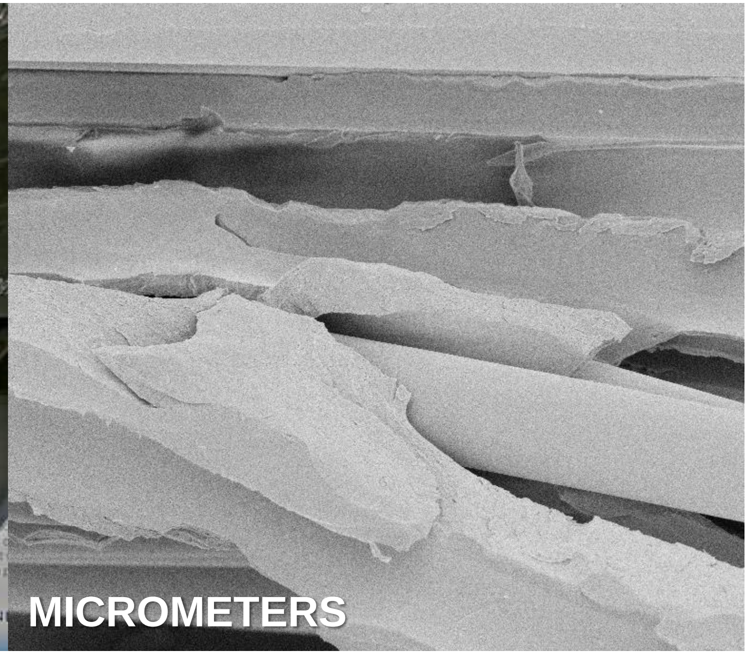
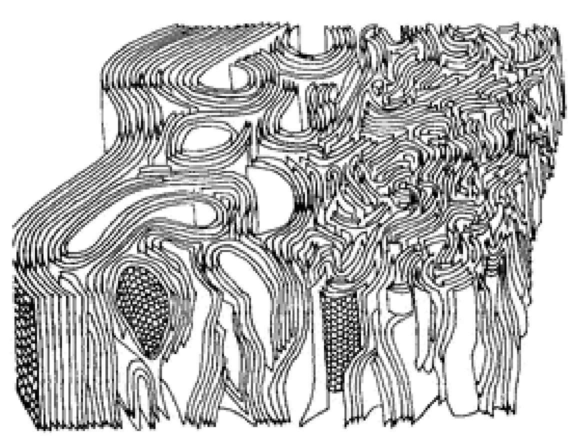
Fachhochschule Nordwestschweiz
Hochschule für Technik

SWISS NANOSCIENCE INSTITUTE
EINE INITIATIVE DER UNIVERSITÄT BASEL UND DES KANTONS AARGAU

Mechanical properties of carbon-based composite materials – about size effects and hierarchies





NANOMETERS

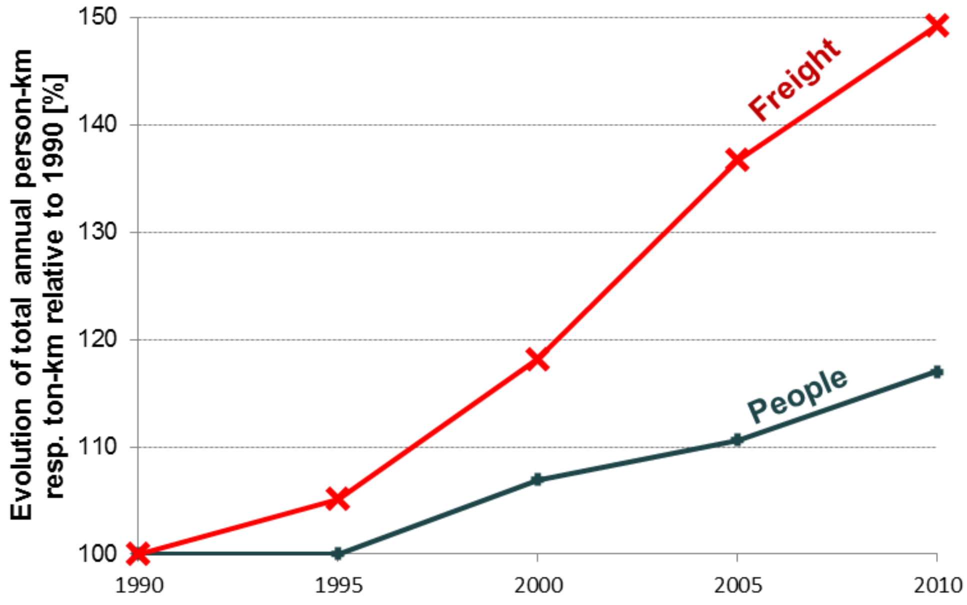
C. Dransfeld, Institute of Polymer Engineering
FHNW University of Applied Sciences and Arts Northwestern Switzerland

Content

- **The relevance of lightweight materials**
- **Carbon fibres and carbon fibre reinforced polymers composites**
- **CNTs and graphene in lightweight materials**
- **Hierarchies and size effects**
- **Conclusion**

Efficient low carbon mobility

- The transportation sector's share of the total energy consumption in 2010 in Switzerland was around 34%
- The need for mobility is continuously increasing
- Optimization in the mobility sector is of highest importance regarding CO2 and pollutant emissions, as well as a general overall reduction of the energy demand



[SCCER Mobility, Bafu 2011]

- Greener engines
- Reduced drag
- **Lightweighting**

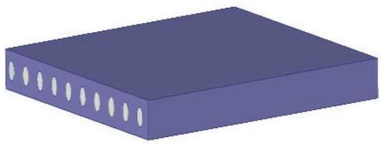
Work of acceleration

$$W = \boxed{m} \cdot a \cdot s$$

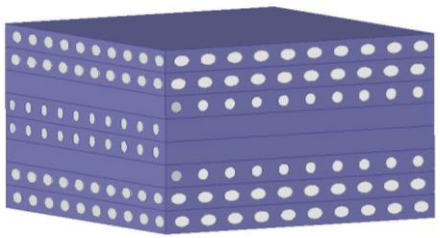
m: vehicle mass, a acceleration, s: distance

Carbon fibre reinforced polymers

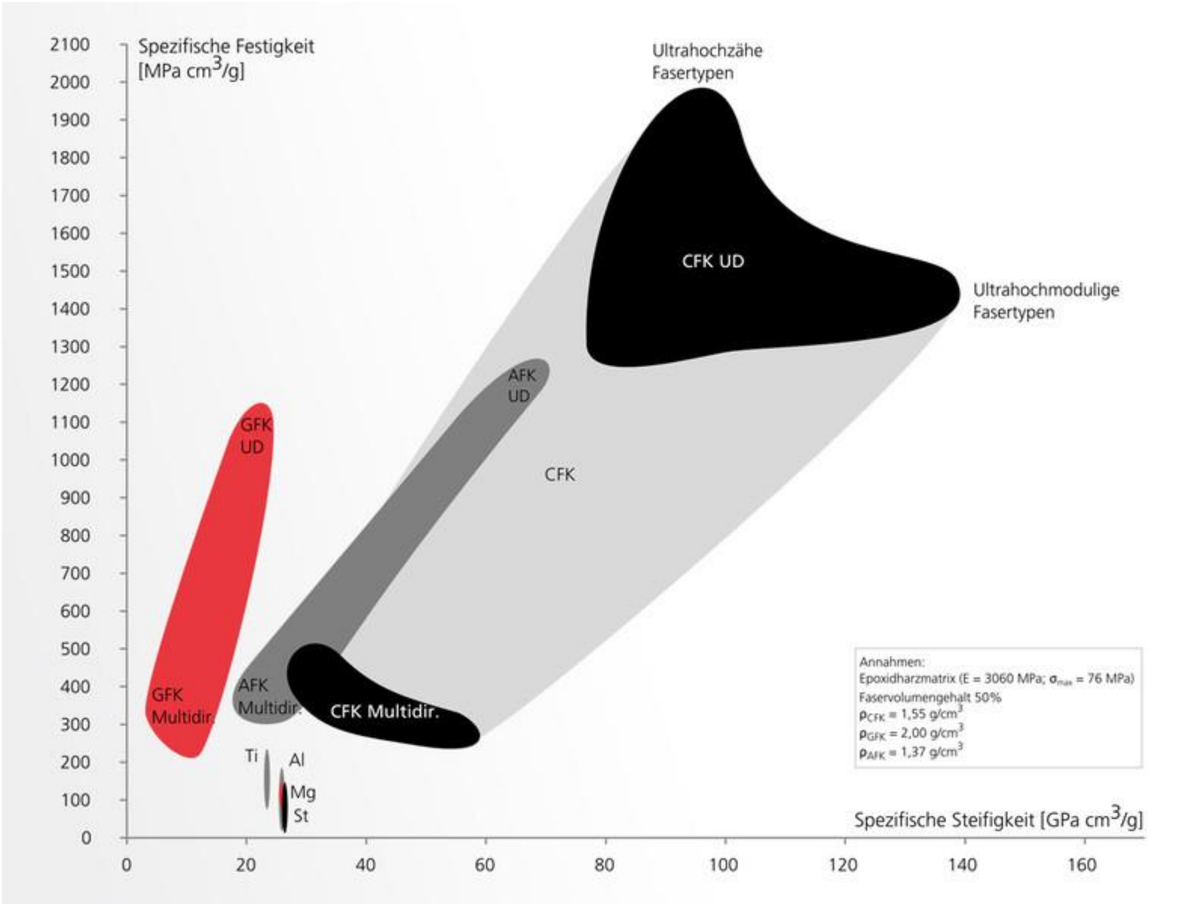
Industrial breakthrough of high performance lightweight materials replacing metals (steel, aluminium or titanium) in load bearing applications.



unidirectional

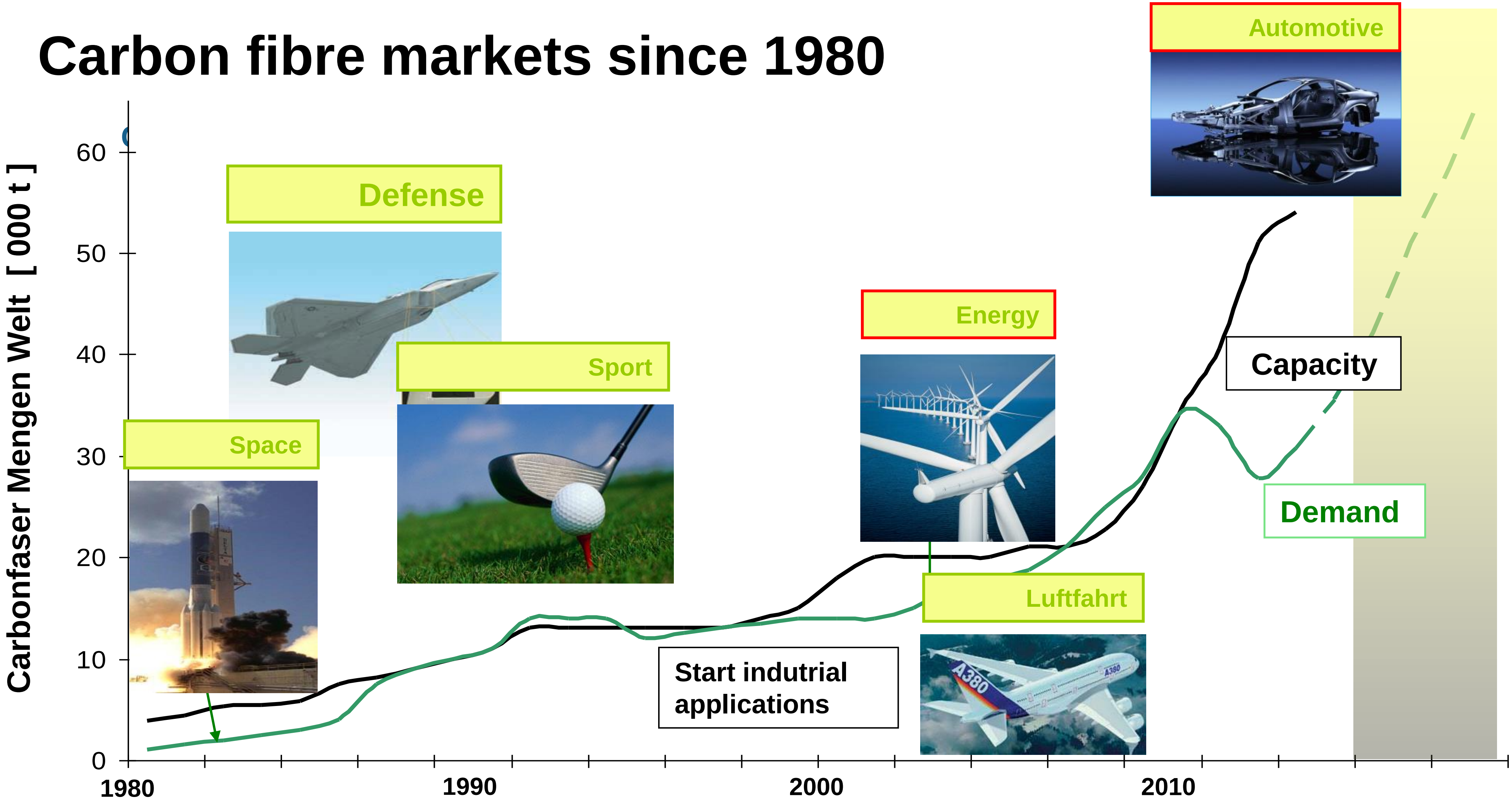


multidirectional



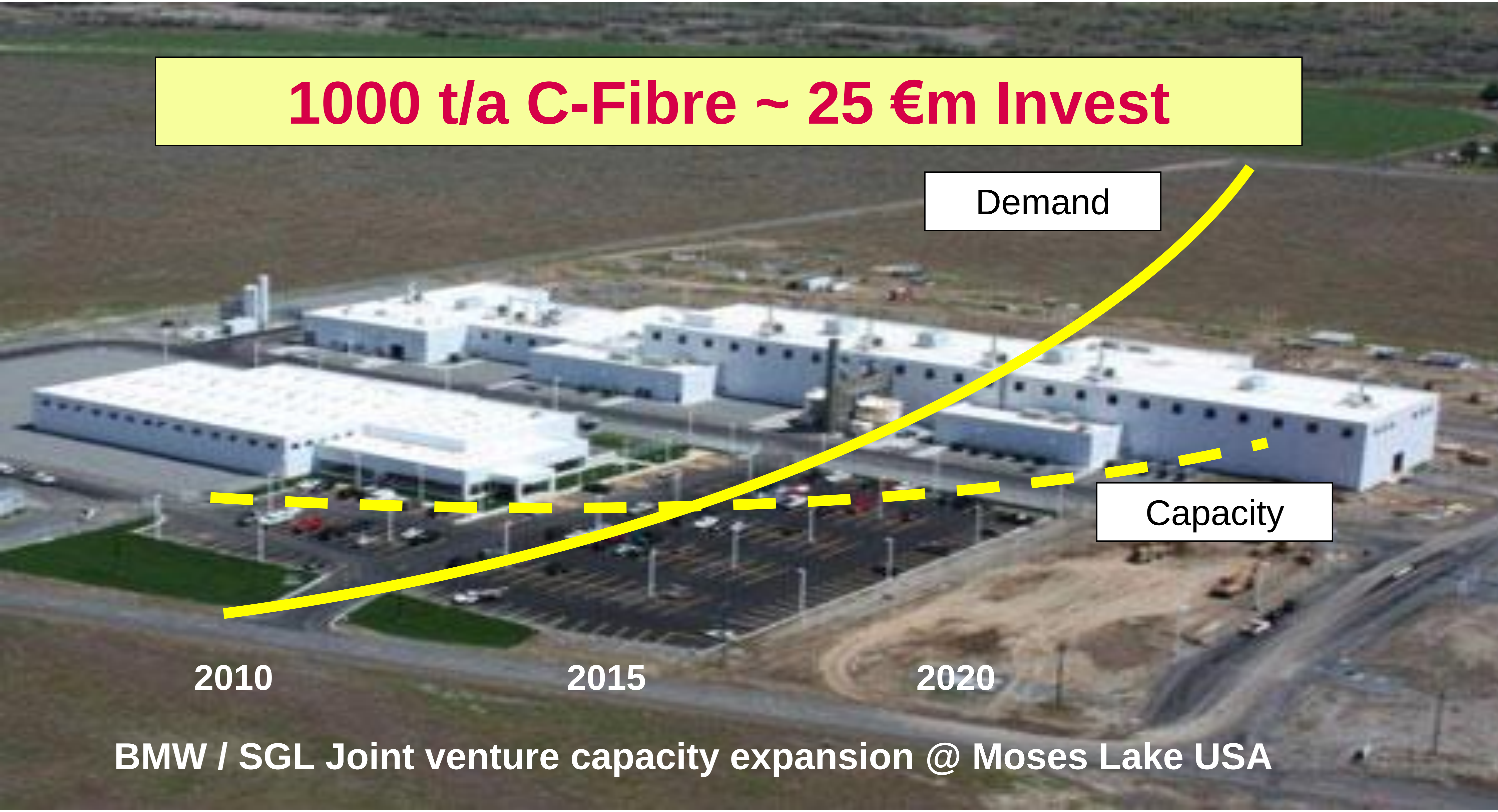
[Roding]

