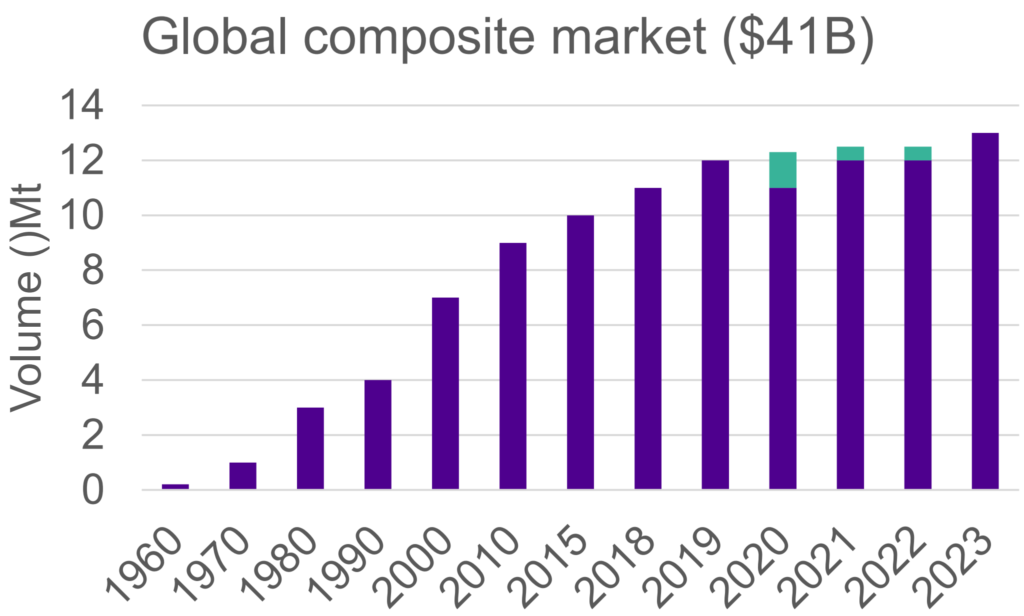
Tampere University
Tampere University of Applied Sciences

Pushing composite boundaries

exploring sustainable reinforcement alternatives from μ-scale characterization to advanced simulations

Jason Govilas

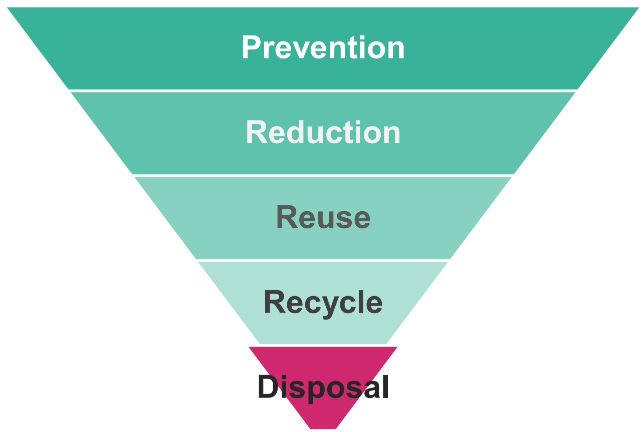
Composite environmental impact



JEC Observer – Overview of the global composites market

Increase in sustainability requirements/ regulations

- reduce CO_2 footprint
- Circular Economy
- Life Cycle Assessment
- waste hierarchy



Composite sustainability

+ lightweight
+ durable
– non-renewable materials / energy intensive production
– challenging to recycle

