Damage identification in 4D images of a nano-engineered composite via a deep-learning tool

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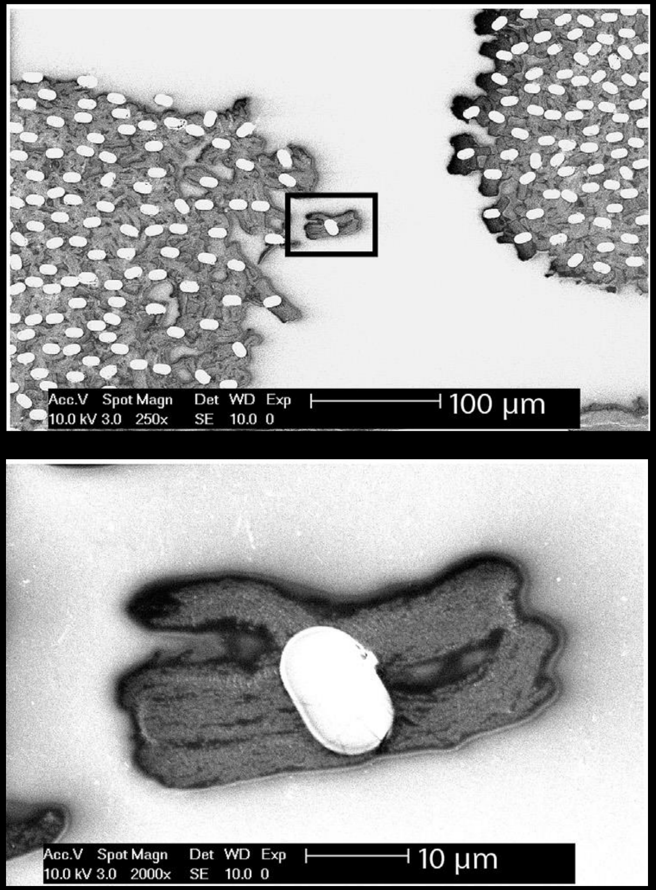
Carbon nanotubes (CNTs) on fibers

- Growing or grafting CNTs on fibers increases their surface area
- At the microscale
  - Enhancing stress transfer between fiber and matrix
  - Reinforcing resin-rich areas
  - Mitigating stress concentration at fiber-matrix interface
- At the macroscale
  - Increasing interfacial shear strength and toughness
  - Improving interlaminar shear strength and toughness
  - Affecting the overall damage in the composite

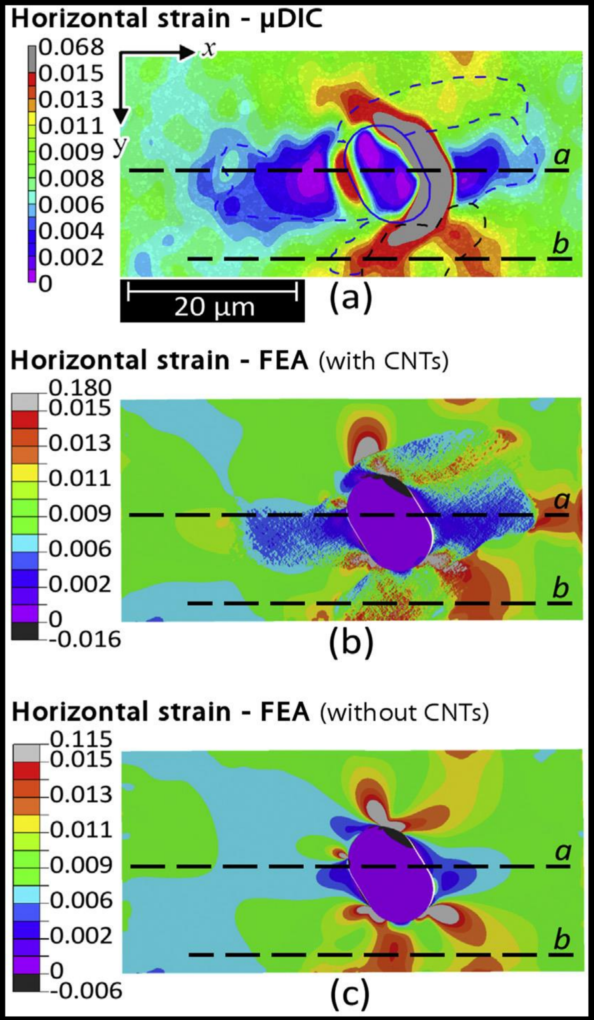


Mehdikhani et al. CSTE, 137 (2016)

Effect of CNTs revealed by in-situ analysis

- 2D strain mapping, via microscale Digital Image Correlation (DIC) of nano-engineered composites: CNT forests aligned with the loading direction can constrain the deformation

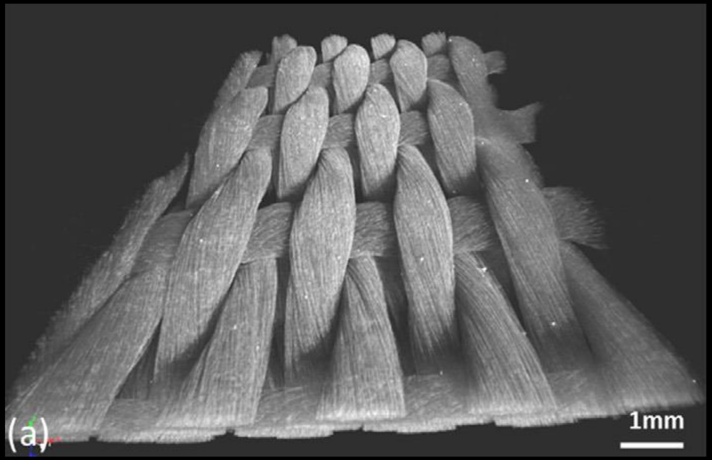
- 3D analysis of deformation and damage development of these nano-engineered composite is needed:
  - Micro-computed tomography (micro-CT) → Image acquisition
  - Digital Volume Correlation or deep learning → damage characterization



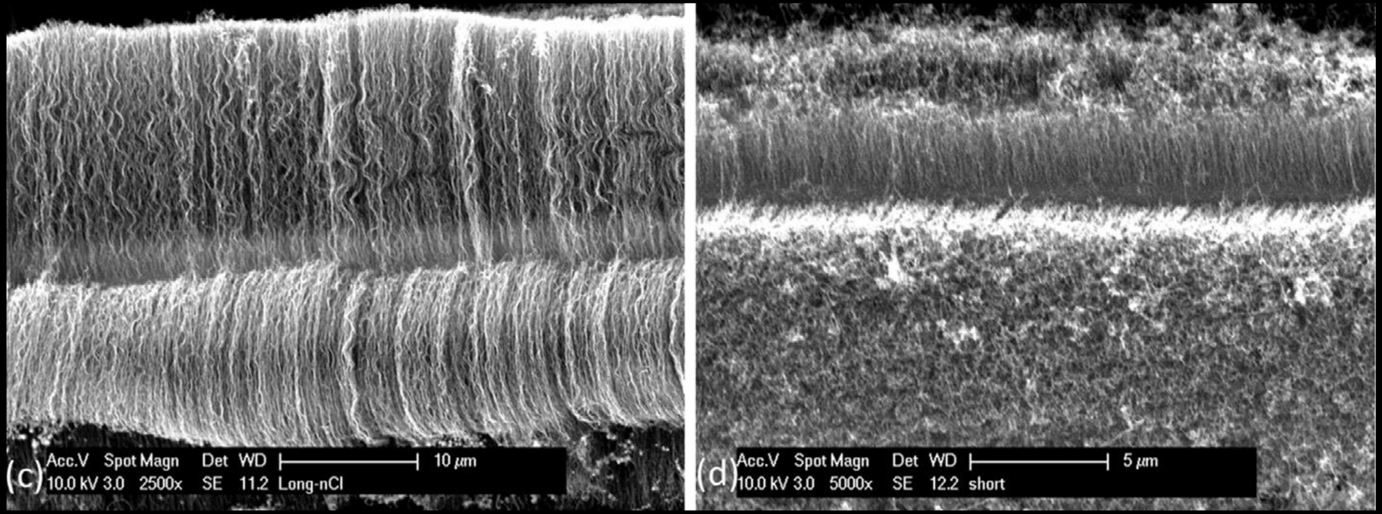
Mehdikhani et al. CSTE, 137 (2016)

