Mimicking helicoidal biological materials to improve strength of synthetic composites

MECHANICS OF BIOLOGICAL AND BIO-INSPIRED MATERIALS

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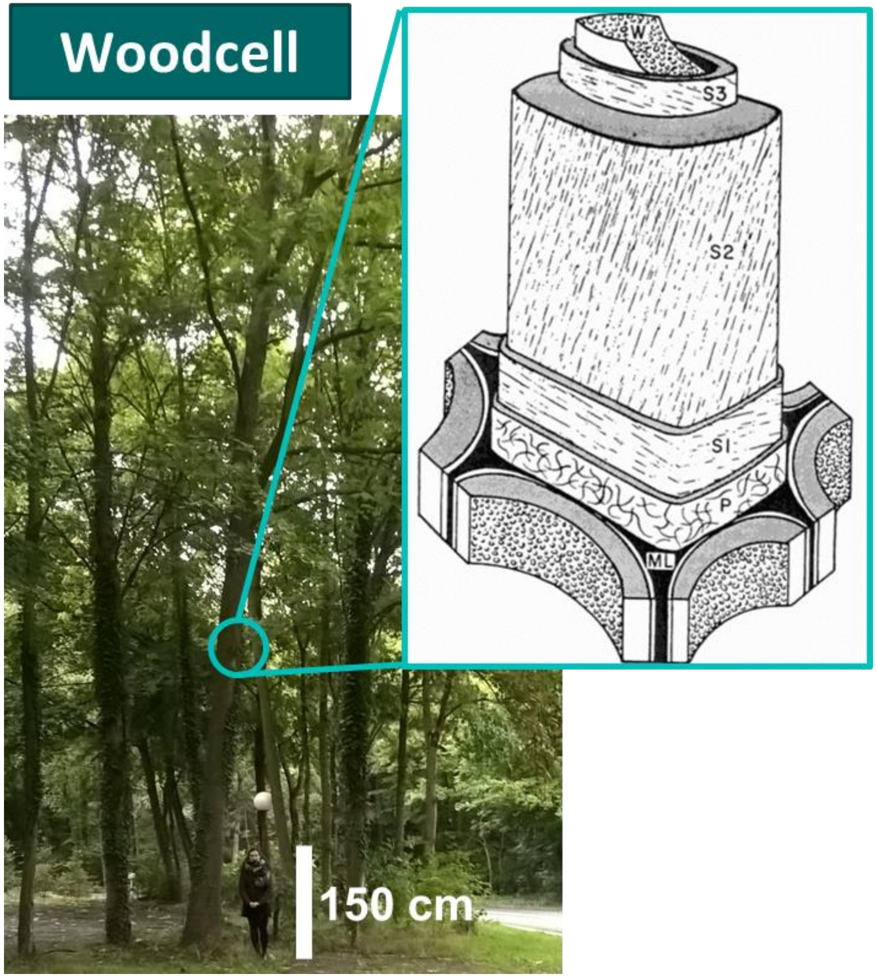
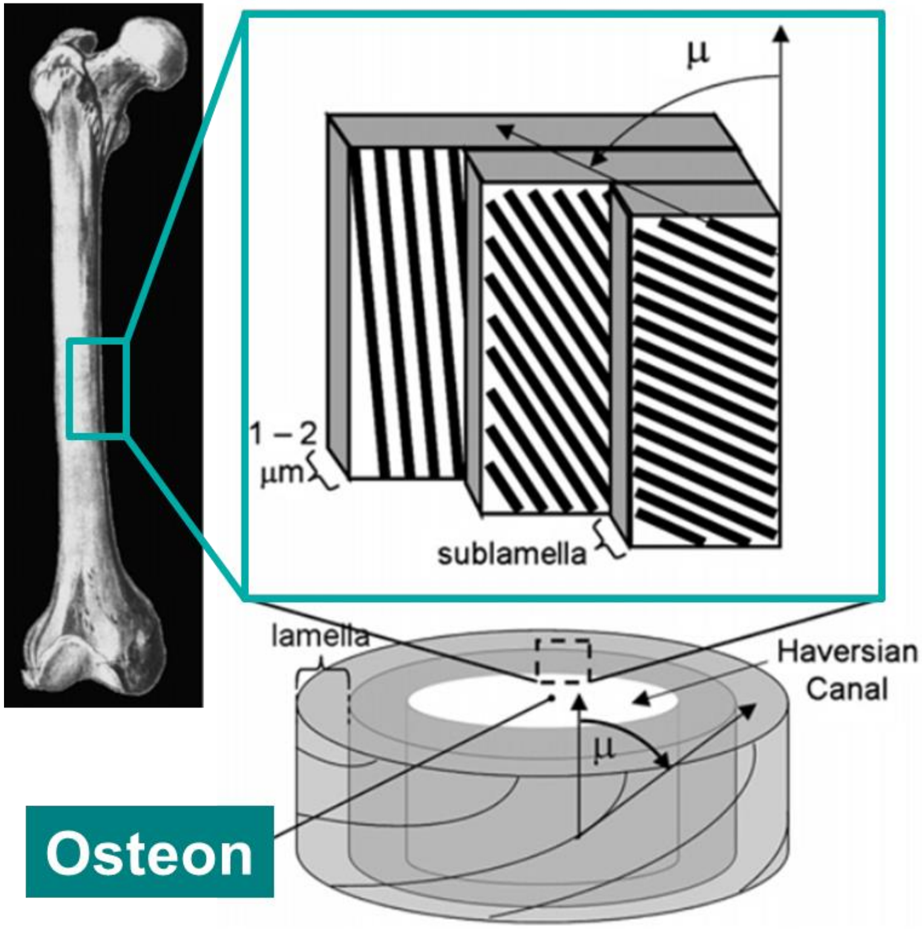
http://www.biomat.ulg.ac.be/