Carbon fibre markets since 1980



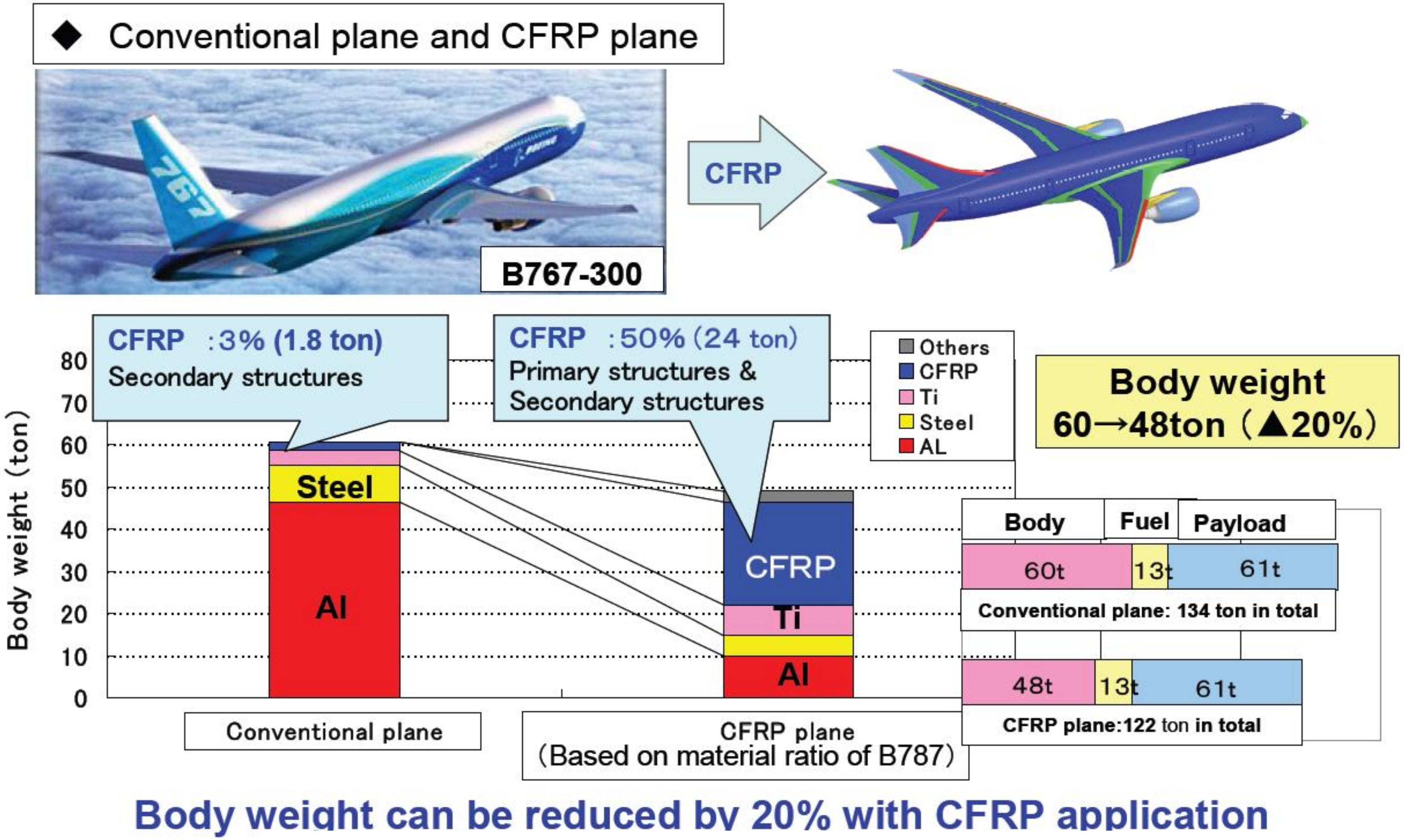
Note: Graph shows estimated net effective capacity based on mix weighting
Source: SGL Group market research

Capacity and Demand till 2020



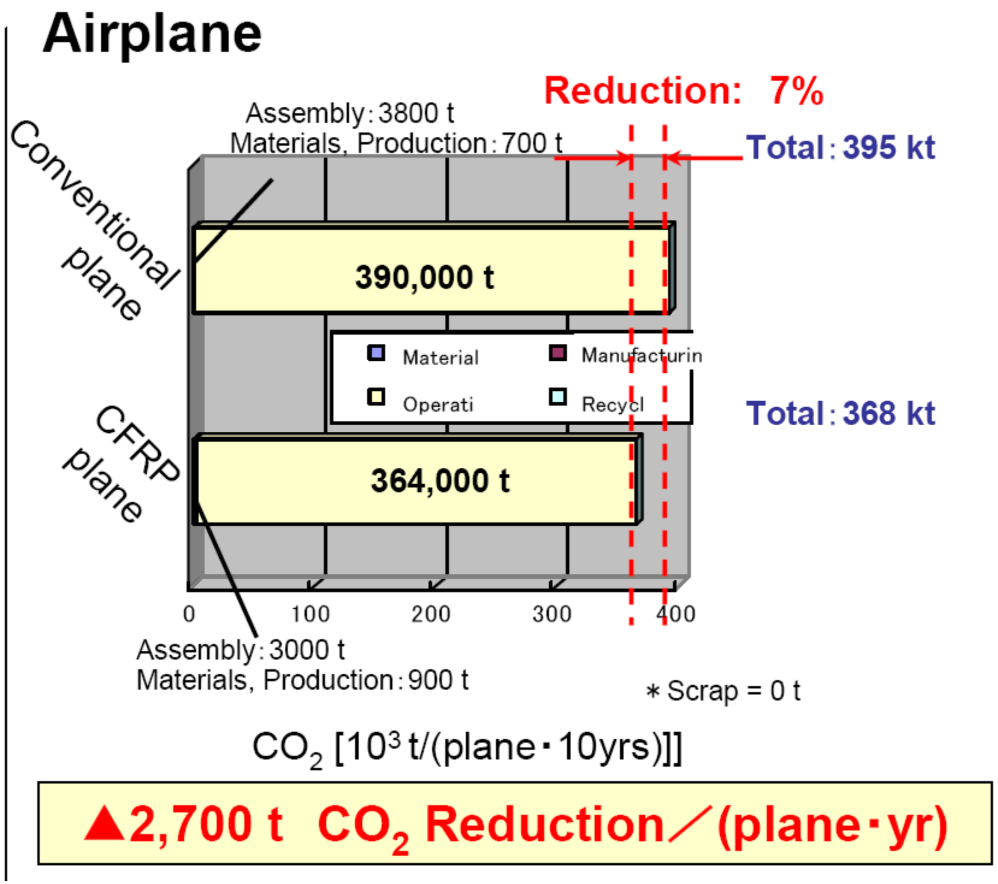
Source Dr. Jäger / SGL Carbon Group

The impact of lightweight with carbon based composites



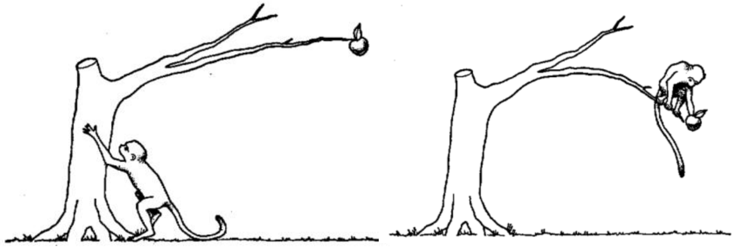
9% Total weight reduction=> 7% Reduction of CO_2 emission

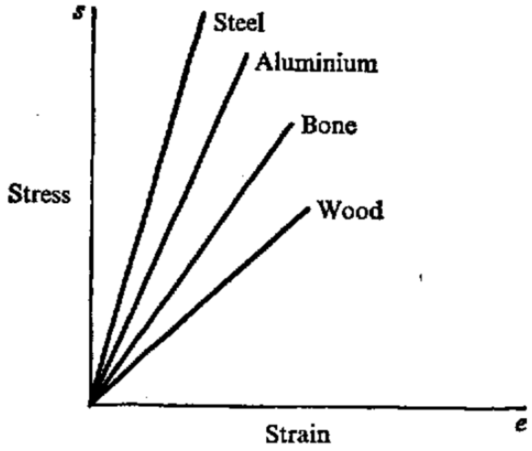
The impact of lightweight with carbon based composites



Achieving lightweight

…by material

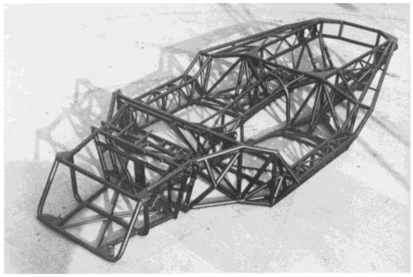


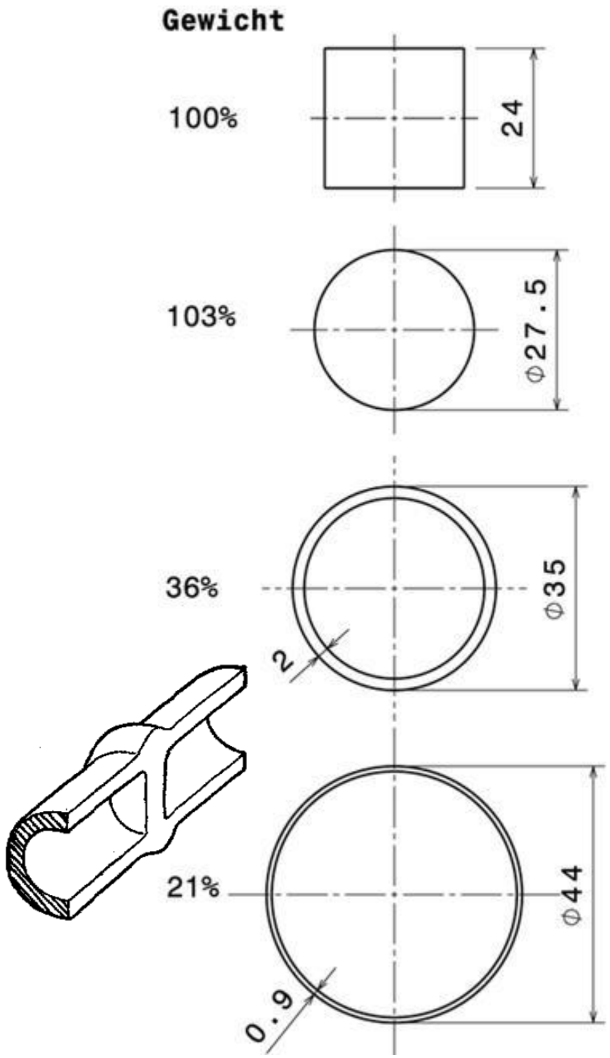


$$\sigma = E \cdot \varepsilon$$

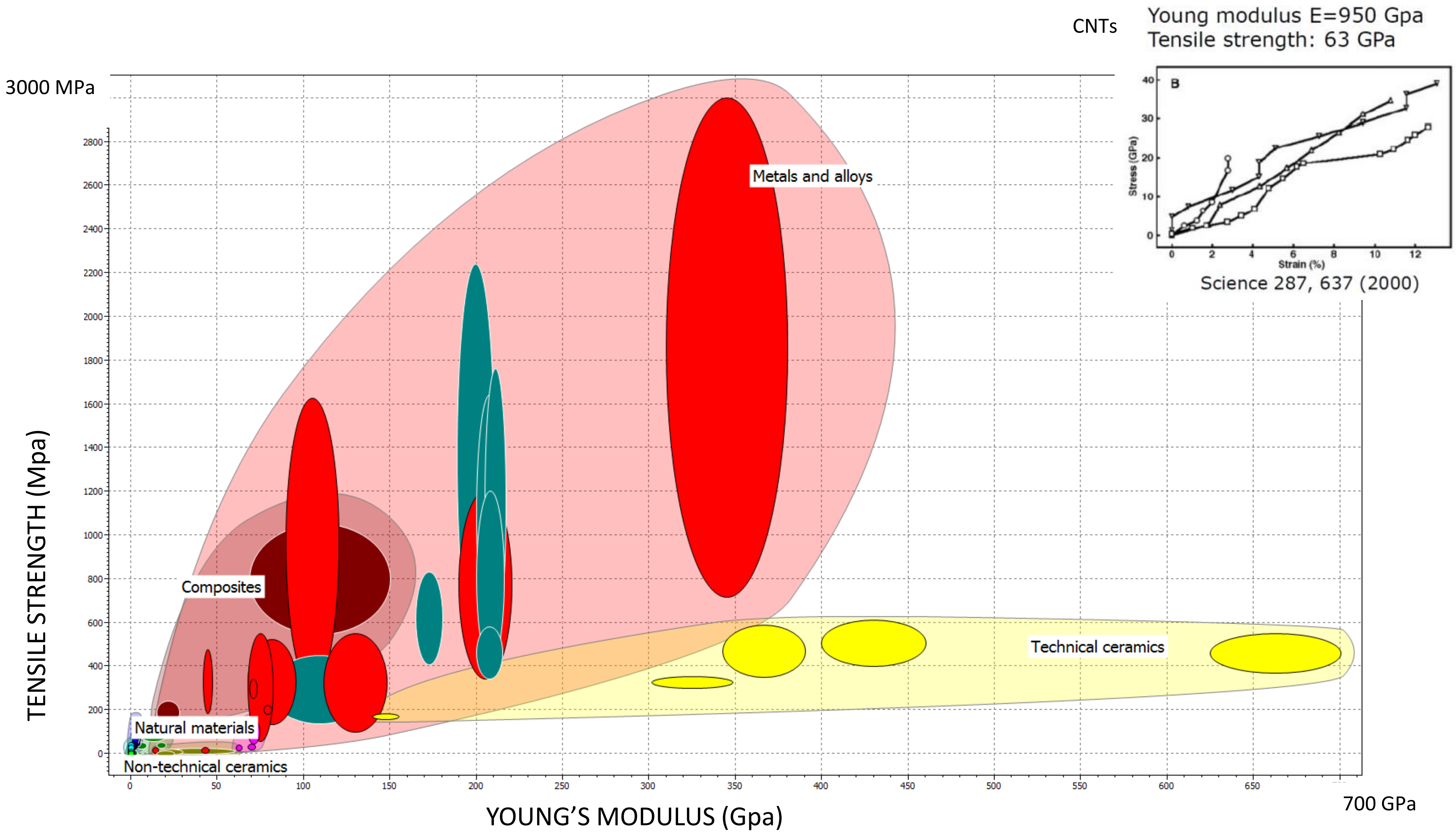
[Gordon 1978]

…by design





Absolute structural performance



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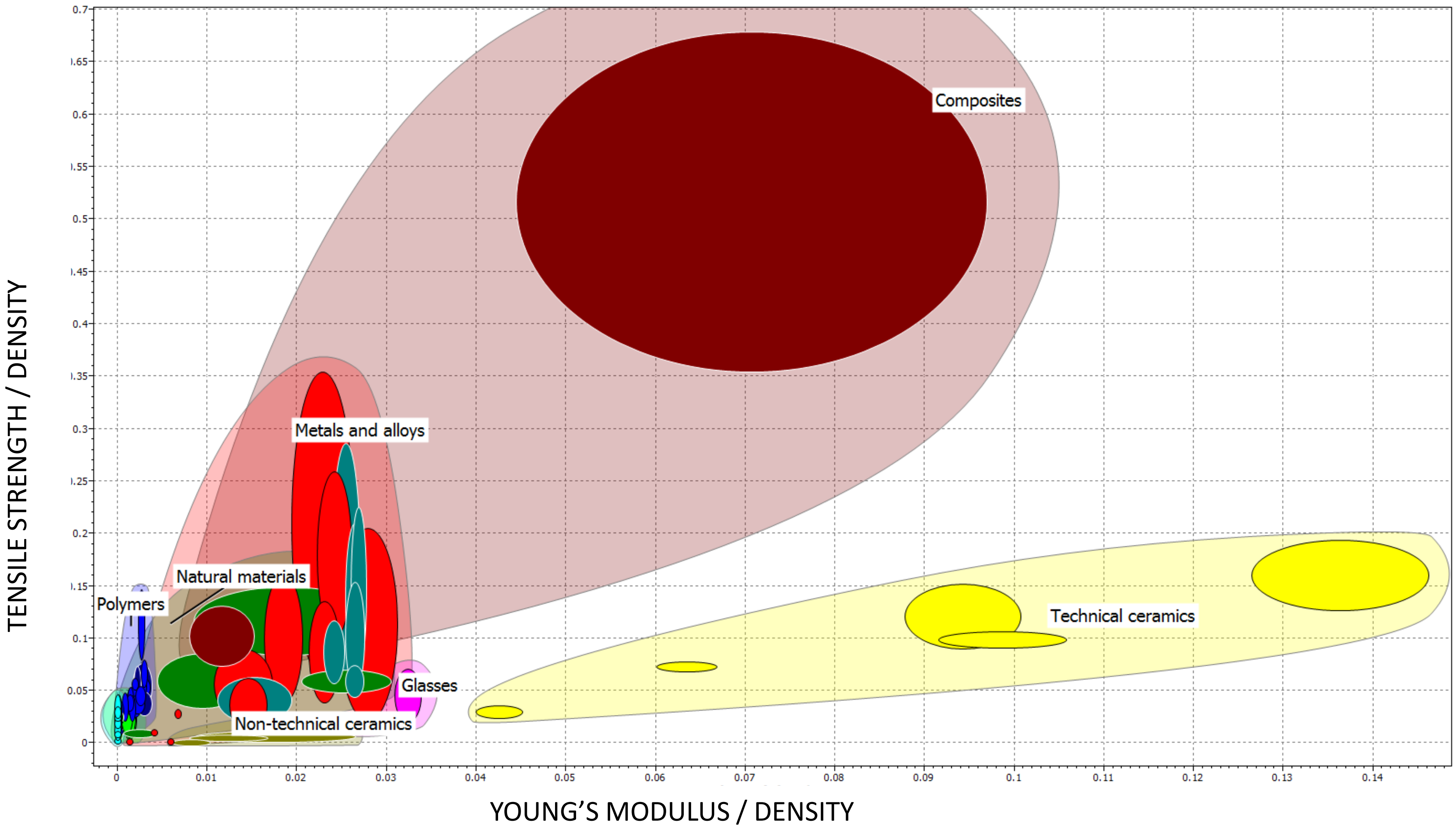
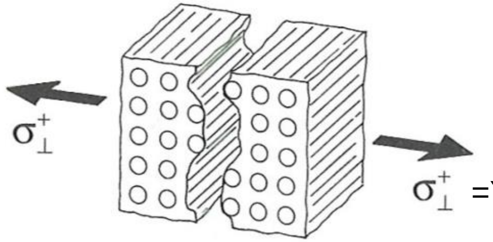
Specific (weight mormalized) performance



