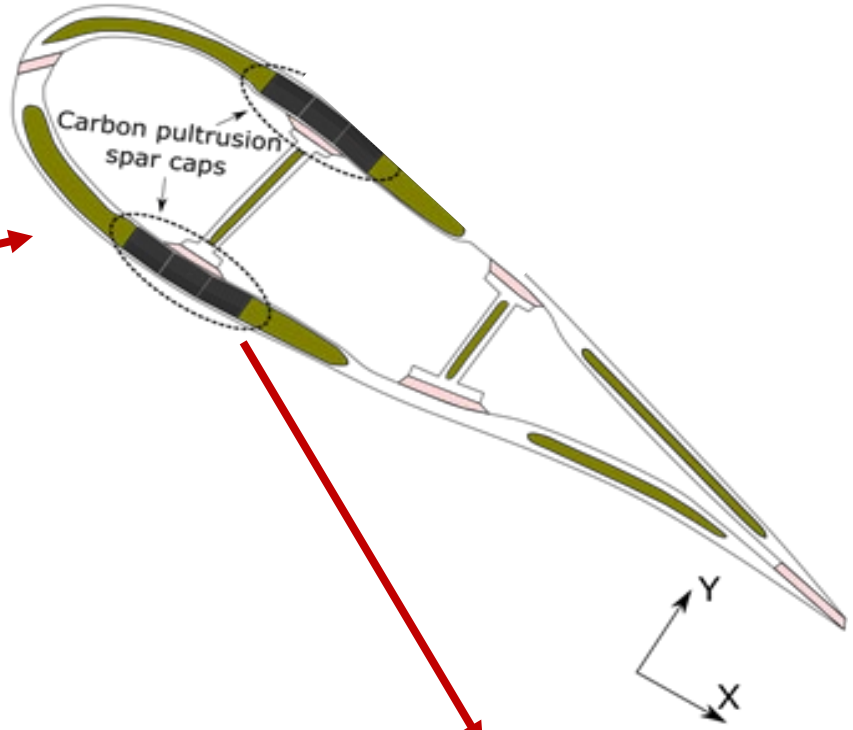
ACCURATE COMPRESSION STRENGTH PREDICTIONS OF COMPOSITES FOR WIND TURBINE BLADES

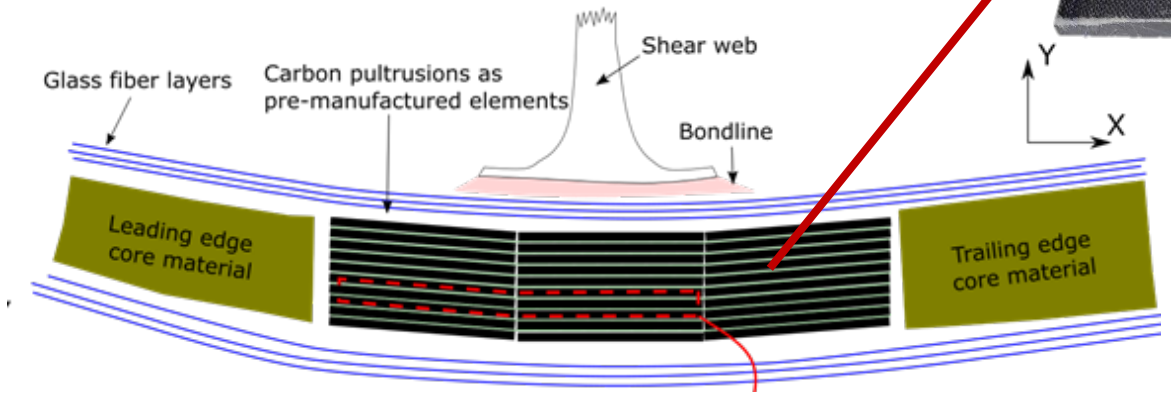
Lars P. Mikkelsen
Composites Manufacturing and Testing
DTU Wind and Energy Systems

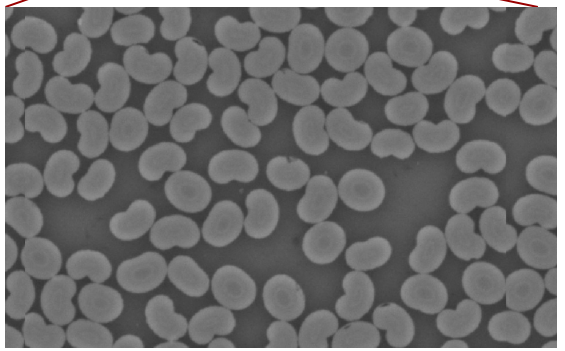
Acknowledgment:

- Ole V. Ferguson, DTU Wind Energy / LM Wind Power
- Niels Jeppesen, DTU Compute / Force Technology
- Reliance MSCA Doctoral network 2023-2027

Pultruded profiles inside the +80 m wind turbine blades







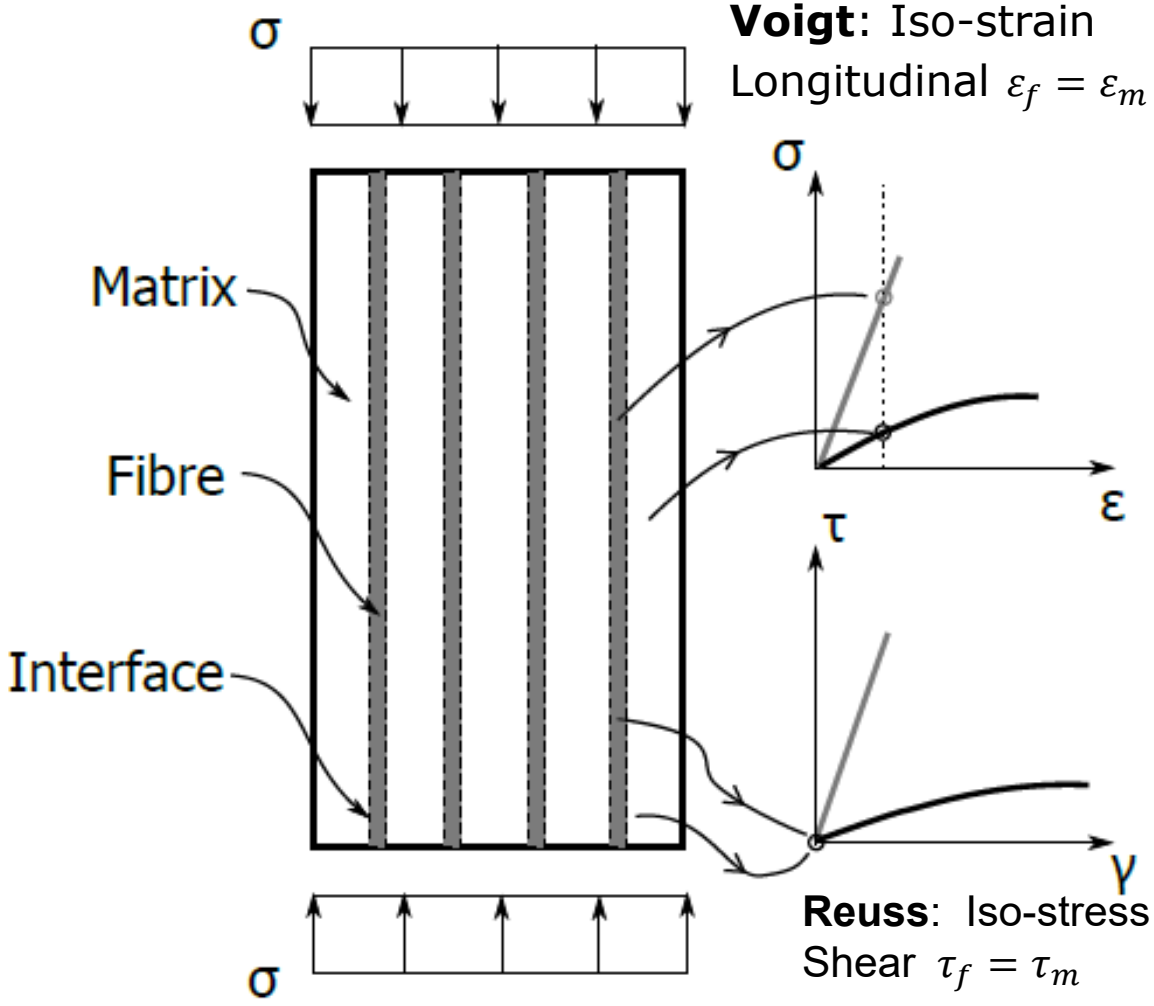
Pultruded carbon fiber profiles

Pictures from Fiberline.com

Casted into blade moulds like this Vestas blade mould

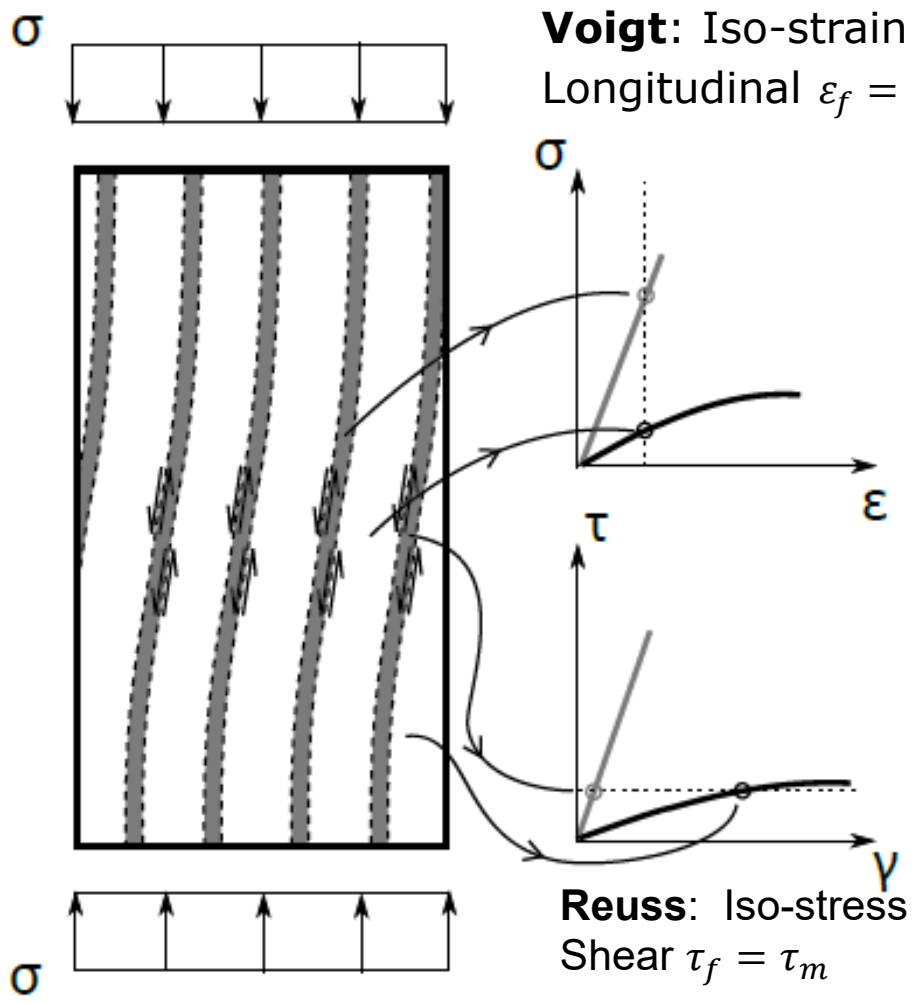
Picture from Vestas for its V236-15.0 MW™ turbine, Blade length 115.5 m

Stress state in compression



Voigt: Iso-strain
Longitudinal $\varepsilon_f = \varepsilon_m$

Reuss: Iso-stress
Shear $\tau_f = \tau_m$

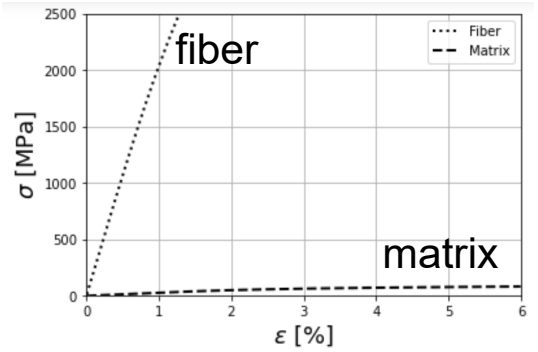


Voigt: Iso-strain
Longitudinal $\varepsilon_f = \varepsilon_m$

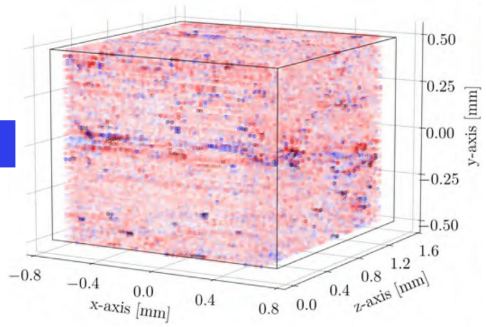
Reuss: Iso-stress
Shear $\tau_f = \tau_m$