Helicoidal structures in nature

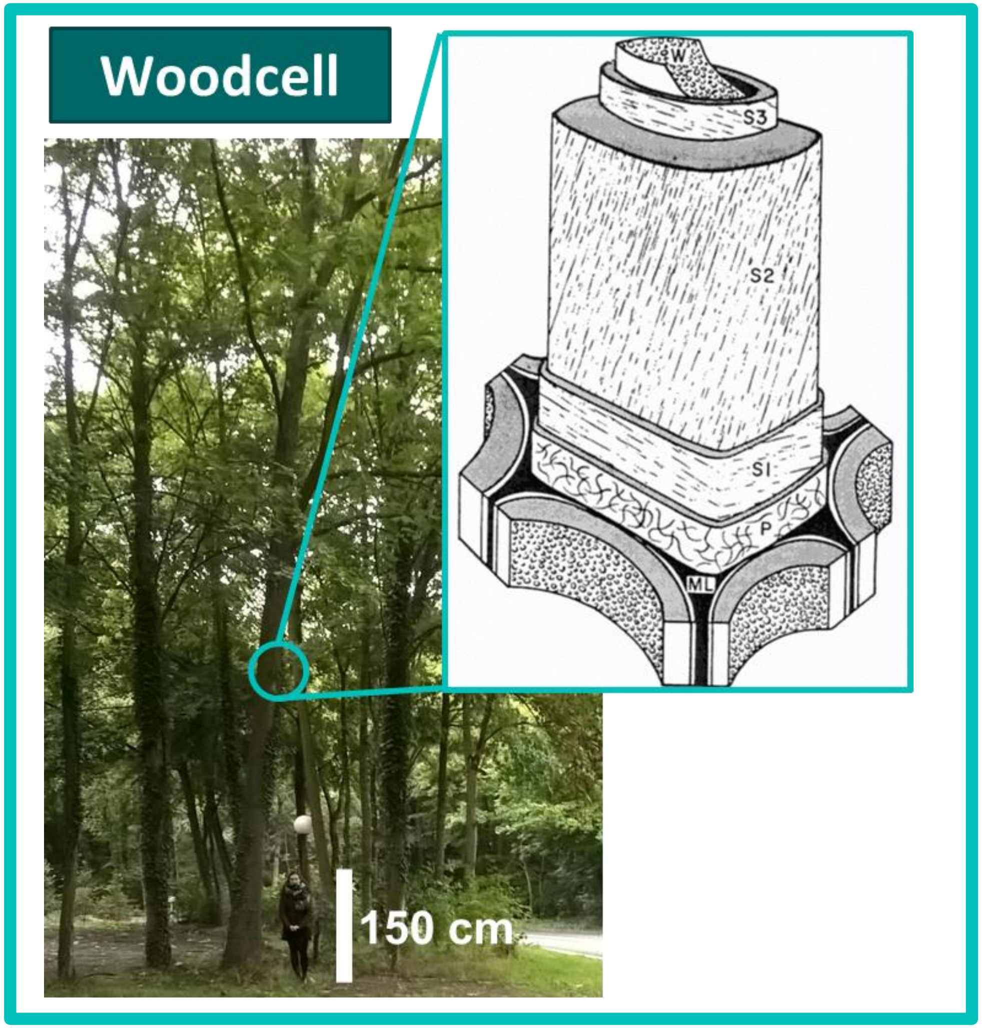


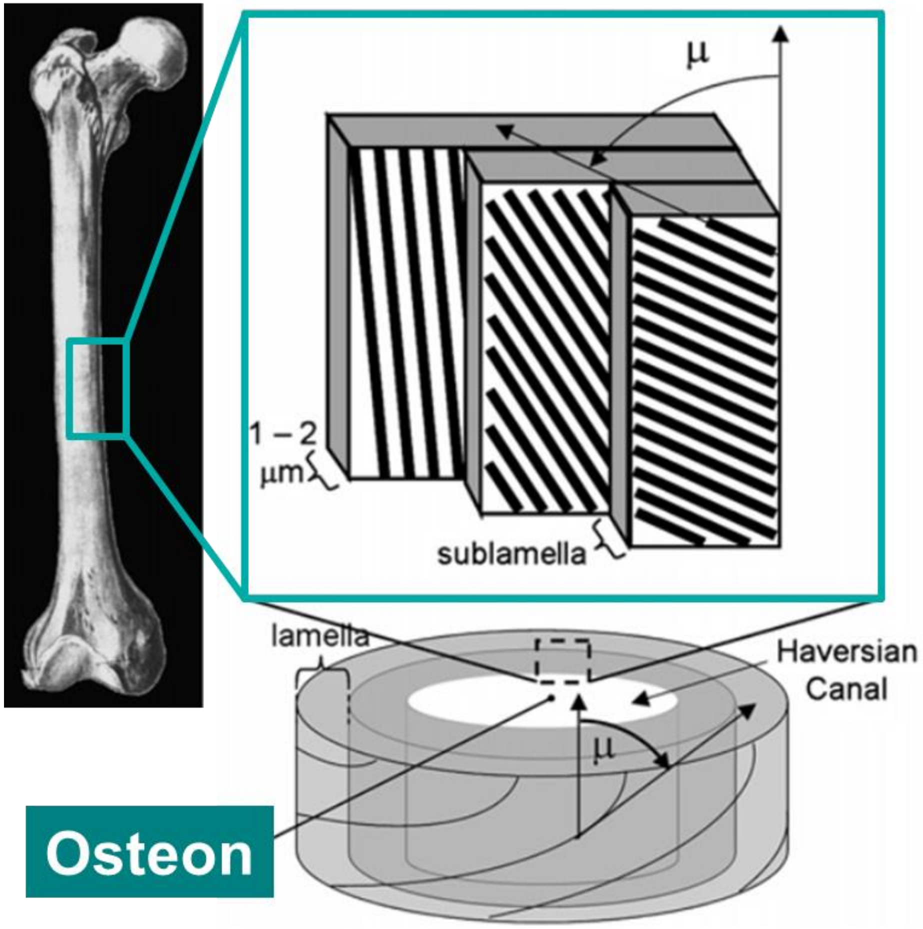


E. Sjöström, *Wood Chemistry, Fundamentals and Applications*, Elsevier, **1993**.

Fratzl, P. & Weinkamer, *Prog. Mater. Sci.* **52,** 1263–13\34 (2007).