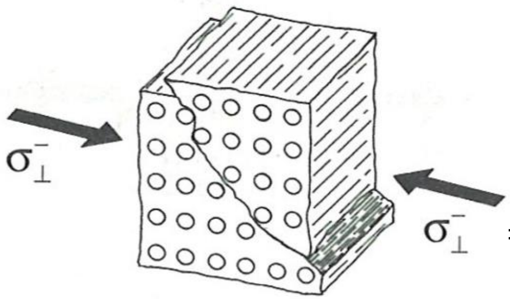
Failure in composites

Matrix failure



=Y_t

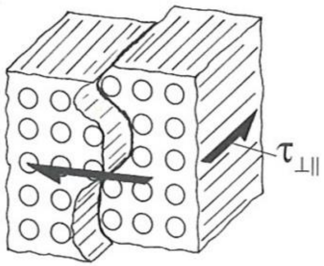
transverse tensile

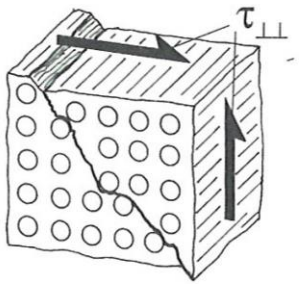


=Y_c

transverse compression

http://youtu.be/U9STWk2Nw00

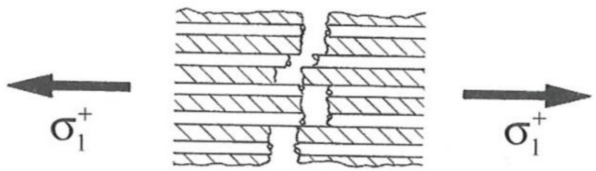


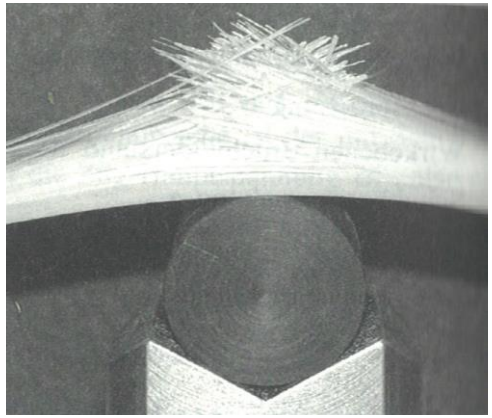


shear

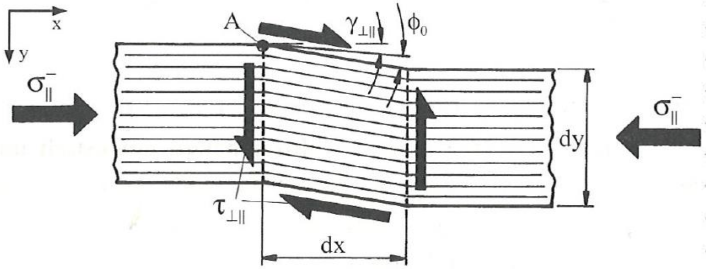
[Schürmann]

Fibre failure



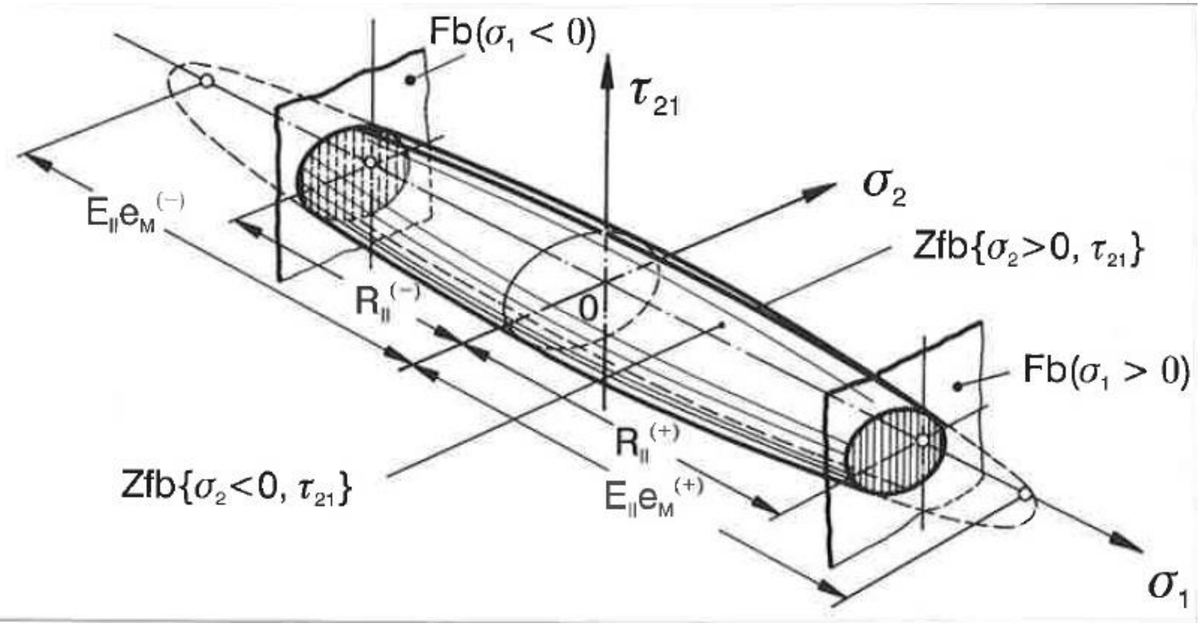


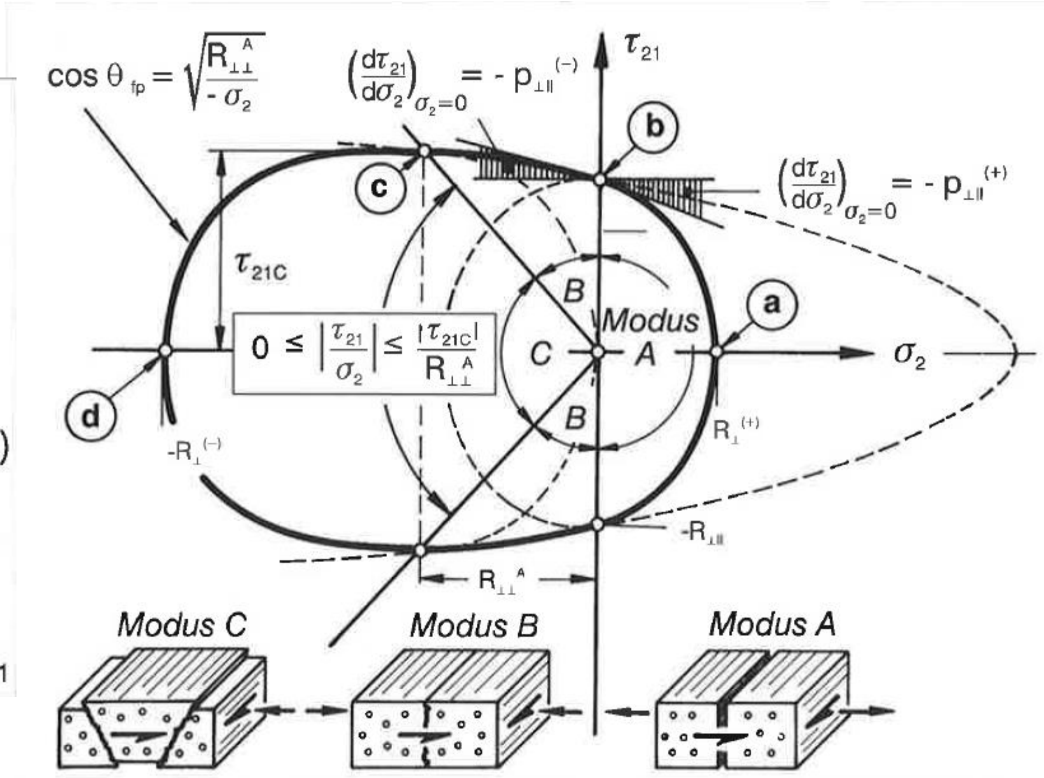
fibre tensile failure



fibre compression kink-band

Analyzing several failure modes at once – Puck's failure envelope

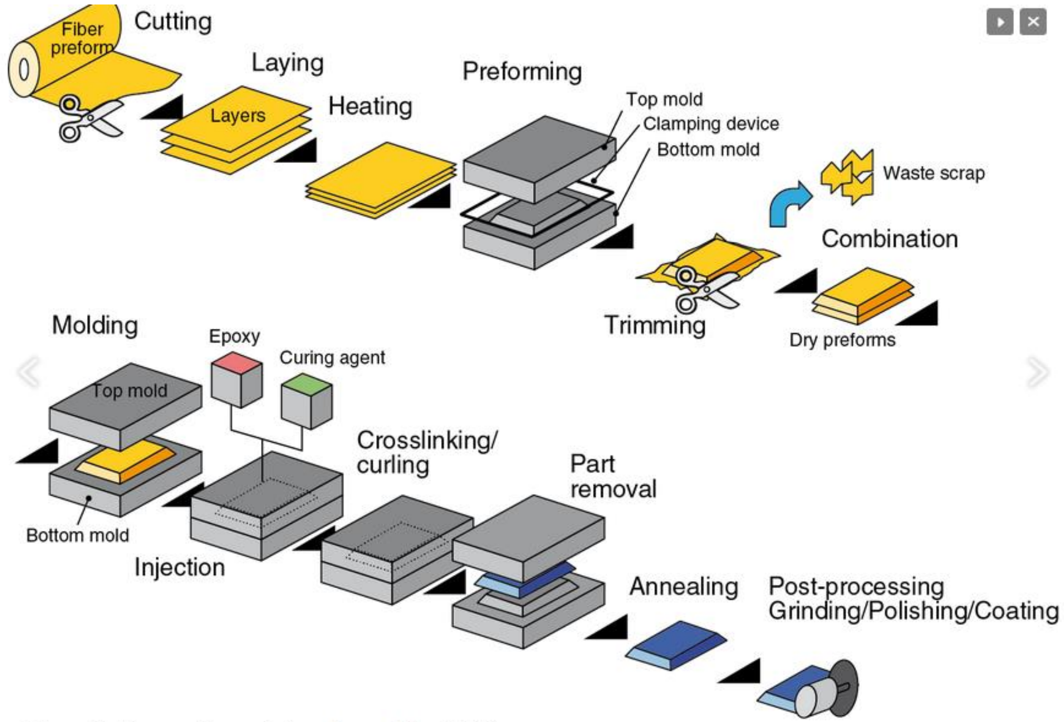




[Puck 1996]

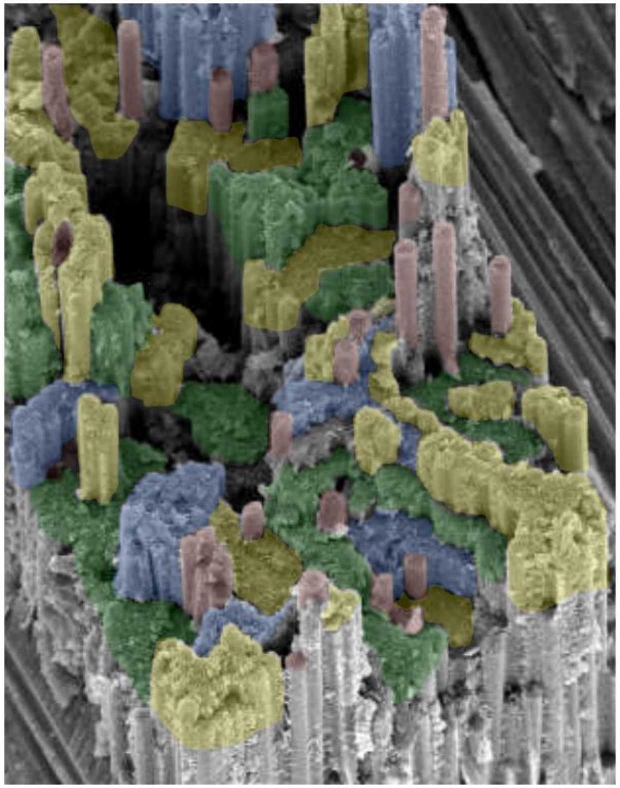
Carbon fiber reinforced polymer composites

Continuous carbon fibers @ 60 vol% embedded in a polymer matrix



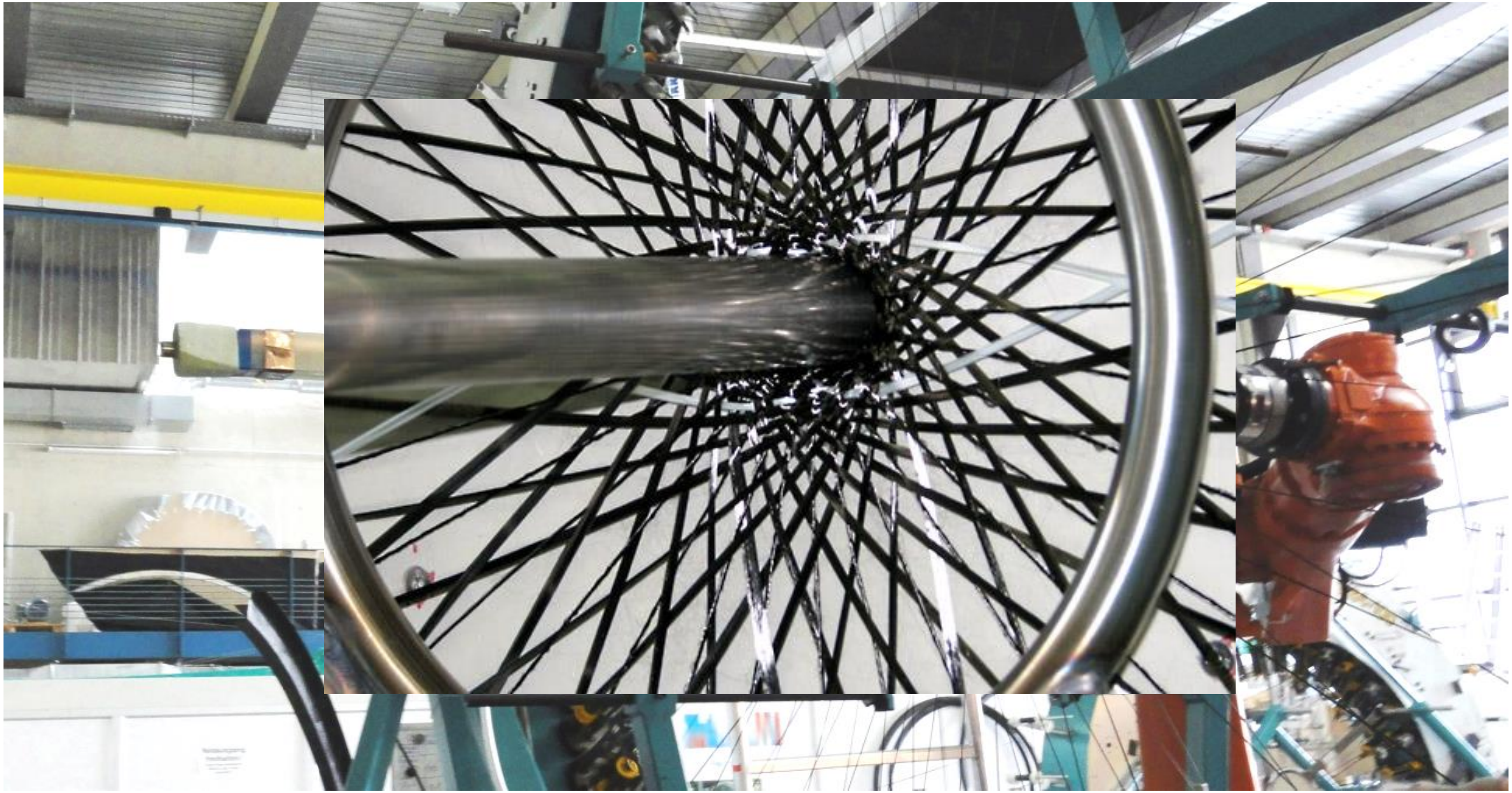
2 Schematic diagram of an resin transfer moulding (RTM) process *Item 2 of 7*

[Henne]



[Pimenta 2014]