Workflow to be presented

Fiber and matrix properties



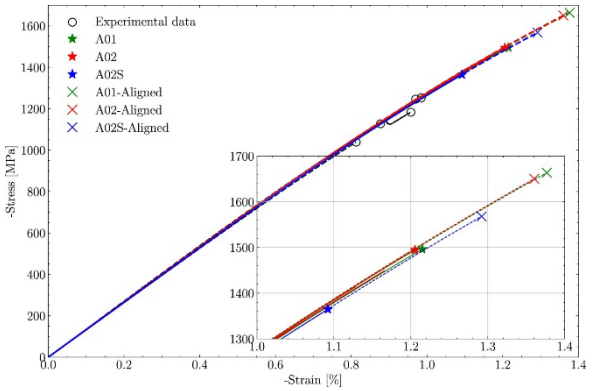
Orientation distribution



Non-linear composite FEM

$$\dot{\sigma}_{ij} = C_{ijkl}(V_f C^{m1}_{ijkl}, C^{m2}_{ijkl}, C^{f}_{ijkl})\dot{\varepsilon}_{kl}$$

Accurate compression prediction



Predict compression strength based on

- **Uniaxial stress-strain curve** of the fiber and matrix material
  - Ramberg-Osgood fitting
- **Material orientation** distribution determined from 3D x-ray scan
  - Python script for Structure tensor analysis
  - User-subroutine mapping using orient.f in Abaqus
- **Geometrical and material non-linear (incremental) finite element model**
  - Umat.f user-subroutine in Abaqus
- **Predict the load-deflection curve** of specific scanned samples
  - No failure criteria but based on load maximum due to material point rotations

Predict compression strength based on

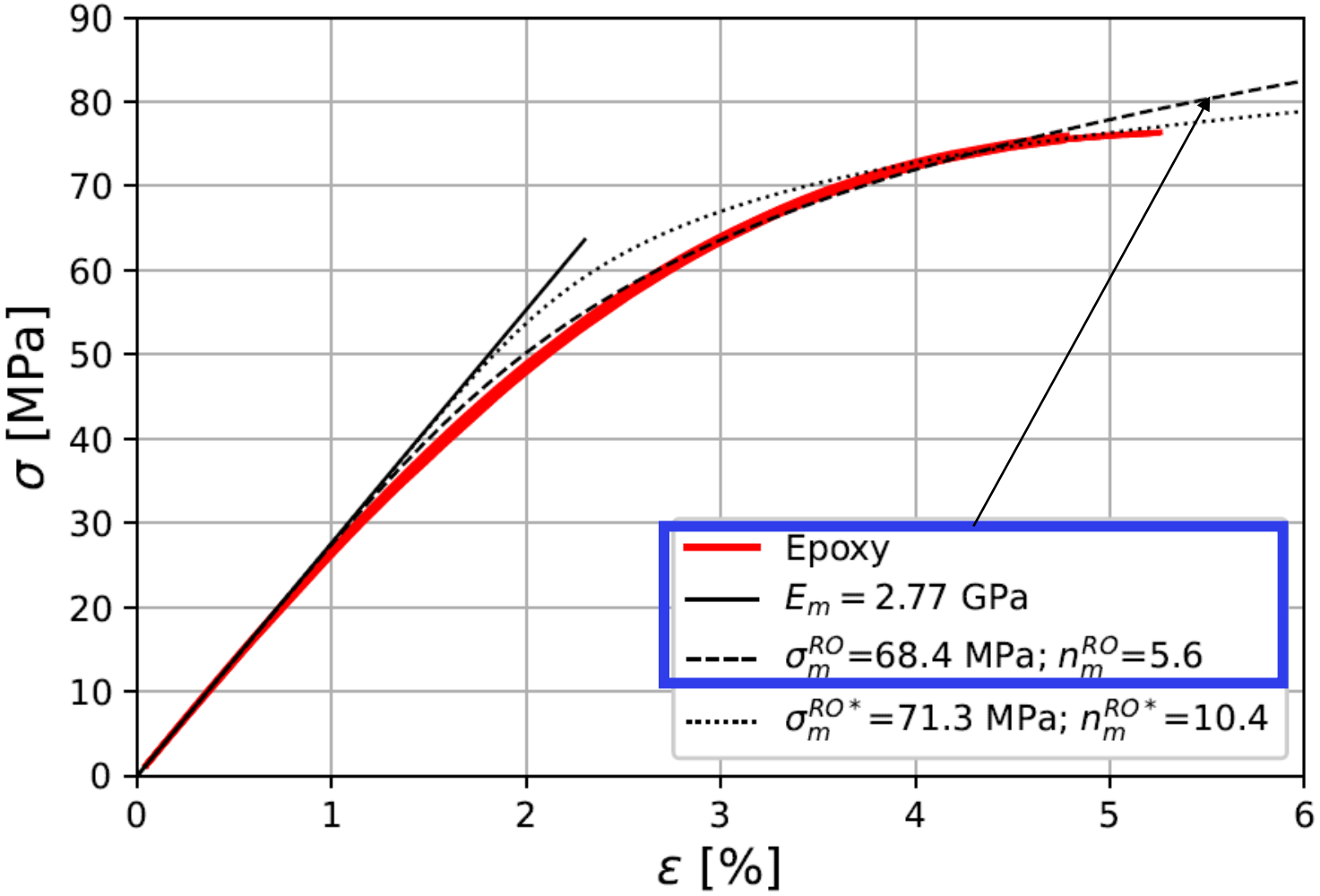
- ***Uniaxial stress-strain curve*** *of the fiber and matrix material*
  - *Ramberg-Osgood fitting*

- **Material orientation** distribution determined from 3D x-ray scan
  - Python script for Structure tensor analysis
  - User-subroutine mapping using orient.f in Abaqus

- **Geometrical and material non-linear (incremental) finite element model**
  - Umat.f user-subroutine in Abaqus

- **Predict the load-deflection curve** of specific scanned samples
  - No failure criteria but based on load maximum due to material point rotations

Mechanical properties of specific epoxy material

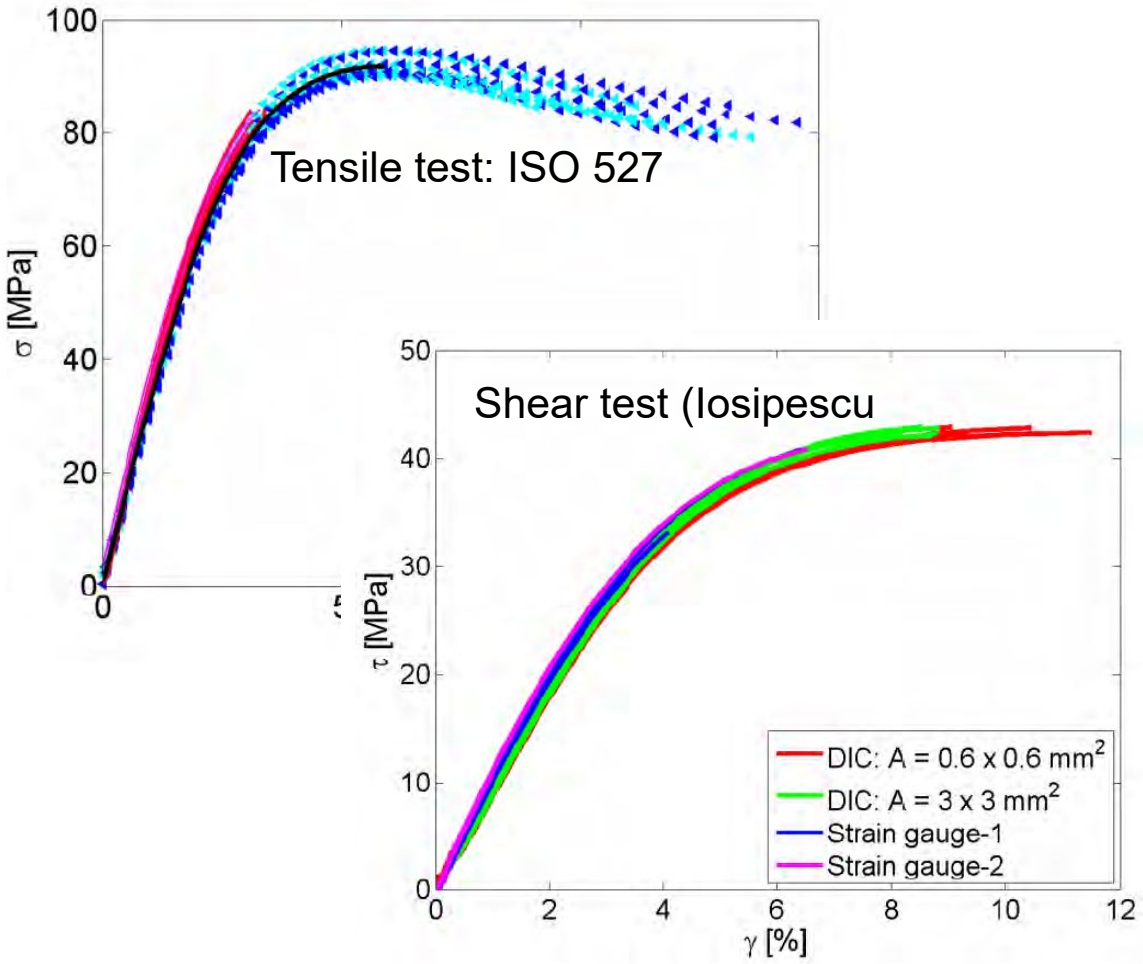


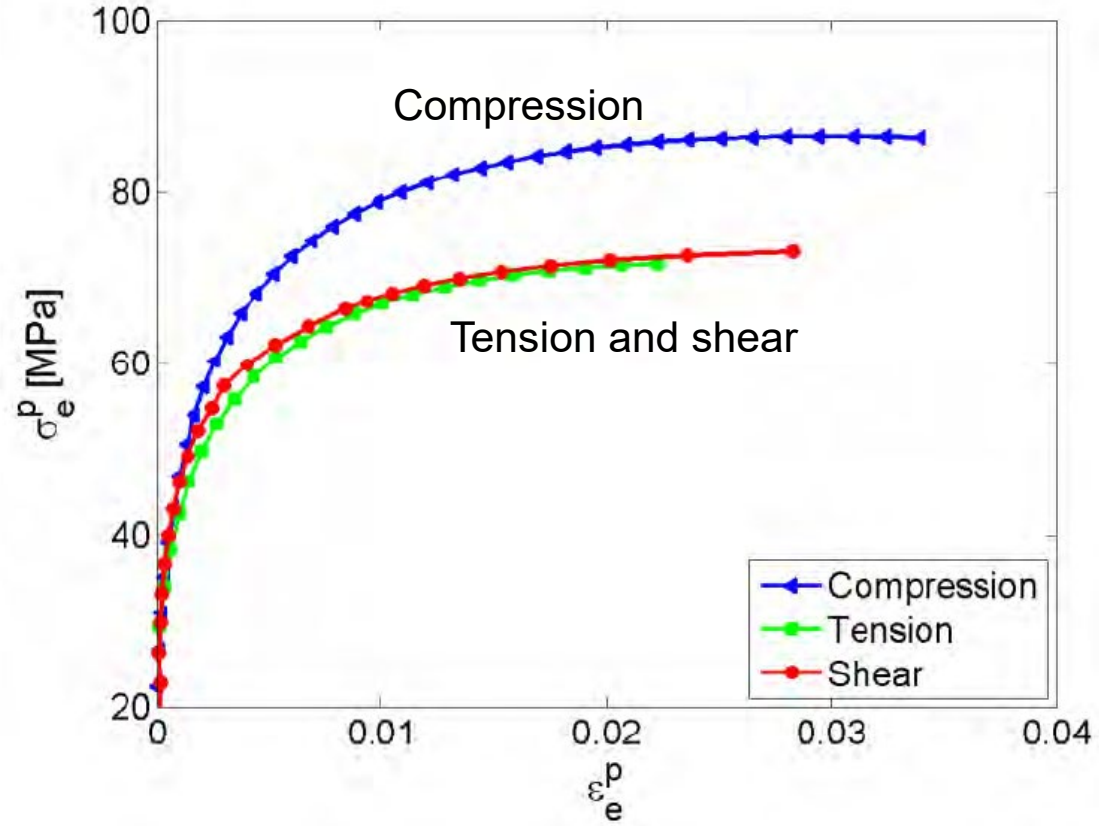
Ramberg-Osgood fitting

$$\epsilon_e = \frac{\sigma_e}{E} + \frac{3}{7}\frac{\sigma^{RO}}{E}\left(\frac{\sigma_e}{\sigma^{RO}}\right)^{n^{RO}}$$