Increasing composite sustainability

Design

Material choice | **Modular design**

- reversible joints
- reversible adhesives

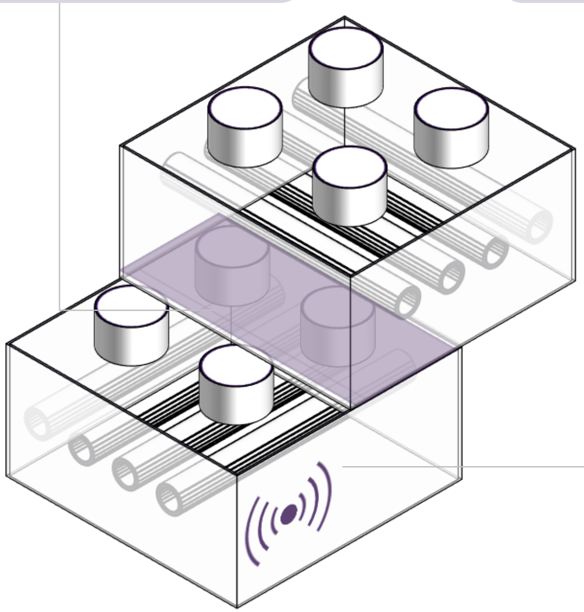
Fabrication

Optimized manufacturing

- reduce energy
- reduce material

Operation

Increased lifespan

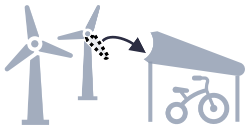


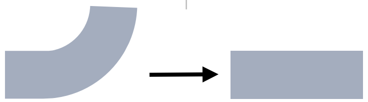
Active monitoring

Repair

End of Life

Repurpose | **Recycle** | **Recovery**





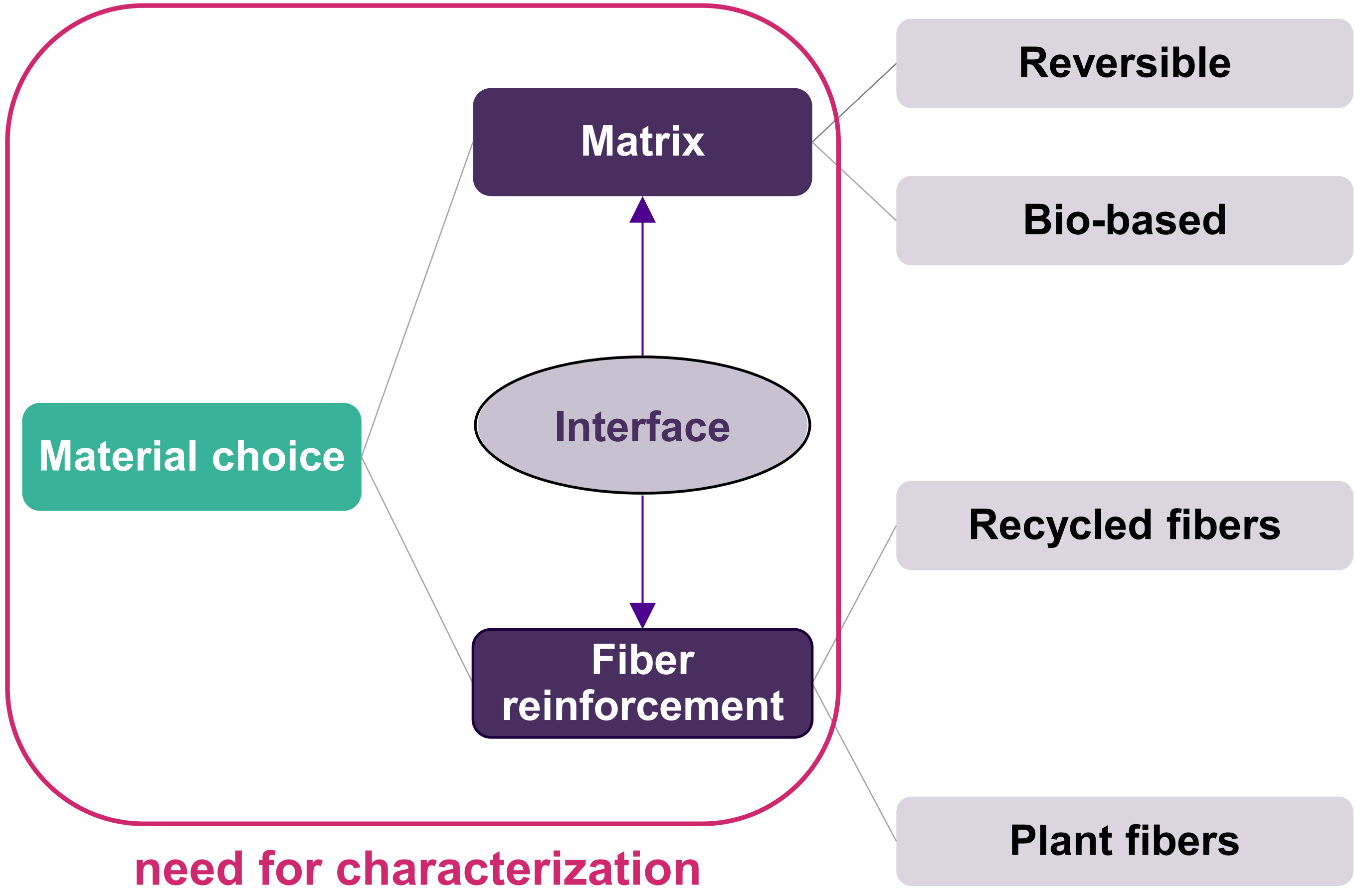
Temperature assisted reshaping

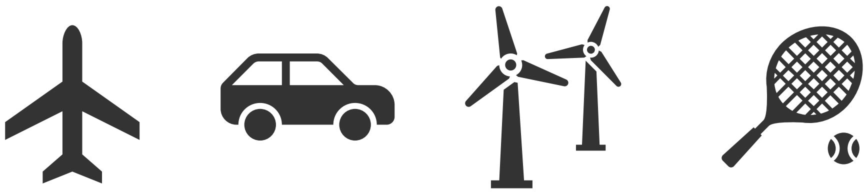
- mechanical
- pyrolysis
- solvolysis
- electrofragmentation
- microwave
- fludized bed

Cement clinker

Mettalurgical processes
Calcium carbide

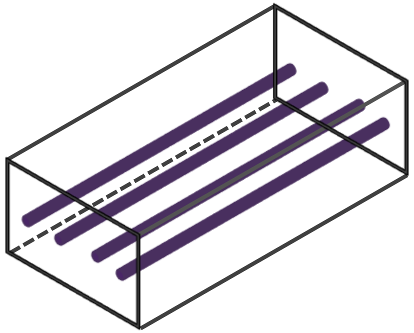
Sustainable composite components



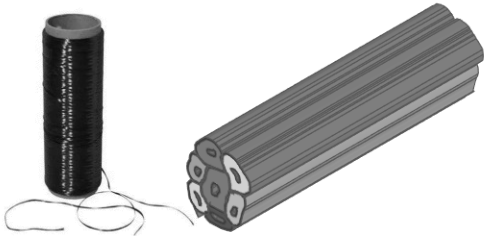


μ-scale – a key to accurate characterization

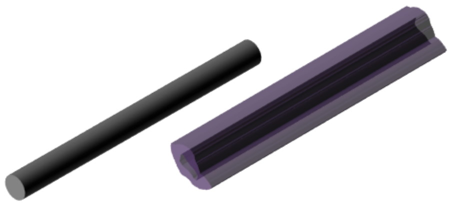
Composite	Yarn/bundle	Single fiber	Nanoscale
~ 10cm	~ 100μm	~ 10μm	~ 10nm



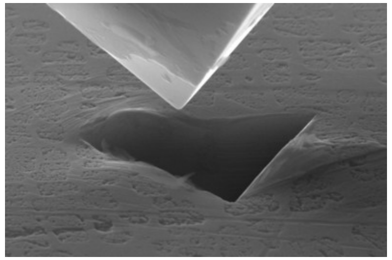
Composite
+ common/normalized tests
+ larger object size
+ averaging over large number of fibers
– ROM simplifying hypotheses
– measurement uncertainties



Yarn/bundle
+ can be present in composite
+ inter-fiber properties
– complex morphology and interactions

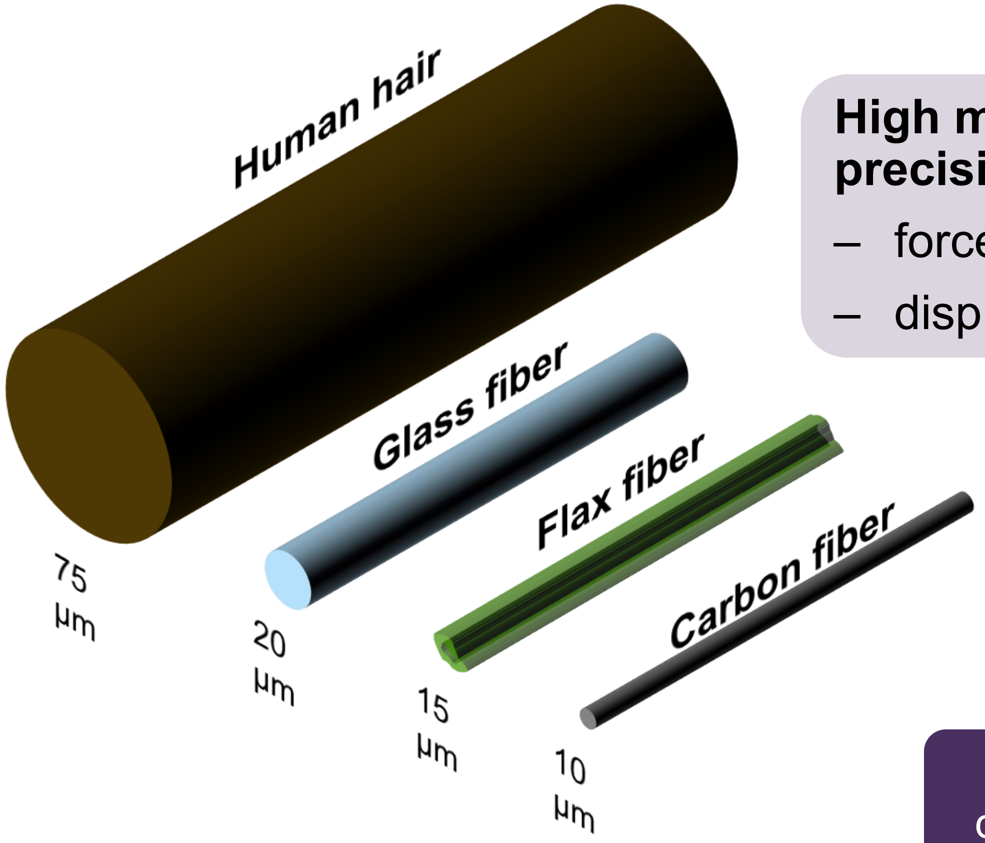


Single fiber
+ basic reinforcement unit
– small size
– complexity
– smaller sample sizes



Nanoscale
+ reveals fiber microstructural properties
– sensitivity to surface preparation
– extremely localized measurements