Wood hierarchical structure





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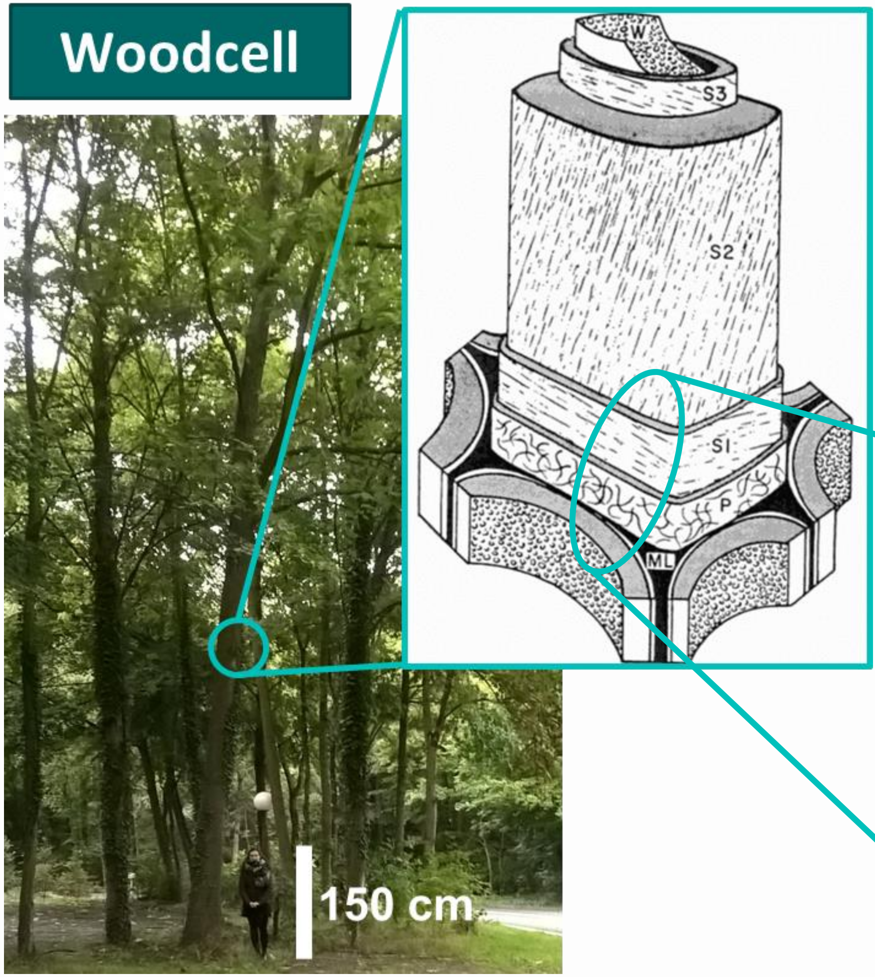
Wood hierarchical structure

Woodcell

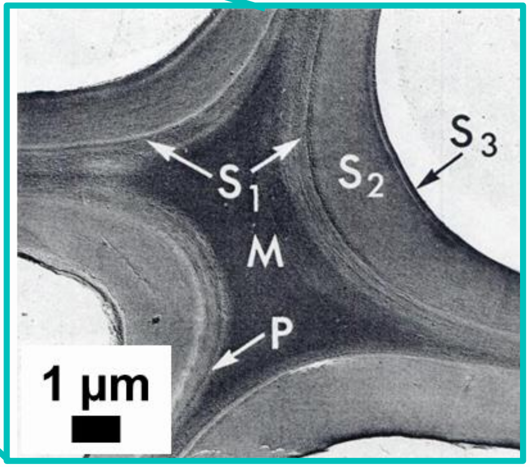


Woodcell wall layers:

S1 = 10% thickness

S2 = 80% thickness

S3 = 3-4 % thickness



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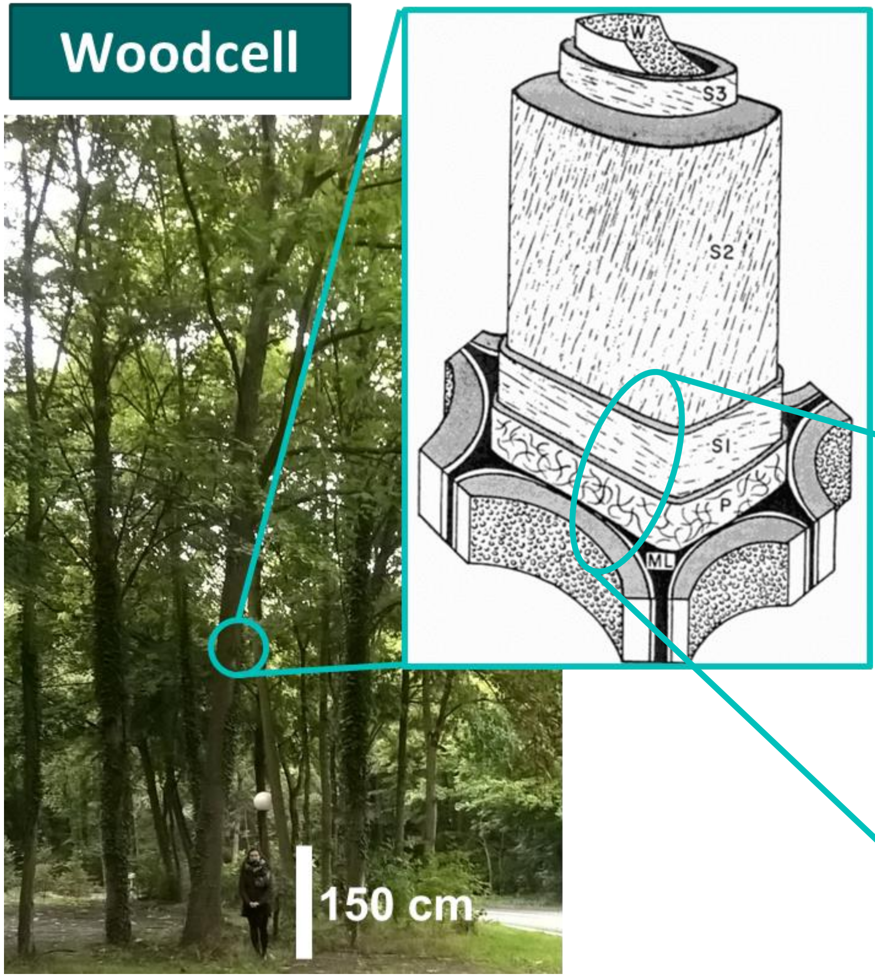
Wood hierarchical structure



Woodcell wall layers:

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S2 = 80% thickness

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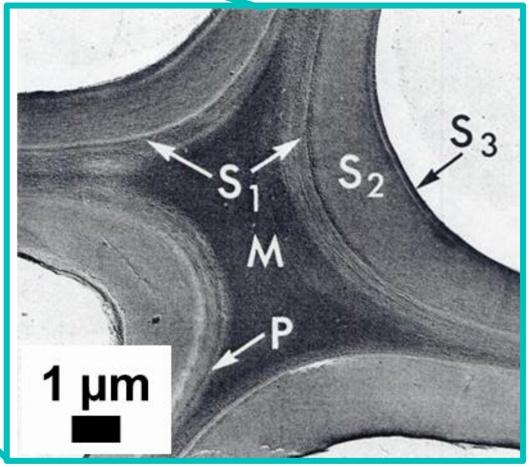
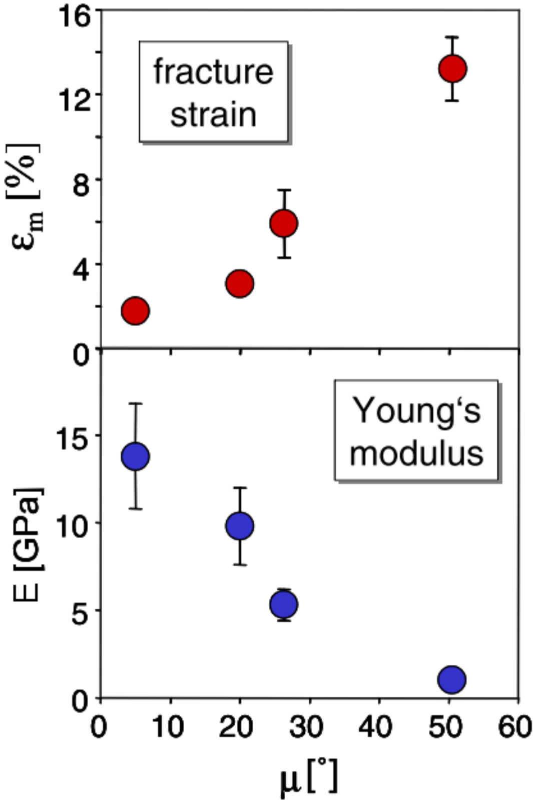


L. J. Gibson, *J. R. Soc. Interface* **2012**, *9*, 2749.
E. Sjöström, *Wood Chemistry, Fundamentals and Applications*, Elsevier, **1993**.

Secondary woodcell

S2 → tunes mechanical properties



Cellulose helicoidal fibers in compliant matrix (lignin and hemicellulose)

↑ microfibril angle (μ)