Braiding with carbon fibres

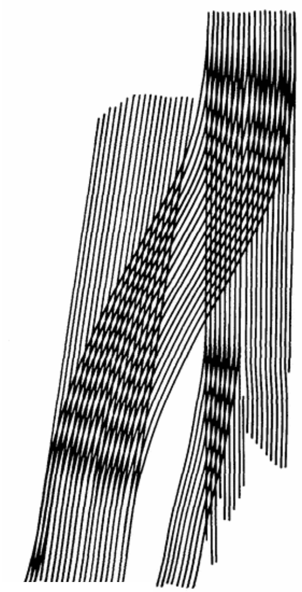


FHNW @ Institute of Aircraft Design – Uni Stuttgart

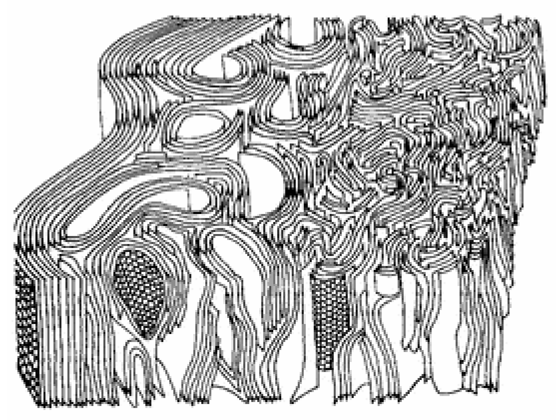
Carbon fibre

Made through graphitisation process of PAN Precursor fibre

SIZE OF SPECIMEN
7 µm x kilometers

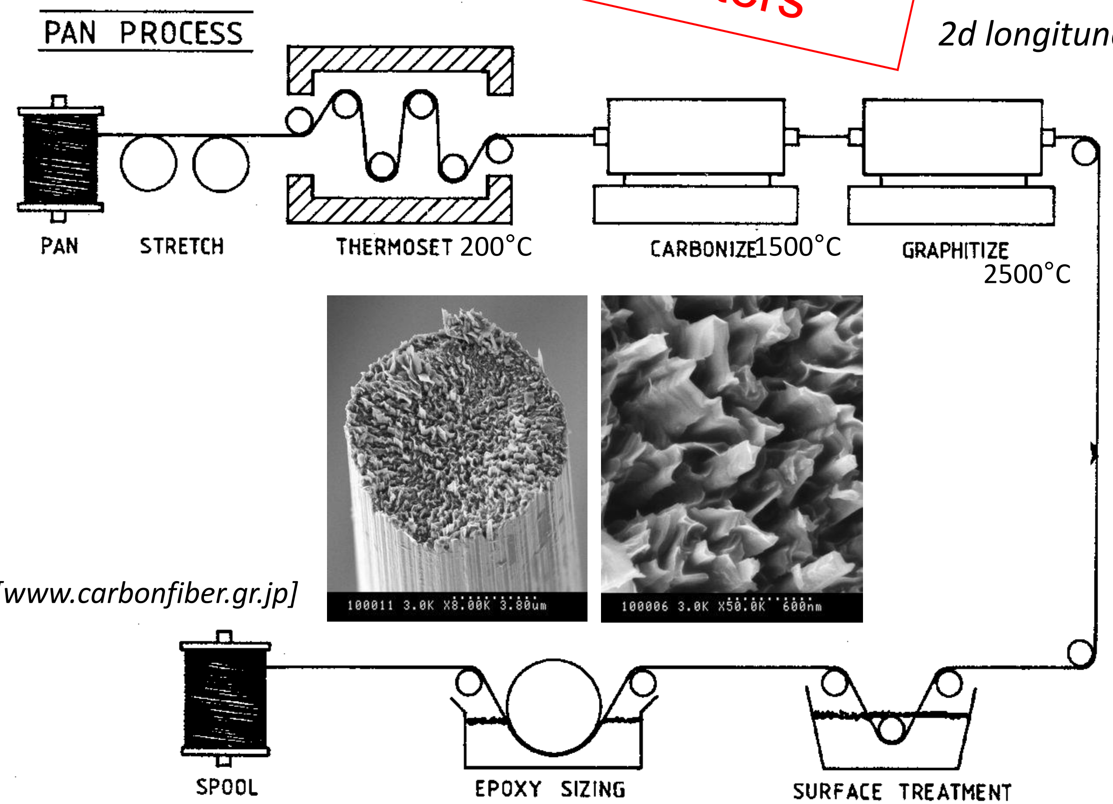


2d longitundinal structure

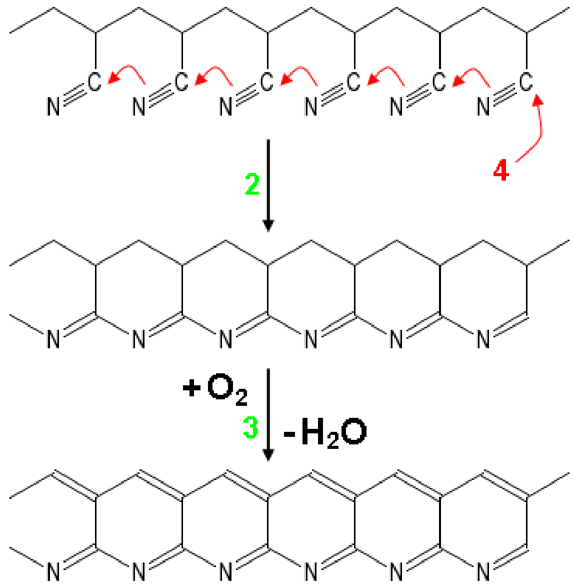


3d representation of structure

[Bennett 1983]

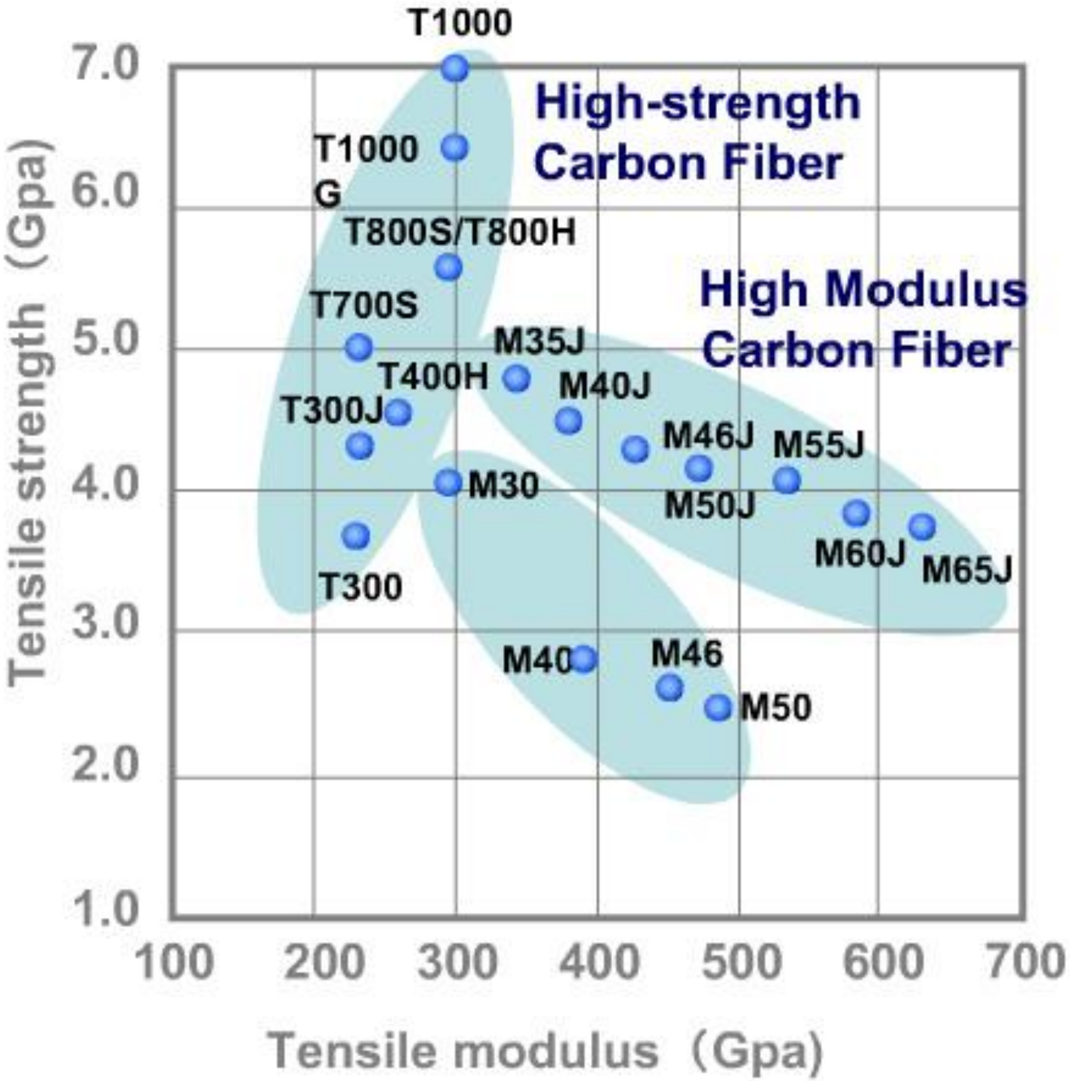


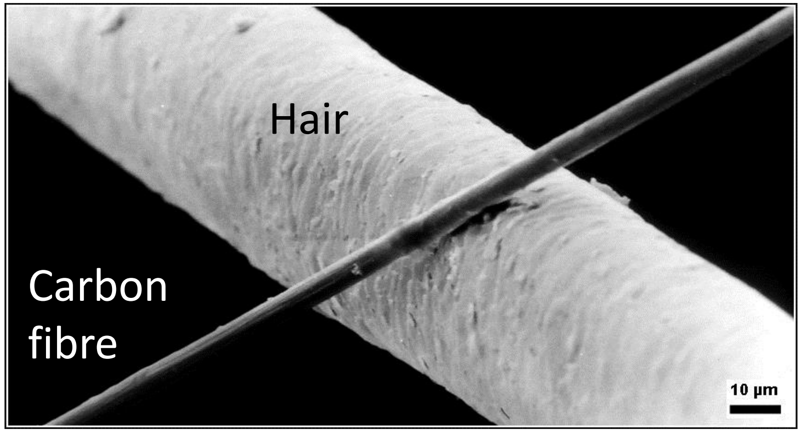
[www.carbonfiber.gr.jp]



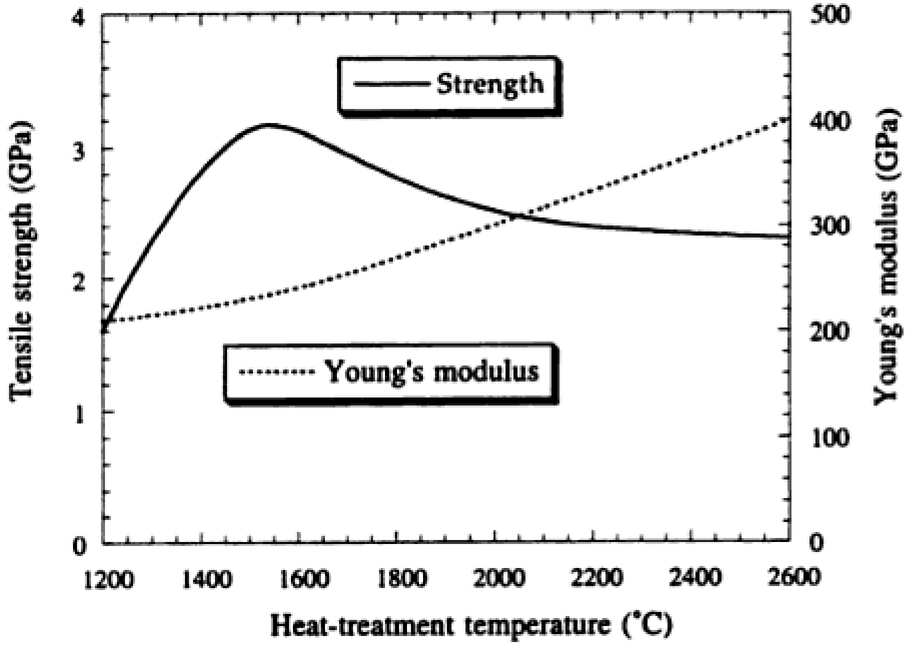
Carbonization of PAN

Properties of carbon fibres





Diameter about 7 µm



[Moreton 1967]

Properties of CNTs and graphene

MWCNT:

Young's Modulus	954 Gpa
Tensile strength	63 GPa

Graphene:

Young's Modulus	1000 GPa
Tensile strength	121 GPa

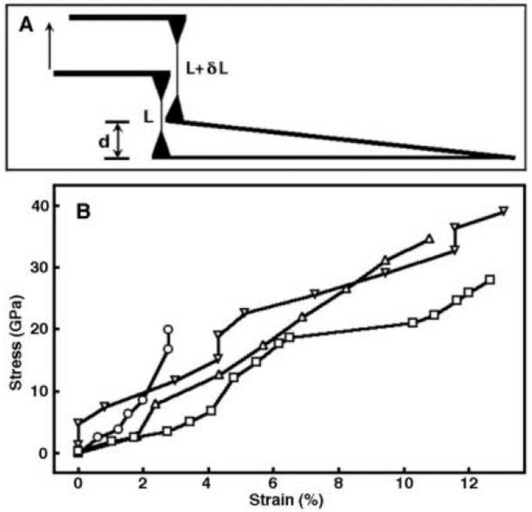
Polymer:

Young's Modulus	1 GPa

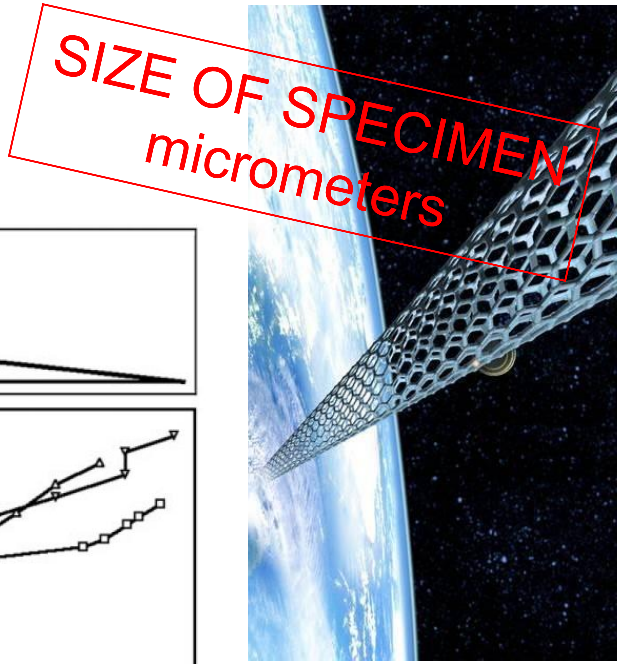
Steel

Young's Modulus	200 GPa

CNT

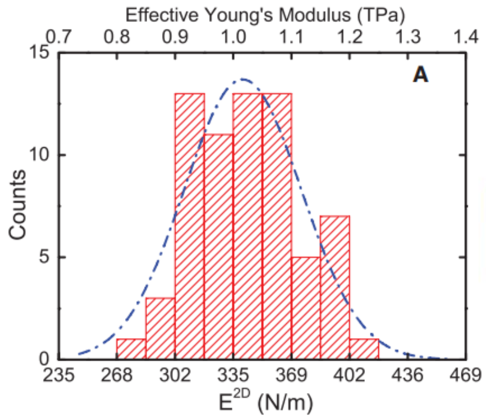


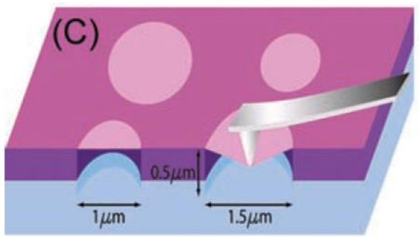
[Yu 2000]



[BBC]

