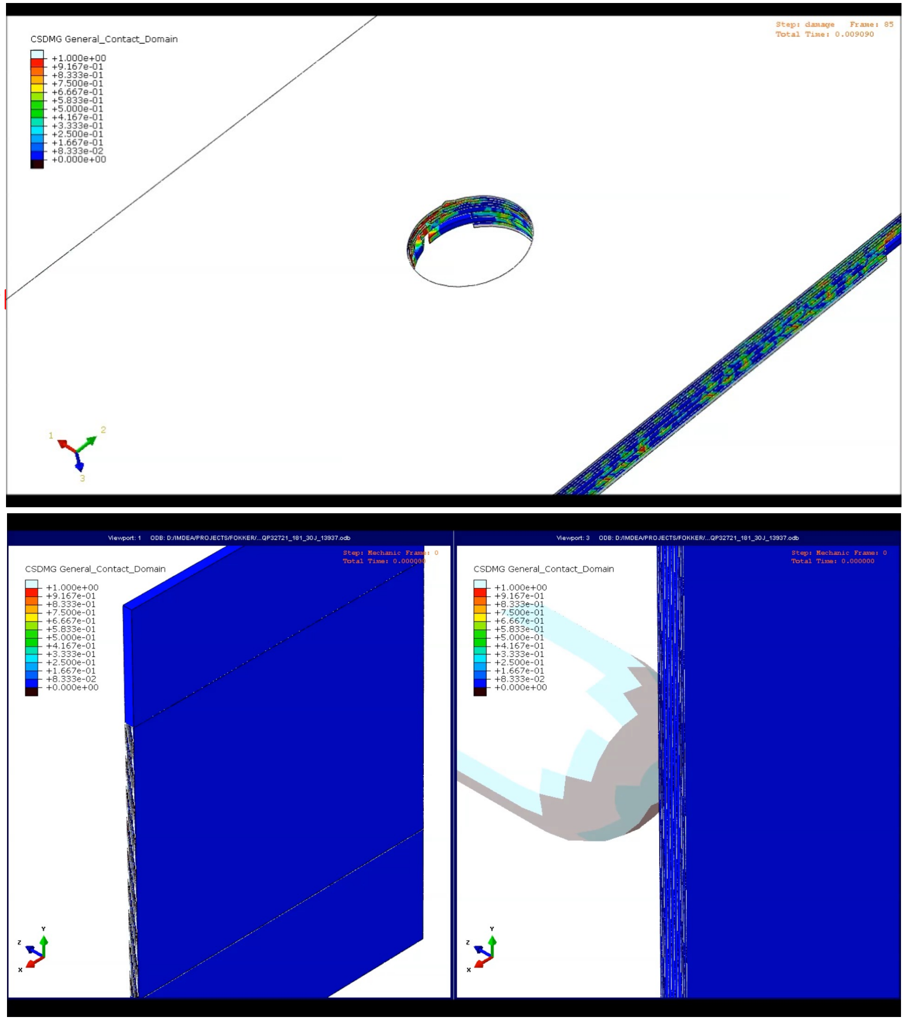
MULTISCALE SIMULATION STRATEGY
COMPUTATIONAL MESOMECHANICS

INTRALAMINAR DAMAGE



INTERLAMINAR DAMAGE



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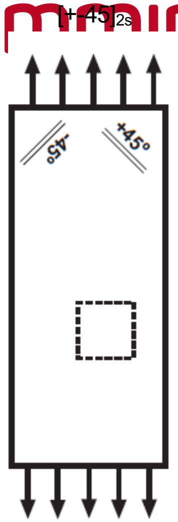
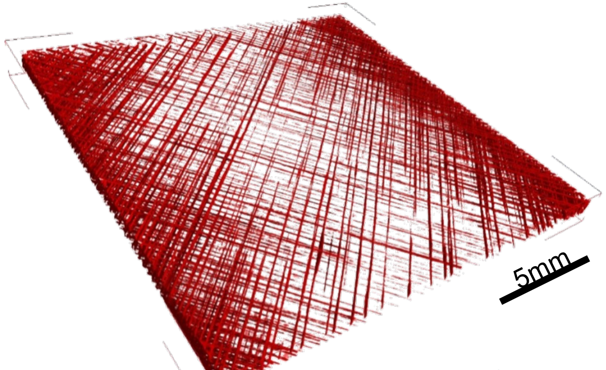
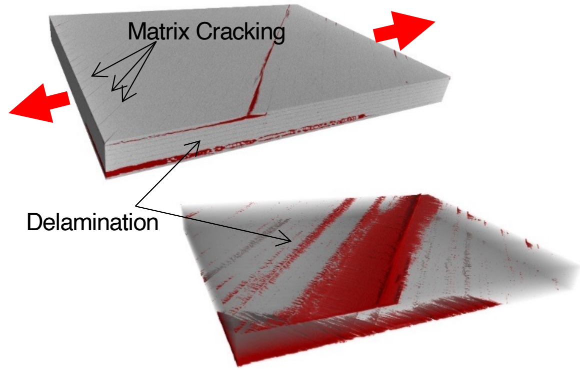
MULTISCALE SIMULATION STRATEGY
COMPUTATIONAL MESOMECHANICS