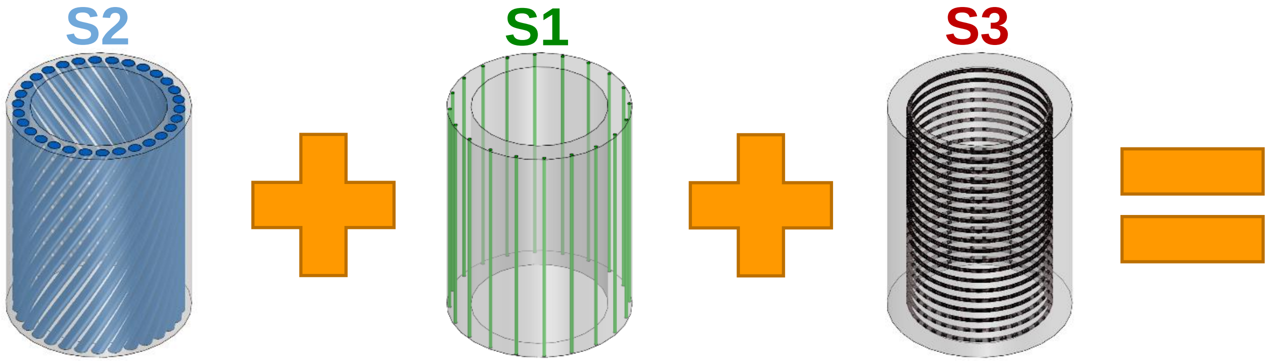
↓ modulus

↑ strain at break

P. Fratzl, R. Weinkamer, *Prog. Mater. Sci.* **2007**, *52*, 1263.

Aim of the study

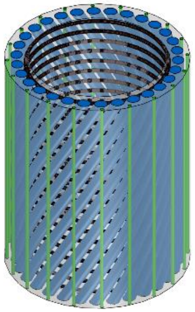
- Behavior of helicoidal composites made of one main layer reinforced with low volume fraction secondary layers:



Biomechanical role?

- Possibility to tranfer construction principles in polymer-based composites

S1 + S2 + S3



Polyjet multimaterial printing

Manufactured structure

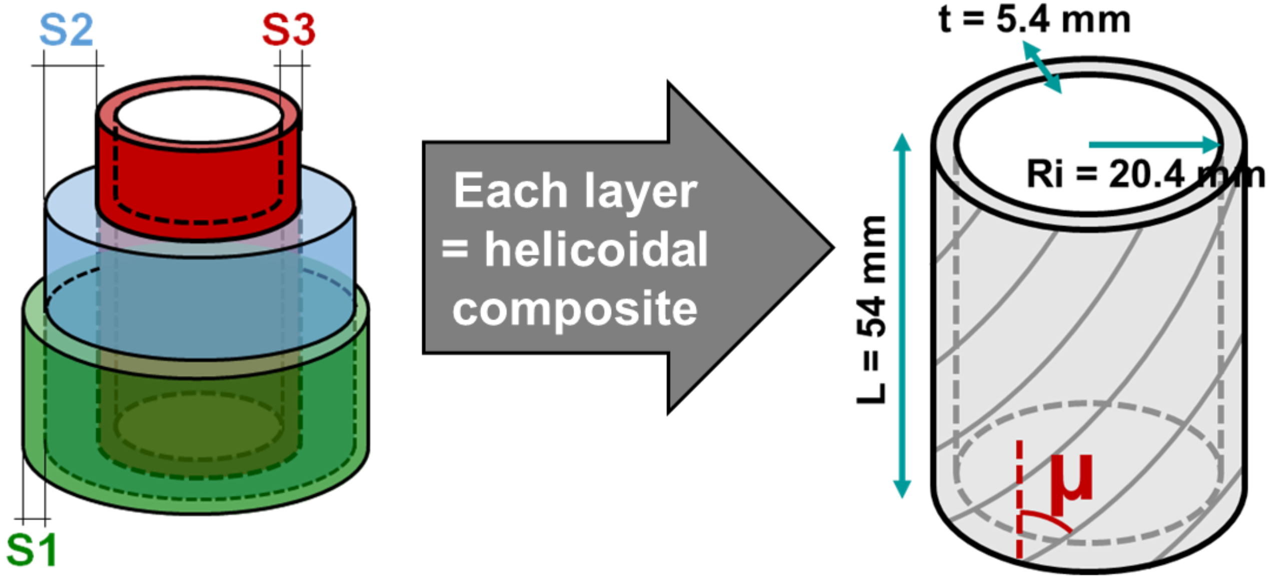
Structure design

Three-layered concentric composite:

- S2 = **main layer - 60% of wall thickness**
- S1 and S3 = **reinforcement layers - 20% of wall thickness**