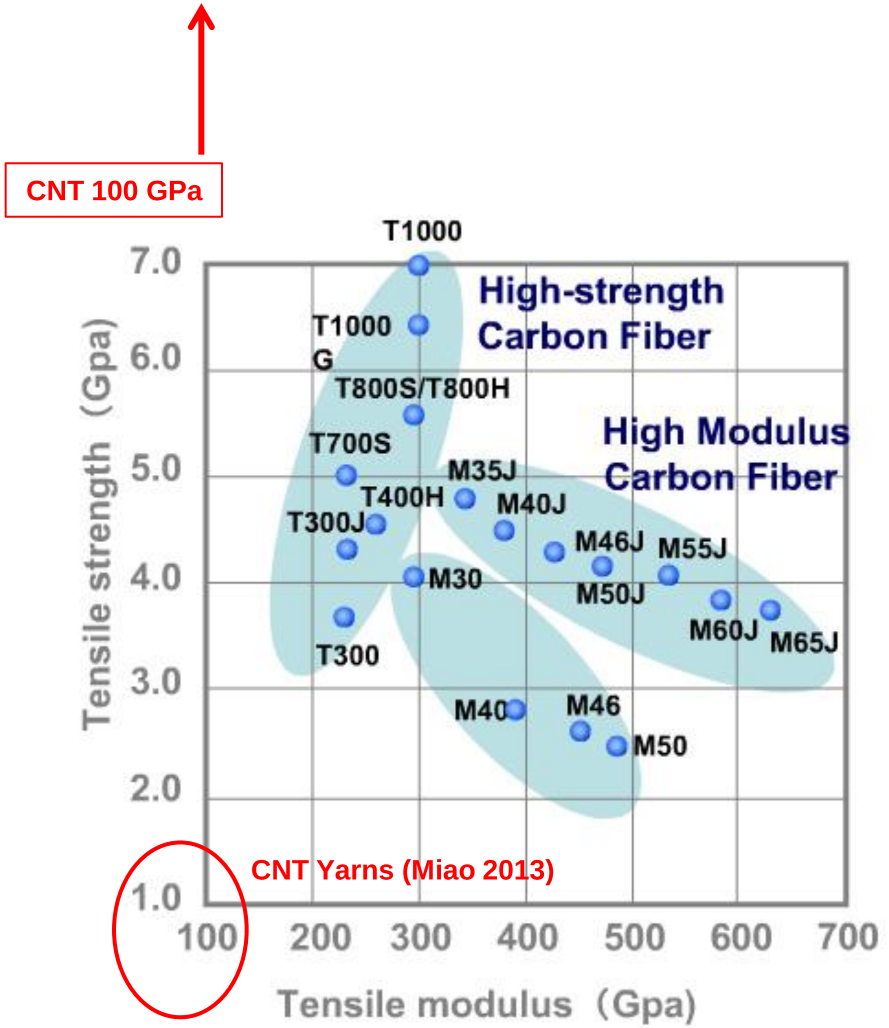
graphene

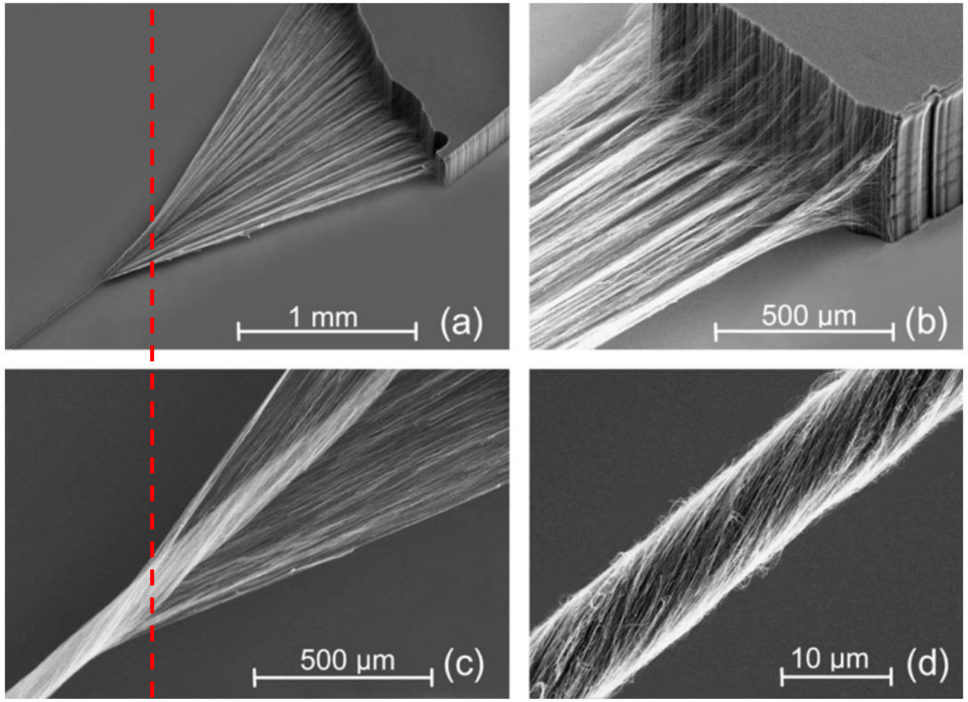




[Lee 2008]

CNT Compared to carbon fibres





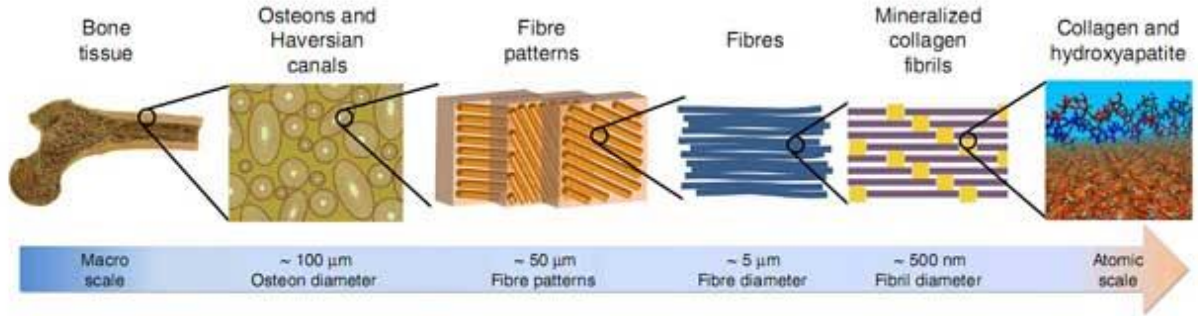
"Drawn "CNT Yarns *[Sears 2010]*

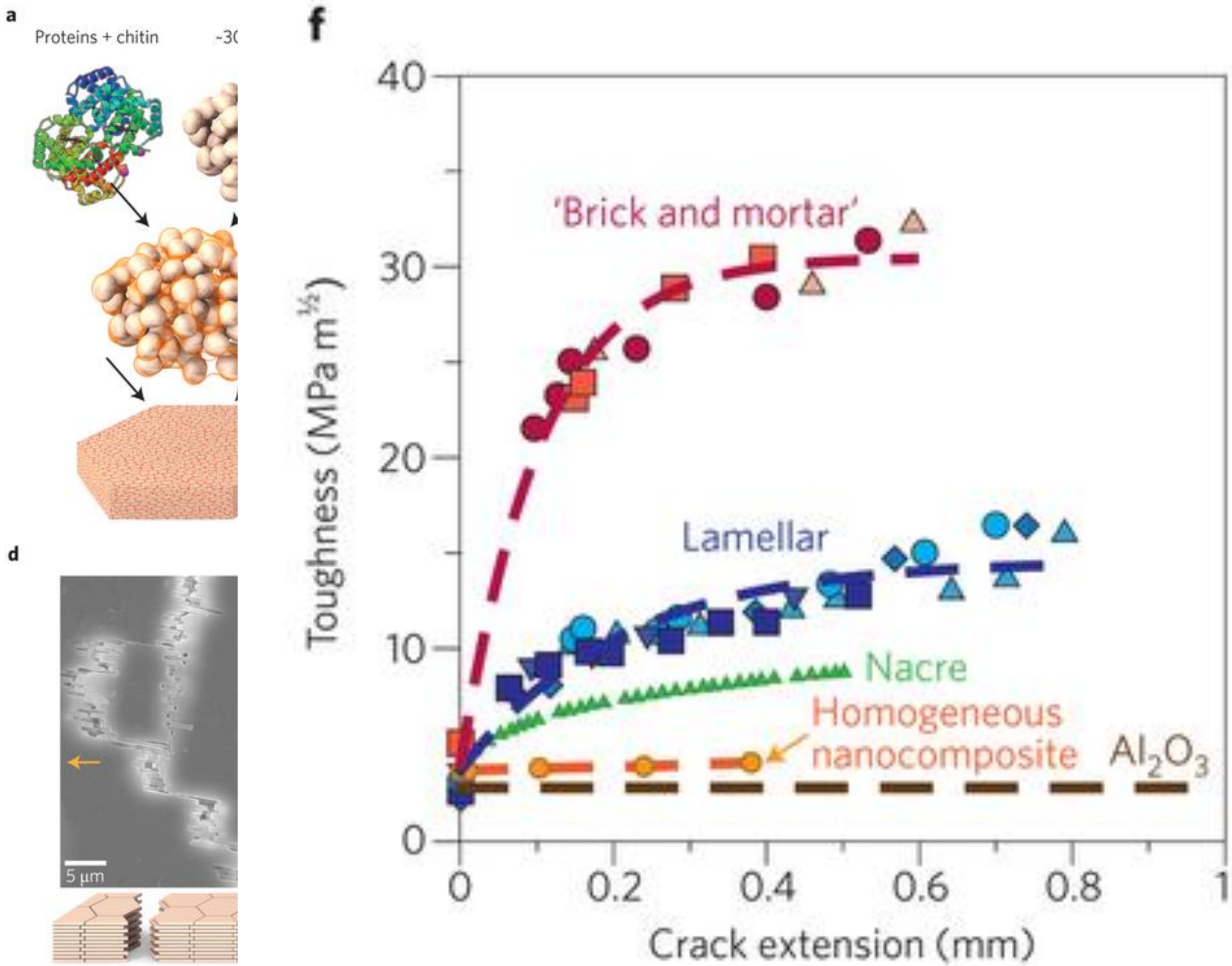
Reasons for weak CNT yarn performance:

- **Discontinuous character of single CNTs (microns)**
- **Low (van der waals) interaction between CNTs**
- **Slippage within MWCNTs**

CNT 1000 GPa

Hierarchies and Size Effects





[Wegst 2015]

Materials in nature generate their strength and fracture tougness through hierarchical structures.

Toughness can be one order of magnitude higher than its constituents

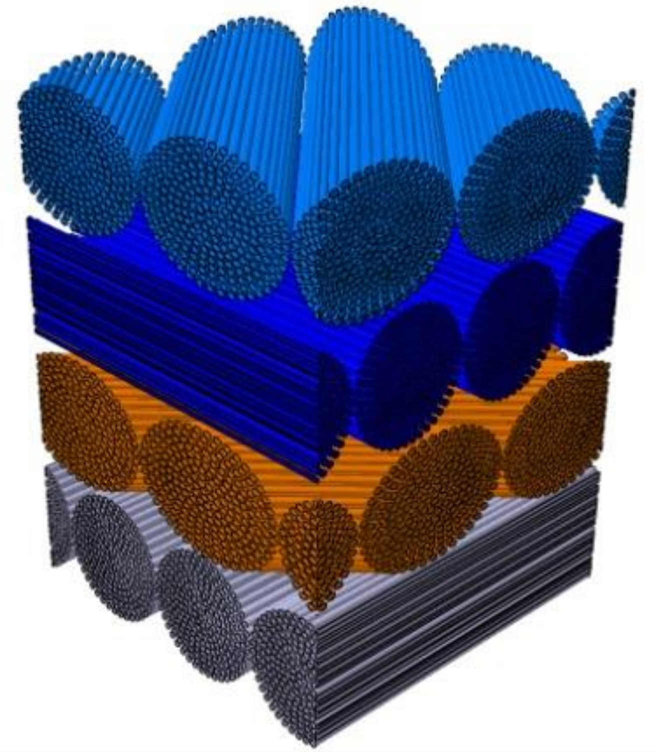
Hierarchies and Size Effects (selected research topics from our group)

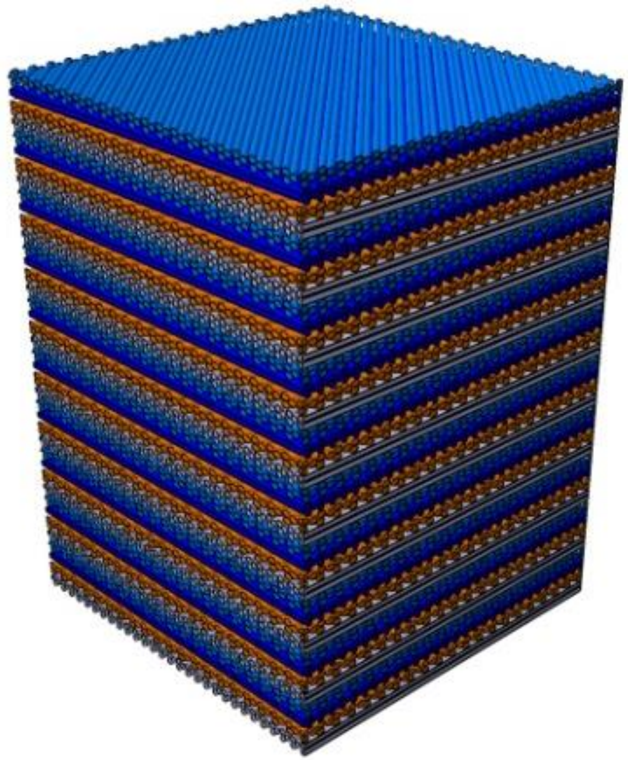
- **Thin ply composites**
- **Pseudo-ductility in discontinuous composites**
- **Hierarchical fiber matrix interfaces**

Thin Ply Composites

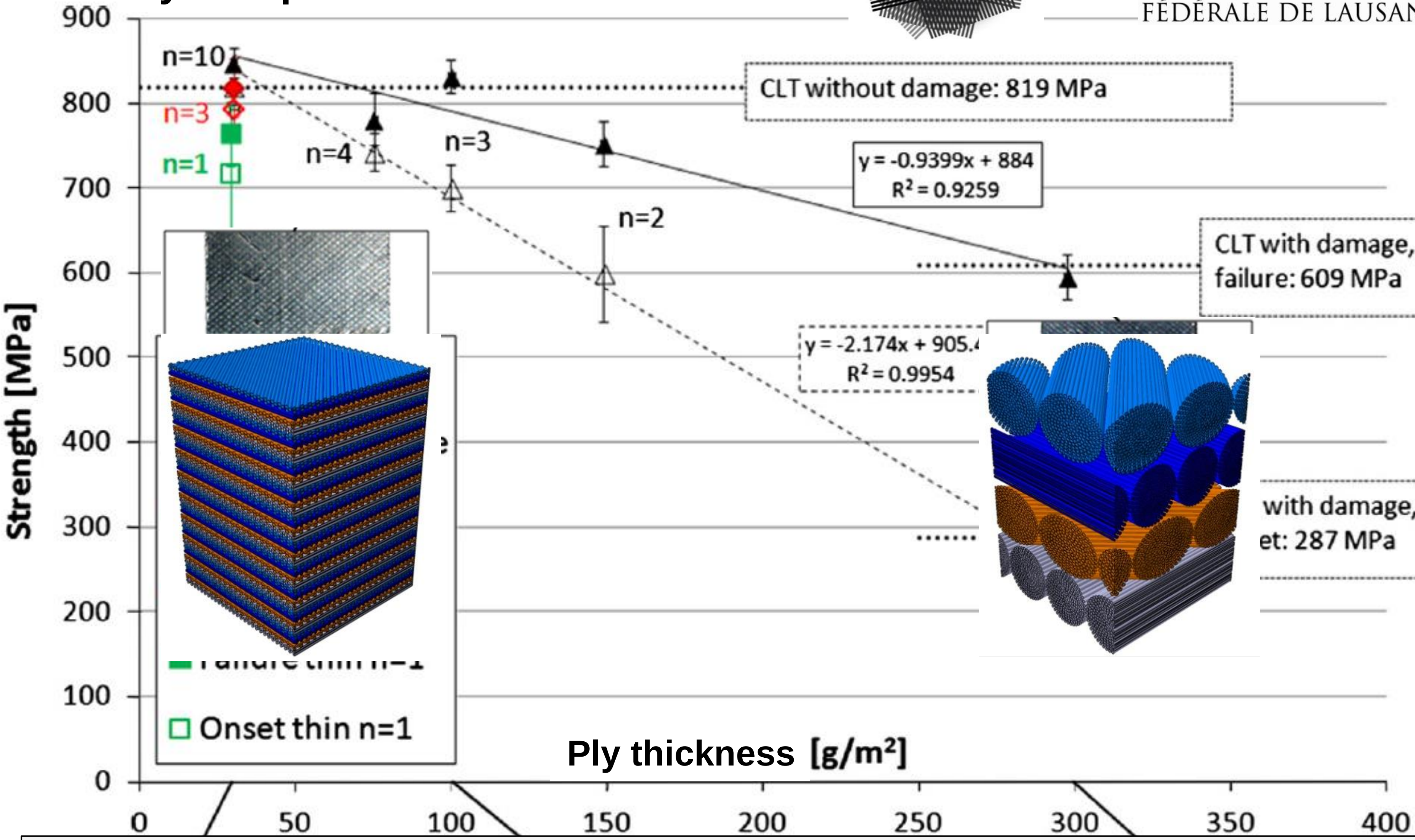
Thick (normal) plies:
0.3 mm - 300 g/m2 fibre weight

(Ultra) thin plies:
0.03 mm - 30 g/m2 fibre weight





Thin Ply Composites

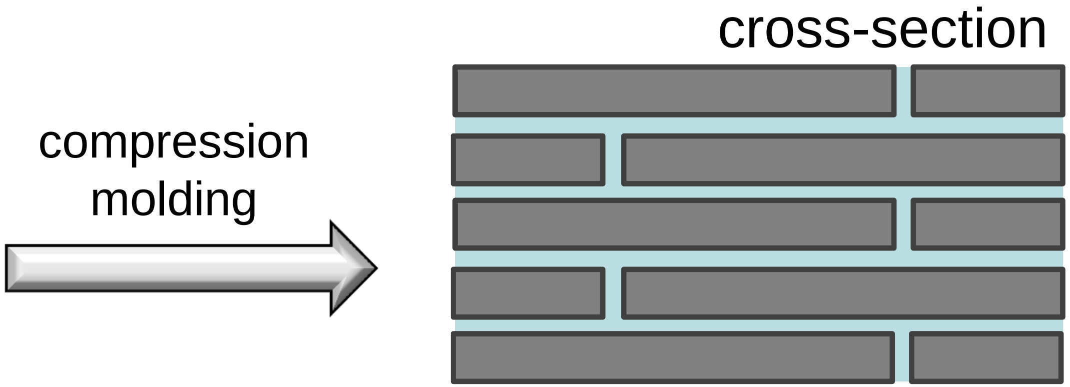


R. Amacher, J. Cugnoni, J. Botsis, L. Sorensen, W. Smith, and C. Dransfeld, "Thin ply composites: Experimental characterization and modeling of size-effects," Composites Science and Technology, vol. 101, pp. 121-132, 9/12/ 2014.