Our nano-engineered composite

- Plain weave textile of alumina fibers
- Grafting CNT with catalyst precursor and ethylene exposure
- Five ply laminates made with VARI
- Mini-specimens with dimensions of $40 \times 7 \times 2\ mm^3$ and fibers in ±45° to the loading orientation
- Two different CNT configuration + Baseline (no CNT)



Aravand et al. Composites: Part A 88 (2016)

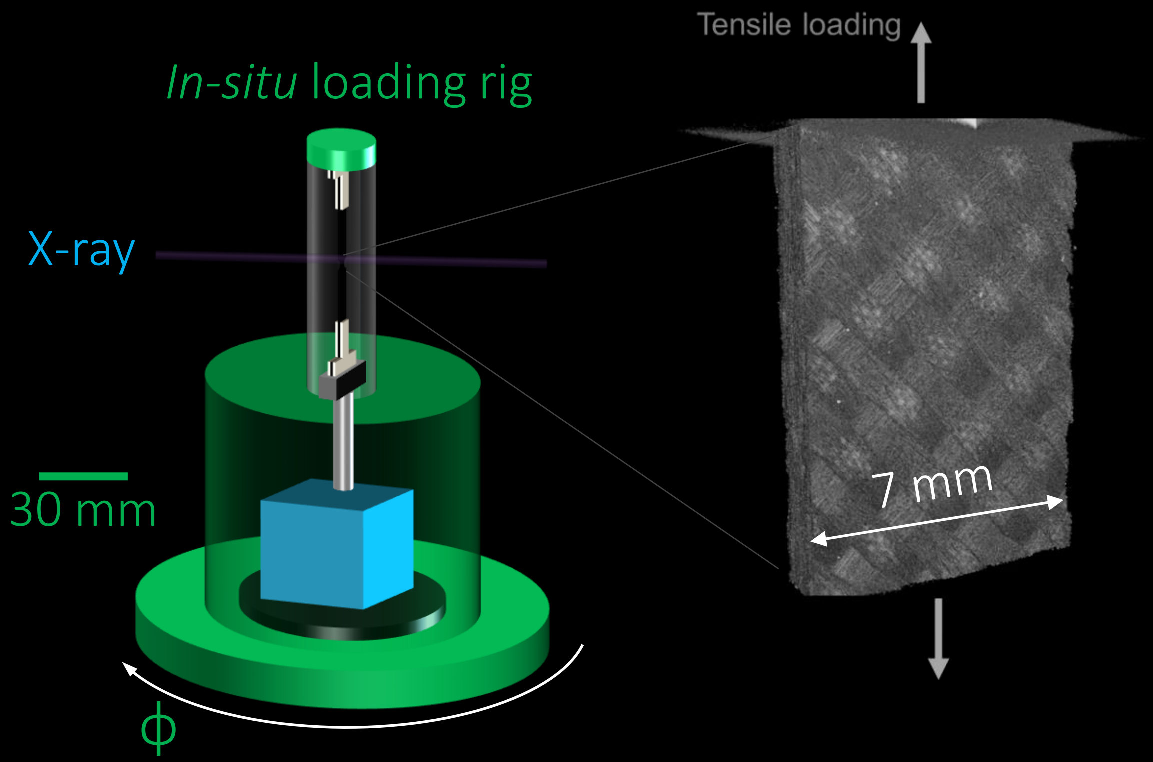


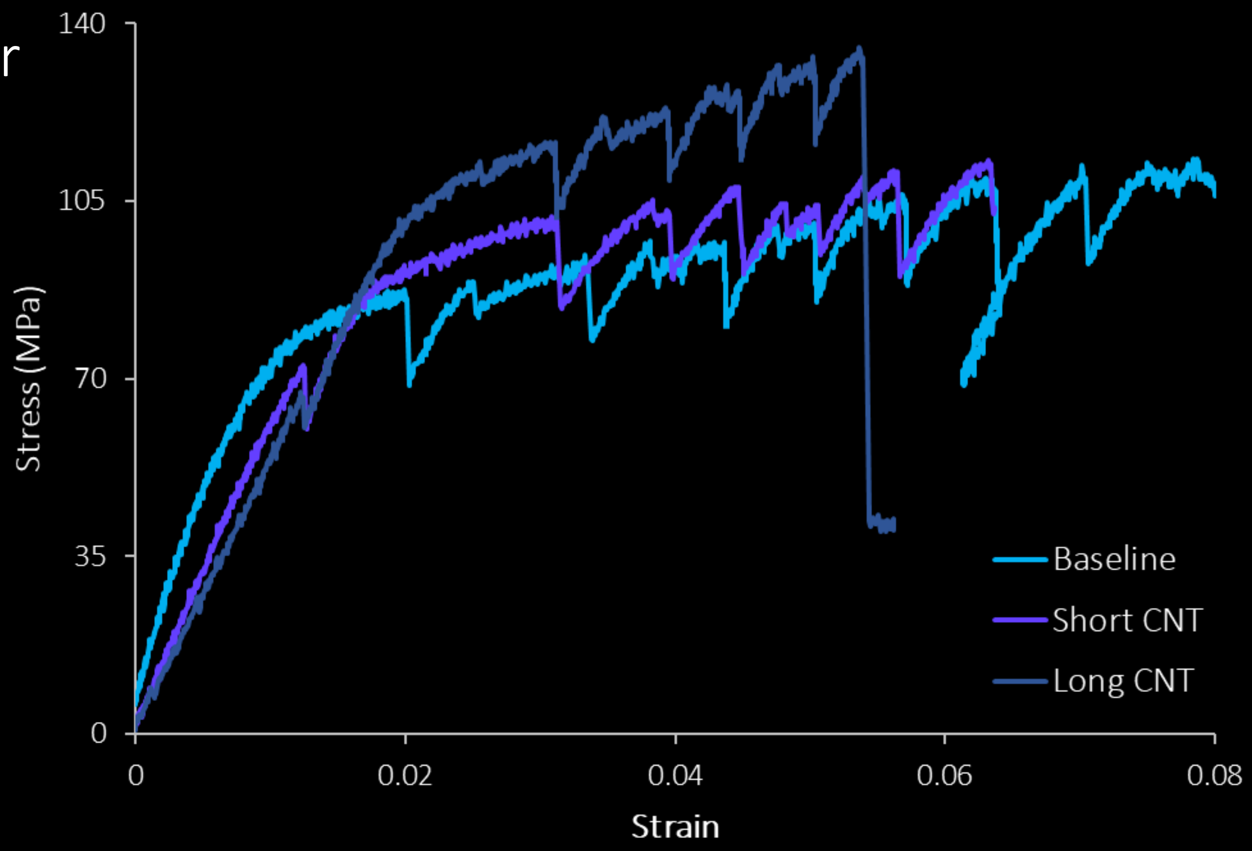
Long CNT ~ 18 μm

Short CNT ~ 5 μm

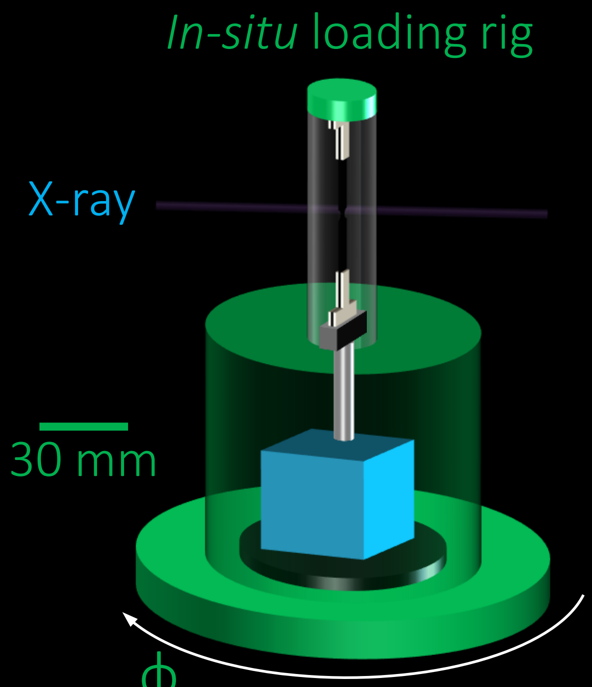
Loading and in-situ imaging

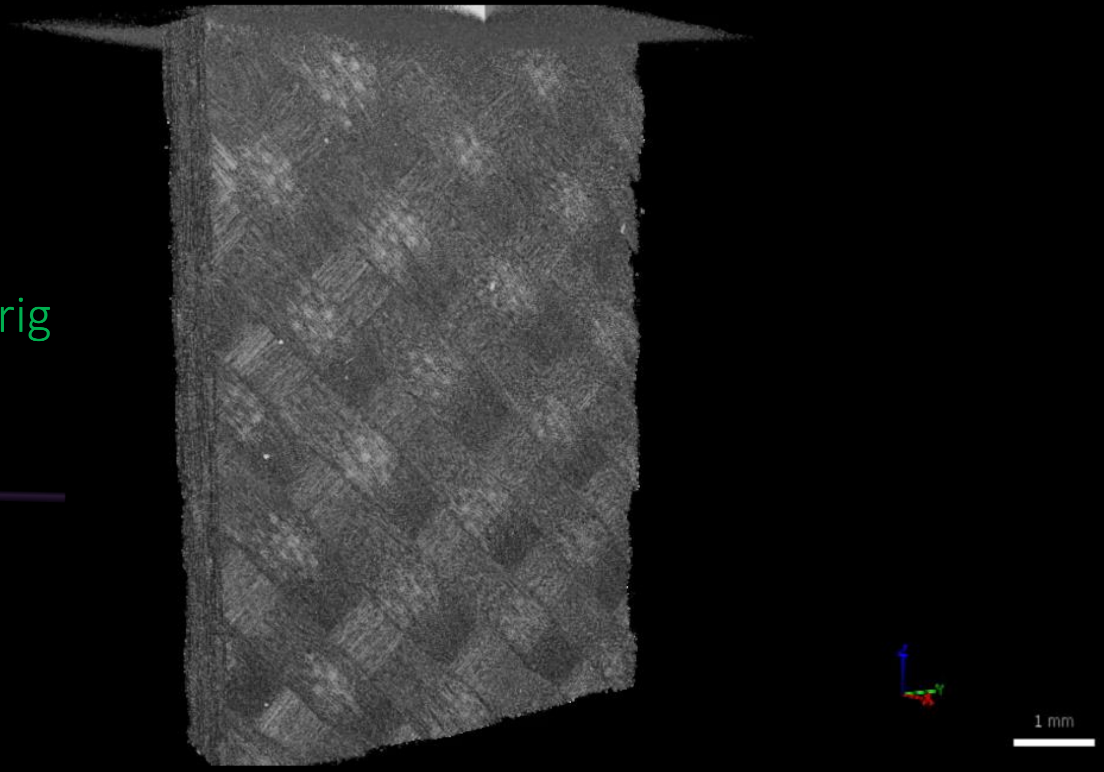
- Hold-at-displacement tensile tests
- Deben CT5000 tensile rig
- In-situ scans in TESCAN UniTOM XL scanner
- Voxel size of 6 µm