Ferguson, Skovsgaard, Jensen, Mikkelsen (2023), https://doi.org/10.1016/j.euromechsol.2023.105011

Mechanical properties of the polymer matrix material - Tension vs shear

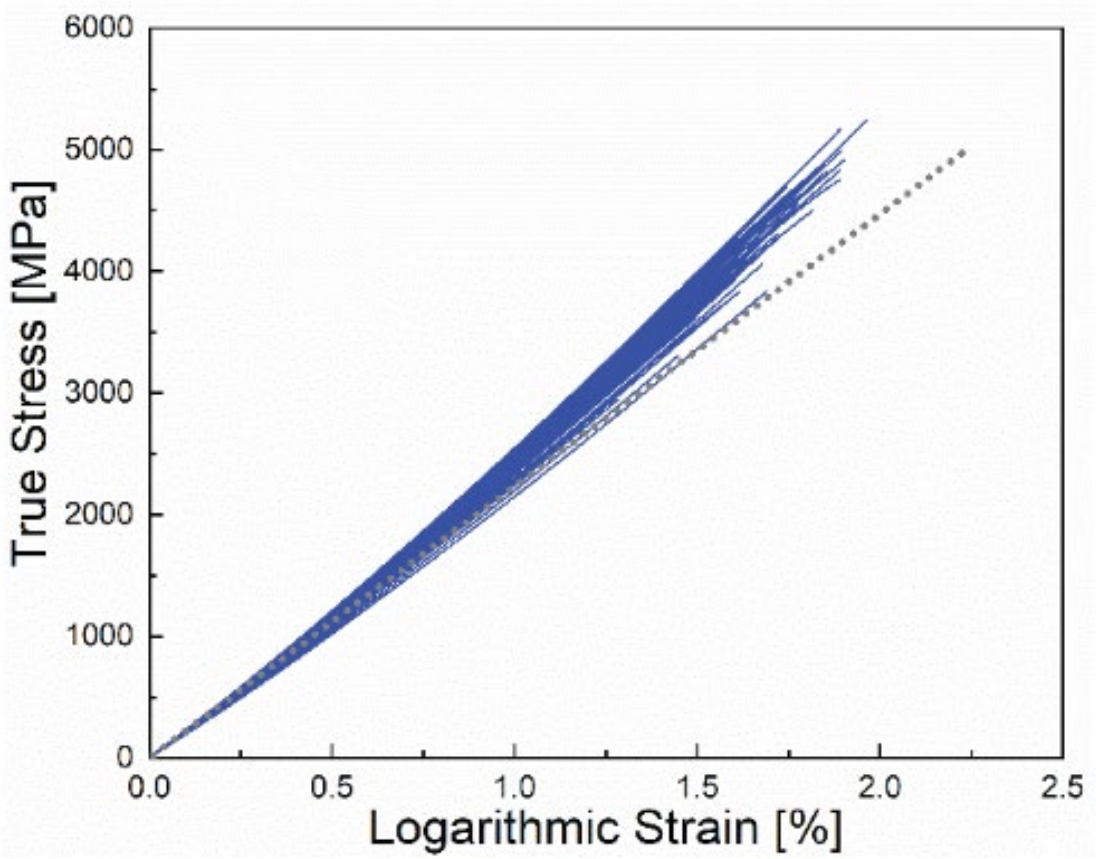


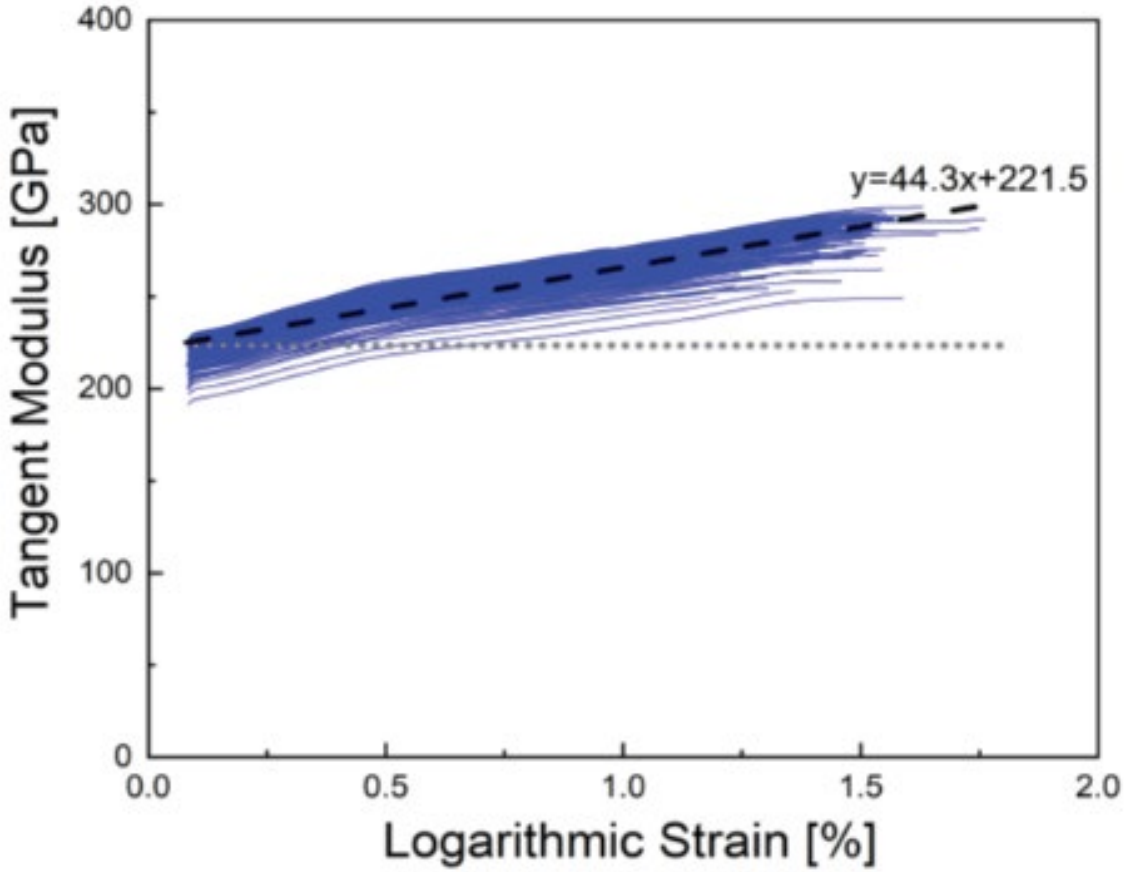


Sanita Zike (2015), PhD report number PhD-050, DTU Wind

Carbon fiber properties in tension

- Non-linear behavour



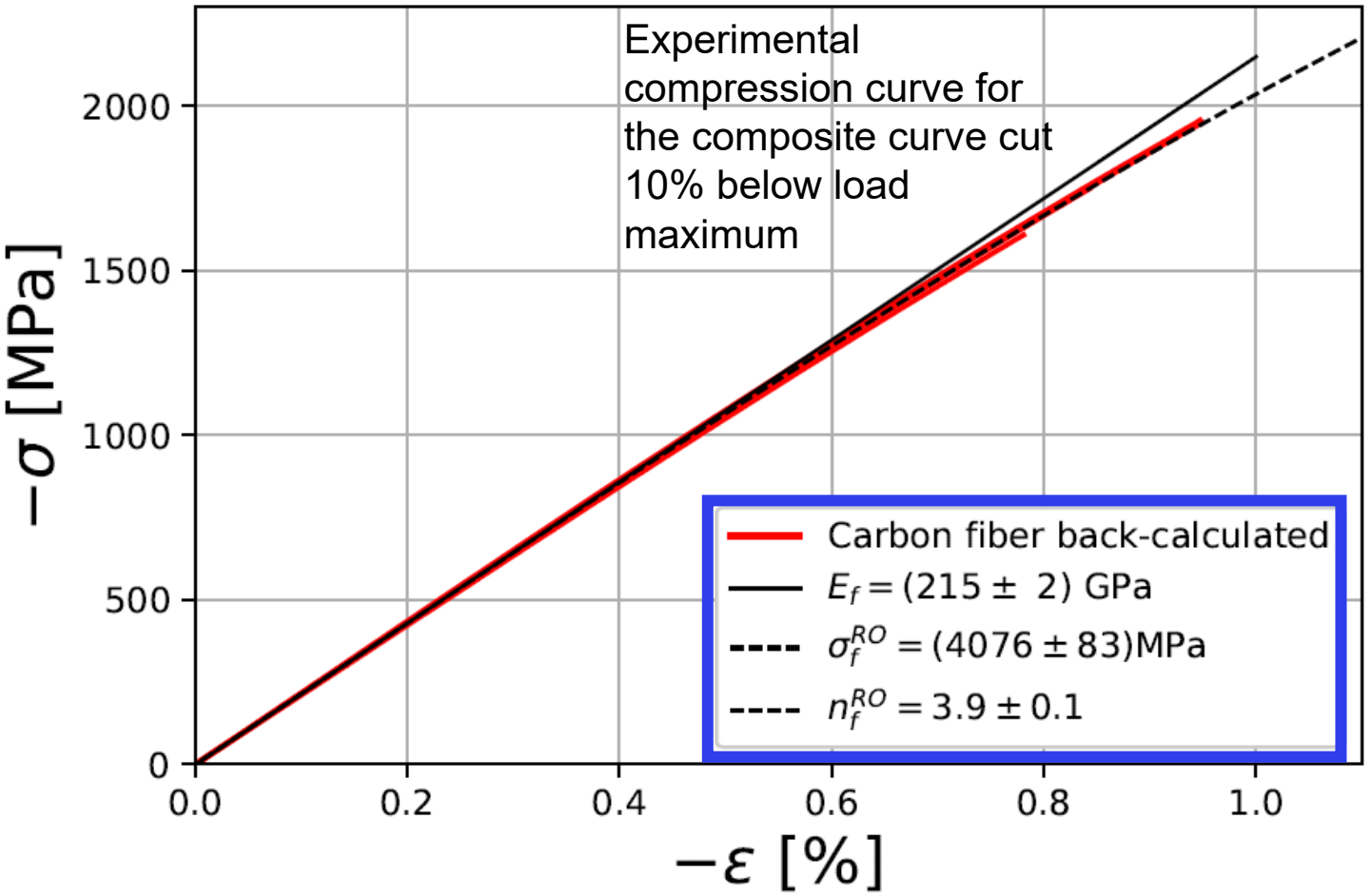


Good agreement between non-linear fibers and Rule of Mixture defined composite behaviour in tension

Kumar, Mikkelsen, Lilholt, Madsen (2020), https://doi.org/10.1088/1757-899X/942/1/012033

Carbon fiber properties in compression

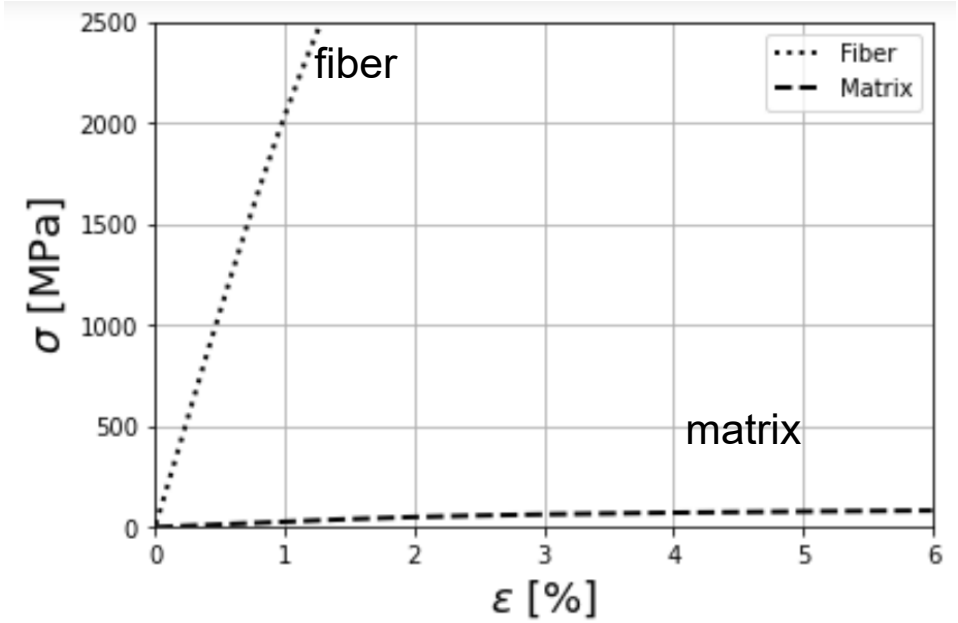
- back calculation from compression test of the composite