Pseudo-ductility in discontinuous composites

Thermoplastic composites – chopped carbon fibre tapes with PEEK matrix

Synthetic brick and mortar material



Strength criterion – Selected model

Shear-lag model by Pimenta & Robinson [4]

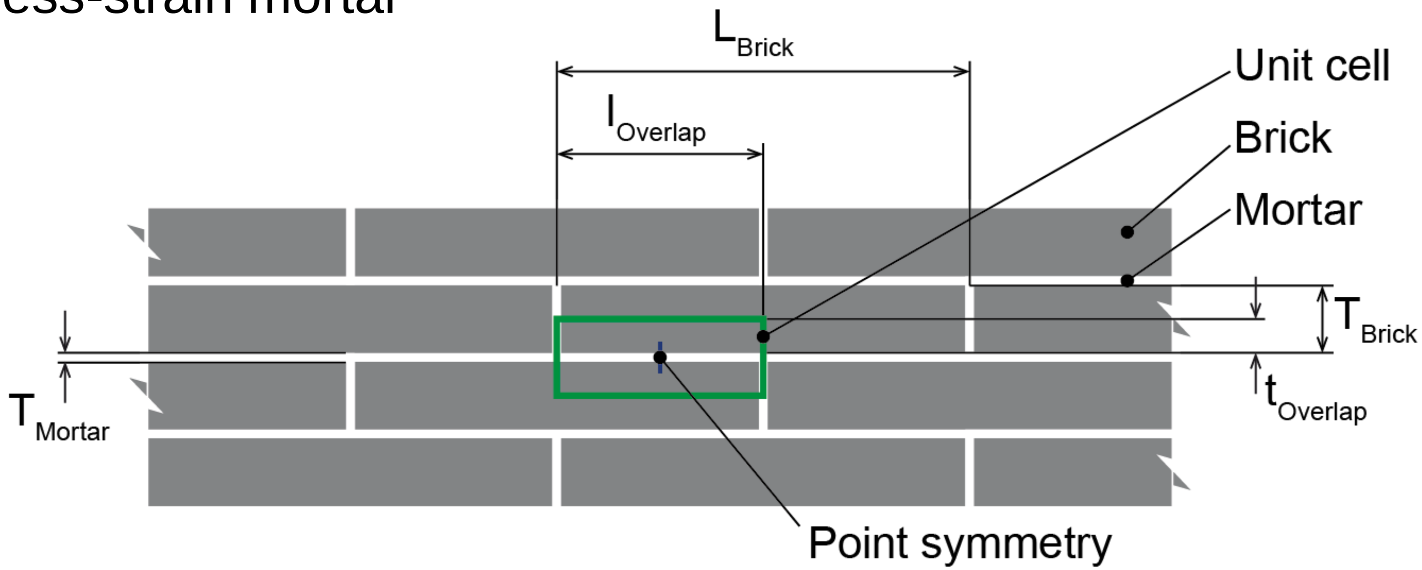
- Unit cell representation
- “Brick and mortar” architecture
- Piecewise linear stress-strain mortar

$$X_S^{\infty} = l^{\mathrm{b}} \cdot S^{\mathrm{m}} / t^{\mathrm{b}}$$

Full plastic mortar (Kelly Tyson)

$$X_{\mathcal{G}}^{\infty} = \sqrt{2 \cdot E^{\mathrm{b}} \cdot \mathcal{G}_{\mathrm{IIc}}^{\mathrm{m}} / t^{\mathrm{b}}}$$

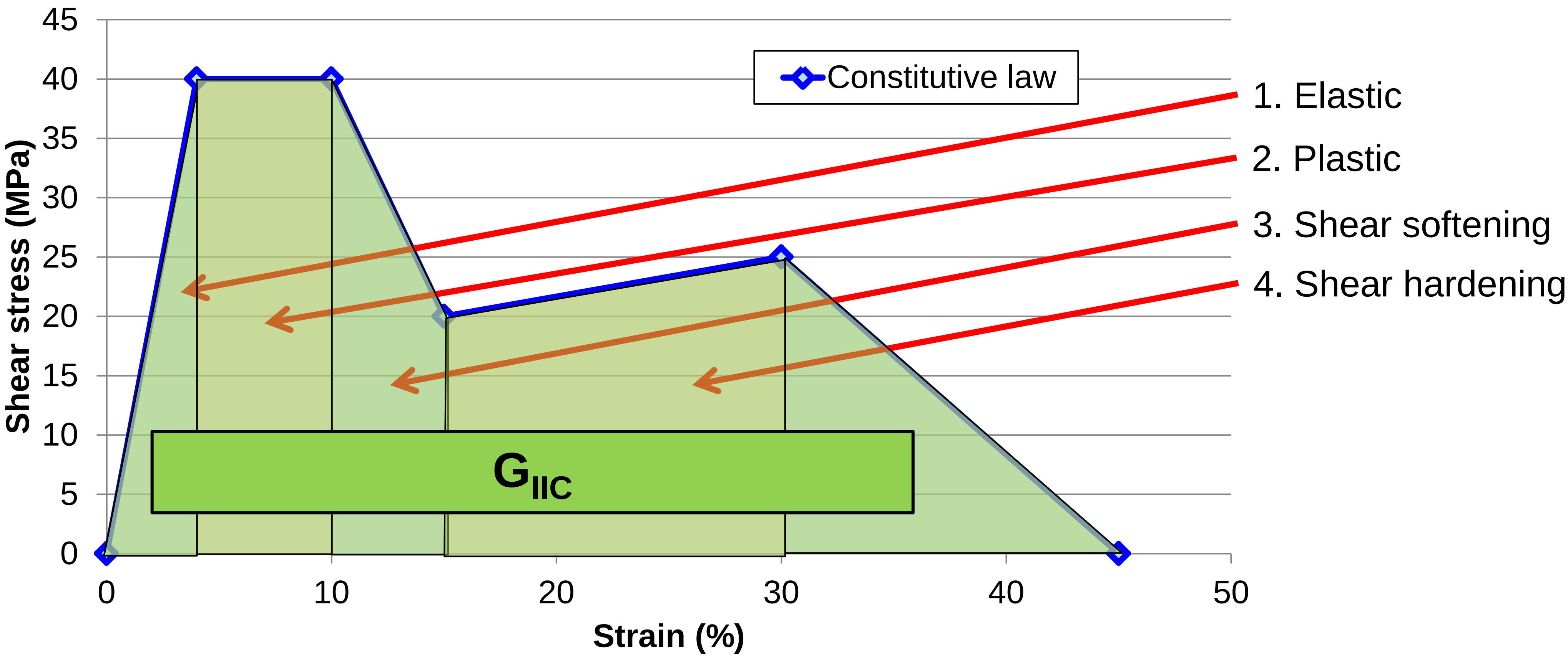
Fracture mechanics approach



Pimenta, Soraia, and Paul Robinson. "An analytical shear-lag model for composites with ‘brick-and-mortar’architecture considering non-linear matrix response and failure." *Composites Science and Technology* 104 (2014): 111-124.

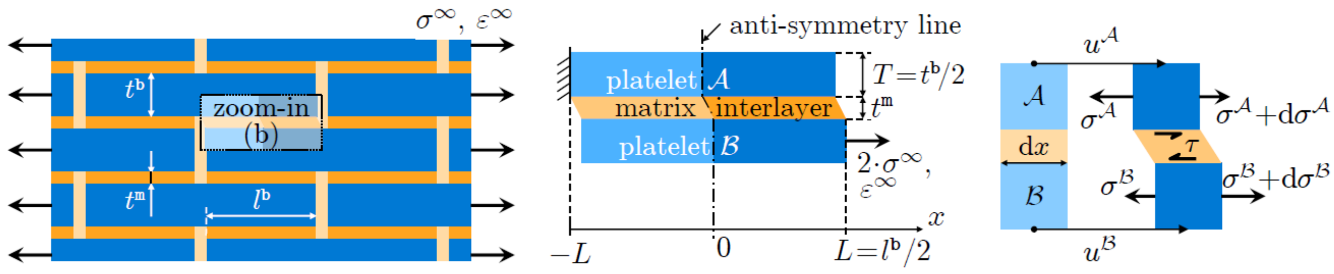
Strength criterion – Constitutive law

Large influence from the mortar constitutive law on the unit cell behavior



Pseudo-ductility in discontinuous composites

Numerical approach predicting non-linear failure based on unit cell

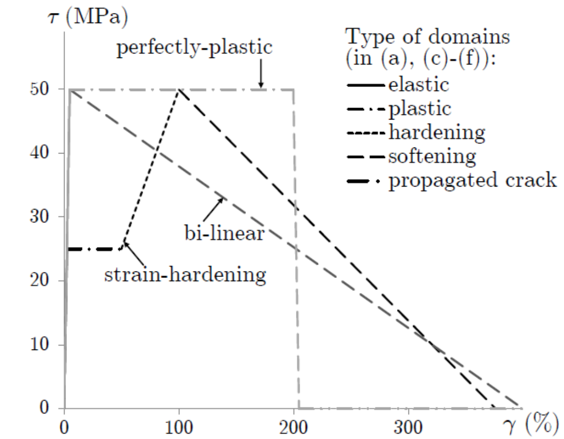


a. Composite with 'brick–and–mortar' architecture.

b. Unit–cell (zoom-in from (a)).

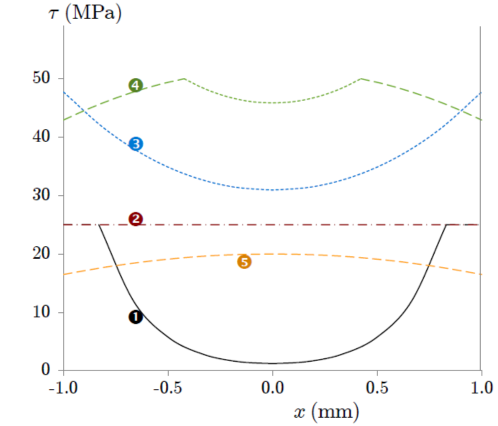
c. Infinitesimal element.

[Pimenta 2014]



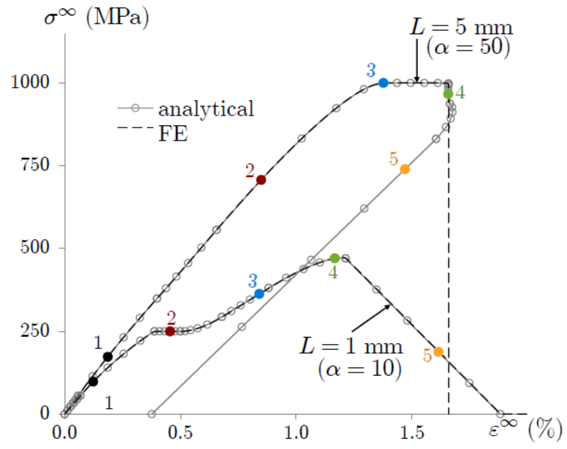
a. Matrix shear responses considered in this study,

"Mortar" constituive law



c. Shear stresses for the strain–hardening matrix, for $L = 1$ mm ($\alpha = 10$).

Shear response in overlap



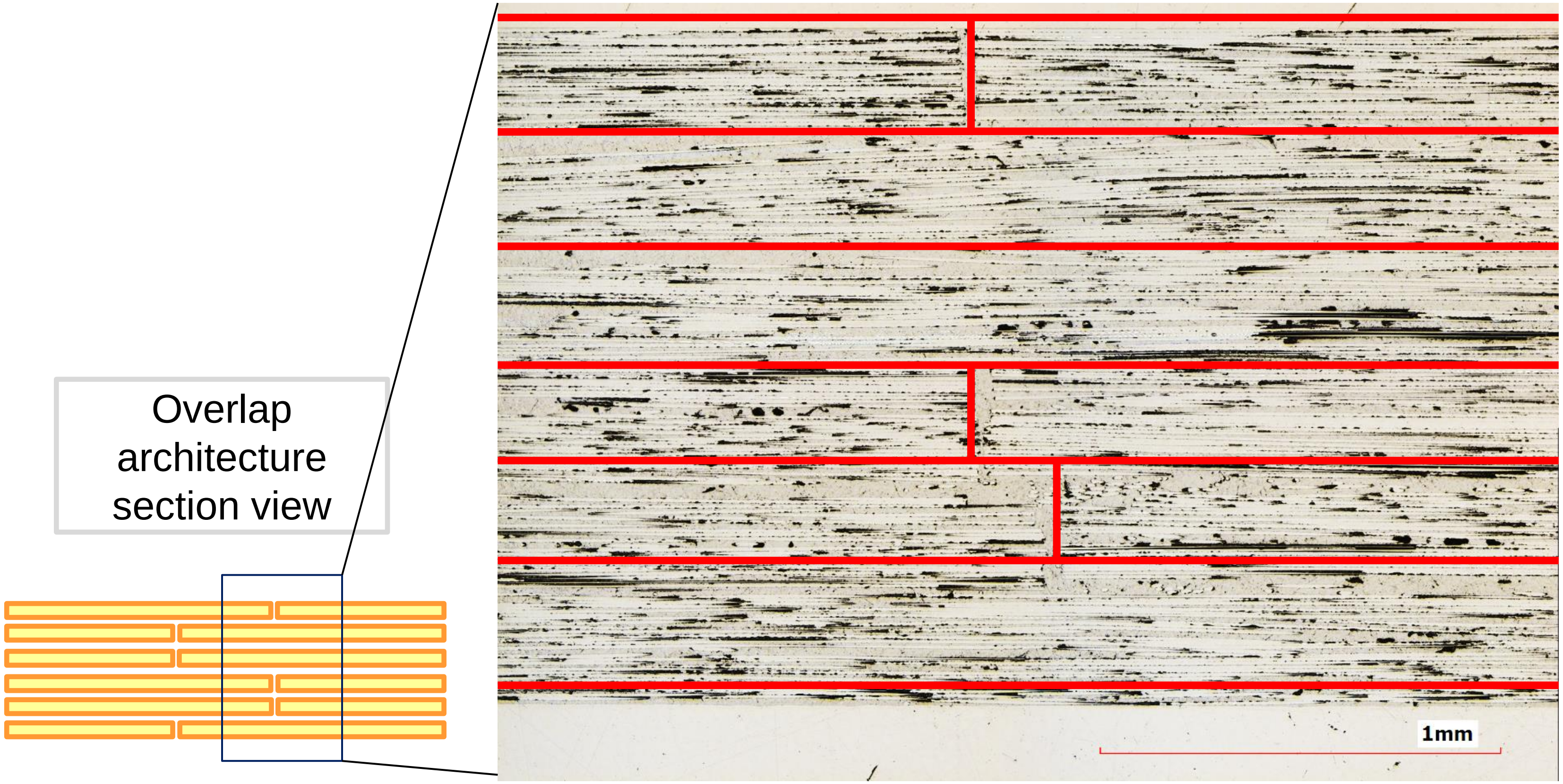
b. Global stress–strain response of composites

Global response

Pseudo-ductility in discontinuous composites

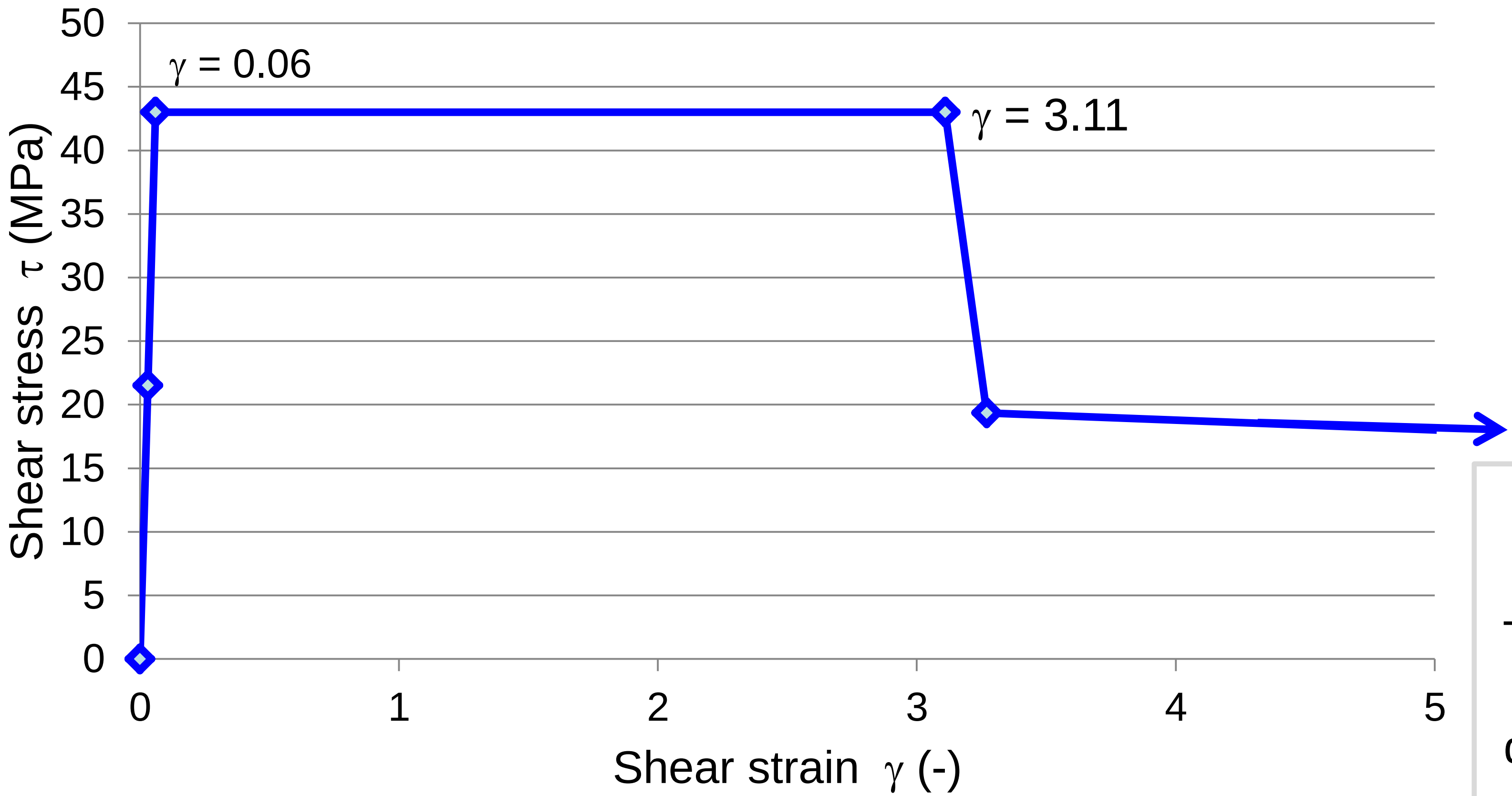
Experimental - S2 glas fibre tape with PA12 matrix