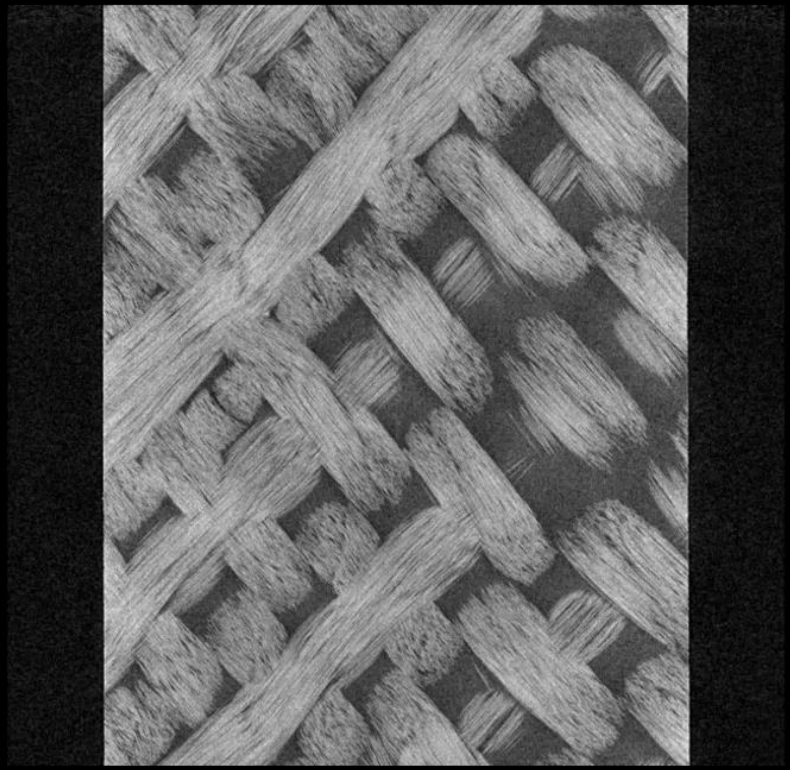




Loading and in-situ imaging

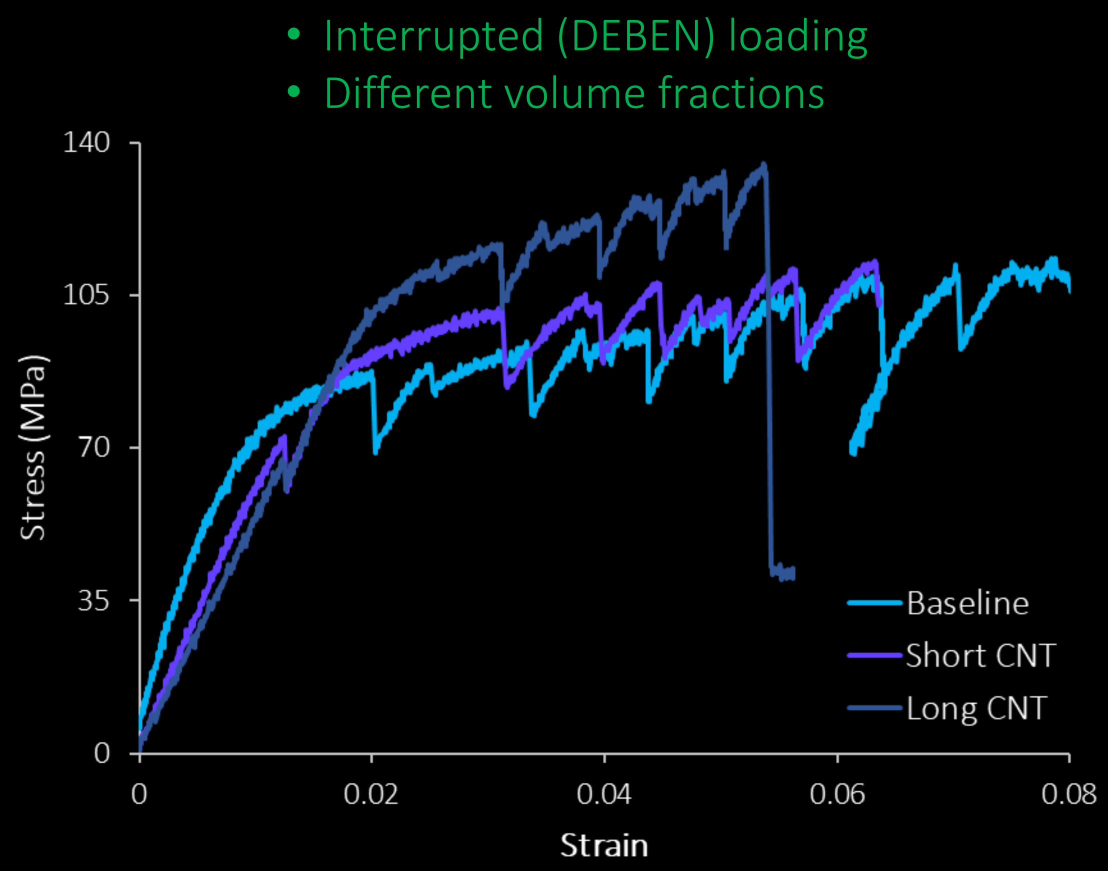


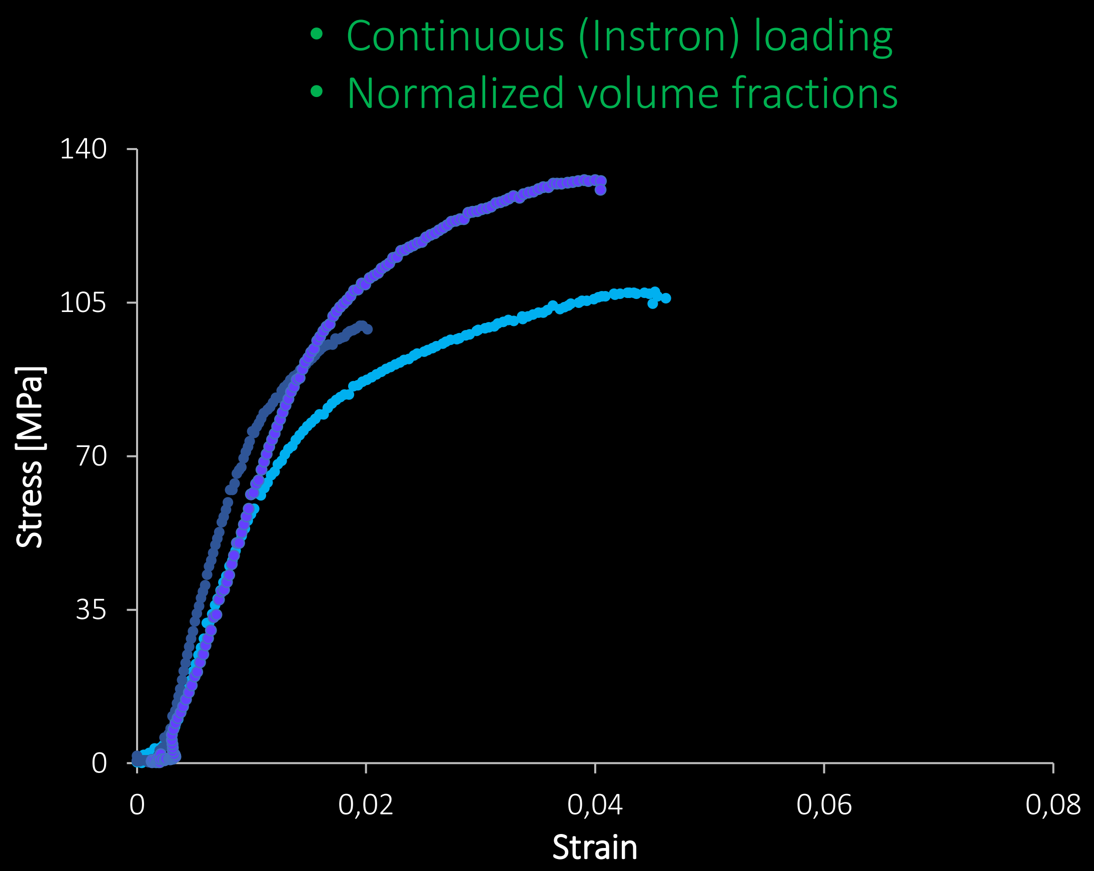




Behavior comparison

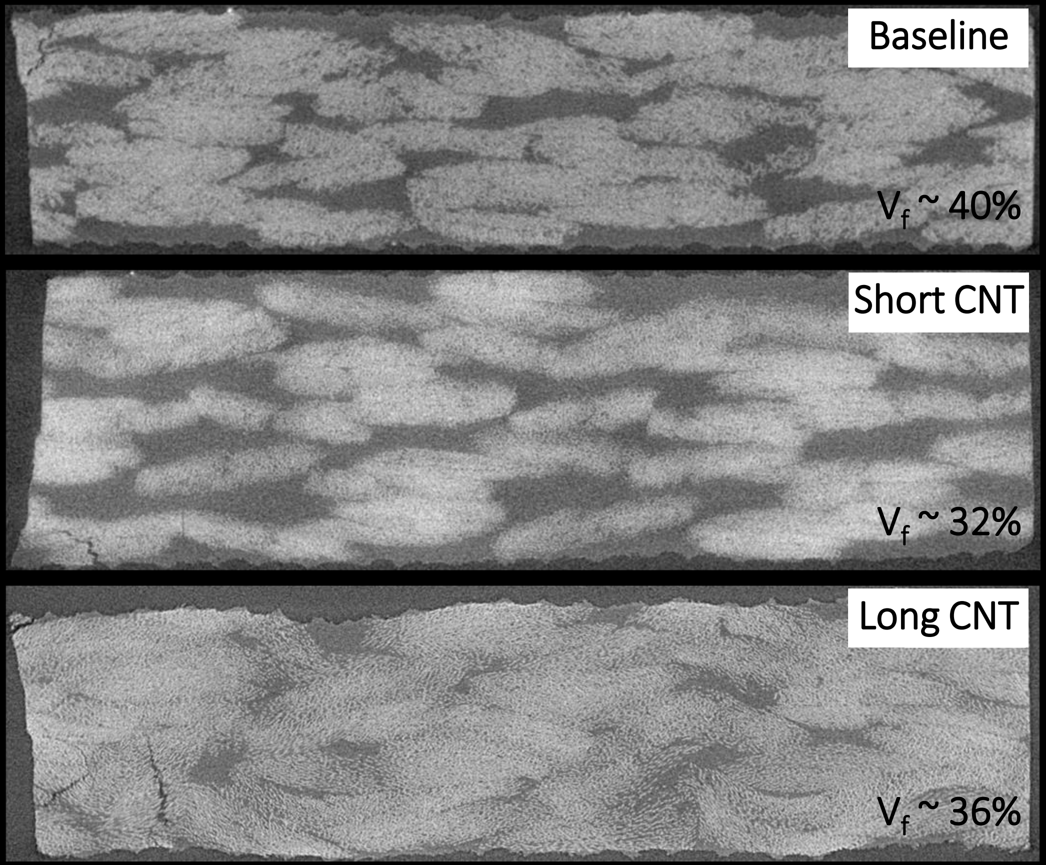
- CNTs caused an increase in the modulus and strength