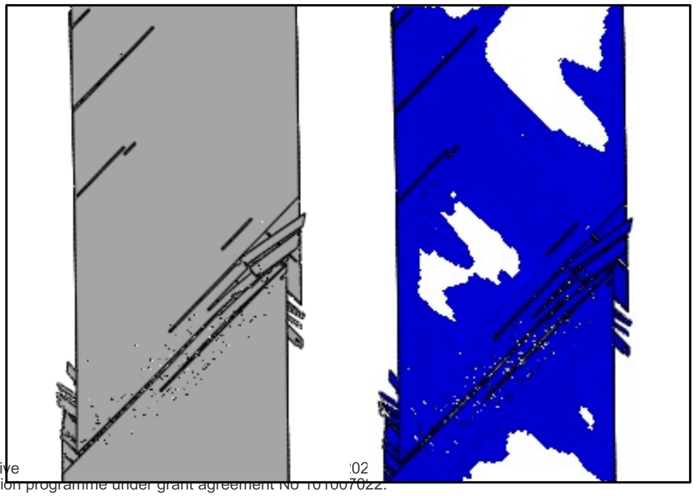


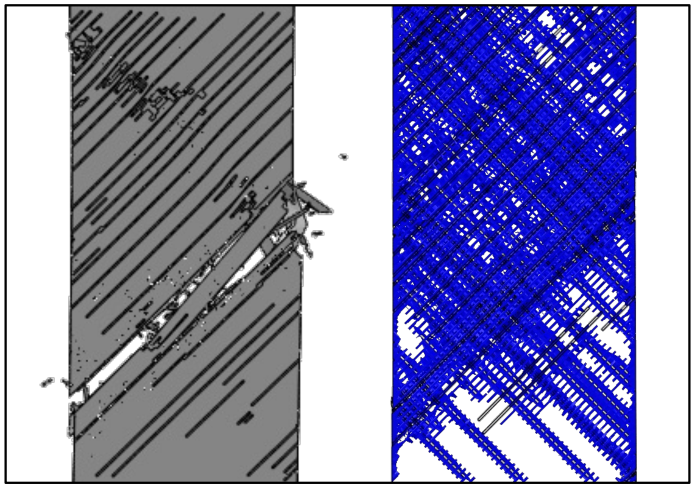


X-Ray Tomography



IN-PLANE SHEAR


NO residual thermal stresses

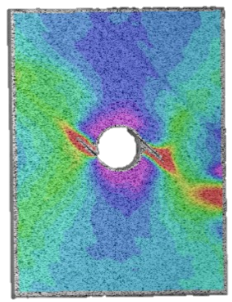

WITH residual thermal stresses

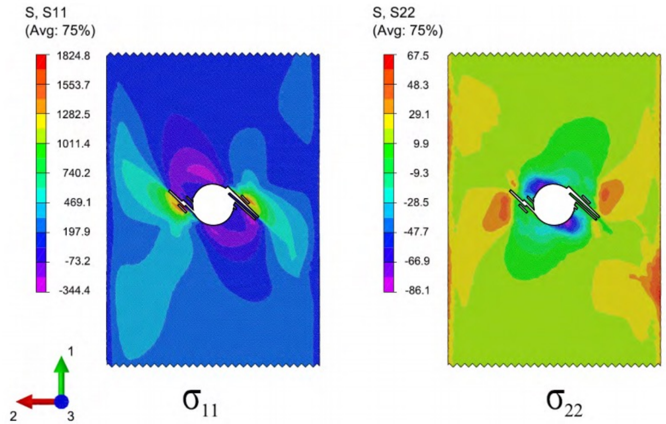
This project has receive ... 202
research and innovation programme under grant agreement No 101007022.