Challenges – size

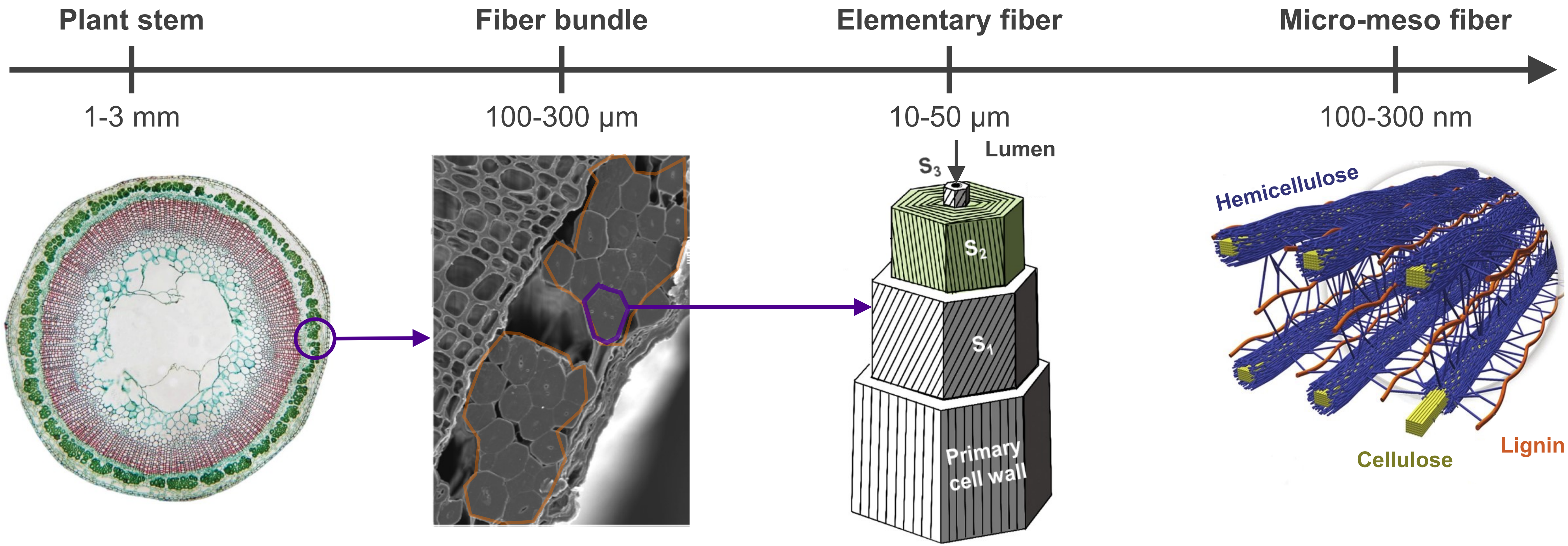


High measurement precision
- force < *mN*
- displacement < *µm*

Scale – physical effects
- adhesion, electrostatic forces > gravity
- diffusion, evaporation

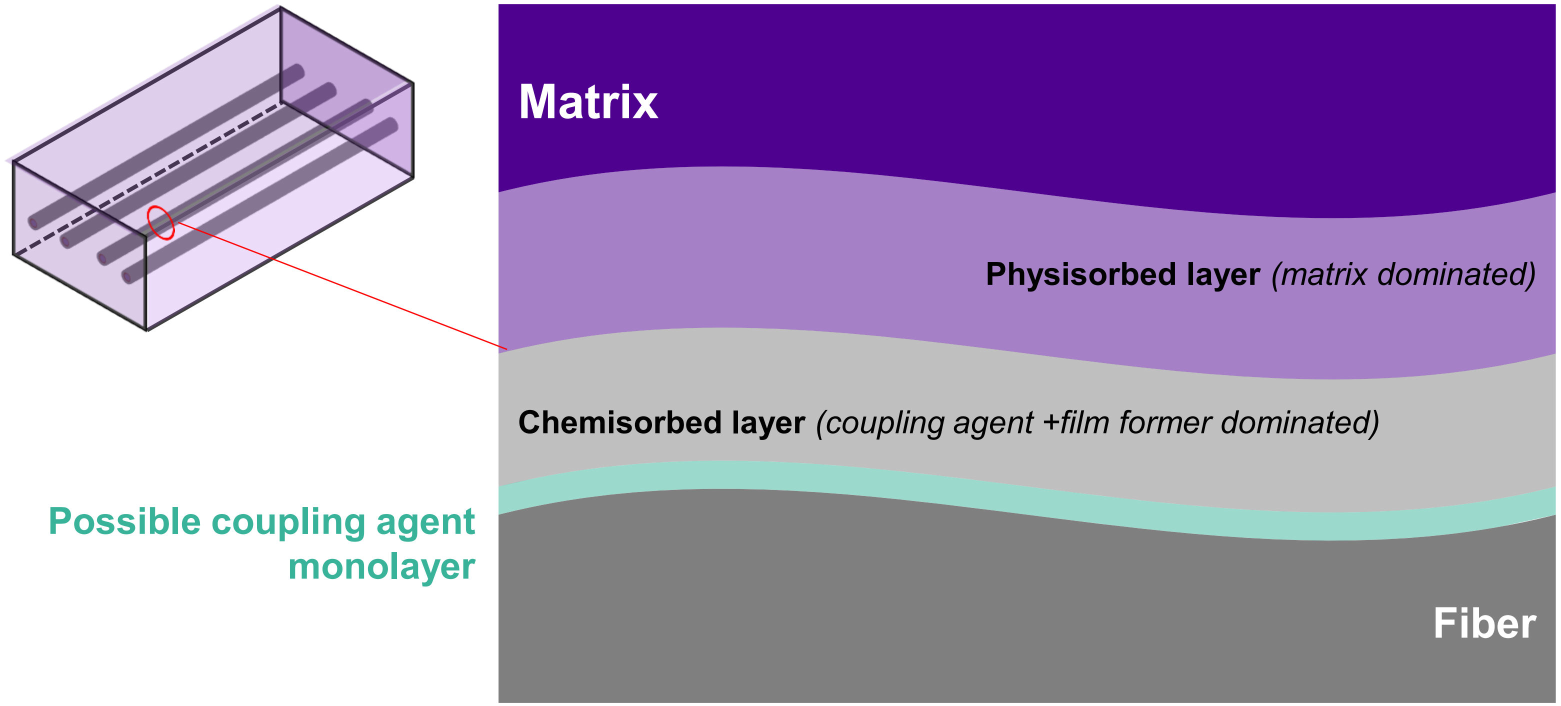
Small size / delicate nature → Difficult sample preparation; Time consuming testing → Small sample size

Challenges – complexity



Sadrmanesh et al. 2019 *Zeng et al. 2015* *Meleli et al. 2020* *Brandt et al. 2013*

Challenges – complexity



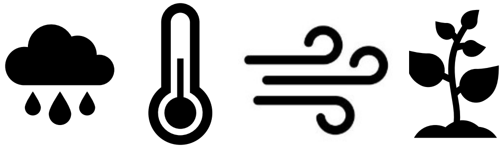
Adapted from Laurikainen, P. (2023).

- **Matrix-fiber adhesion =** complex physico-chemical interaction
- **Commercial sizing =** carefully optimized
- **Adhesion after recycling =** difficult to predict & understand

Challenges – variability

Plant fibers

Growing conditions



Processing

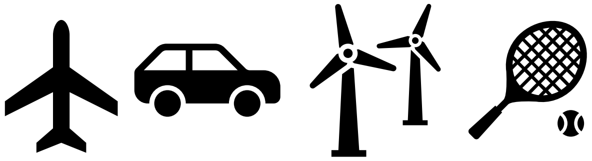
- retting
- skutching
- hackling

libecohomestores.com

libecohomestores.com

Recycled fibers

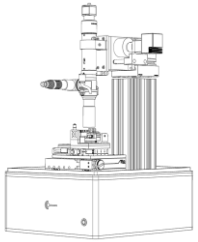
Operation conditions



Recycling process

- Mechanical recycling
- Solvolysis
- Pyrolysis
- Electrofragmentation
- Microwave pyrolysis
- Fluidised-bed pyrolysis