- But reduced the failure strain!





Deep-learning based characterization of cracks

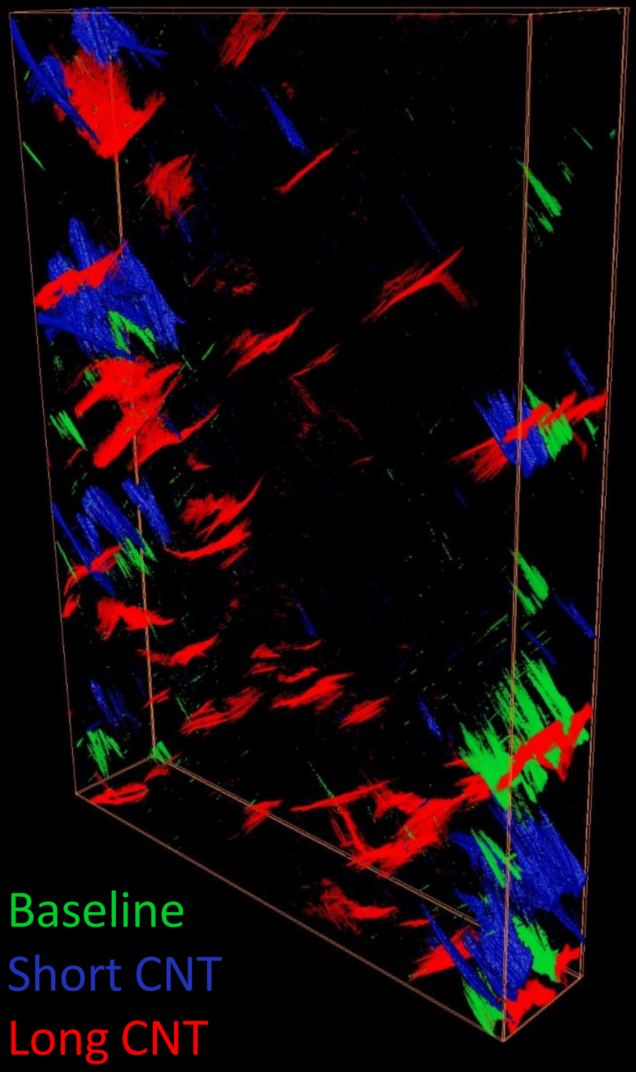
- Cracks are very small and similar in contrast to the composite → hard to detect with conventional image processing