Overlap architecture section view



Strength criterion – Constitutive law

Evonik PA12-2159 G_{IIc} = 1.9 kJ/m^2



Down to
γ = 28, τ = 0
To comply with energy dissipation G_{IIc}

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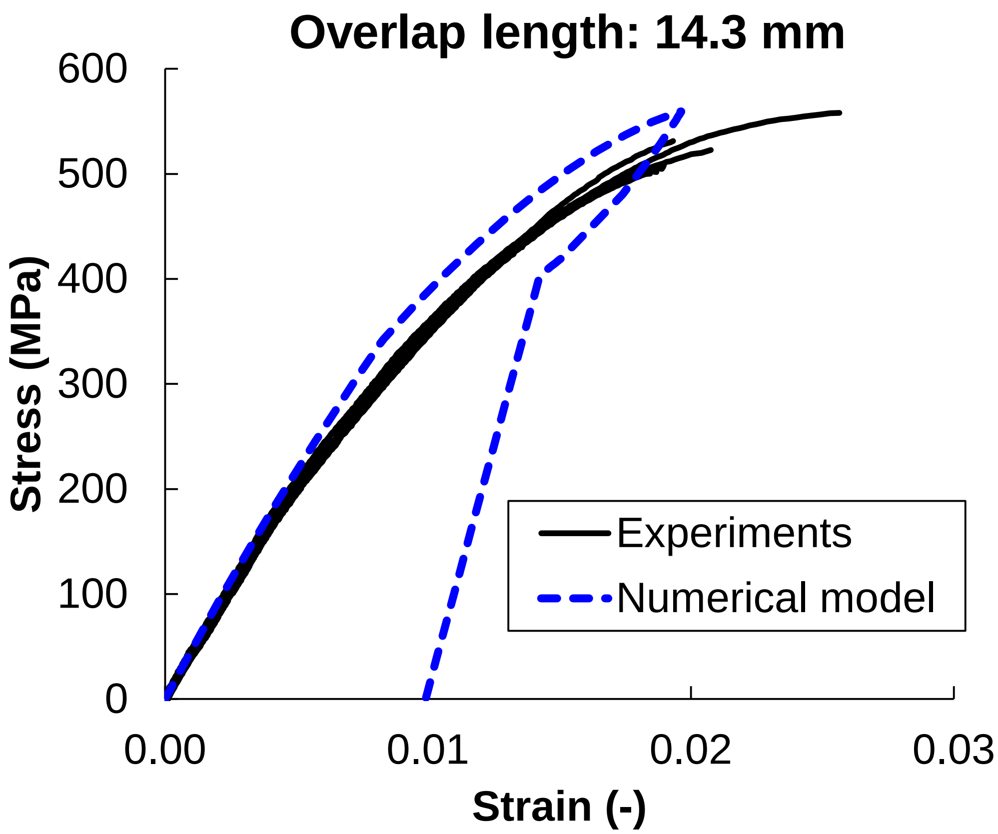
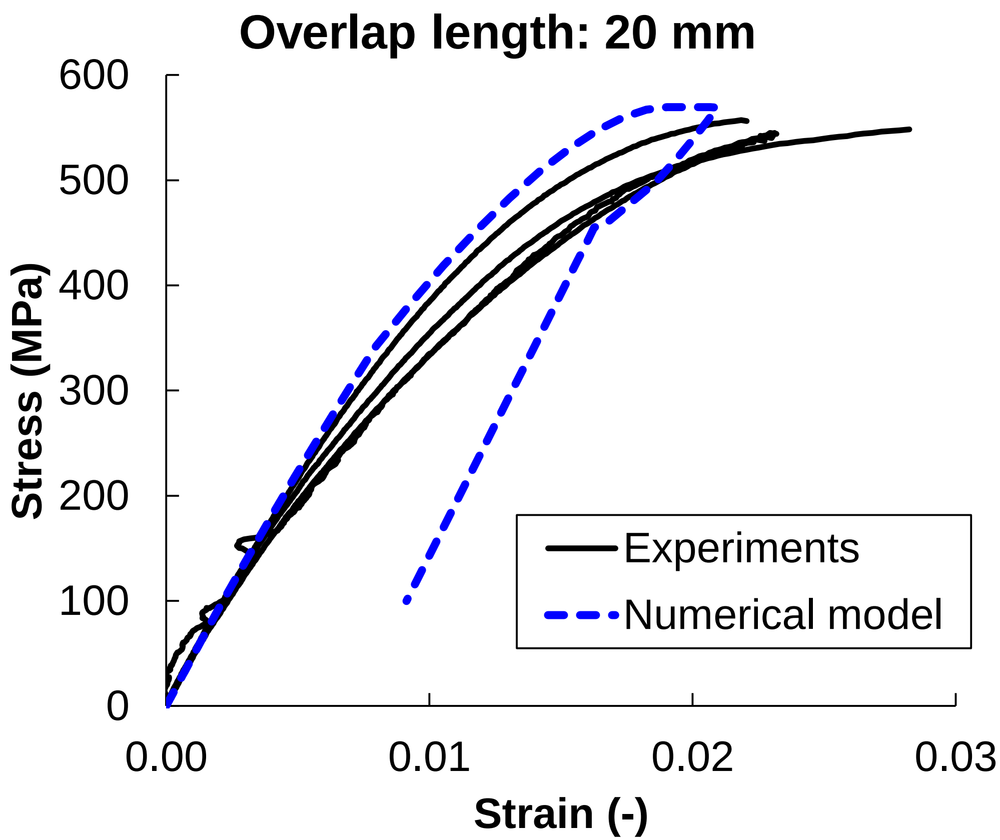
Imperial College London

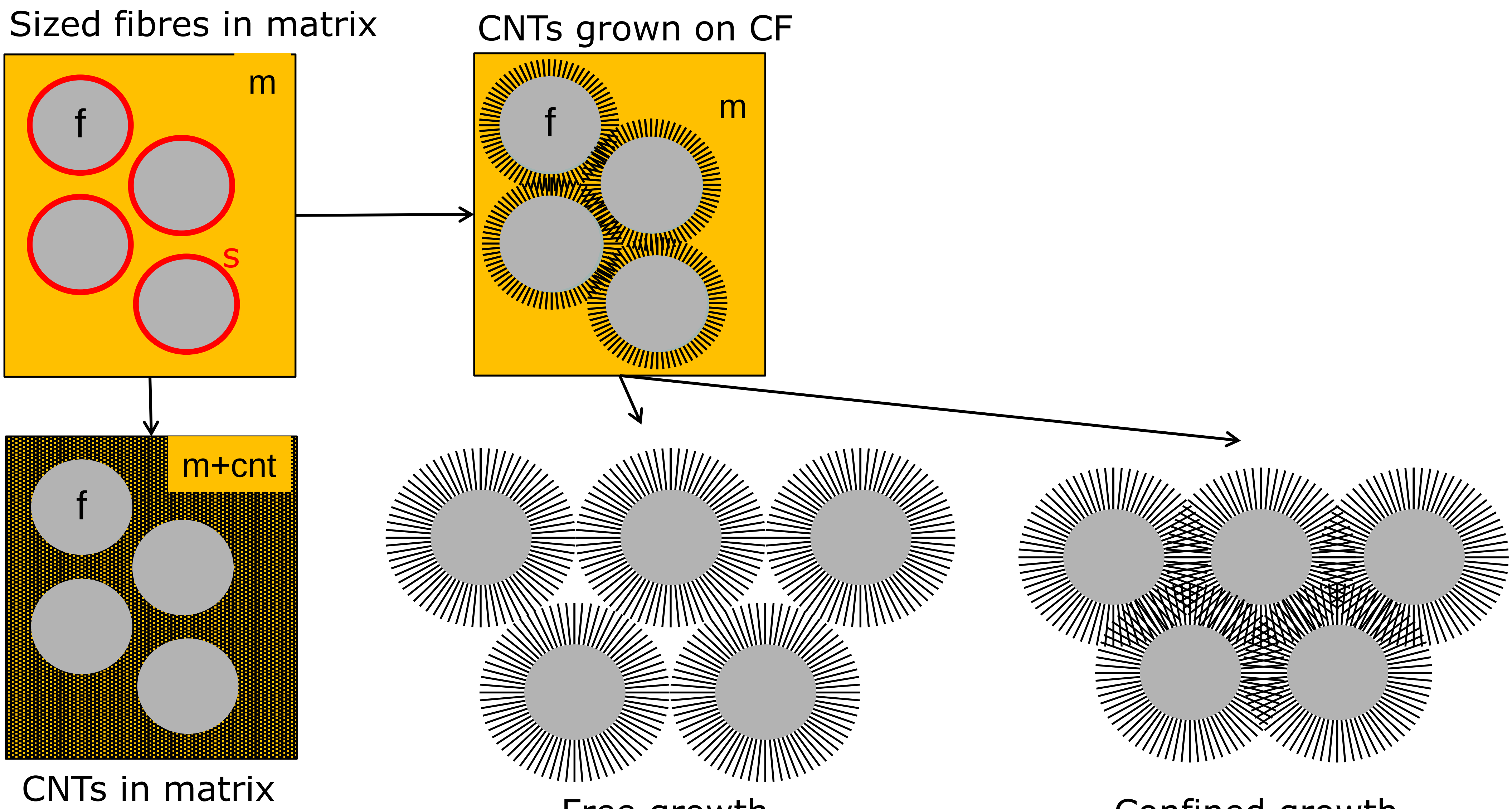
Pseudo-ductility in discontinuous composites





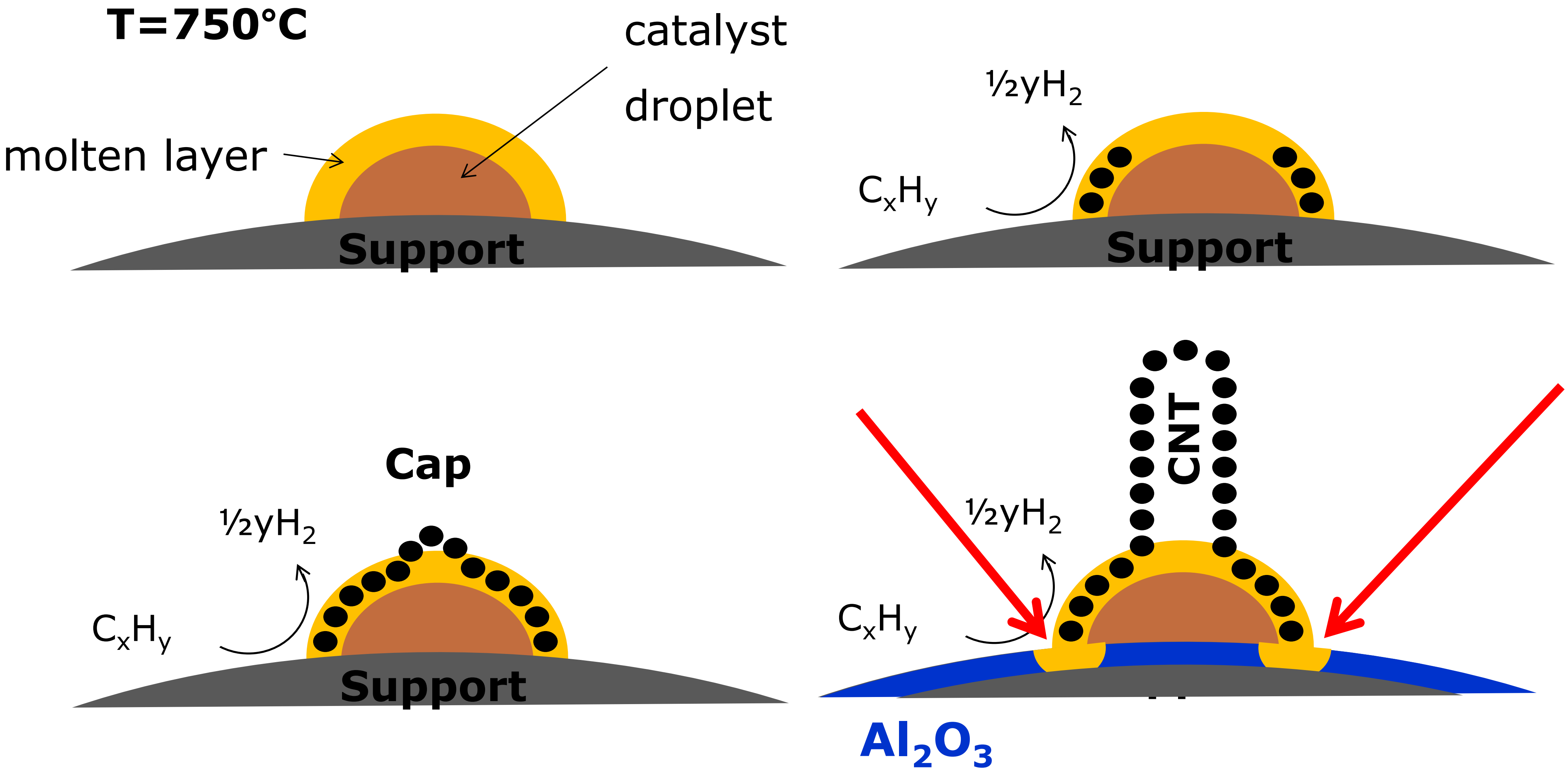
B. Bachmann, L. Giger, K. Masania, C. Dransfeld, and J. Maldondado, "Experimental study of the stress transfer in discontinuous composites on the basis of a unit cell model " presented at the International Conference of Composite Materials ICCM20, Copenhagen, Denmark, 2015.

Hierarchical fiber-matrix interfaces



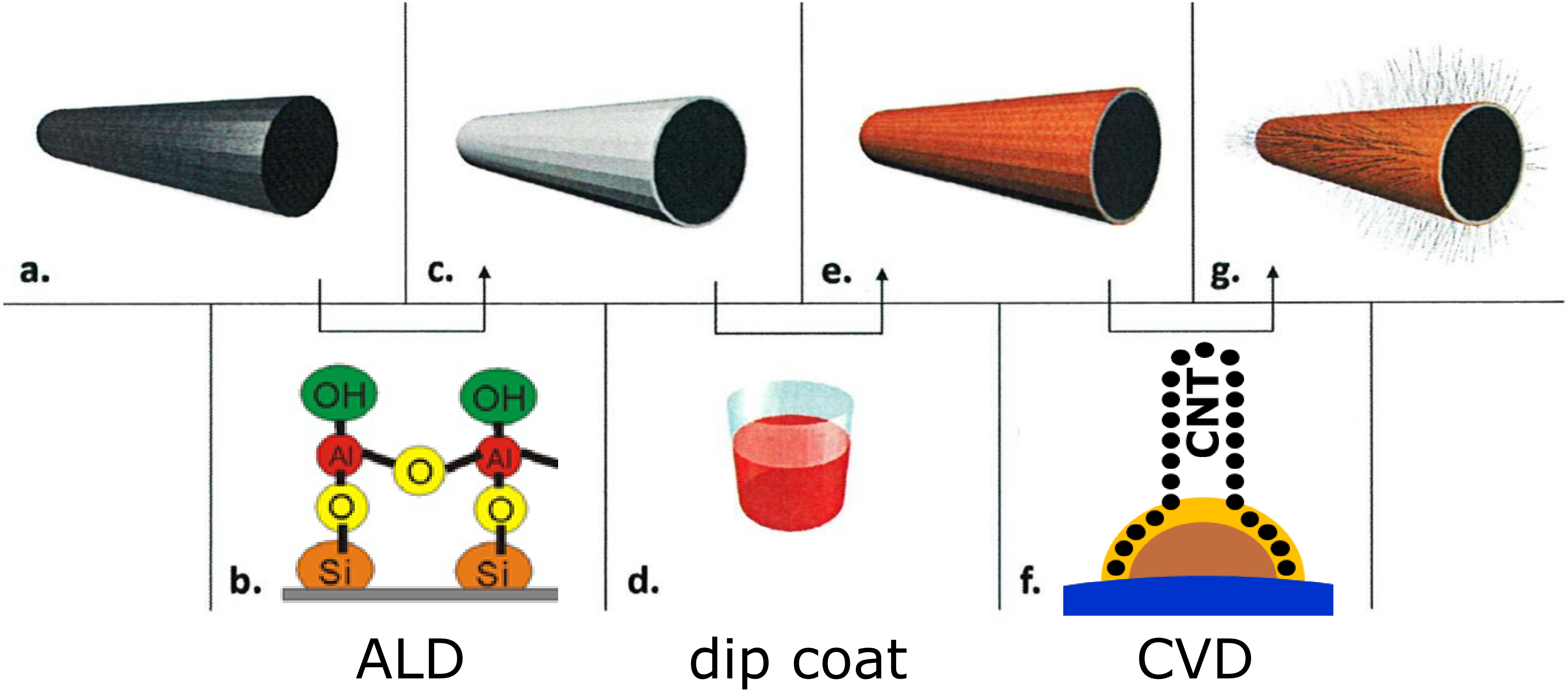
Reproduced from: Qian, H., et al., Journal of Materials Chemistry, 2010.