Challenges – overview and solutions



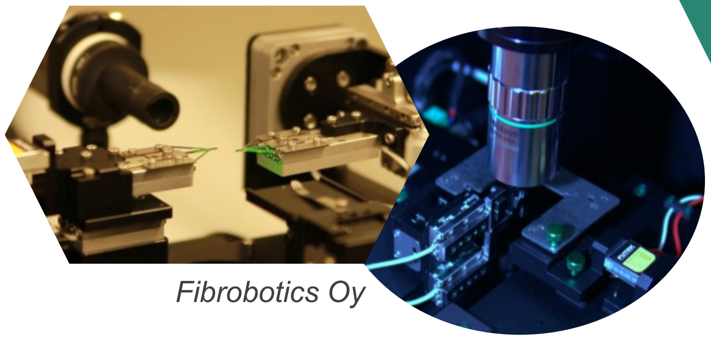
Size

µmechatronics

Automation

Low sample size

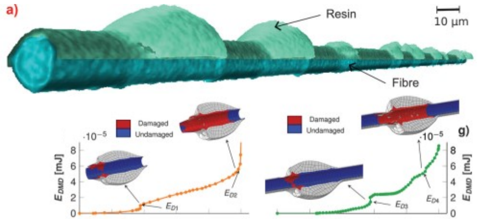
Variability

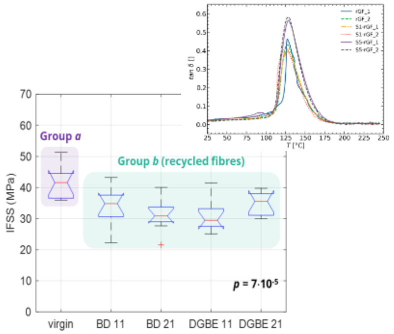


Fibrobotics Oy

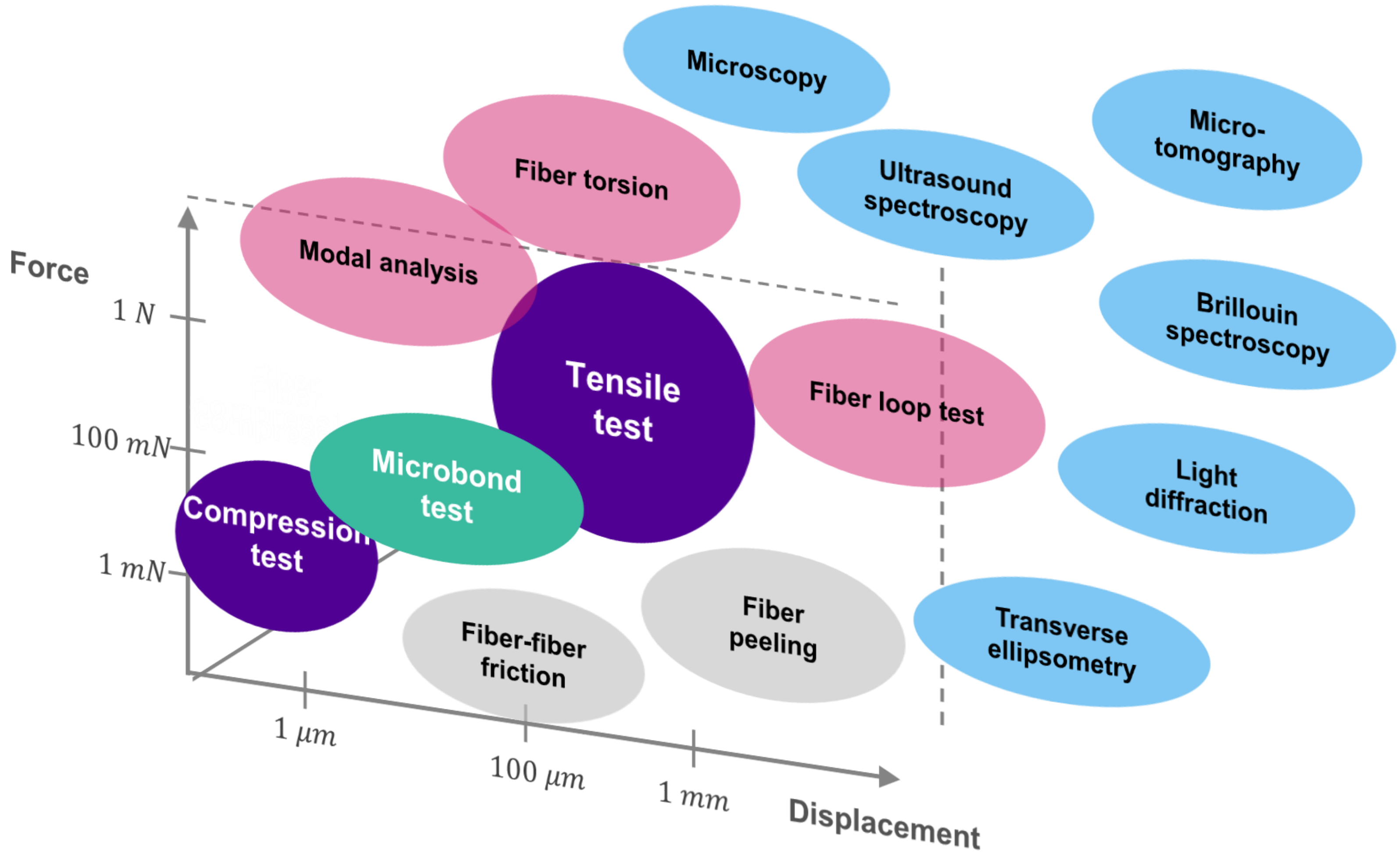
Complexity

- Finite Element Analysis
- Chemical Analysis
- Microscopy / tomography

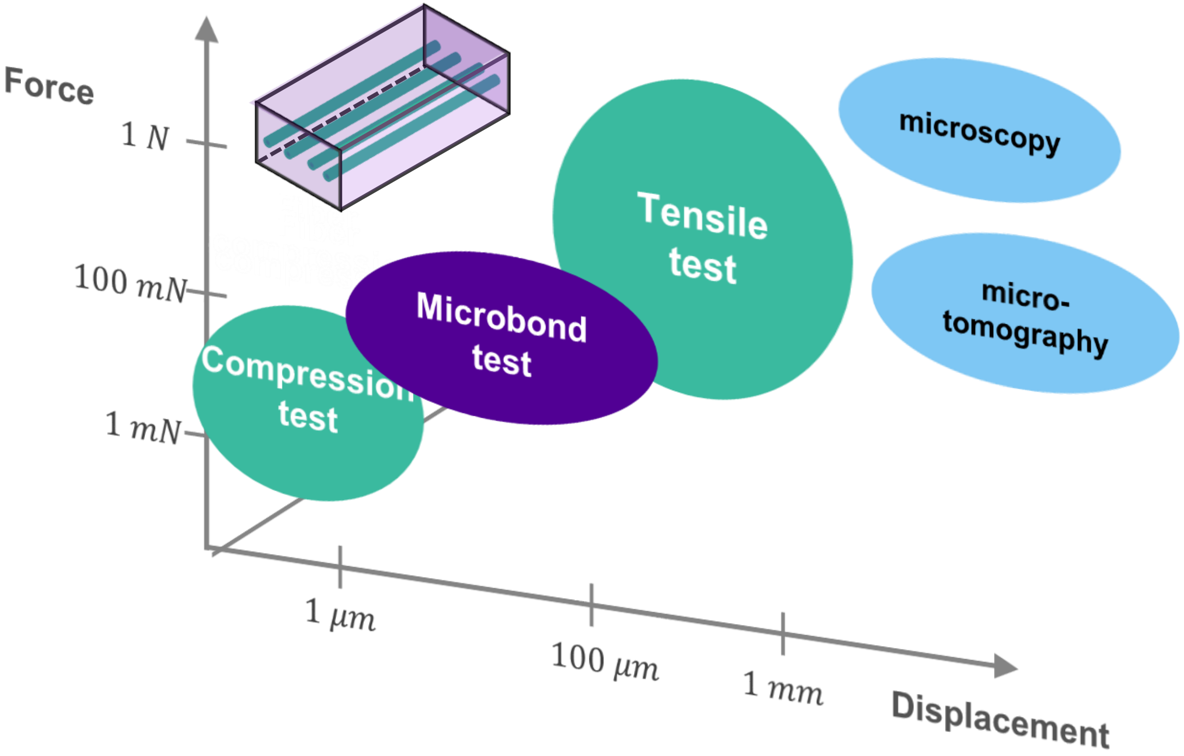




µ-scale fiber characterization



µ-scale fiber characterization



Plant fibers = complex geometry — Morphology characterization

Fibers ~ transversely isotropic

E_L/E_T ratio = high

E_L → tensile testing

E_T → transverse compression

Fiber / matrix interface = critical to composite performance

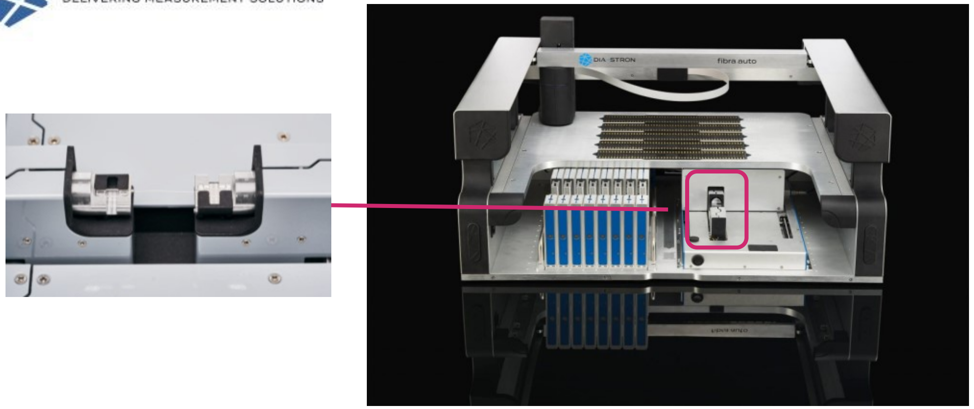
Microbond testing

Tensile testing

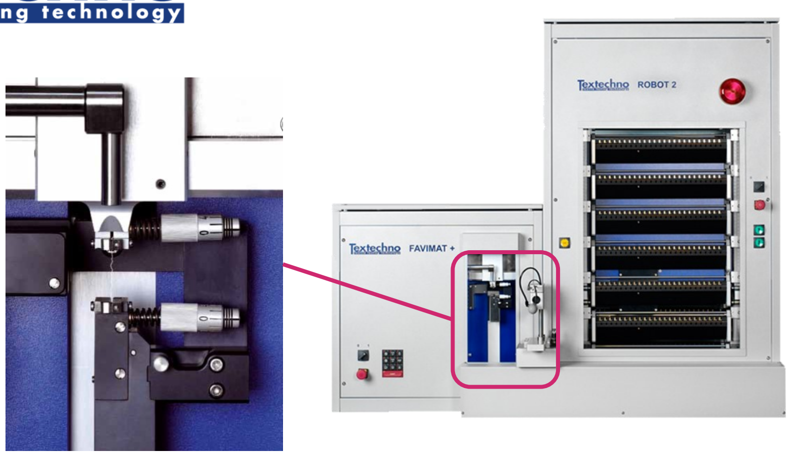
- Standardized test *(ASTM. C1557)*
- Commercially available micromechanical characterization setups
- Automated sample swapping

Fiber	Glass	Carbon	Aramid	Flax
Tensile modulus E_L *(GPa)*	75	250	80	60
Tensile strength E_T *(GPa)*	2.5	4.0	3.2	1.0