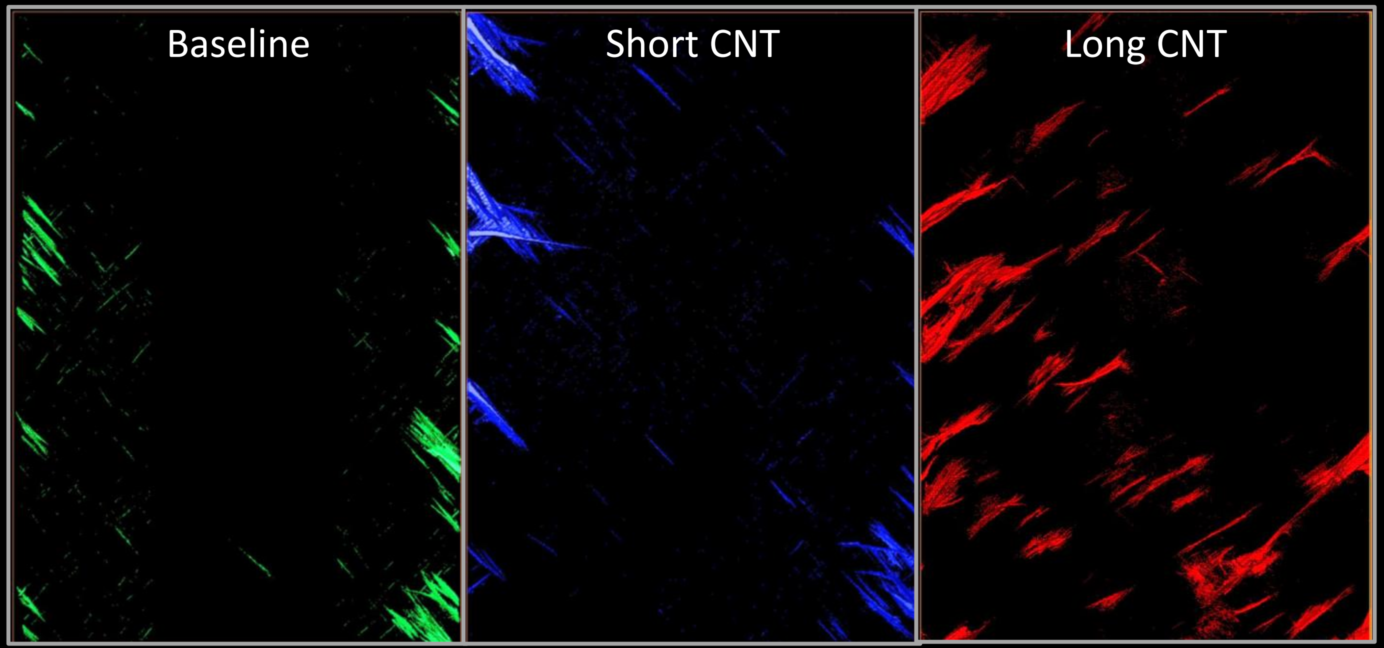


- A deep-learning-based tool: *RootPainter*
- Needs manual training for crack detection
- For each material, training on slices from all loading steps combined

Smith et al., New Phytologist (2022)