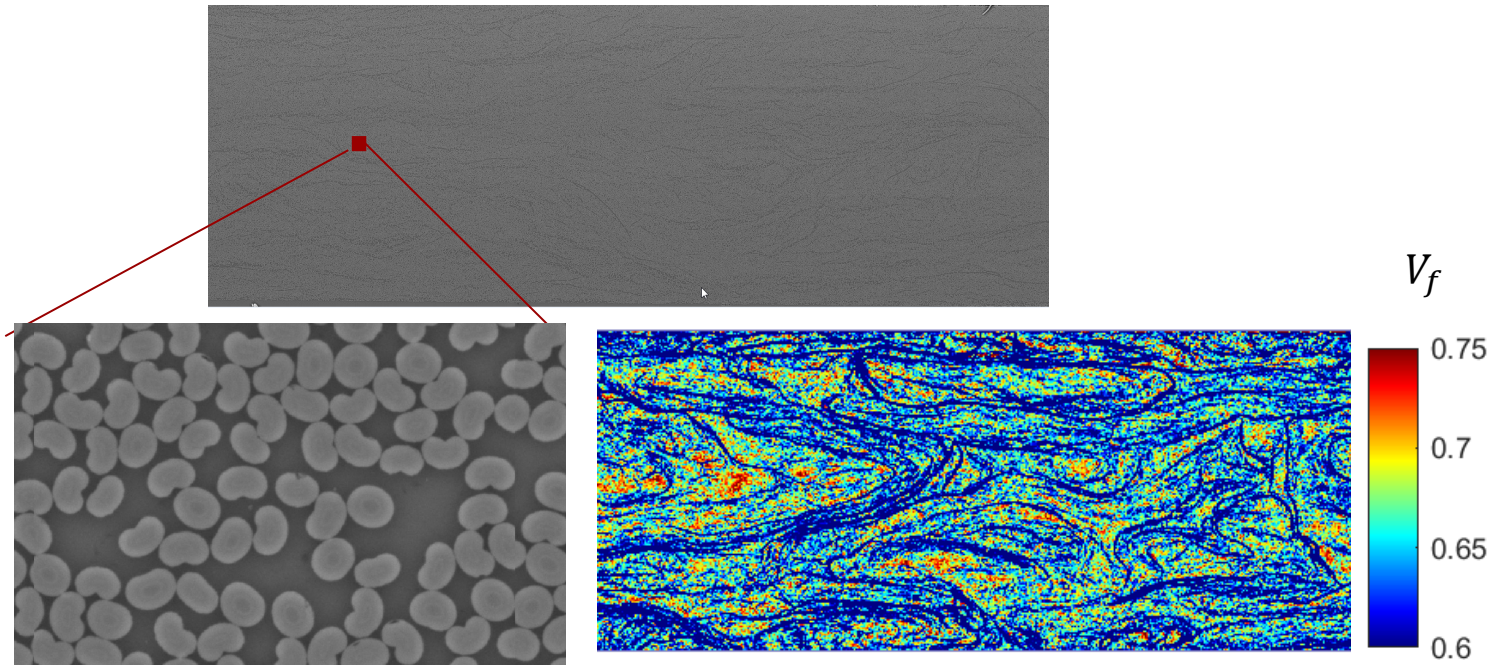


Ramberg-Osgood fitting

$$\epsilon_e = \frac{\sigma_e}{E} + \frac{3}{7}\frac{\sigma^{RO}}{E}\left(\frac{\sigma_e}{\sigma^{RO}}\right)^{n^{RO}}$$

Properties of pultruded carbon fiber composite





Material properties	E [GPa]	σ_0 [MPa]	n	ν
Carbon fibers	215 ± 2	4076 ± 83	3.9 ± 0.1	0.26
Epoxy matrix	2.77 ± 0.01	68.4 ± 0.2	5.6 ± 0.1	0.4

$V_f = 0.62$

Kumar et al. (2021) doi:10.5281/zenodo.5092028

Predict compression strength based on

- **Uniaxial stress-strain curve** of the fiber and matrix material
  - Ramberg-Osgood fitting

- ***Material orientation*** *distribution determined from 3D x-ray scan*
  - *Python script for Structure tensor analysis*
  - *User-subroutine mapping using orient.f in Abaqus*

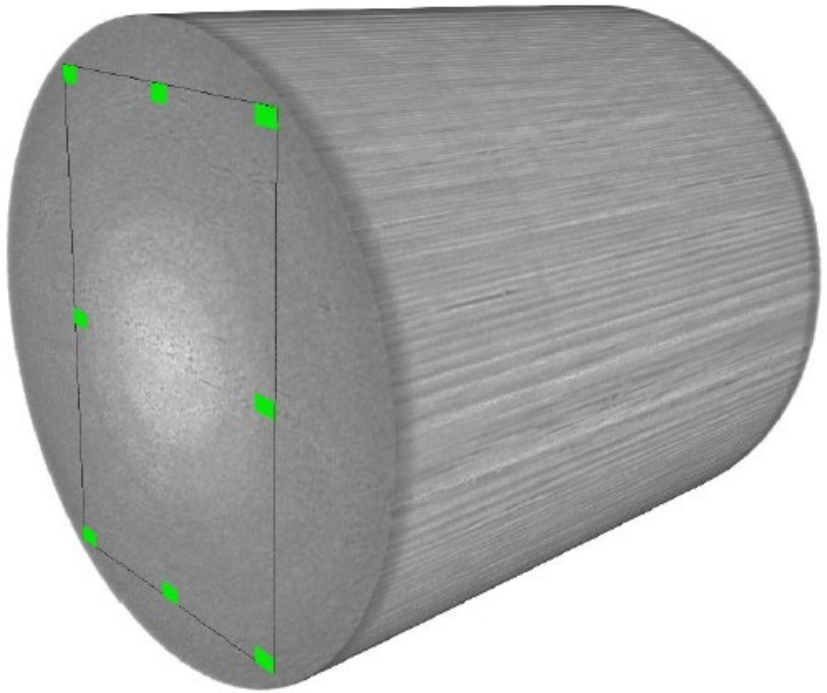
- **Geometrical and material non-linear (incremental) finite element model**
  - Umat.f user-subroutine in Abaqus

- **Predict the load-deflection curve** of specific scanned samples
  - No failure criteria but based on load maximum due to material point rotations

3D x-ray tomography (Zeiss Versa 520) - carbon fiber composites

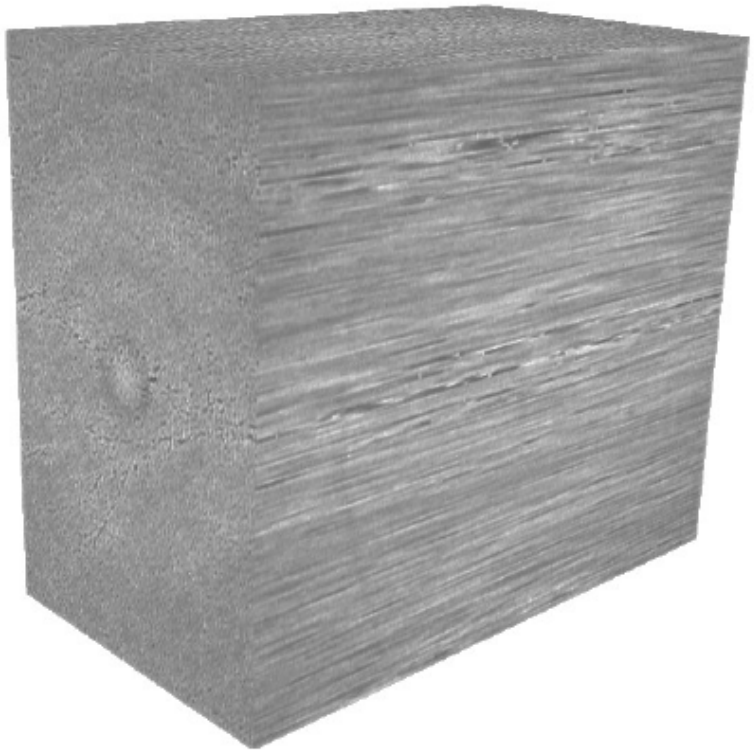
Scan samples

5×5 mm^2 cross-section



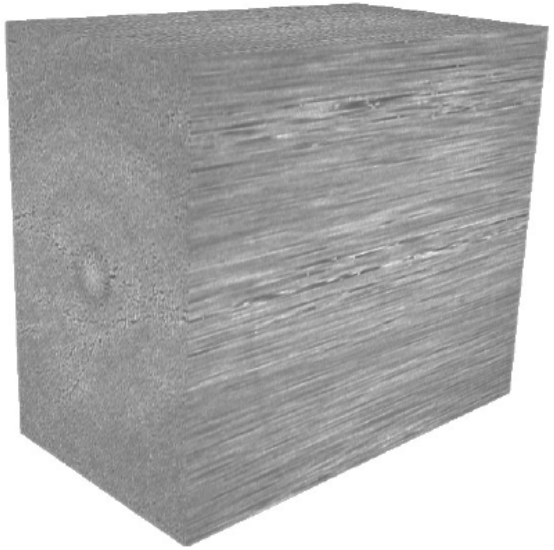
$2 \times 2 \times 2$mm^3 Field of View (FoV)

Voxel size: 1.98 microns, $d_f = 7$ microns



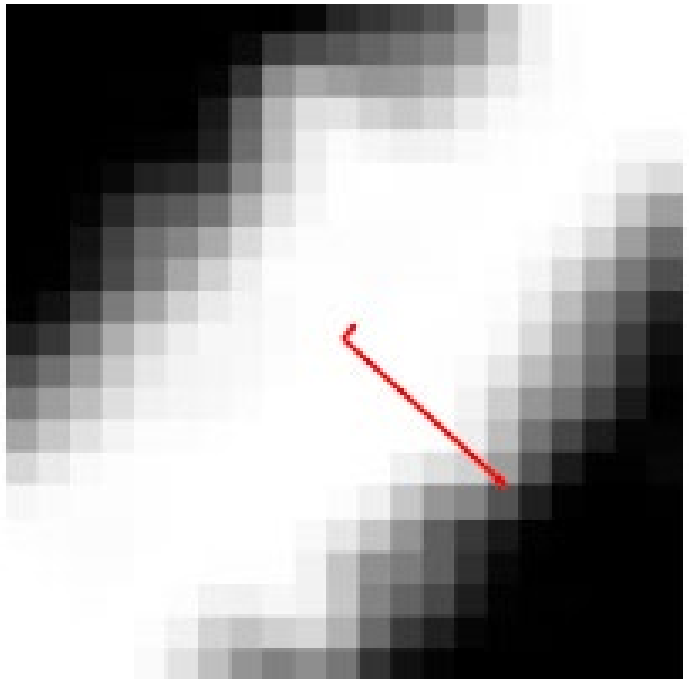
$1.56 \times 1.01 \times 1.77\text{mm}^3$ FoV