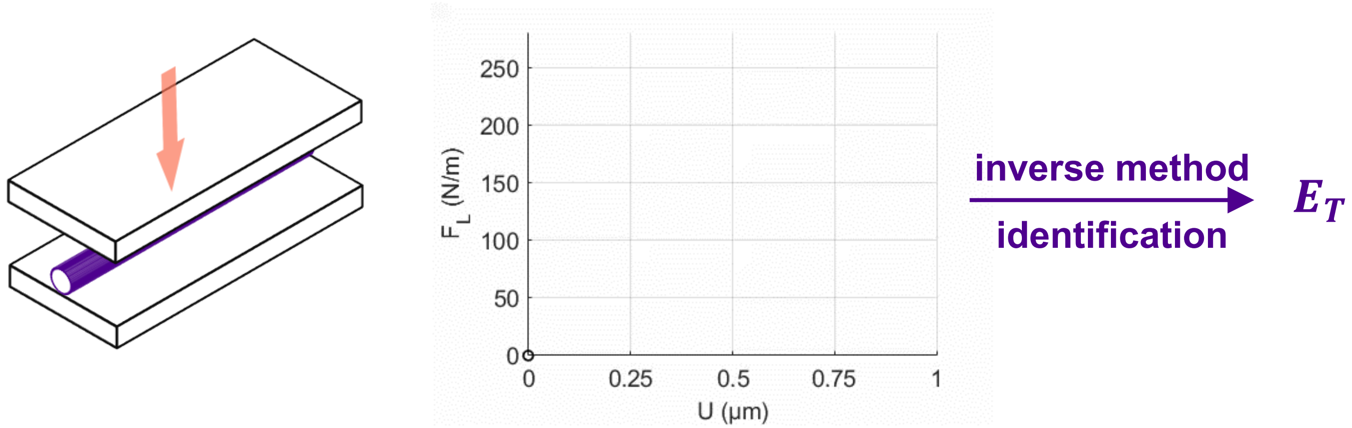
DIA–STRON
DELIVERING MEASUREMENT SOLUTIONS



Textechno
textile testing technology

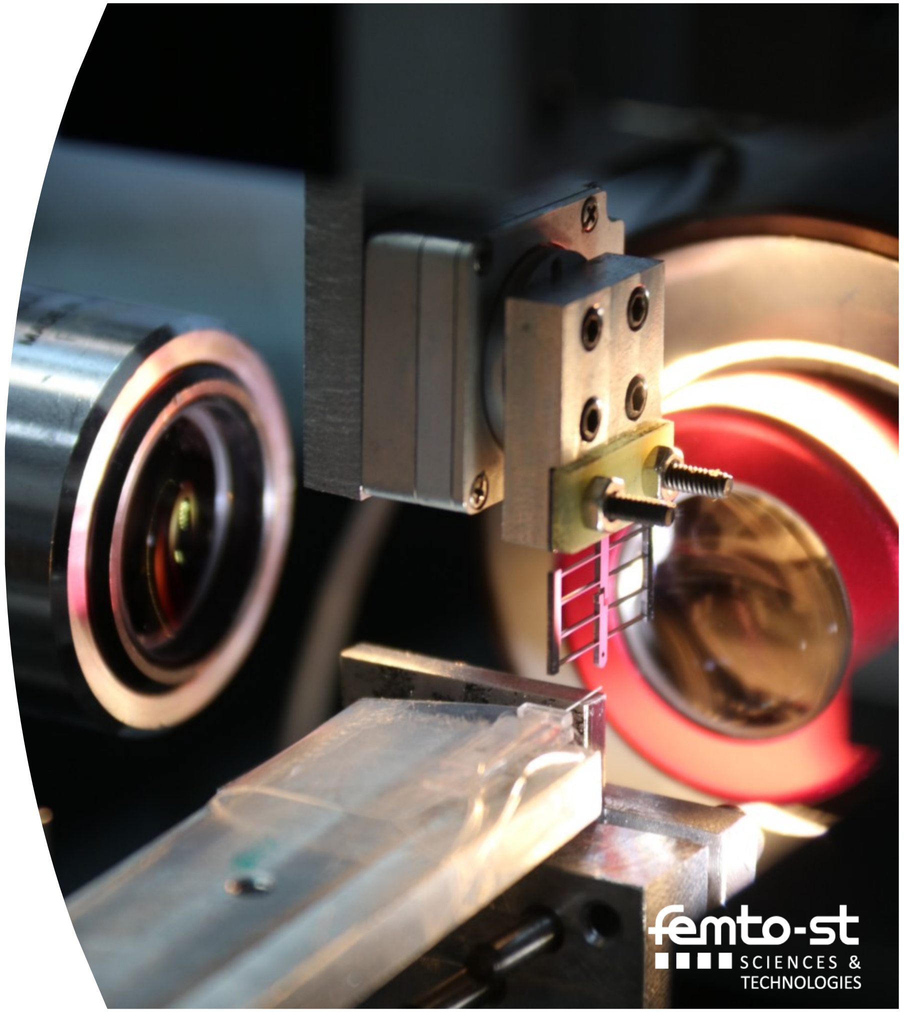


Transverse compression

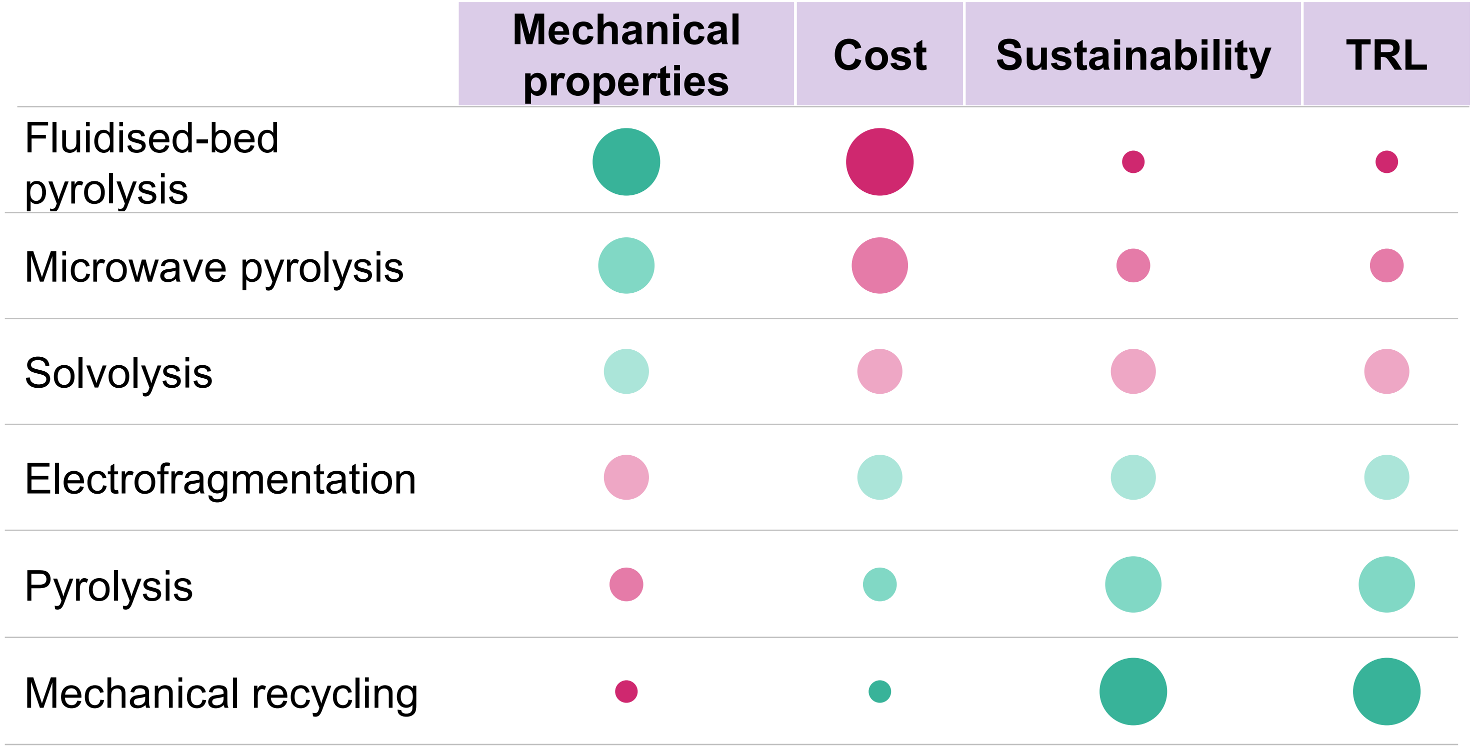


- No commercially available setups
- No standard testing method

Fiber	Carbon	Aramid	Flax
Transverse modulus E_T (GPa)	8.0	2.0	1.7
E_L/E_T	31	40	35



Recycled fiber mechanical properties



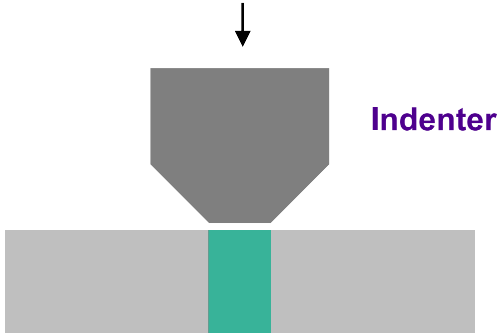
- **No statistically significant loss in mechanical properties after recycling = possible**
- Compromise between cost, sustainability and TRL

Interface characterization

Single-fiber fragmentation test

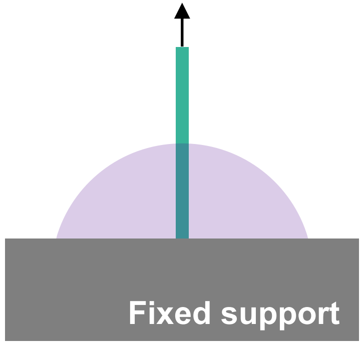
- + good composite replication conditions
