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

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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

\[
W = m \cdot a \cdot s
\]

m: vehicle mass, a: acceleration, s: distance

[SCCER Mobility, Bafu 2011]
Carbon fibre reinforced polymers

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

unidirectional

multidirectional
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

1000 t/a C-Fibre ~ 25 €m Invest

BMW / SGL Joint venture capacity expansion @ Moses Lake USA

Source Dr. Jäger / SGL Carbon Group
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The impact of lightweight with carbon based composites

◆ Conventional plane and CFRP plane

Body weight can be reduced by 20% with CFRP application
9% Total weight reduction => 7% Reduction of CO₂ emission
The impact of lightweight with carbon based composites

Airplane

Conventional plane

Assembly: 3800 t
Materials, Production: 700 t

Total: 395 kt

CFRP plane

Assembly: 3000 t
Materials, Production: 900 t

Total: 368 kt

Reduction: 7%

\[ \text{CO}_2 \ [10^3 \text{t}/(\text{plane} \cdot 10\text{yrs})] \]

\[ \Delta 2700 \text{ t} \quad \text{CO}_2 \text{ Reduction}/(\text{plane} \cdot \text{yr}) \]

Copyright 2008 The Japan Carbon Fiber Manufacturers' Association
Achieving lightweight

...by material

...by design

\[ \sigma = E \cdot \varepsilon \]

[Gordon 1978]
Absolute structural performance

- Tensile strength (MPa): 3000
- Young's modulus (GPa): 700

Carbon nanotubes (CNTs)

CNWs Young modulus E=950 Gpa
Tensile strength: 63 GPa

Graph showing tensile strength and Young's modulus for different materials, including metals and alloys, composites, technical ceramics, and non-technical ceramics.
Specific (weight normalized) performance

![Graph showing specific performance of different material classes]

- TENSILE STRENGTH / DENSITY
- YOUNG’S MODULUS / DENSITY

Composites
Metals and alloys
Natural materials
Polymers
Glasses
Non-technical ceramics
Technical ceramics
Failure in composites

Matrix failure

- transverse tensile
  \[ \sigma_{\perp}^+ = Y_t \]
- transverse compression
  \[ \sigma_{\perp}^- = Y_c \]
- shear

Fibre failure

- fibre tensile failure
- fibre compression kink-band

\[ \sigma_{\parallel}^- \]

http://youtu.be/U9STWk2Nw00

[Schürmann]
Analyzing several failure modes at once – Puck’s failure envelope

\[ \cos \theta_p = \sqrt{\frac{R_{11}^A}{\sigma_2}} \]

\[ \frac{d\tau_{21}}{d\sigma_2} |_{\sigma_2=0} = P_{11}^{(-)} \]

\[ \frac{d\tau_{21}}{d\sigma_2} |_{\sigma_2=0} = P_{11}^{(+)} \]

\[ 0 \leq |\tau_{21}| \leq |\tau_{21C}| \]

\[ \frac{R_{11}^A}{\sigma_2} \]

\[ Modus A \]

\[ Modus B \]

\[ Modus C \]

\[ Fb(\sigma_1 < 0) \]

\[ Zfb\{\sigma_2 > 0, \tau_{21}\} \]

\[ \sigma_1 \]

\[ \sigma_2 \]

\[ Fb(\sigma_1 > 0) \]

\[ Zfb\{\sigma_2 < 0, \tau_{21}\} \]

\[ E_{II} e_M^{(-)} \]

\[ E_{II} e_M^{(+)} \]

\[ R_{II}^{(-)} \]

\[ R_{II}^{(+)} \]

\[ \tau_{21} \]

\[ \tau_{21C} \]

\[ Modus \]

\[ [Puck 1996] \]
Carbon fiber reinforced polymer composites

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

[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

[www.carbonfiber.gr.jp]

[www.carbonfiber.gr.jp]

[www.carbonfiber.gr.jp]
Properties of carbon fibres

- Diameter about 7 μm

[Moreton 1967]
Properties of CNTs and graphene

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus</th>
<th>Tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWCNT:</td>
<td>954 GPa</td>
<td>63 GPa</td>
</tr>
<tr>
<td>Graphene:</td>
<td>1000 GPa</td>
<td>121 GPa</td>
</tr>
<tr>
<td>Polymer:</td>
<td>1 GPa</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>200 GPa</td>
<td></td>
</tr>
</tbody>
</table>

[CNT]

Graphene:

[Yu 2000]

Polymer:

[BBC]

Steel

[Lee 2008]
CNT Compared to carbon fibres

- **CNT 100 GPa**
- **CNT 1000 GPa**

### Reasons for weak CNT yarn performance:
- Discontinuous character of single CNTs (microns)
- Low (van der waals) interaction between CNTs
- Slippage within MWCNTs

**“Drawn CNT Yarns [Sears 2010]”**

- **High-strength Carbon Fiber**
- **High Modulus Carbon Fiber**

**CNT Yarns (Miao 2013)**
Materials in nature generate their strength and fracture toughness 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
Pseudo-ductility in discontinuous composites

Thermoplastic composites – chopped carbon fibre tapes with PEEK matrix

Synthetic brick and mortar material

compression molding

cross-section
Strength criterion – Selected model

Shear-lag model by Pimenta & Robinson [4]

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

\[ X_s^\infty = l^b \cdot S^m / t^b \]

Full plastic mortar (Kelly Tyson)

\[ X_G^\infty = \sqrt{2 \cdot E^b \cdot G^m_{IIc} / t^b} \]

Fracture mechanics approach

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

b. Unit-cell (zoom-in from (a)).
c. Infinitesimal element.

“Mortar” constitutive law

Shear response in overlap

Global response
Pseudo-ductility in discontinuous composites

Experimental - S2 glas fibre tape with PA12 matrix
Strength criterion – Constitutive law

Evonik PA12-2159  $G_{llc} = 1.9 \text{ kJ/m}^2$

Down to $\gamma = 28$, $\tau = 0$
To comply with energy dissipation $G_{llc}$
Pseudo-ductility in discontinuous composites

Overlap length: 14.3 mm

Overlap length: 20 mm

Hierarchical fiber-matrix interfaces

Sized fibres in matrix

CNTs grown on CF

CNTs in matrix

Free growth

Confined growth

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

\[ T = 750^\circ C \]

catalyst
droplet

molten layer

Support

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

ALD
dip coat
CVD

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

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

Confirmed by ptychographic X-ray computed tomography and TEM


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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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