Overall crack volume fraction



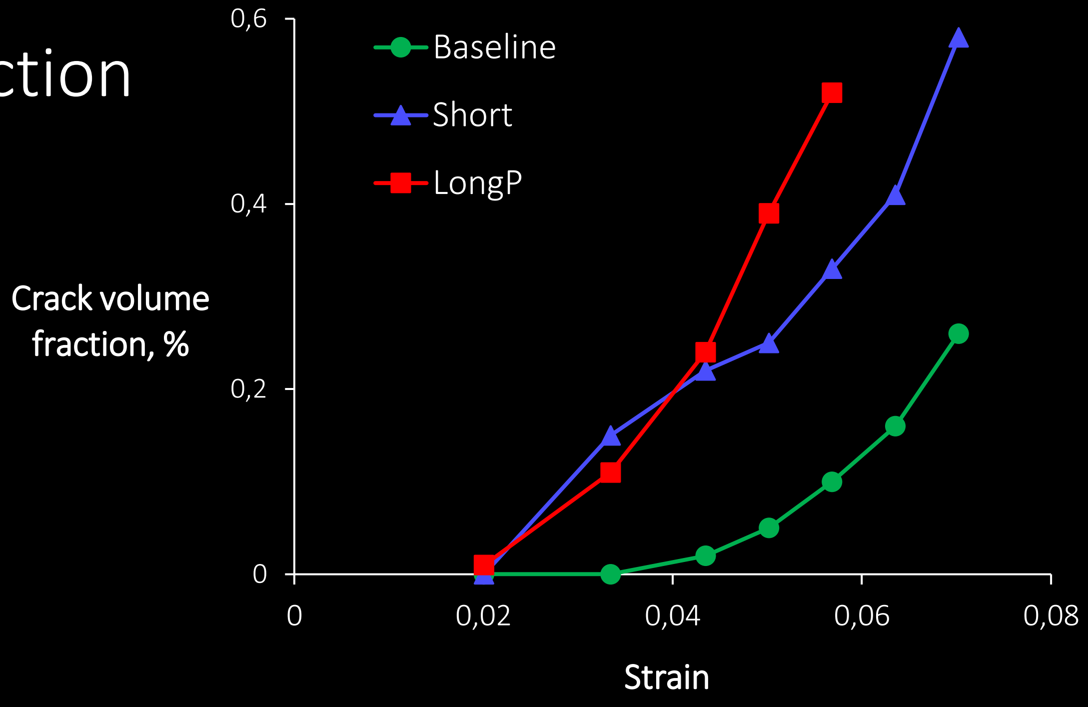


at ~ 0.06 applied strain

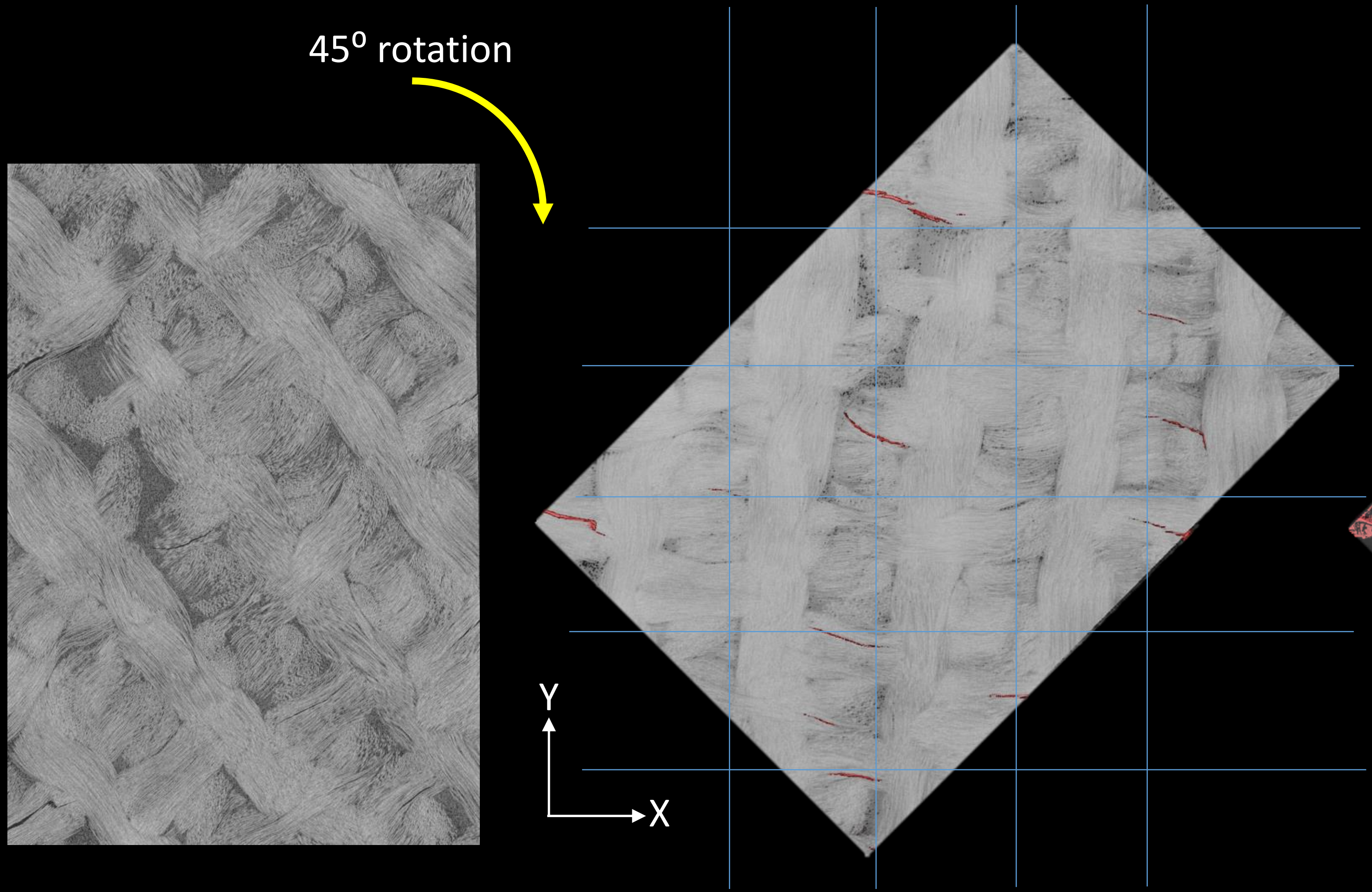
Overall crack volume fraction

Materials with CNTs

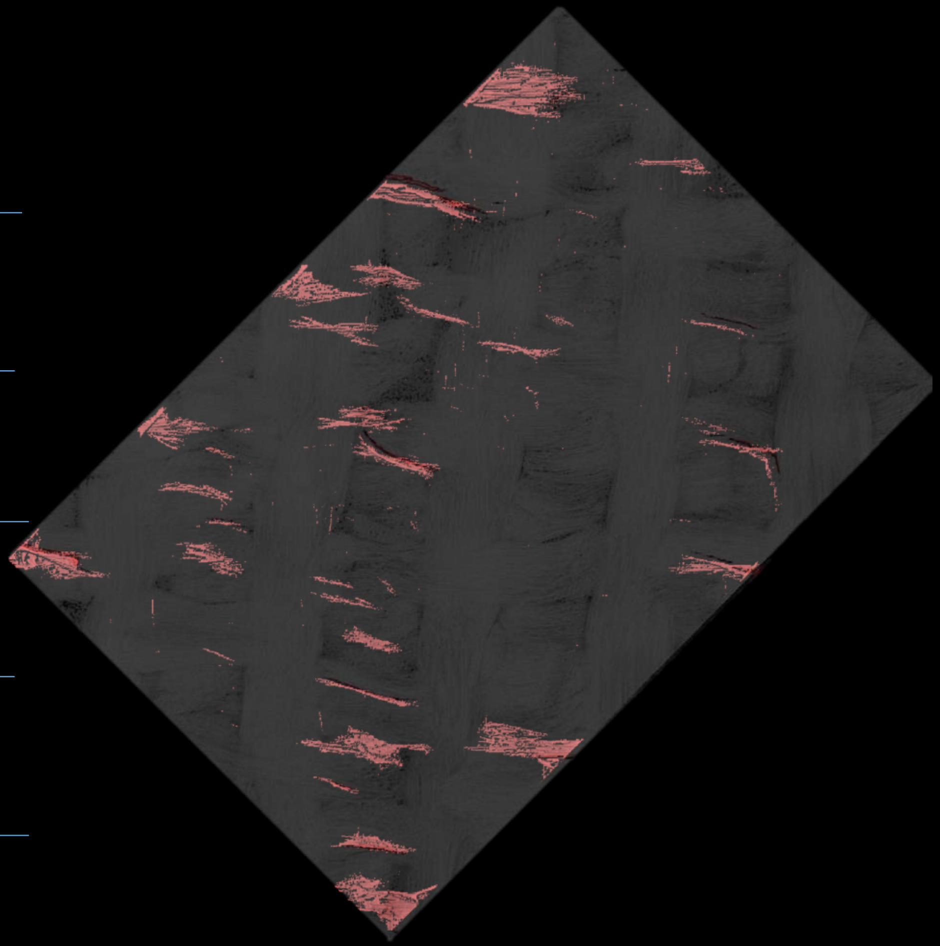
- More diffused damage
- Significantly earlier crack initiation
- Higher increase rate of crack volume fraction
- Much higher crack volume fraction



Local crack volume fraction (in Long CNT)



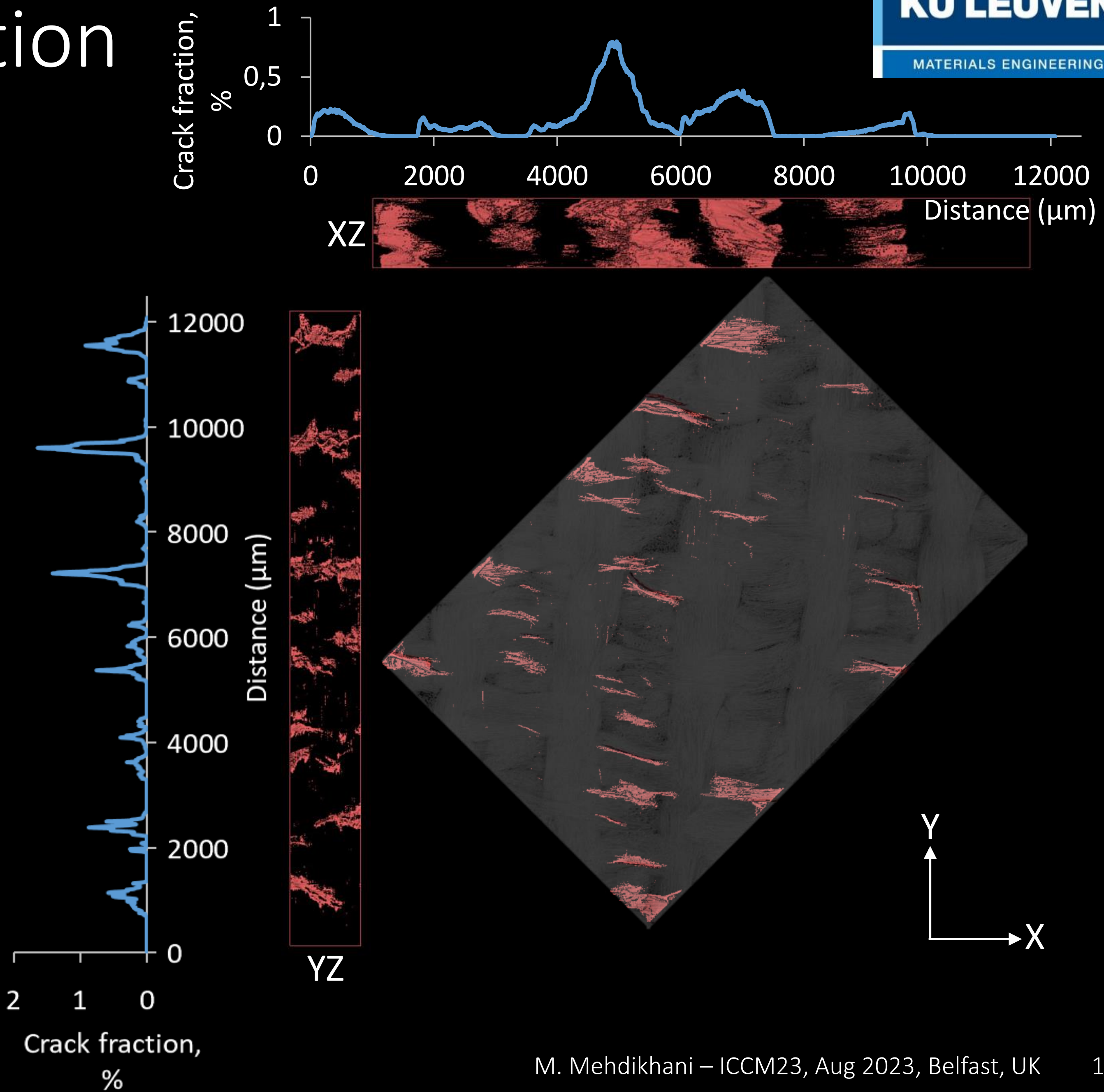
To align the fiber bundles with the image coordinate system X-Y