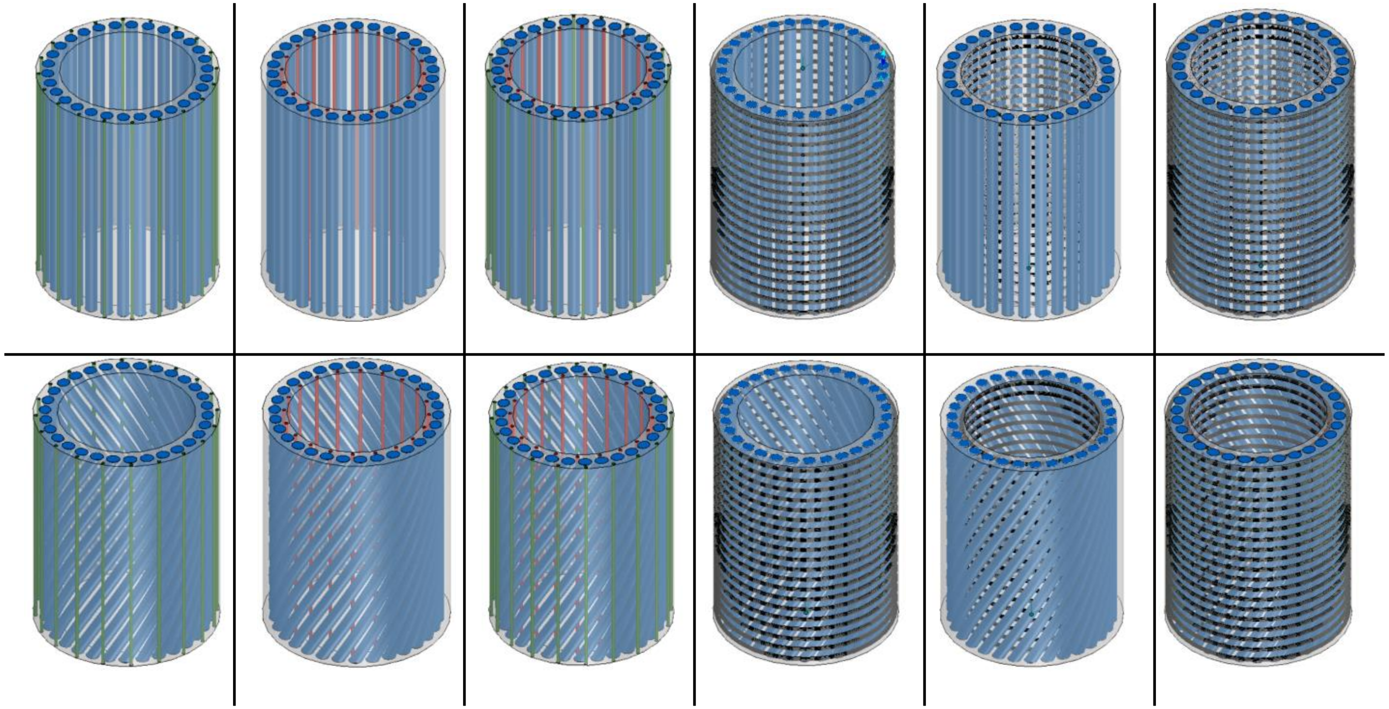
Compliant matrix + stiff fibers

- S2→ 2.8 mm – 30% Volume fraction
- S1 and S3→ 0.75 mm



Studied parameters

- Main layer (S2) orientation