- + fiber strength, IFFS, IFFT
- + simple test setup
- – sample preparation complexity
- – transparent/ translucent matrix
- – failure strain: fiber << matrix

Push-out test



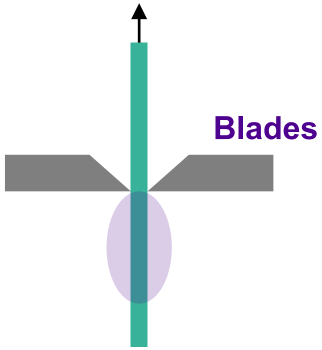
- + can performed on composite samples
- – fiber splitting
- – difficult fracture detection
- – challenging indenter placement
- – sensitive to polishing quality

Pull out test



- + direct IFSS measurement
- – sample preparation complexity
- – challenging for brittle fibers
- – stress concentrations

Microbond test

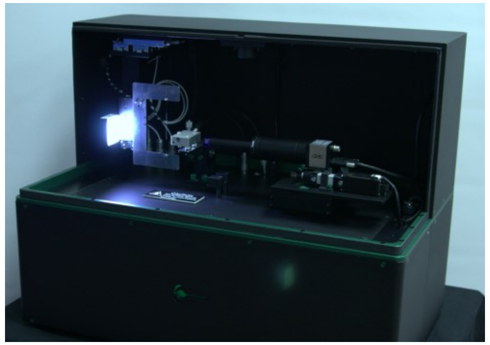


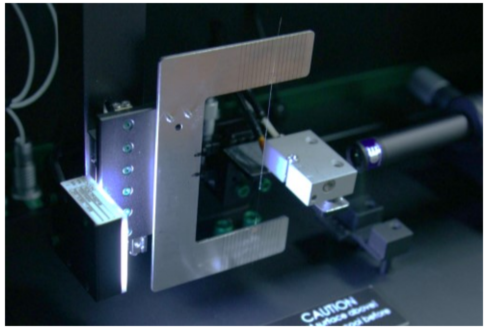
- + applicable to any fiber/matrix
- + easy sample preparation
- + large sample sizes
- – altered resin behavior
- – influence of meniscus/film