Hierarchical fiber-matrix interfaces
`Degradation of TS during CVD: etching the CF



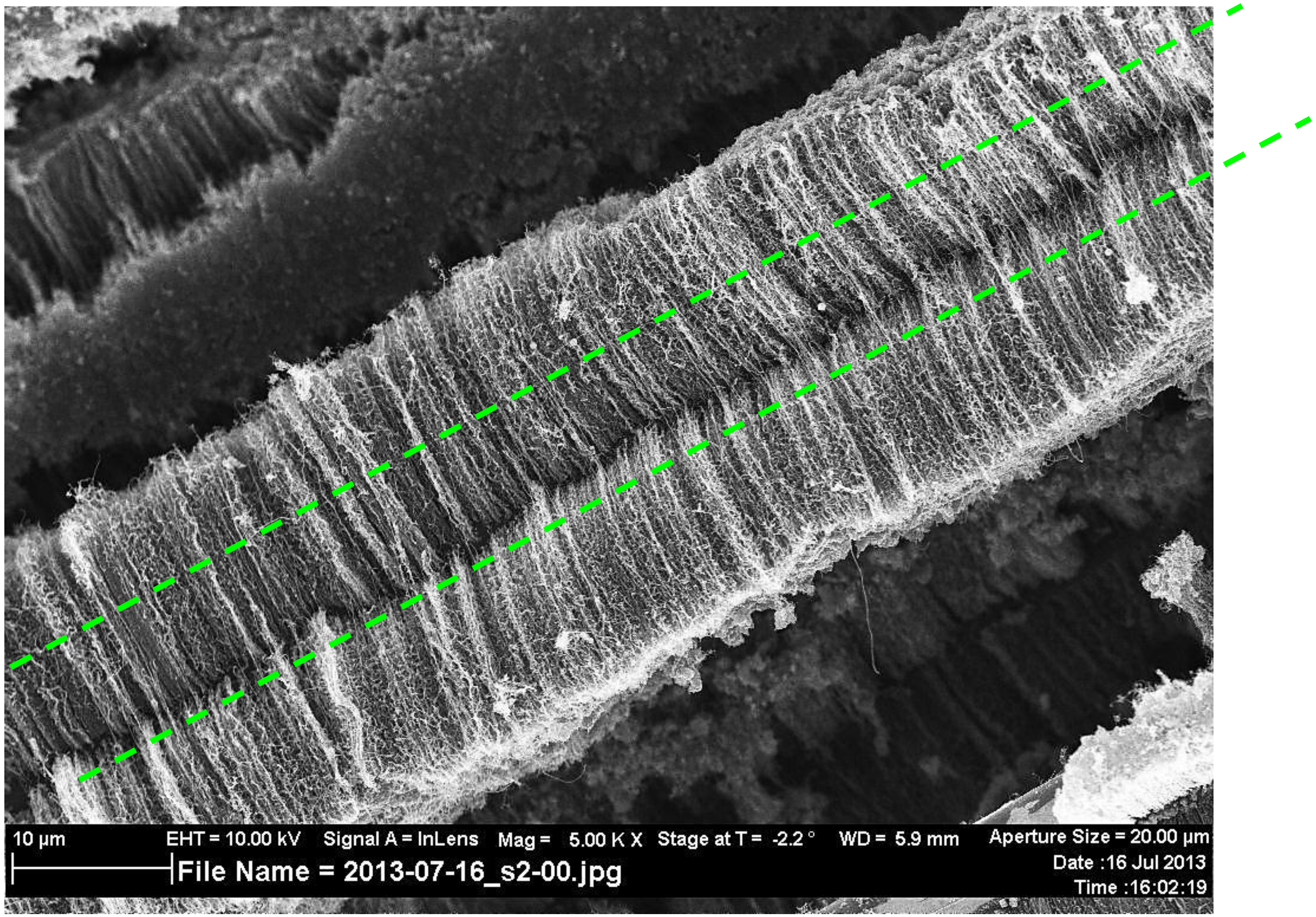
Reproduced from: J. Furer. Growth of Single -Wall Carbon Nanotubes by Chemical Vapour Deposition for Electrical Devices. PhD thesis, University of Basel, 2006.

Hierarchical fiber-matrix interfaces
Optimized method for CNT growth on CF

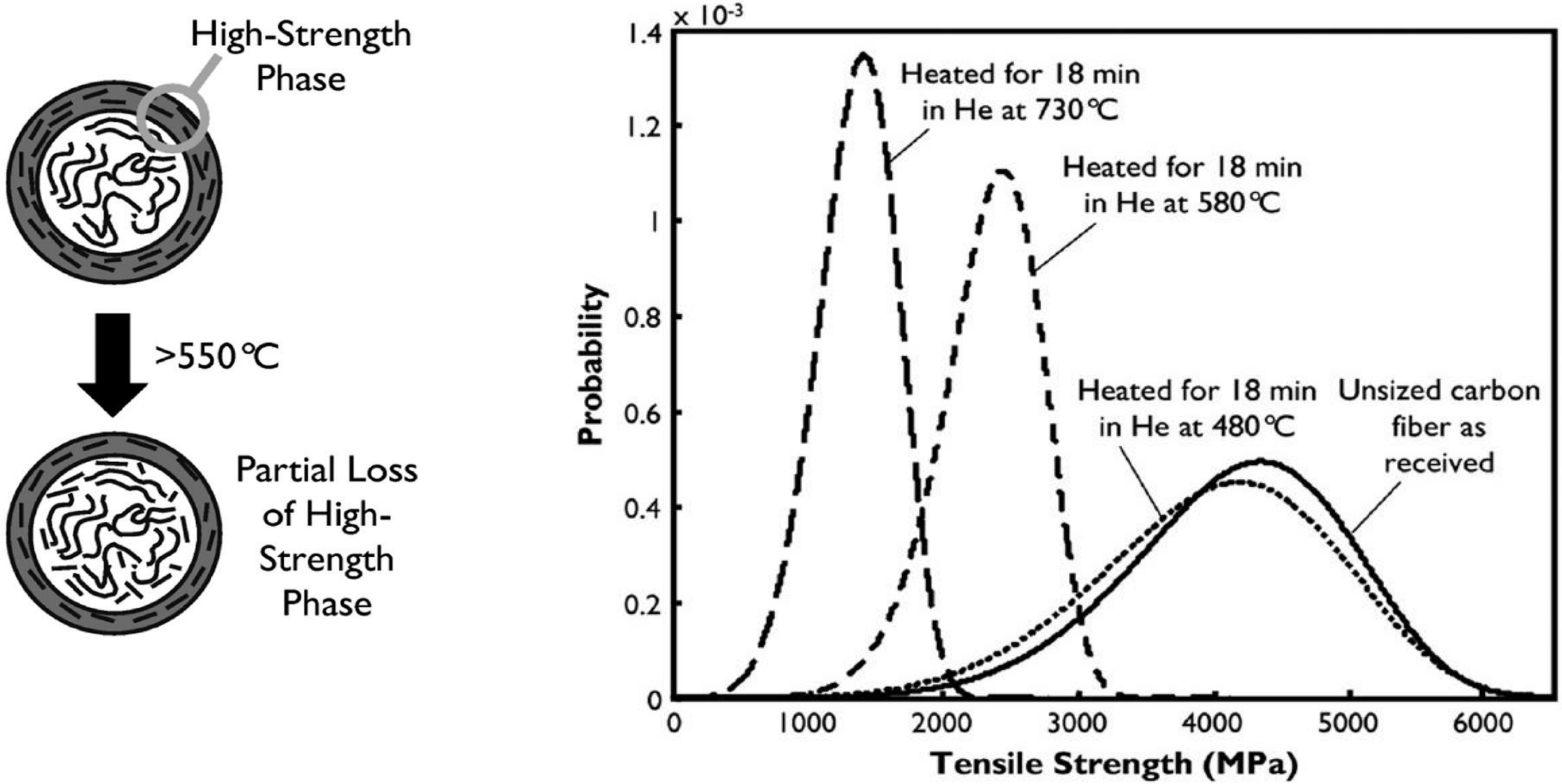


Perrin, M., et al., Master thesis, 2009.

Hierarchical fiber-matrix interfaces
10µm long CNTs on CF

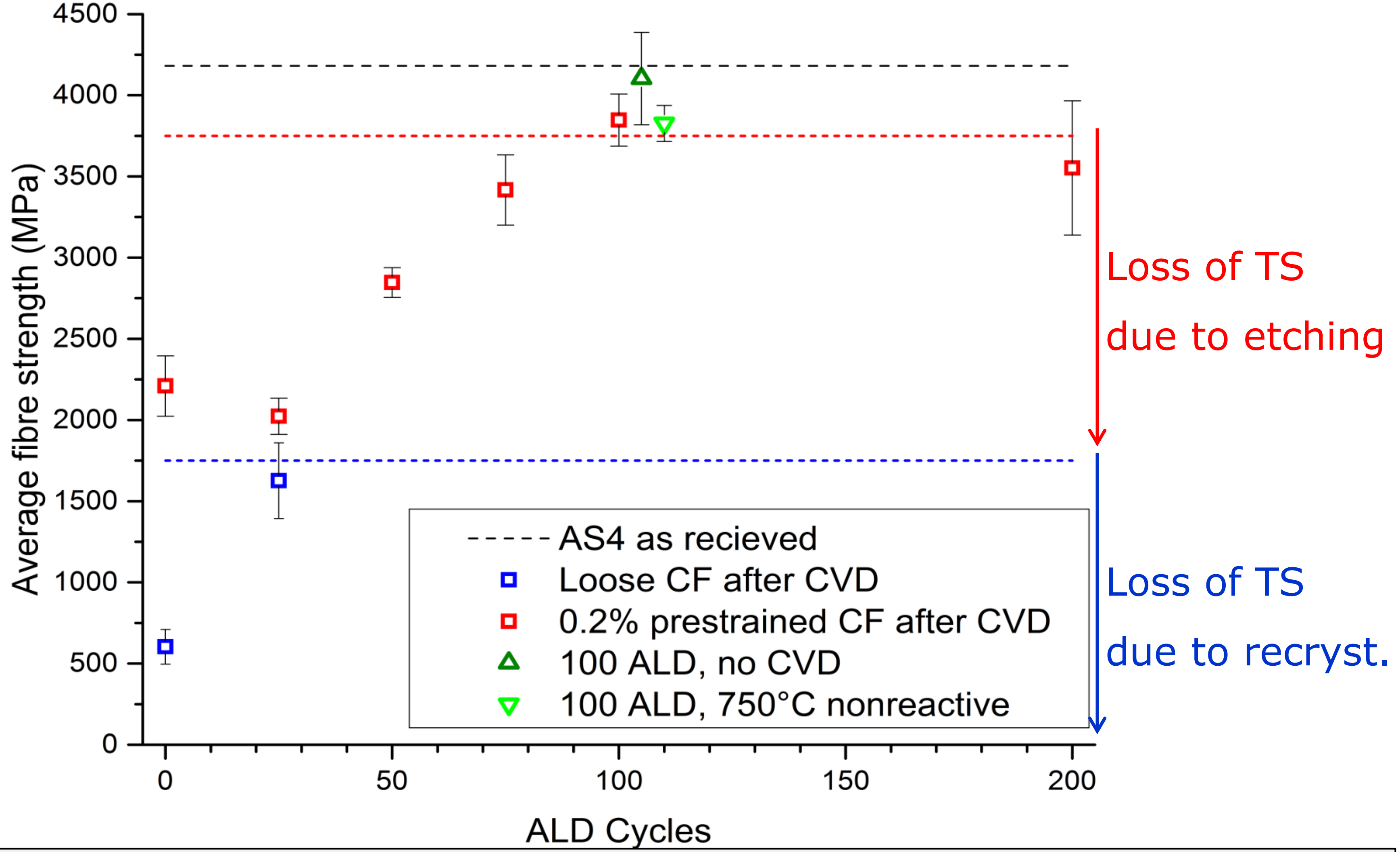


Hierarchical fiber-matrix interfaces
Reduction of TS during CVD: high temp. degradation



Steiner S., et al., ACS Appl. Mater. Interfaces 2013, 5, 4892−4903

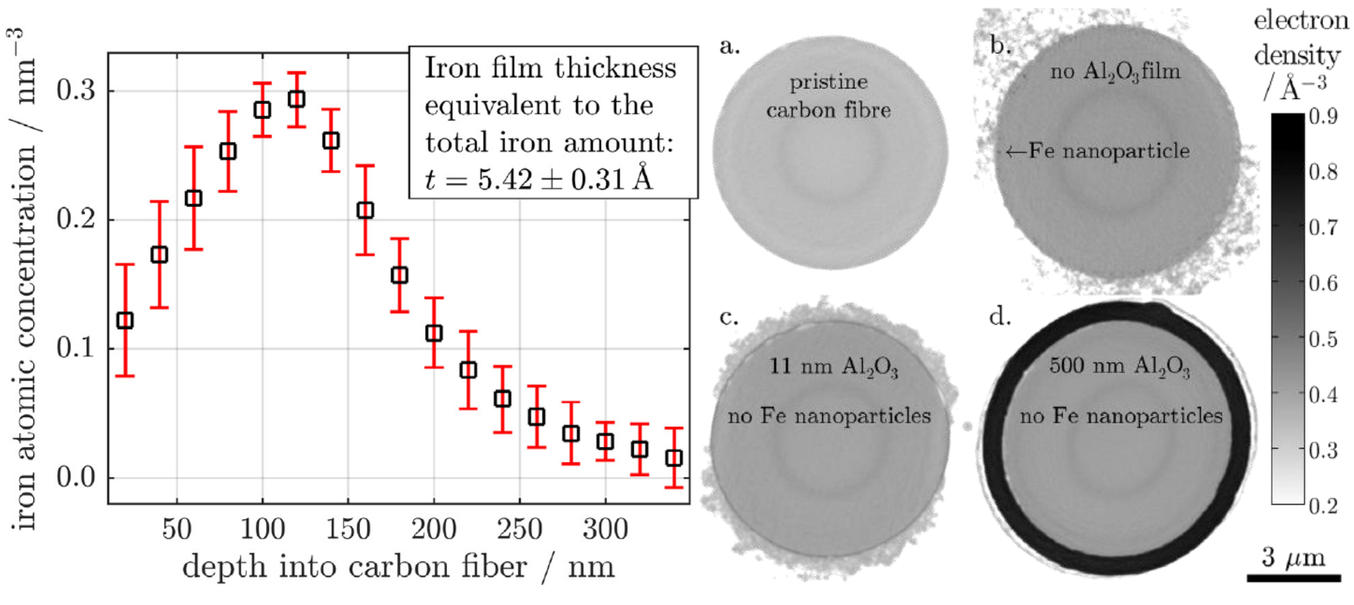
Hierarchical fiber-matrix interfaces
Result: losses in fibre tensile strength



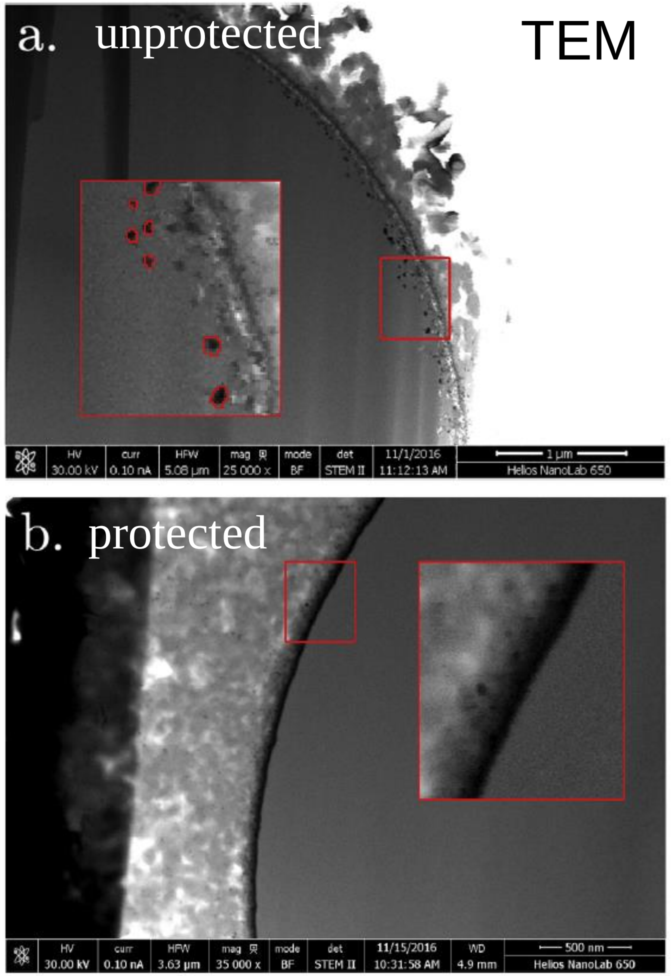
S. Vogel, C. Dransfeld, B. Fiedler, and J. Gobrecht, "Protective effect of thin alumina layer on carbon fibre to preserve tensile strength during CNT growth by CVD," presented at the ECCM 16 -16th European Conference on Composite Materials, Seville, 2014.

Losses in fibre tensile strength, iron catalyst particles migrate into carbon fibre through carbon interdiffusion

Confirmed by ptychographic X-ray computed tomography and TEM



PXCT



TEM

W. Szmyt, S. Vogel, A. Diaz, M. Holler, J. Gobrecht, M. Calame, and C. Dransfeld, "Protective effect of ultrathin alumina film against diffusion of iron into carbon fiber during growth of carbon nanotubes for hierarchical composites investigated by ptychographic X-ray computed tomography," **Carbon**, vol. 115, pp. 347-362, 5// 2017.

Conclusions

Carbon fibres based composites will have a large future impact on mobility

Future potential is based on understanding hierarchies and size effects

Nature is proposing attractive concepts

Novel challenges in research and technology development

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