Material orientation segmentation - Structure tensor method



3D X-ray scan

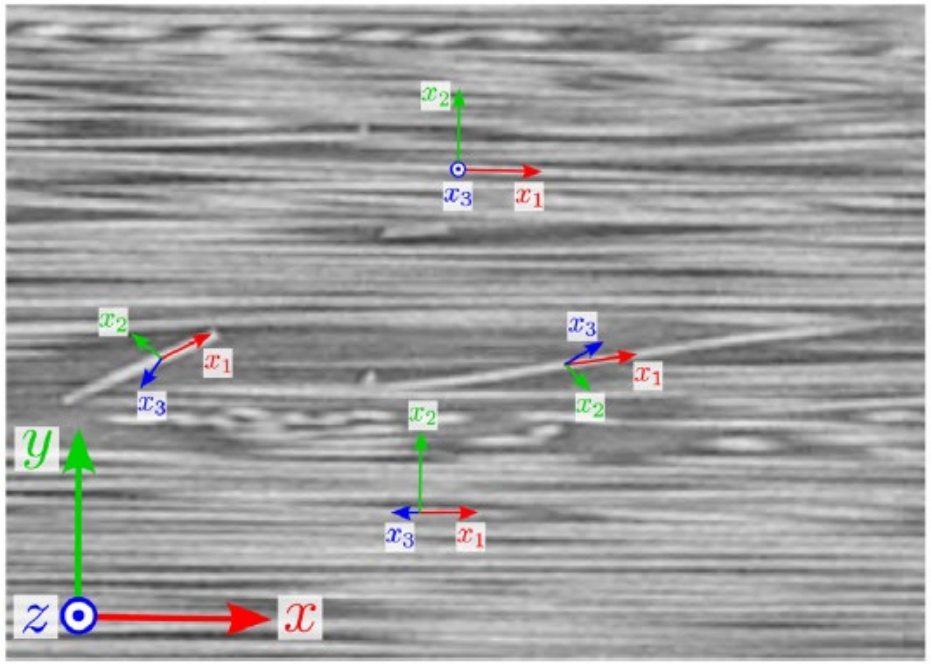
Structure tensor method in 2D

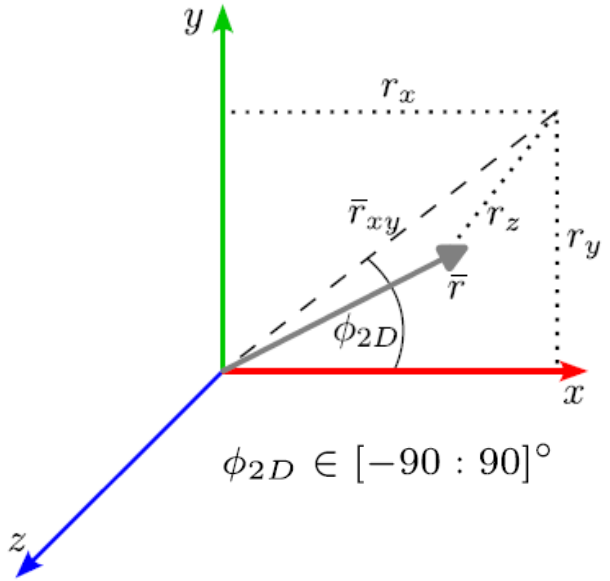


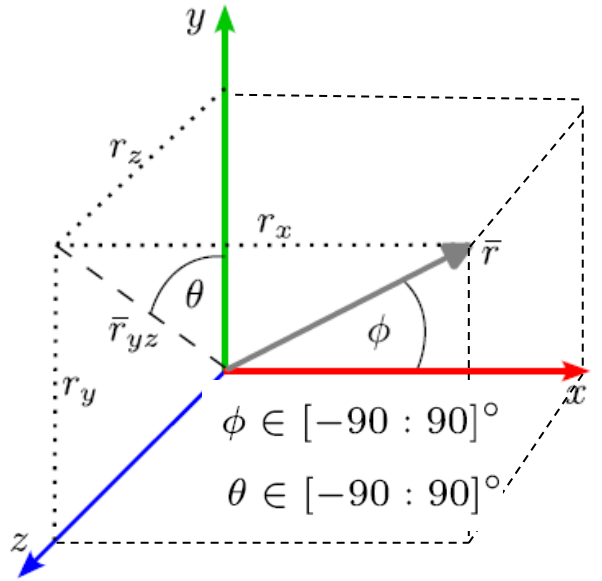
- σ : Noise scale
  - computing derivatives
- ρ : Integration scale
  - averaging over the neighborhood
- Value of ρ : scale with fiber-diameter
  - Small give local orientation
  - Large captures the overall orientation
- Dominating direction is given by the smallest eigenvector

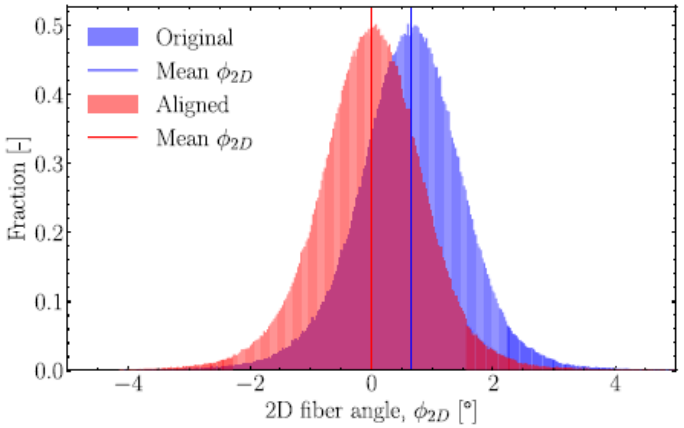
Jeppesen, Mikkelsen, Dahl, Christensen, Dahl (2021), https://doi.org/10.1016/j.compositesa.2021.106541

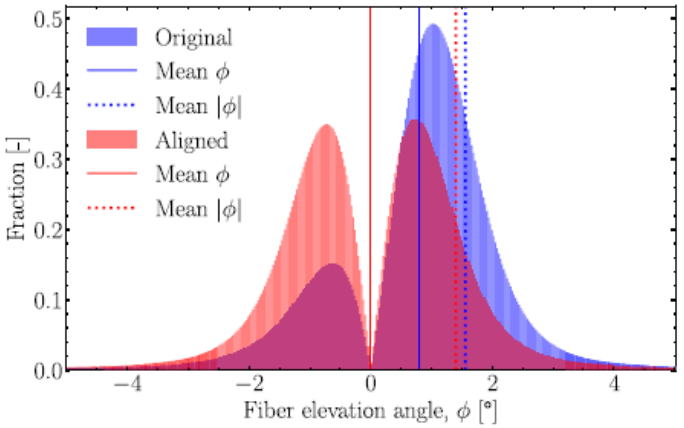
Fiber orientation in 3D





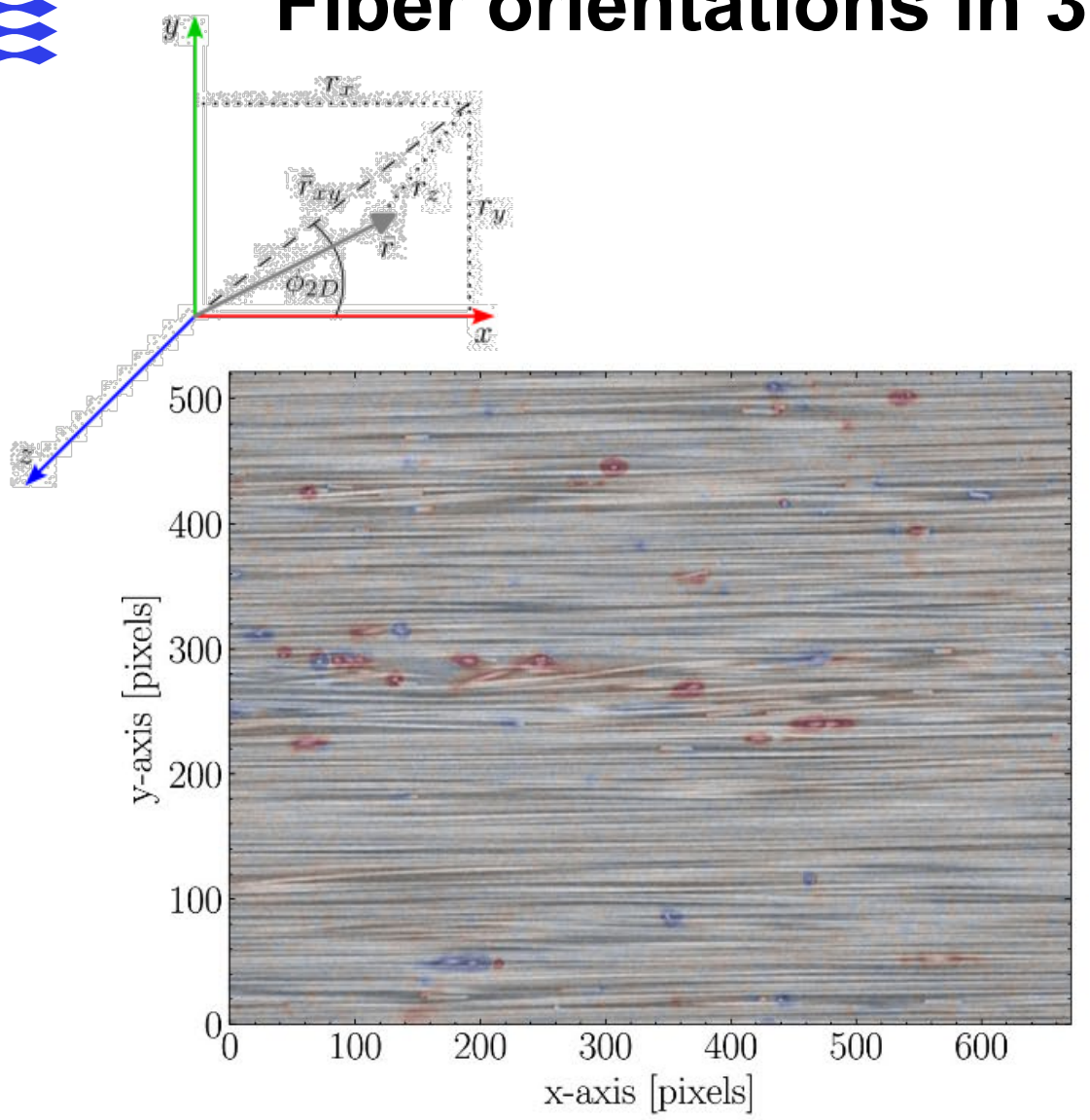




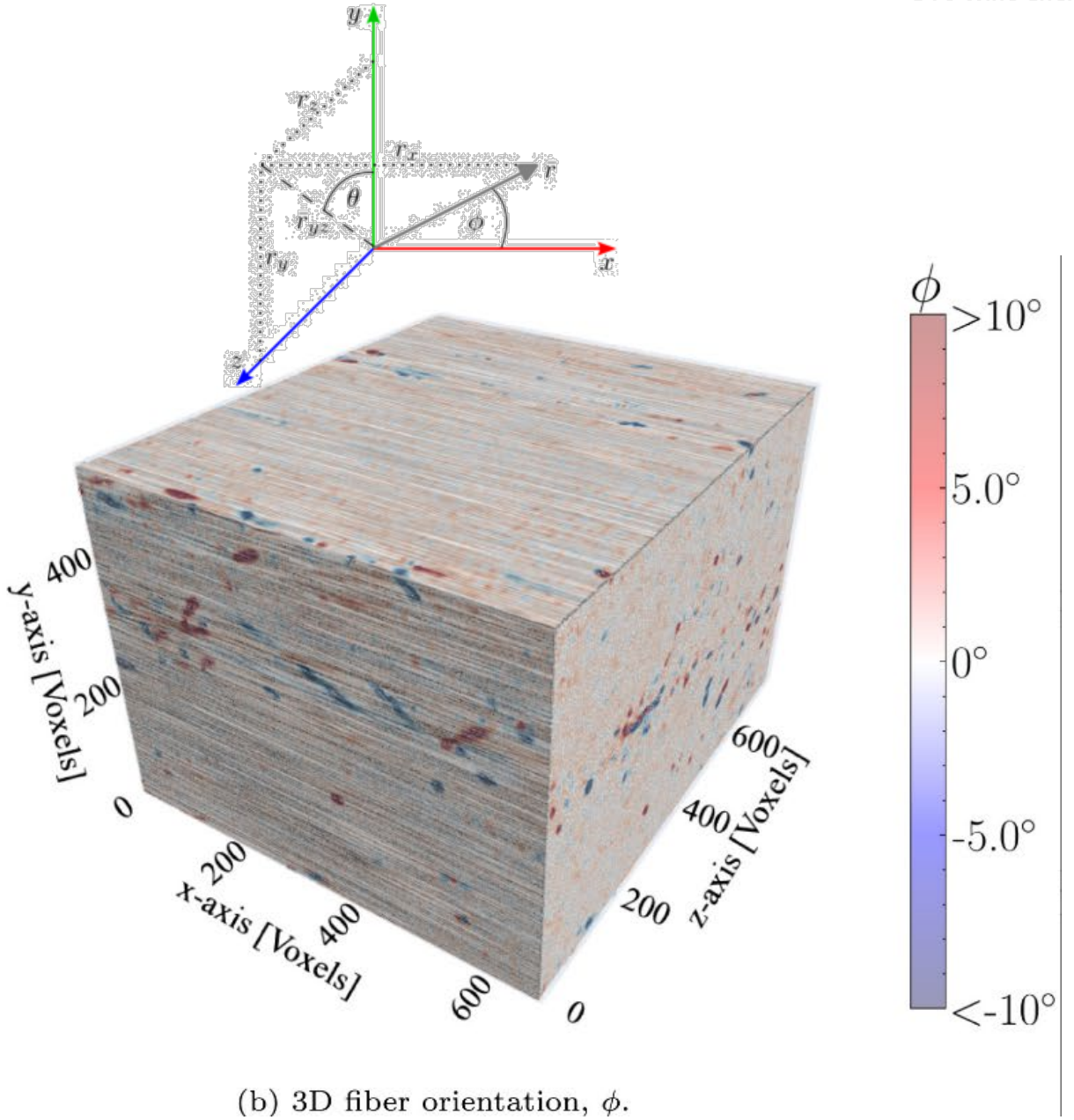


Ferguson, Skovsgaard, Jensen, Mikkelsen (2023), https://doi.org/10.1016/j.euromechsol.2023.105011

Fiber orientations in 3D



(a) 2D fiber orientation, ϕ_{2D}.