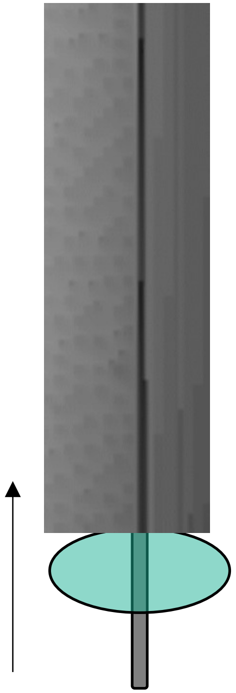
Microbond testing

FIBROBOTICS

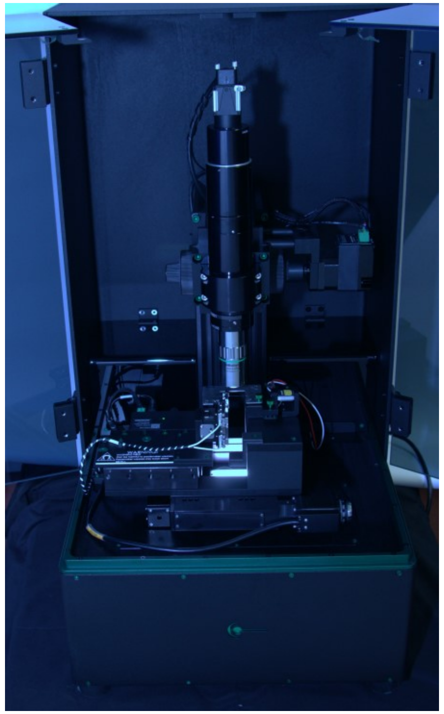
Sample preparation: *FIBRODROP*

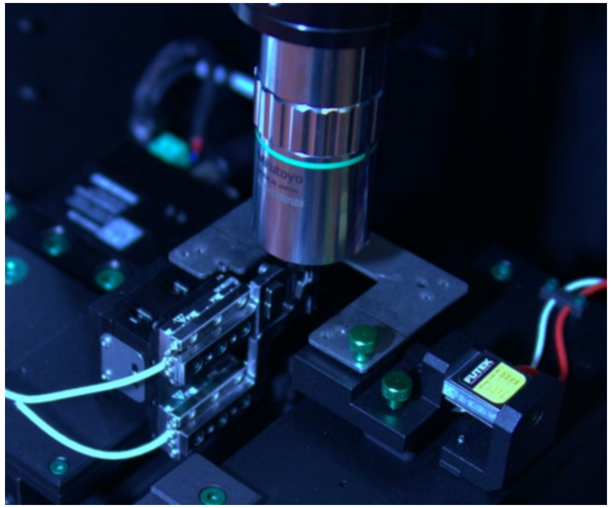






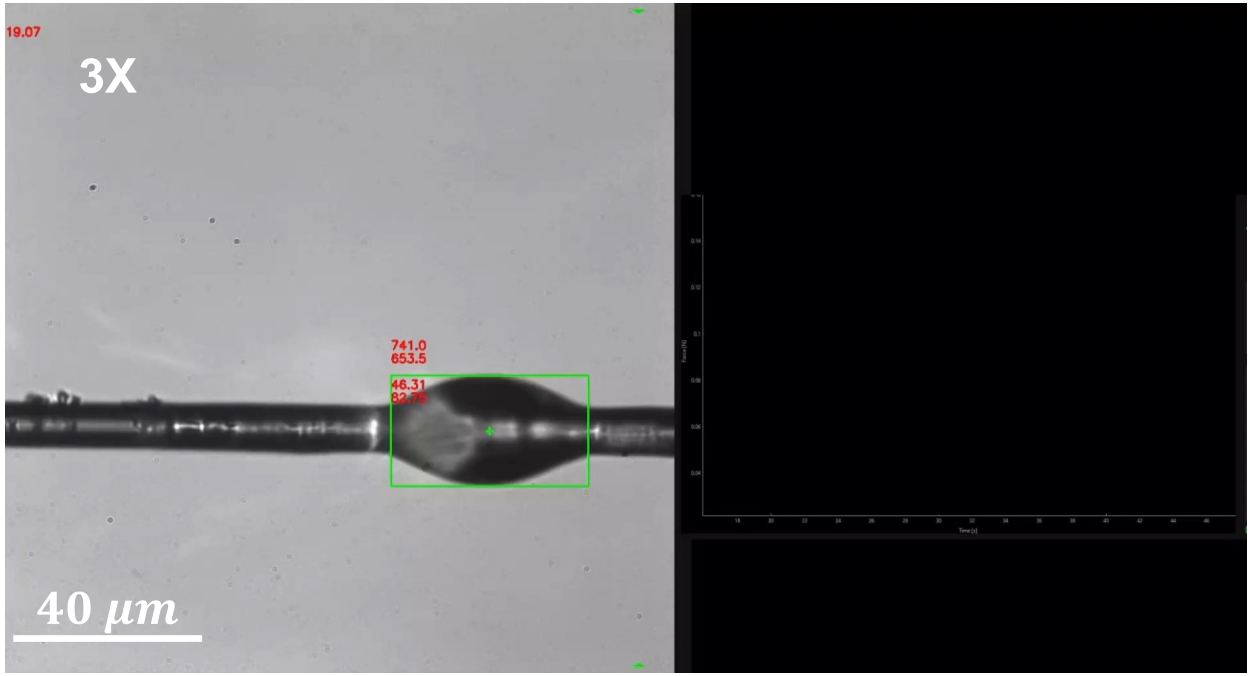
Sample testing: *FIBROBOND*

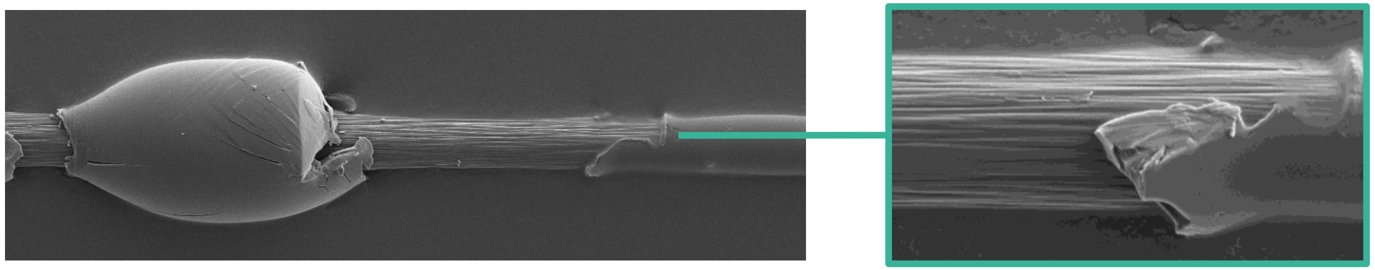




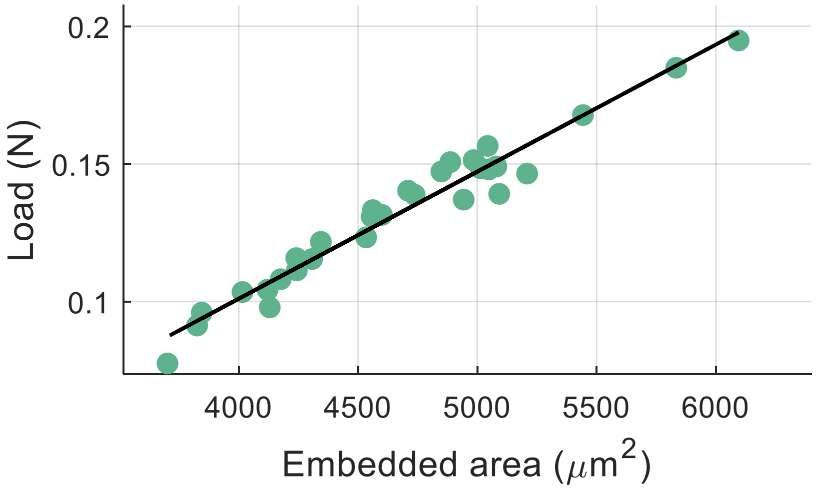
Microbond testing

FIBROBOTICS

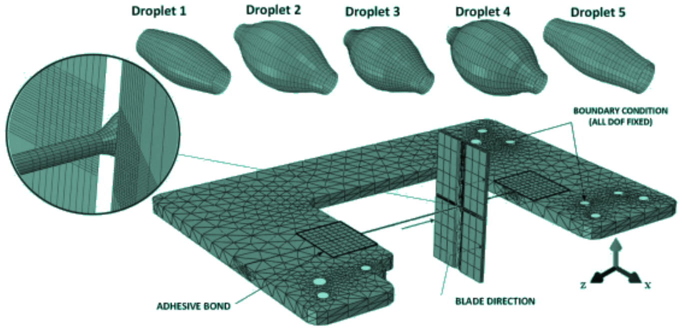




Interfacial shear strength (IFSS)