$[45/0/-45/90/(-45_2/45_2)_2]_s$

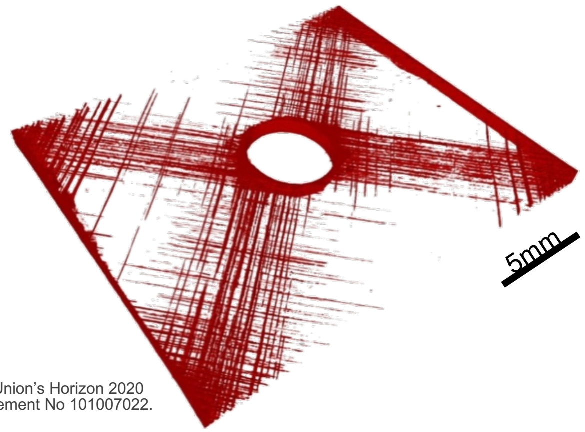
OPEN-HOLE TENSION

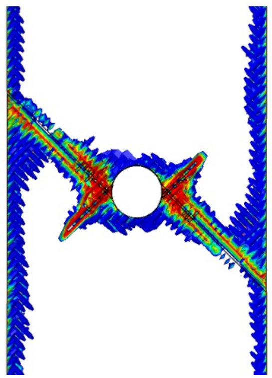
Digital Image Correlation

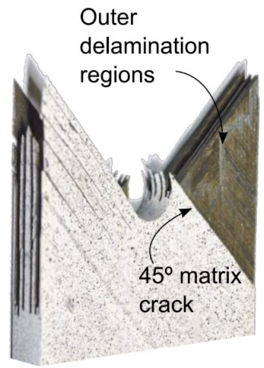




X-Ray Tomography







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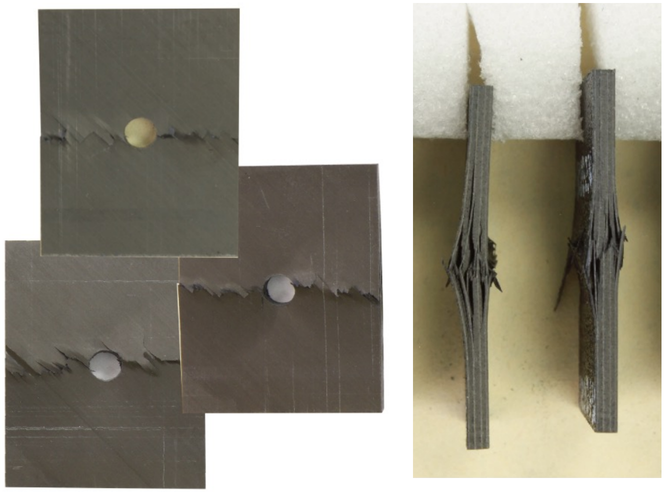
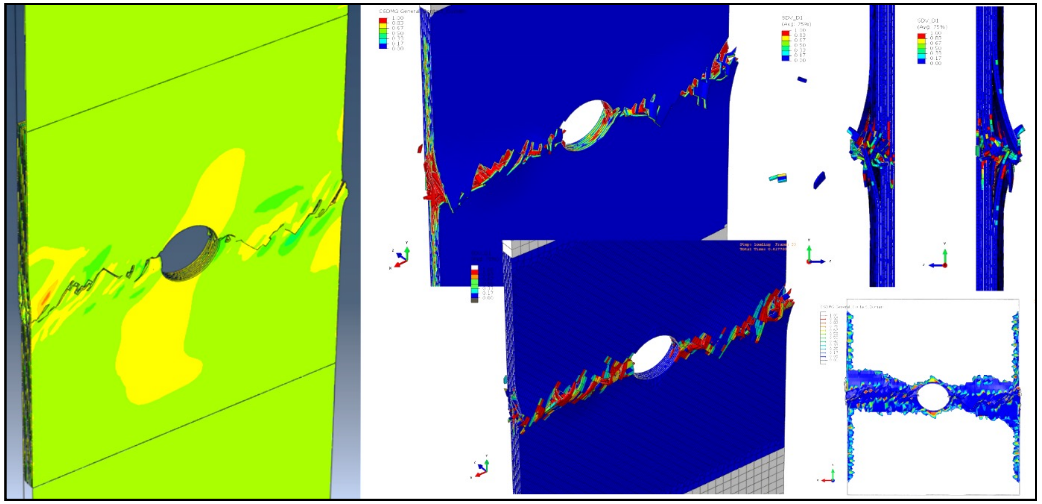
OPEN-HOLE COMPRESSION

[45/0/-45/90]$_{2s}$

Experiments



FEM



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AS4/8552

Laminate	Test strength (MPa)	Predicted strength (MPa)	Error (%)
In-Plane Shear	97.5	94	-3.6
Plain Tension - QI	663	673	1.5
Plain Compression – QI	540	570	5.6
Plain Tension - [50/40/10]	1076	1040	-3.3
Plain Compression - [50/40/10]	831	757	-8.9
Plain Tension – [10/80/10]	436	458	4.9
Plain Compression – [10/80/10]	391	404	3.4
Plain Tension - [30/40/30]	761	770	1.1
Plain Compression – [30/40/30]	540	603	11.5
Open-Hole Tension - QI	371	401	7.9
Open-Hole Compression - QI	304	306	0.6
Open-Hole Tension - [30/40/30]	446	402	-9.8
Open-Hole Compression - [30/40/30]	311	299	-3.9