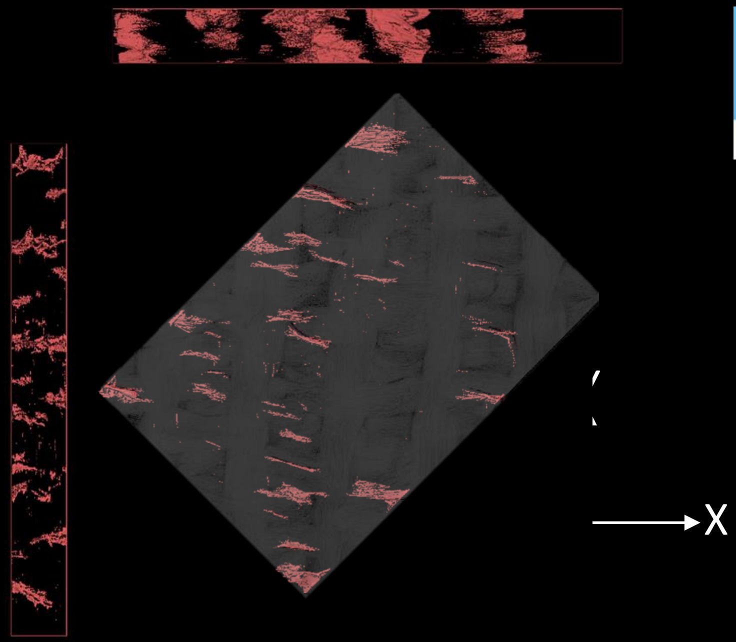
Rotated segmented slices

Local crack volume fraction

For the *Long CNT* material,
cracks tend to appear inside the bulk,
corresponding to the fiber bundles.



Crack diffusion



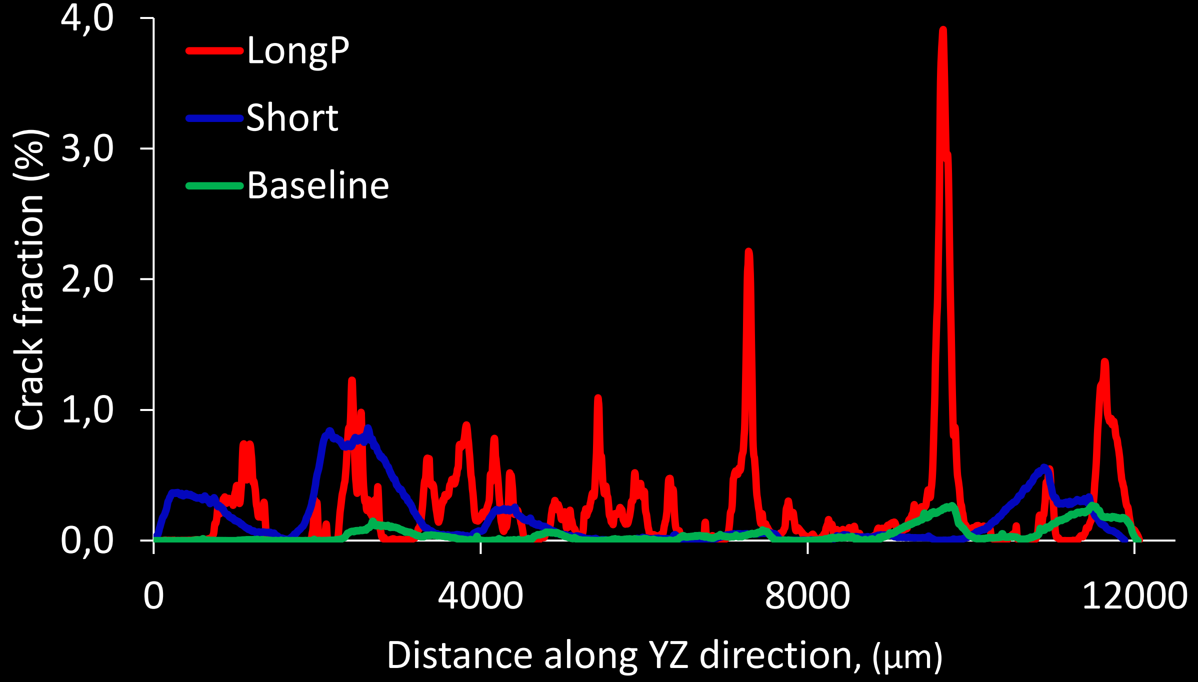
Long CNT

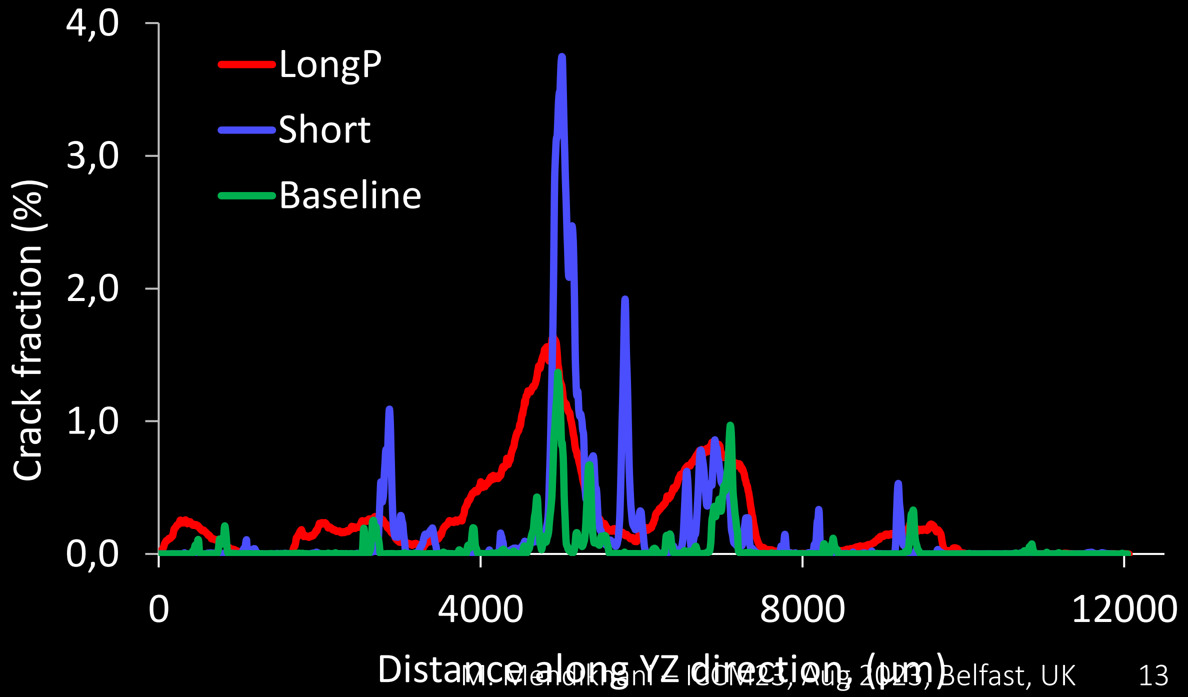
diffused cracks over the fiber bundles

well-distributed (broader peaks in graph)