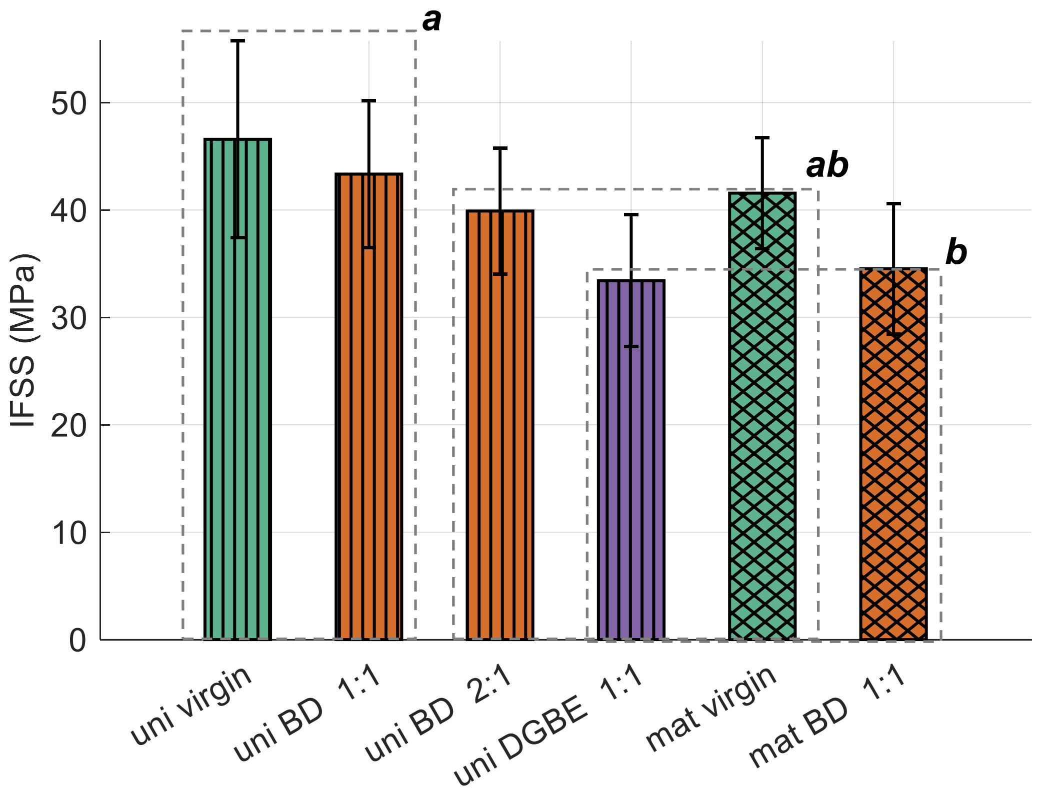


Finite element models



Dsouza et al. 2020

Microbond results



- **Recycling can have minimal/ no impact on interface properties**
- **Large sample size:**
  - 100 fibers
  - 3000 individual droplets measurements

Fiber	**Glass**	**Carbon**	**Aramid**	**Flax**
Interfacial Shear Strength (MPa)	~40	~50	~30	23

Past and on-going work

Ongoing work

Recycled fiber interfaces characterization, *Jesse Savolainen, Jason Govilas*

PhD research

Characterisation and Validation of the microscale testing of fibre matrix interphases, *Pekka Laurikainen*

Interfacial toughening strategies for impact and fatigue tolerant structural **biocomposites**, *Farzin Javanshour*

Numerical and Experimental developments for improved fiber-matrix interphase characterization *Royson Dsouza*

Exploring mechanical adhesion in fiber reinforced composites with **Aramid and Recycled Carbon Fibers**, *Sarianna Palola*

FIBROBOTICS

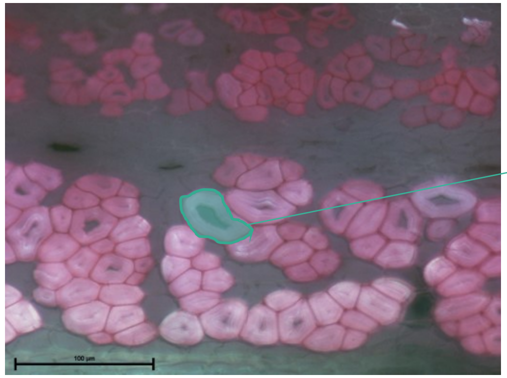
RI. SE

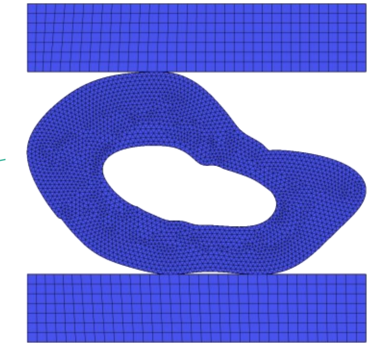
KTH VETENSKAP OCH KONST

University of Patras

Morphology characterization

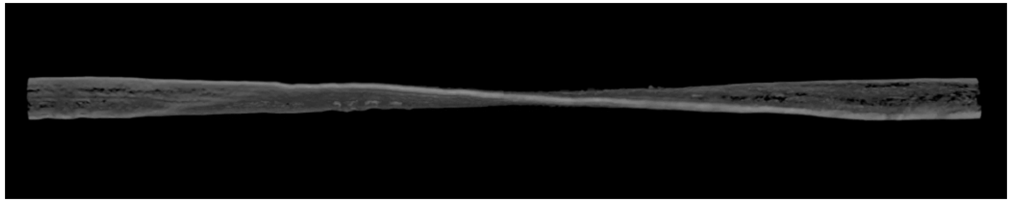
Optical microscopy





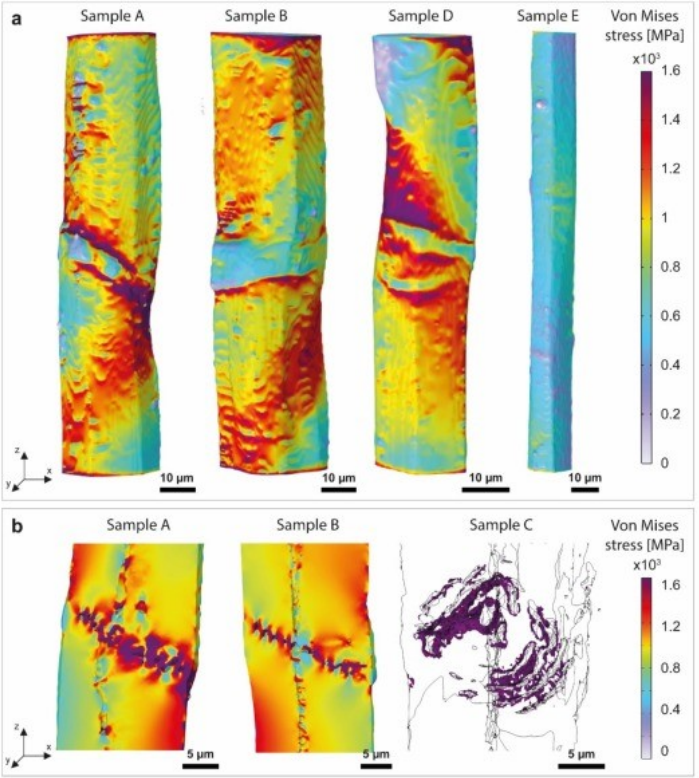
Govilas et al. 2023

Optical tomography



FIBROBOTICS

Microtomography



Quereilhac et al. 2024

Take-home message

- **μ-mechanical testing** = essential approach for accurate fiber property characterization
- **Holistic approach (mechanics, automation, modeling, chemistry) =** essential to tackle fiber complexity
- **Sustainable reinforcement alternatives**
  - plant fibers : comparable properties to synthetic fibers, unique advantages/disadvantages
  - recycled fibers: wide variety of property/cost choices
- **Tampere university innovation =** leader in the field of μ-scale fiber characterization
- **Future work:**
  - experimental testing development
  - standardization of existing tests
  - devellopement supporting methods (numerical models, data science)

Tampere University
Tampere University of Applied Sciences

Thank you for your attention !