Stiff

Medium - shear dominated

Soft

Soft

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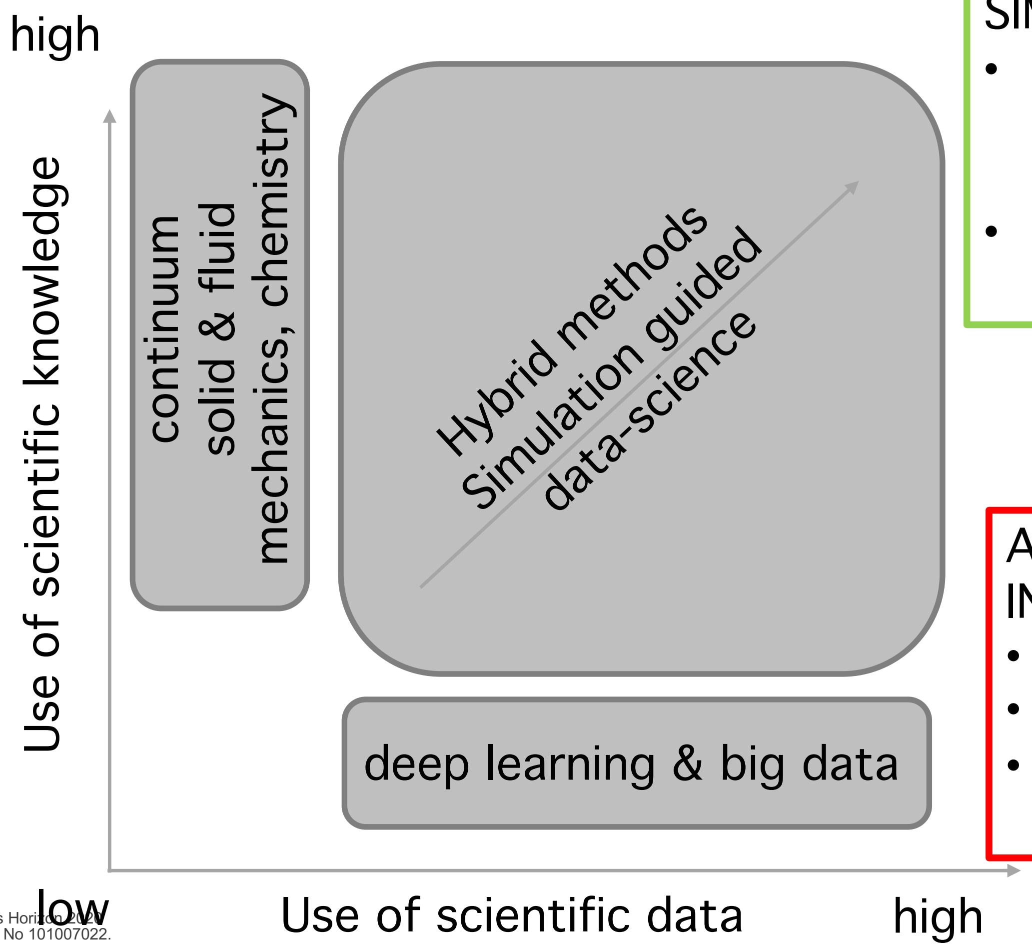
VIRTUAL TESTING
- Physically-based ✓
- Time consuming ✗
- On-the-fly ✗



SIMULATION GUIDED AI
- Trustworthy AI (physically-constrained)
- Reduce of tests for data-sets

ARTIFICIAL INTELLIGENCE
- Hidden patterns ✓
- Black-box ✗
- Experimental trials are expensive ✗

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advantages

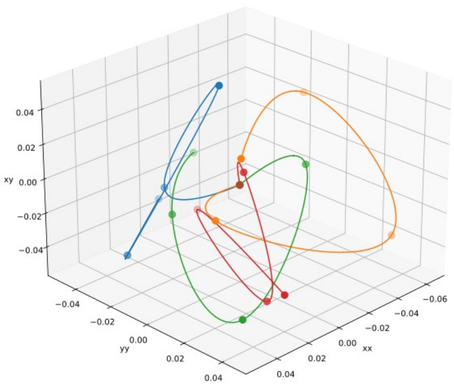
- Close to the actual failure mechanisms
- Influence of microstructure and constituents properties
- Influence of the lay-up, stacking sequence, etc.

disadvantages

- Time consuming
- Requires expertise on modelling

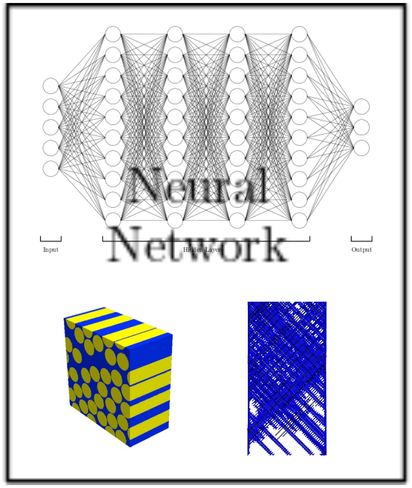
Digital twin

Strain history



$$\begin{bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \varepsilon_{23}\\ \varepsilon_{13}\\ \varepsilon_{12}\end{bmatrix}$$