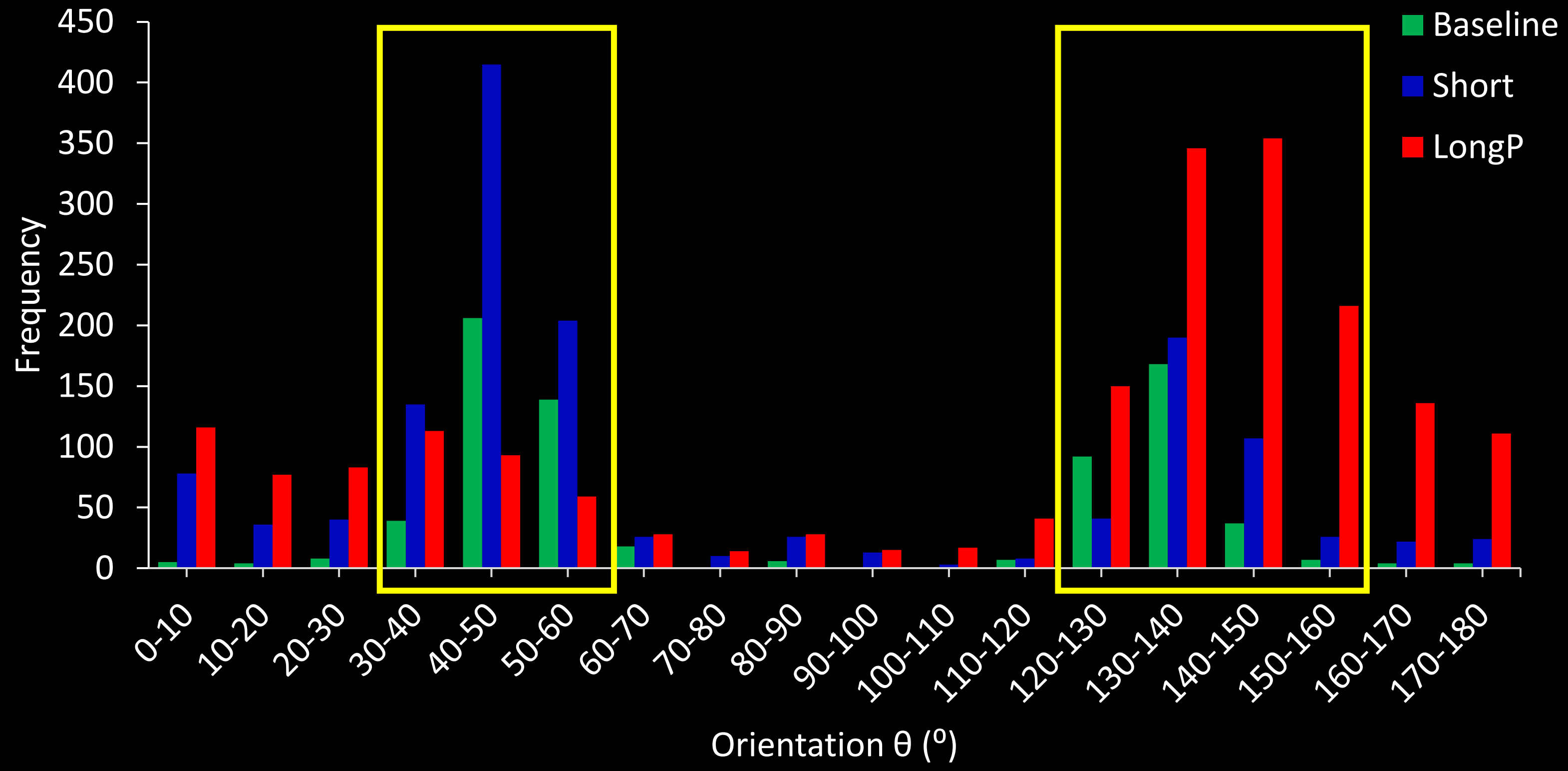
Short CNT and Baseline

high crack fraction closer to specimen edges



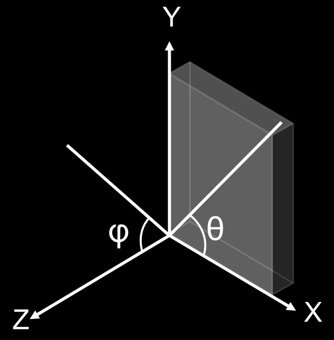


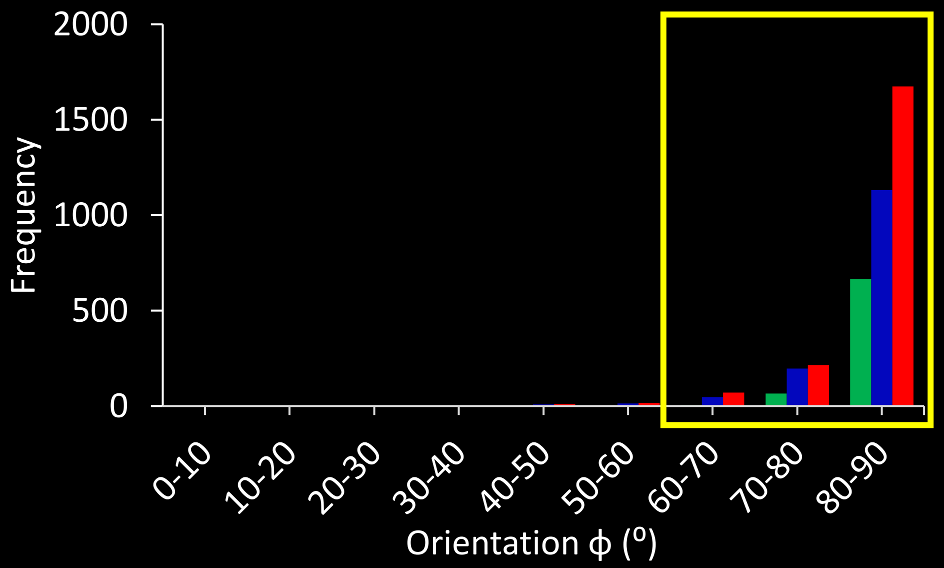
Crack orientation



Preferential crack orientation for all materials

- Cracks aligned with fiber bundles





Conclusion

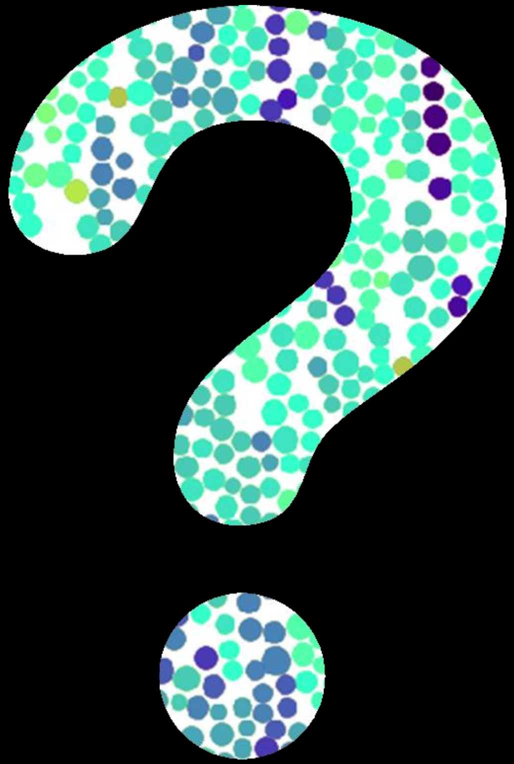
- The deep-learning-based tool, RootPainter, proves promising for the identification of cracks in micro-CT images.

- CNTs cause earlier formation of matrix cracks and higher crack volume, despite increasing the modulus and strength of the composite.

- Crack development during loading depends on the configuration of CNTs:
  - For Long CNT composites with high compaction, cracks tend to appear more diffusedly inside the bulk, corresponding to fiber bundles.
  - For Short CNT and Baseline, cracks are less diffused, appearing mostly at the specimen edges.

Thanks for your attention!

Funding and support



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