- Reinforcement position
- Reinforcement orientation



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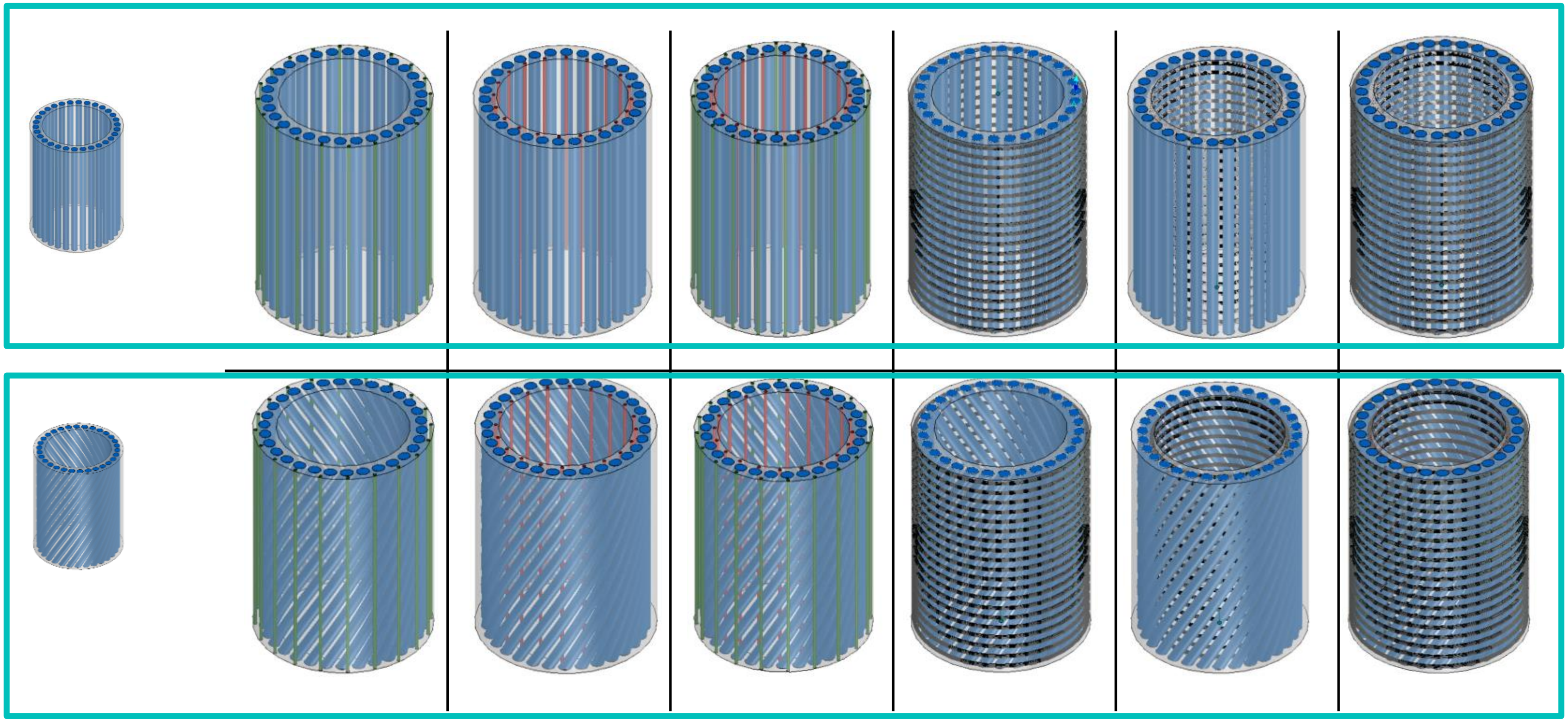
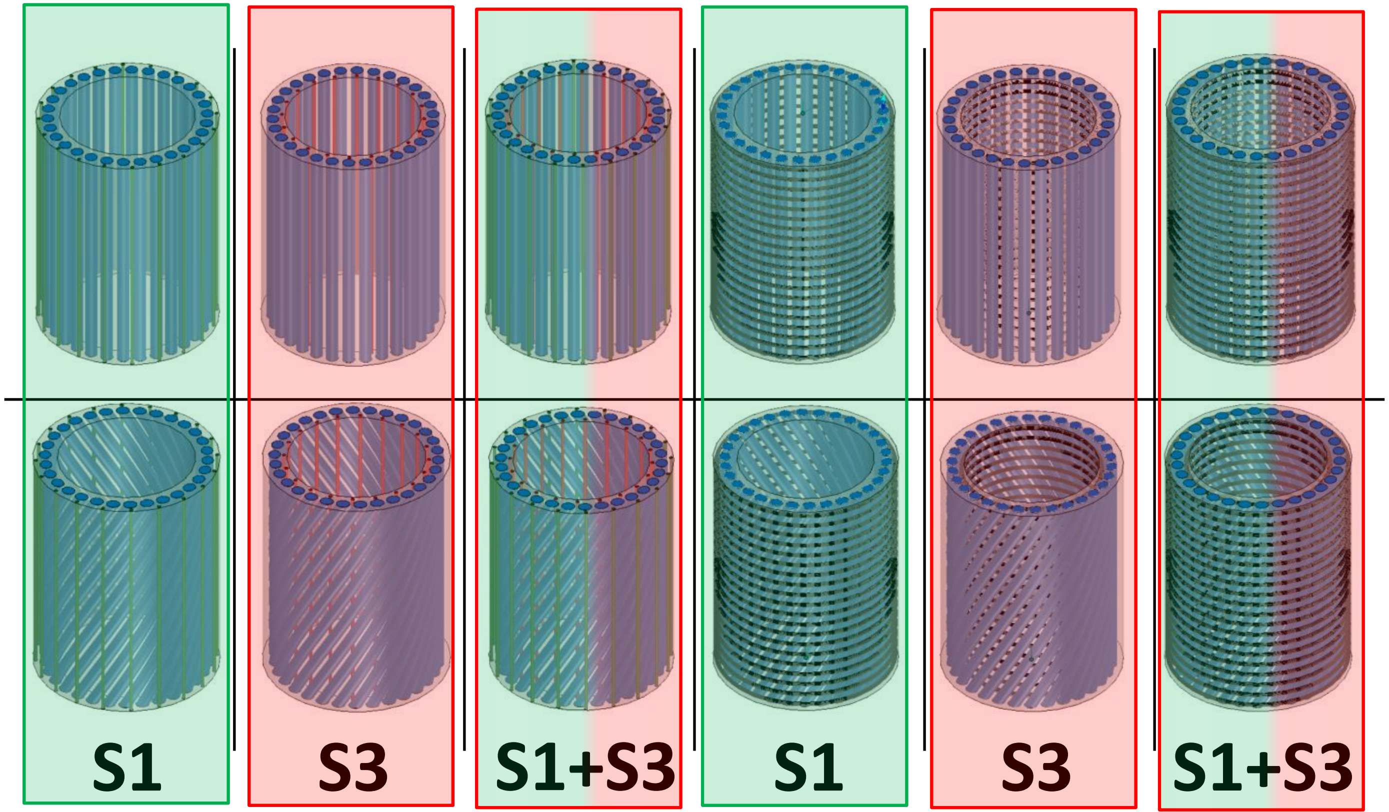