→



→

Stress results

$$\begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{bmatrix}$$

Forward Mechanical Problem

Micro & Mesomechanics

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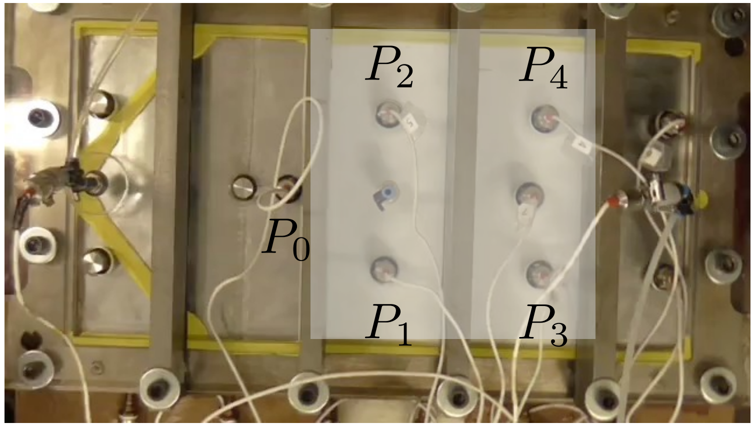
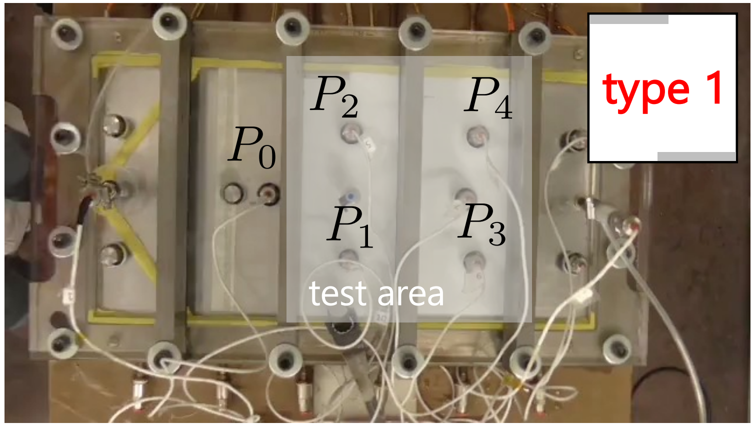
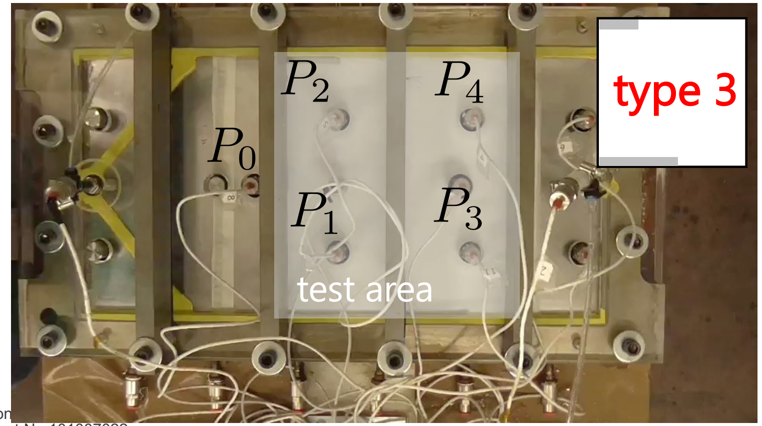
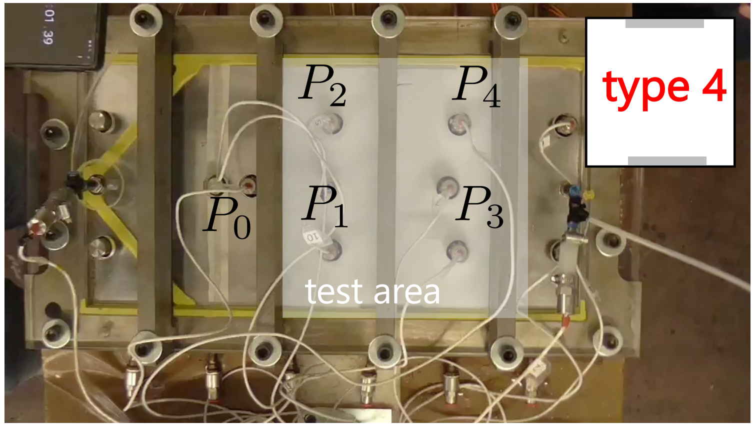
Some similar work … for manufacturing