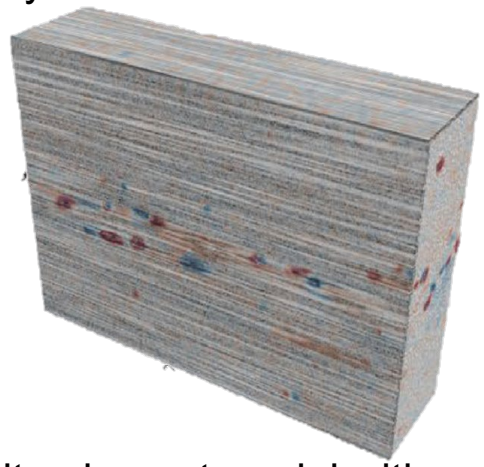


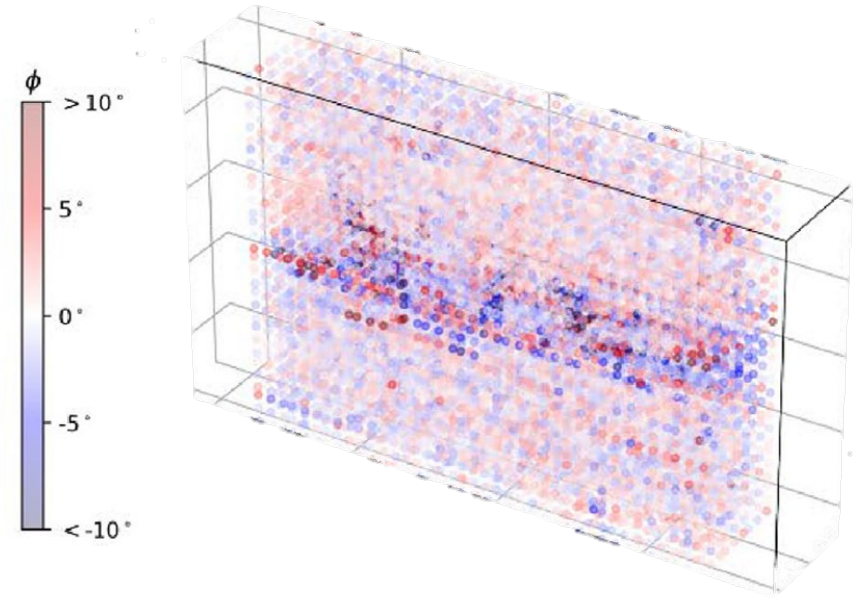
(b) 3D fiber orientation, ϕ.

Ferguson, Skovsgaard, Jensen, Mikkelsen (2023), https://doi.org/10.1016/j.euromechsol.2023.105011

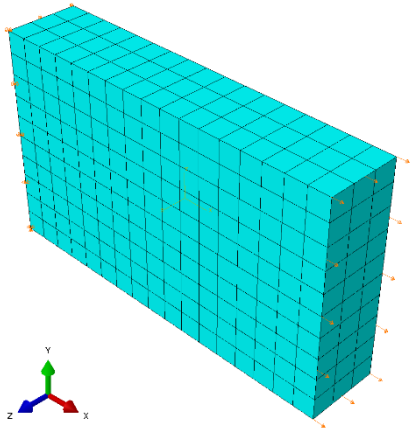
Mapping orientations on 3D mesh using Python

Structure tensor segmented X-ray scan





Finite element model with 27 integration points in each element



Include file for orient.f user subroutine

```
 real*8 PHI0(27,510)
 DATA (PHI0(I,1), I=1,27)/ 0.017368, -0.031673, -0.014482,
&  0.018769, 0.010712, 0.010693,
&  0.014257, 0.012763, 0.018017,
&  0.035512, 0.014058, 0.023765,
&  -0.015539, 0.051035, 0.029493,
&  0.023953, 0.022386, 0.025526,
&  0.014869, 0.033055, 0.021708,
&  0.026972, 0.037397, 0.031630,
&  0.026637, 0.020749, 0.006356/
 DATA (PHI0(I,2), I=1,27)/ 0.011867, 0.011318, 0.040157,
&  0.012012, 0.000498, 0.003448,
&  0.025139, 0.019827, 0.018580,
```

```
 real*8 THETA0(27,510)
 DATA (THETA0(I,1), I=1,27)/ -0.460082, -1.008942, -1.448212,
&  -0.468504, 0.951642, 0.233209,
&  0.372499, -0.511249, 0.396310,
```

```
      SUBROUTINE ORIENT(T,NOEL,NPT,LAYER,KSPT,COORDS,BASIS,
     1 ORNAME,NNODES,CNODES,JNNUM)
C
      INCLUDE 'ABA_PARAM.INC'
C
      CHARACTER*80 ORNAME
      CHARACTER*256  JOBNAME, OUTDIR, FILENAME
C
      DIMENSION T(3,3),COORDS(3),BASIS(3,3),CNODES(3,NNODES)
      DIMENSION JNNUM(NNODES)

      INCLUDE 'A01crop_THETA.f'
      INCLUDE 'A01crop_PHI.f'

      T(1,1) =  DCOS(PHI0(NPT,NOEL))
      T(1,2) = -DSIN(PHI0(NPT,NOEL))
      T(1,3) =  0.
      T(2,1) =  DCOS(THETA0(NPT,NOEL))*DSIN(PHI0(NPT,NOEL))
      T(2,2) =  DCOS(THETA0(NPT,NOEL))*DCOS(PHI0(NPT,NOEL))
      T(2,3) = -DSIN(THETA0(NPT,NOEL))
      T(3,1) =  DSIN(THETA0(NPT,NOEL))*DSIN(PHI0(NPT,NOEL))
      T(3,2) =  DSIN(THETA0(NPT,NOEL))*DCOS(PHI0(NPT,NOEL))
      T(3,3) =  DCOS(THETA0(NPT,NOEL))

      RETURN
      END
```


Ferguson, Mikkelsen (2023), https://doi.org/10.1016/j.simpa.2023.100523

Predict compression strength based on

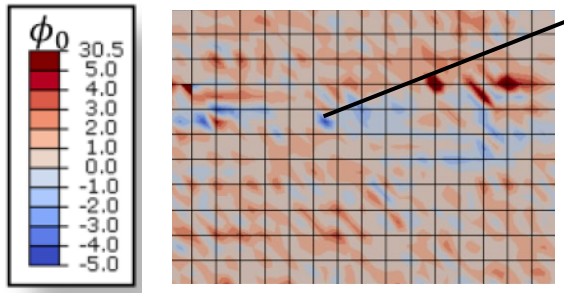
- **Uniaxial stress-strain curve** of the fiber and matrix material
  – Ramberg-Osgood fitting

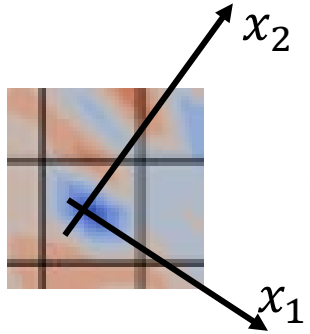
- **Material orientation** distribution determined from 3D x-ray scan
  – Python script for Structure tensor analysis
  – User-subroutine mapping using orient.f in Abaqus

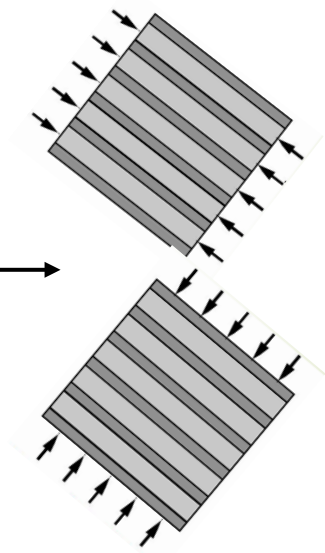
- ***Geometrical and material non-linear (incremental) finite element model***
  – *Umat.f user-subroutine in Abaqus*

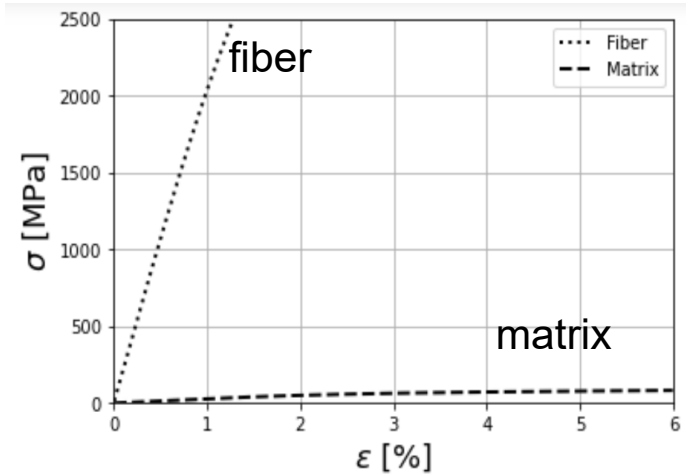
- **Predict the load-deflection curve** of specific scanned samples
  – No failure criteria but based on load maximum due to material point rotations

Incremental non-linear composite (Abaqus)









Abaqus solution increment:

Update ϕ ; σ_{ij}^{m1}; σ_{ij}^{m2}; σ_{ij}^{f}

Umat.f

Voigt: Iso-strain and rotation of fiber and matrix

$$\dot{u}_{1,1}^{f} = \dot{u}_{1,1}^{m} \qquad \dot{u}_{2,1}^{f} = \dot{u}_{2,1}^{m}$$

Reuss: Iso transverse and shear stress of fiber and matrix

$$\dot{\sigma}_{22}^{f} = \dot{\sigma}_{22}^{m} \qquad \dot{\sigma}_{12}^{f} = \dot{\sigma}_{12}^{m}$$

Fibres: $E_f; \nu_f; \sigma_f^{RO}; n_f^{RO}$

$$\dot{\sigma}_{ij}^{f} = C_{ijkl}^{f}(\sigma_e^{f})\dot{\varepsilon}_{kl}^{f}$$

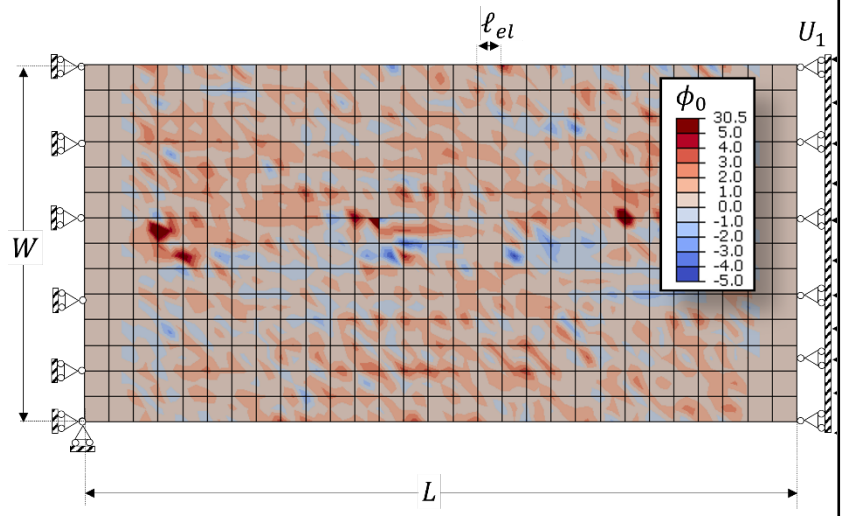
Matrix: $E_m; \nu_m; \sigma_m^{RO}; n_m^{RO}$

$$\dot{\sigma}_{ij}^{m1} = C_{ijkl}^{m}(\sigma_e^{m1})\dot{\varepsilon}_{kl}^{m1}$$
$$\dot{\sigma}_{ij}^{m2} = C_{ijkl}^{m}(\sigma_e^{m2})\dot{\varepsilon}_{kl}^{m2}$$