no race-tracking









This project has received funding from the European Union
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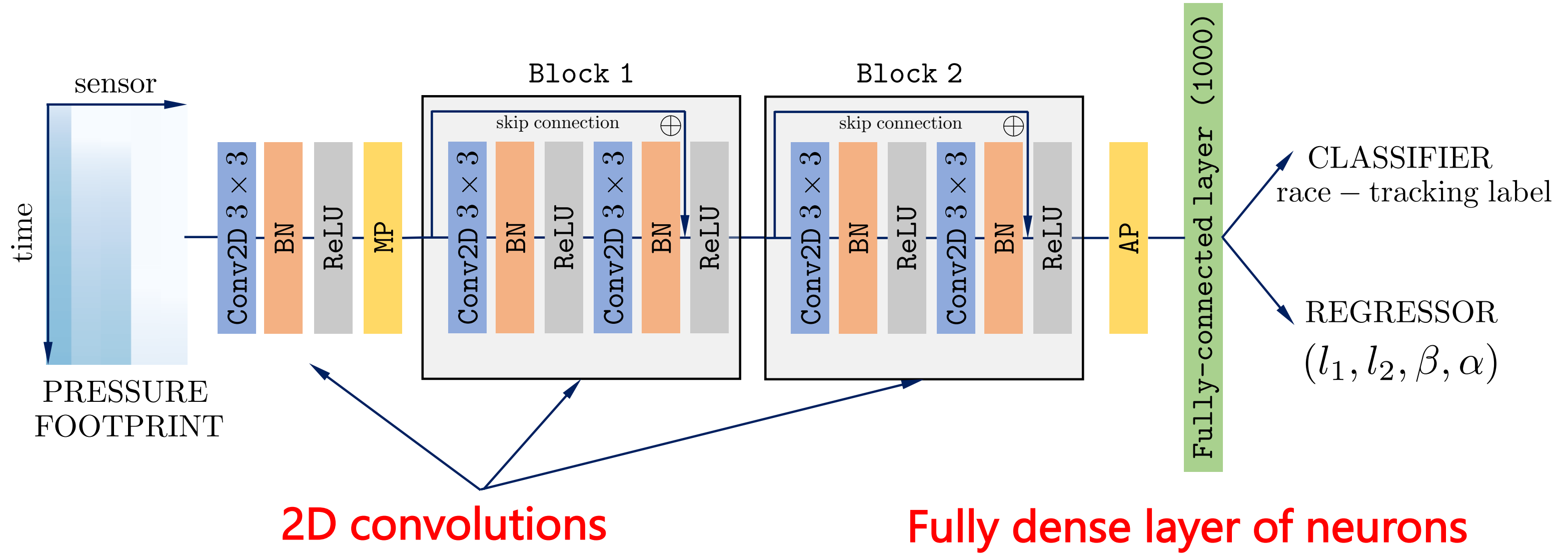
TRAINING THE NETWORK

PyTorch

- 2000 OpenFoam simulations as data-sets
- Deep Residual Learning for Image Recognition ResNet*
- Classification optimization based on CE loss (cross-entropy)
- Regression optimization based on MSE loss (mean square error)



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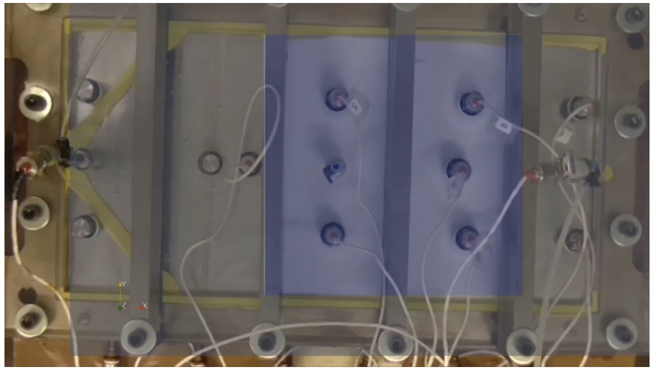
*Deep Residual Learning for Image Recognition , He, Zhang, Ren and IEEE Conference on Computer Vision and Pattern Recognition, 2016

Some similar work … for manufacturing

no RT



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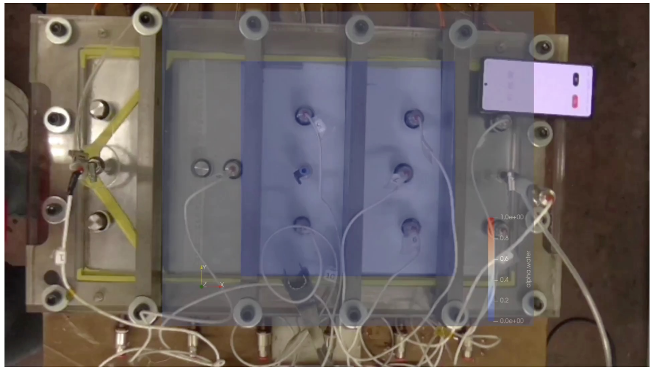

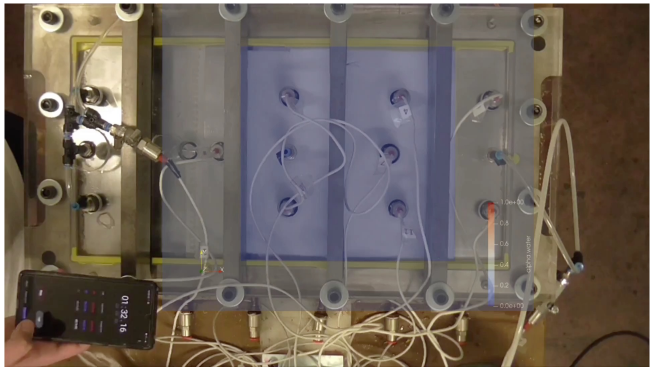

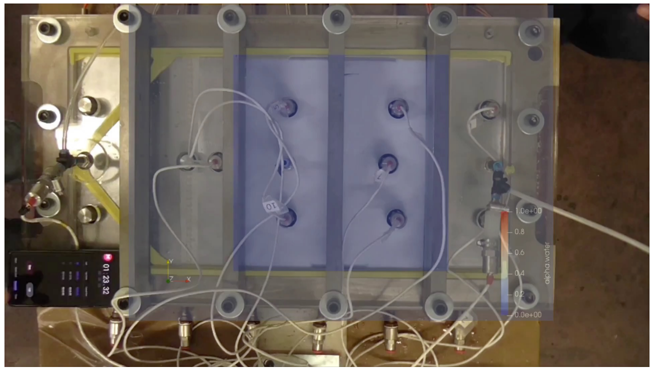

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SIM-EXP OVERLAID VIDEOS

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Thank you for your attention

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