Composite: $V_f = 0.62$

$$\dot{\sigma}_{ij} = C_{ijkl}(V_f C_{ijkl}^{m1}, C_{ijkl}^{m2}, C_{ijkl}^{f})\dot{\varepsilon}_{kl}$$

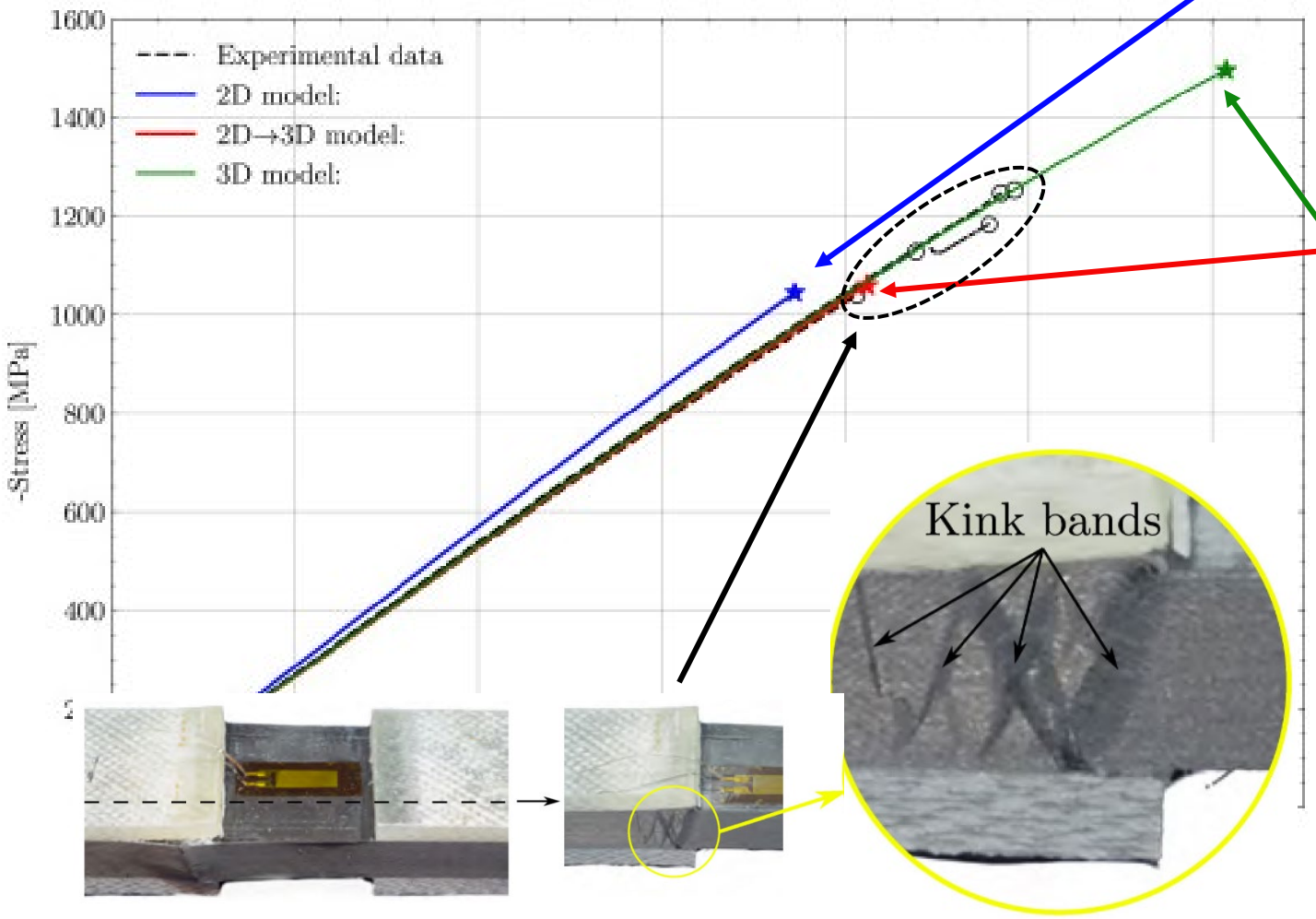
Jensen and Christoffersen (1997); Skovsgaard and Jensen (2018)

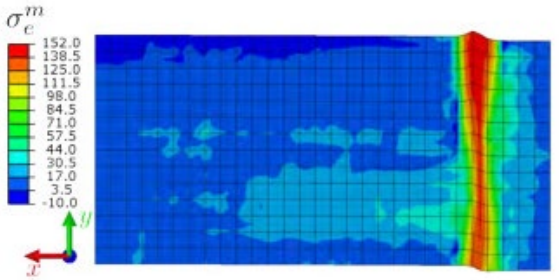

ℓ_{el}
U_1
ϕ_0
30.5
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
W
L

Predict compression strength based on

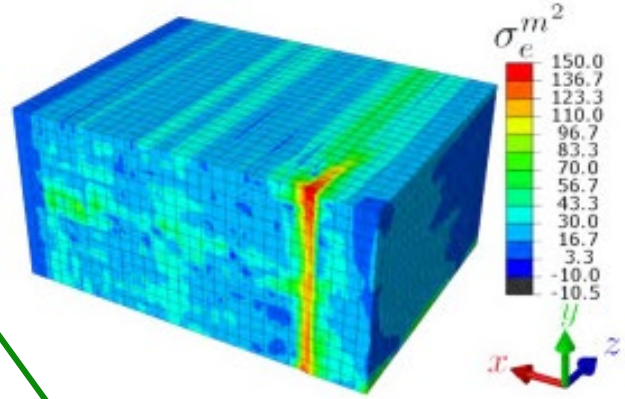
- **Uniaxial stress-strain curve** of the fiber and matrix material
  - Ramberg-Osgood fitting
- **Material orientation** distribution determined from 3D x-ray scan
  - Python script for Structure tensor analysis
  - User-subroutine mapping using orient.f in Abaqus
- **Geometrical and material non-linear (incremental) finite element model**
  - Umat.f user-subroutine in Abaqus
- ***Predict the load-deflection curve*** *of specific scanned samples*
  - *No failure criteria but based on load maximum due to material point rotations*

Predictions in 3D

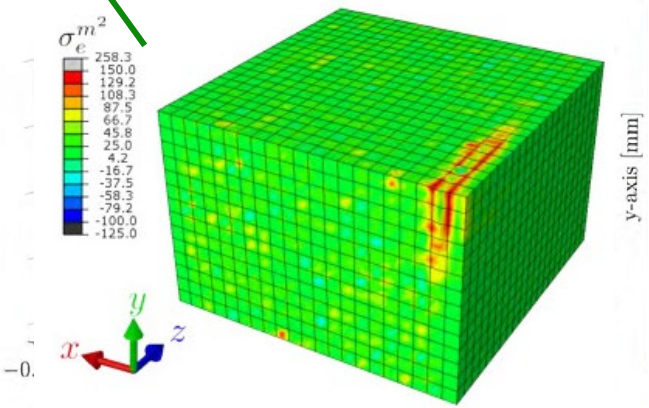




(a) 2D FE model with integration points presented in Fig. 7a.



(b) 2D→3D FE model with integration points presented in Fig. 7b.

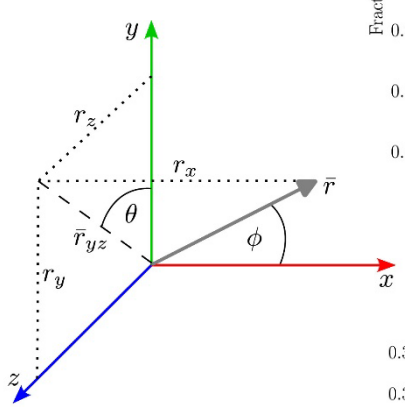


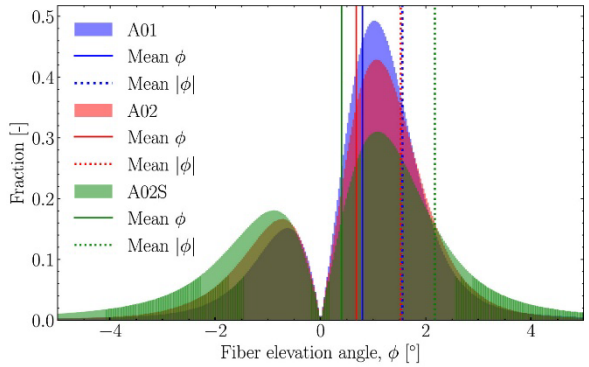
(c) 3D FE model with integration points presented in Fig. 7c.

Ferguson, Skovsgaard, Jensen, Mikkelsen, https://doi.org/10.1016/j.euromechsol.2023.105011

Modelling 3 different 2 mm FoV scans

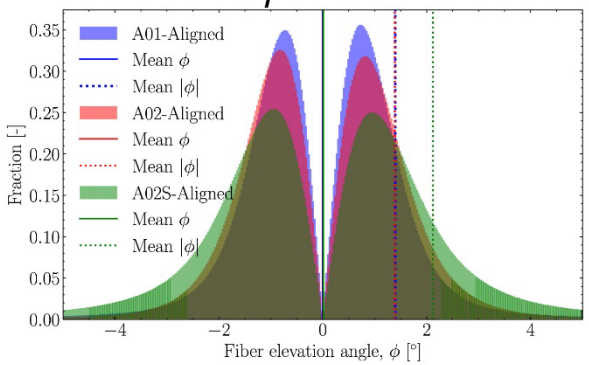
$\bar{\phi} \in [0.5; 1.0]°$



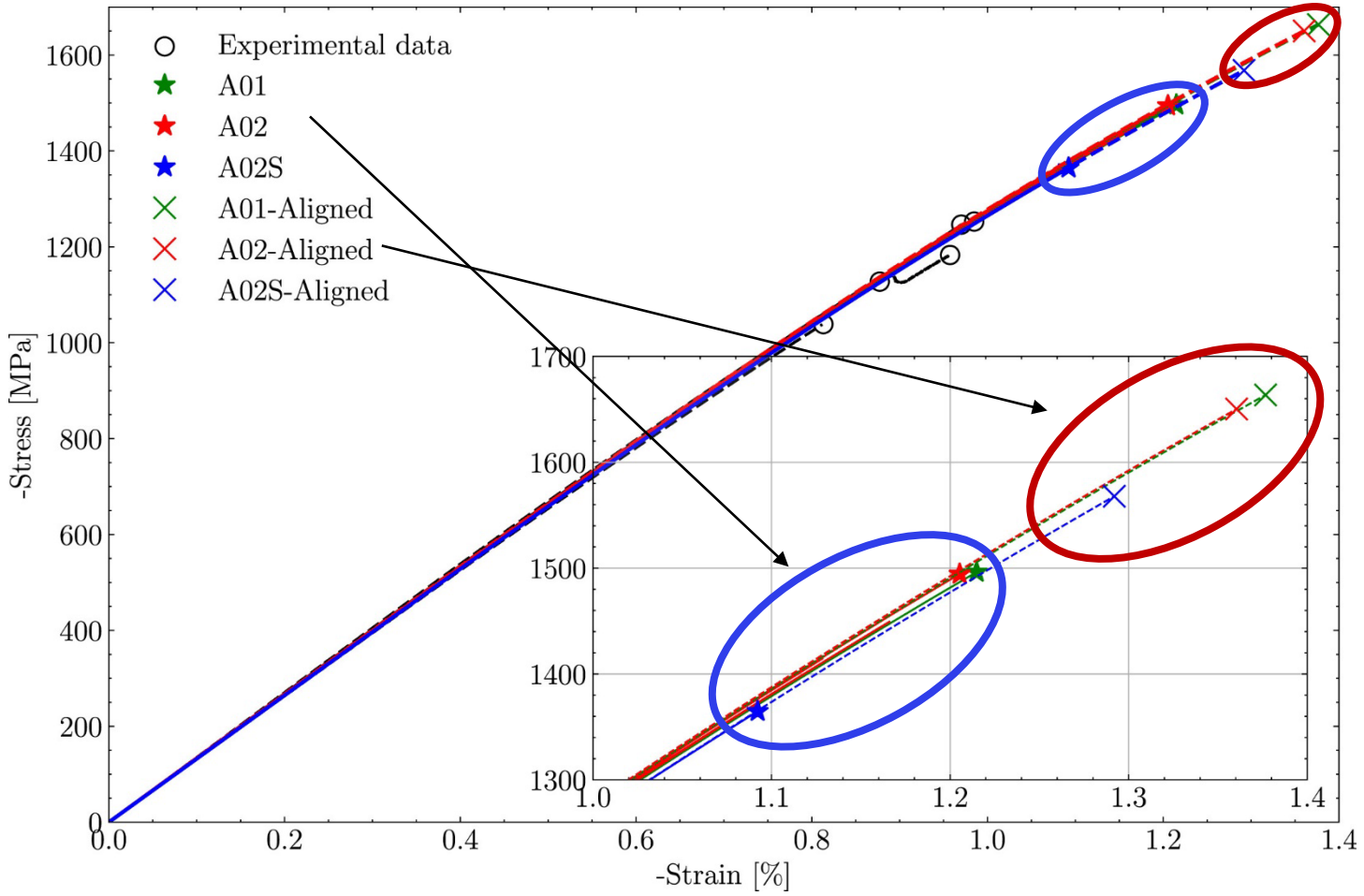


(a) Original fiber orientation distribution.

$\bar{\phi} \equiv 0°$



(b) Aligned fiber orientation distribution.



Ferguson, Skovsgaard, Jensen, Mikkelsen, https://doi.org/10.1016/j.euromechsol.2023.105011

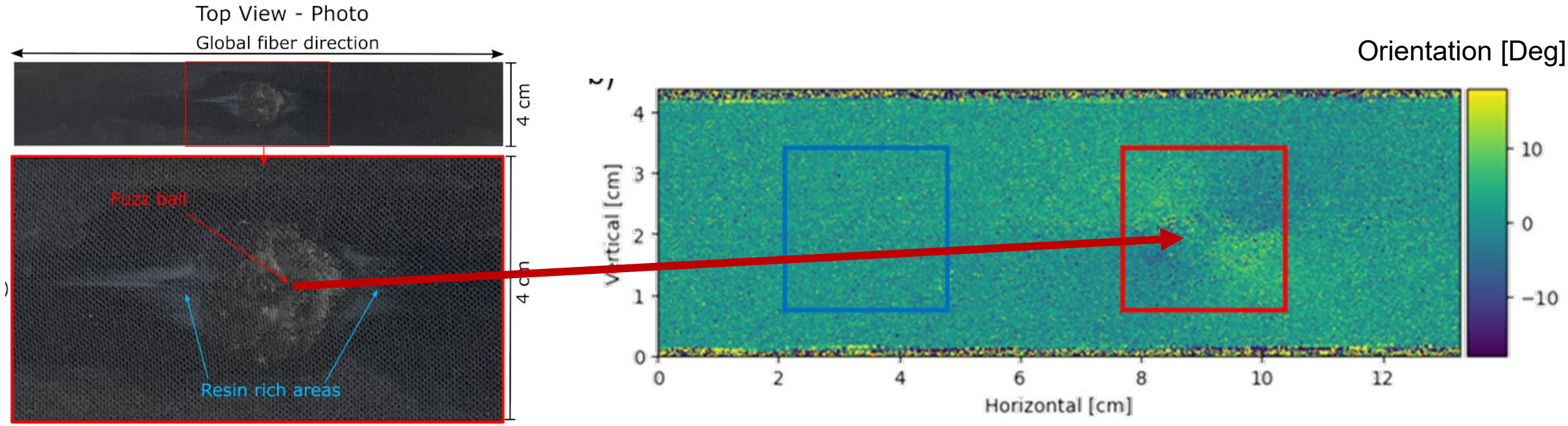
Conclusion

- Properties in model
  - Stress strain curve of matrix material
  - Stiffness of stress-strain curve for fiber material
  - Fiber volume fraction
  - Fiber orientation distribution

- Finite Element Model
  - Non-linear composite material model
  - No failure criteria, load maximum due to local material point rotation during loading

  Prediction
  - Realistic compression strength predictions
  - Show high dependency on small rotation with respect to the overall fiber orientation

Larger FoV using lab based X-ray scattering techniques



Slyamov, …, Mikkelsen, *IOP Conf. Ser.: Mater. Sci. Eng.* In press, 43rd Risø Int. Symp. on Materials Science, 2023

43rd Risø International Symposium on Materials Science

Composites for wind energy: Manufacturing, operation and end-of-life

Composites for wind energy: Manufacturing, operation and end-of-life

4 - 7 September 2023

The focus of the 43rd Risø Symposium is on composites for wind energy. This symposium takes a life cycle perspective and addresses manufacturing, performance during operation and end-of-life of composites for wind energy. Over the last 40 years, wind turbine blades have grown an order of magnitude. Today, the longest blades are exceeding 100 meters and weighing 50 tons. Because of this growth in blade size, the cost of wind energy can now compete with fossil-based energy sources on market terms.

As society is thriving towards a zero-emission future, the wind energy sector is foreseen to further expand. Longer wind turbine blades with improved overall lifetime, reliability, recyclability, sustainability, operability and maintainability are some of the objectives set on this component. To address these upcoming and ambitious requirements, the symposium welcomes contribution dedicated to the manufacturing, the operation and performance, as well as end-of-life strategies for wind turbine blades.

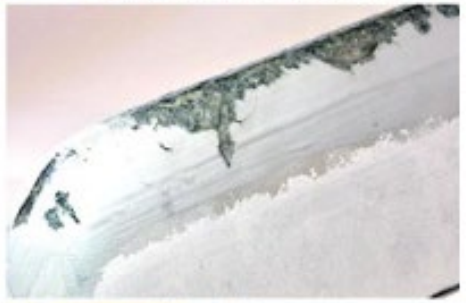
Important Dates

15 March 2023: Abstract submission

01 July 2023: Paper submission

https://www.morressier.com/call-for-papers/63ff34e08d36d800127feb22

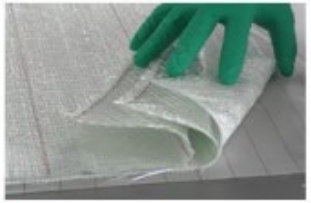
31 August 2023: Registration deadline



Manufacturing

Characterization and development of manufacturing processes for wind turbine blades

Existing and alternative manufacturing technologies, constrains and new opportunities, process characterization, cure kinetics and residual stresses, modelling, manufacturing defects, repair.



Operation

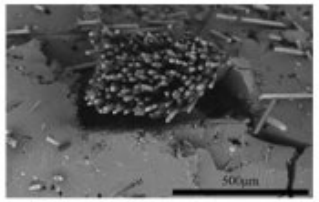
Experimental characterization, mechanical properties and performance of composites for wind turbine blades

Structural design and performance of blade structures; Key composite design properties: stiffness, strength, fracture and fatigue resistance; Materials development: hybrid, bio-based, thermoplastic composites and smart materials; adhesive joints and fibre/matrix interfaces; Leading edge erosion, repair, structural health monitoring. Micro and macro structural characterization using X-ray tomography and ultrasound; Novel test methods for composites under static and cyclic loading; development of test methods for structural elements, e.g. ply-drops and wrinkles, and full-scale testing of blades.

End-of-life

Strategies to address the end-of-life challenges of composites and of wind turbine blades

Reuse and lifetime extension, recyclable composite, composite recycling processes, repurposing, decommissioning, life-cycle analysis (LCA). Recycling of manufacturing waste and end-of-use wind turbines, recycling processes and products incorporating recycled materials, material substitution in wind turbine blades increasing the recycled content.



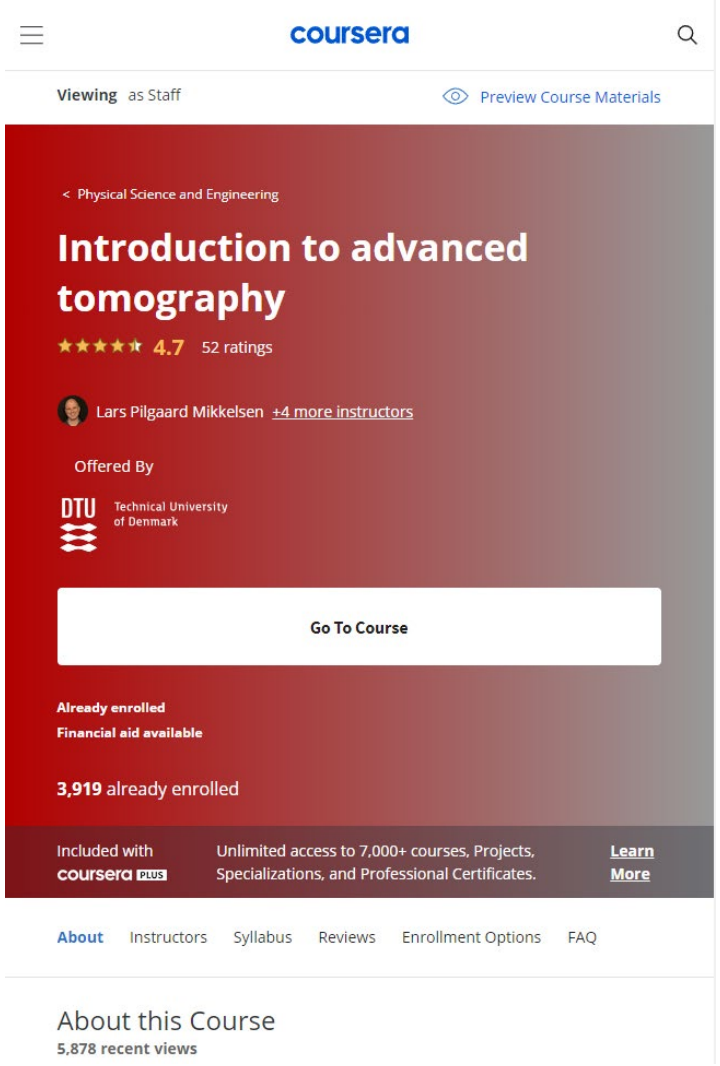
Registration

The registration fee is DKK 4500 (approx. EUR 600), and covers access to lectures, lunch and refreshments all days, conference dinner, and social arrangements. The registration fee for students is DKK 2000 (approx. EUR 270).

Contact

Lars P. Mikkelsen, Chairman
Justine Beauson, Chairwoman
E-mail: symp43@windenergy.dtu.dk
Website:
https://wind.dtu.dk/about/symposium-on-materials-science

Coursera course and 8th CINEMAX PhD summer school on X-ray tomography to FE-modelling of materials



Venue

Fuglsang Manor on Lolland in Southern Denmark

Only € 900 covering accommodation and Including all meals

www.fuglsangherregaard.dk

Technical University of Denmark and University of Copenhagen present

The 8th International Summer School

CINEMAX

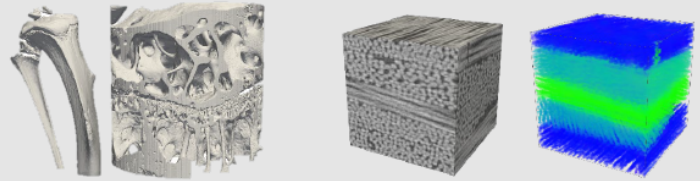
First Announcement

21-25 August 2023

For PhD students, Post Docs and industrial researchers

Lectures and exercises cover the full pipeline from data acquisition through reconstruction and segmentation to modelling based on real 3D data.
The online Coursera course must be completed before arrival:
https://www.coursera.org/learn/cinemaxe
(a fee of € 44 applies to complete the honors track of the coursera course)

3D imaging and modelling of natural and synthetic materials

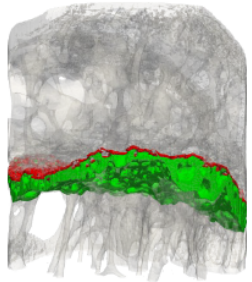


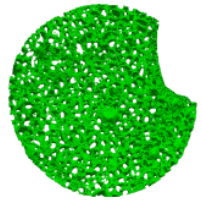
http://www.conferencemanager.dk/CINEMAXVIII

Key dates

Registration deadline: 15 July 2023
(limited number of participants, first come – first served)
Poster abstracts by: 15 August 2023

You will work with real problems on your own laptop!
Please contact **Signe Dan Jensen <sidje@dtu.dk>** to receive further details directly.





Hands on exercise with 3D imaging on site!