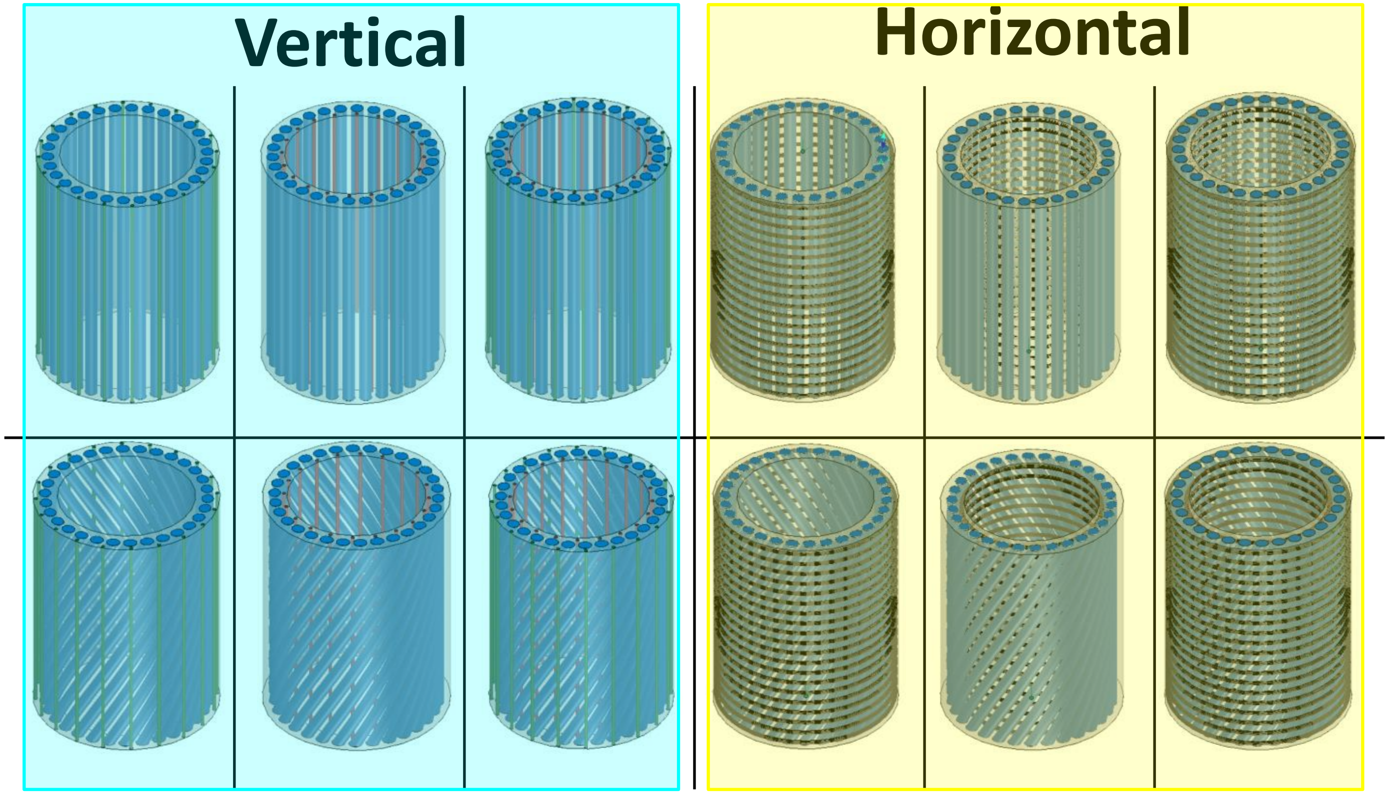
Studied parameters

- Main layer (S2) orientation
- **Reinforcement position**
- Reinforcement orientation



Studied parameters

- Main layer (S2) orientation
- Reinforcement position
- **Reinforcement orientation**

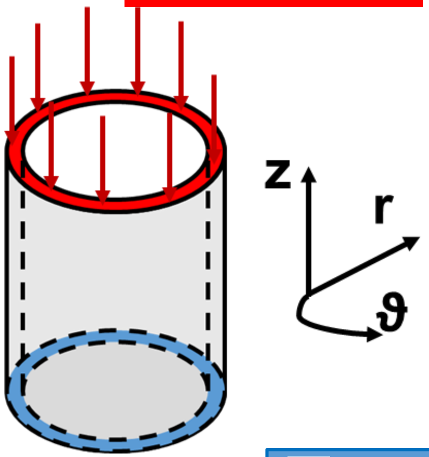


Stiffness and buckling load

Free rotation

No radial displacement

$\varepsilon_z = -0.1\ \%$



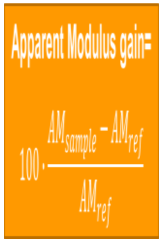
Fixed base $\bar{U} = 0$

Finite element simulations

→ Fibers: 2 GPa
→ Matrix: 33 MPa
→ $E_{fibers}/E_{matrix} = 60$

Reference configuration

→ Only S2 layer



Apparent Modulus gain=

$$100 \cdot \frac{AM_{sample} - AM_{ref}}{AM_{ref}}$$

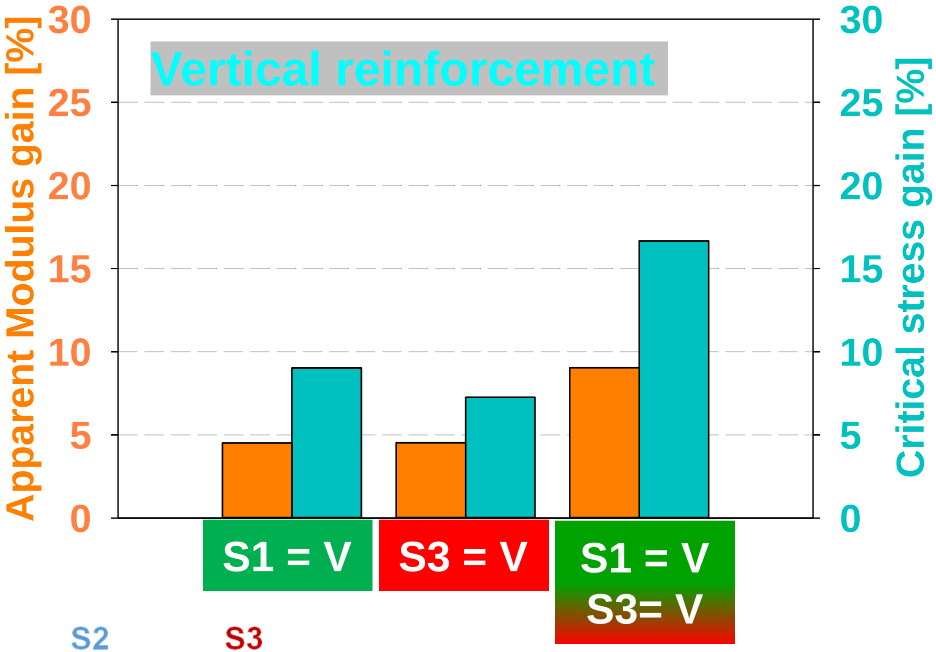
Apparent Modulus gain=

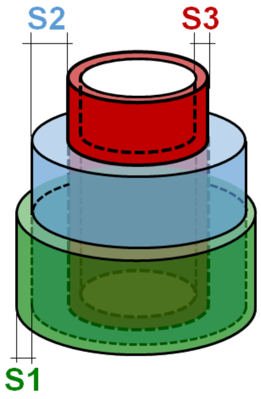
$$100 \cdot \frac{AM_{sample} - AM_{ref}}{AM_{ref}}$$

Buckling Stress gain=

$$100 \cdot \frac{BS_{sample} - BS_{ref}}{BS_{ref}}$$

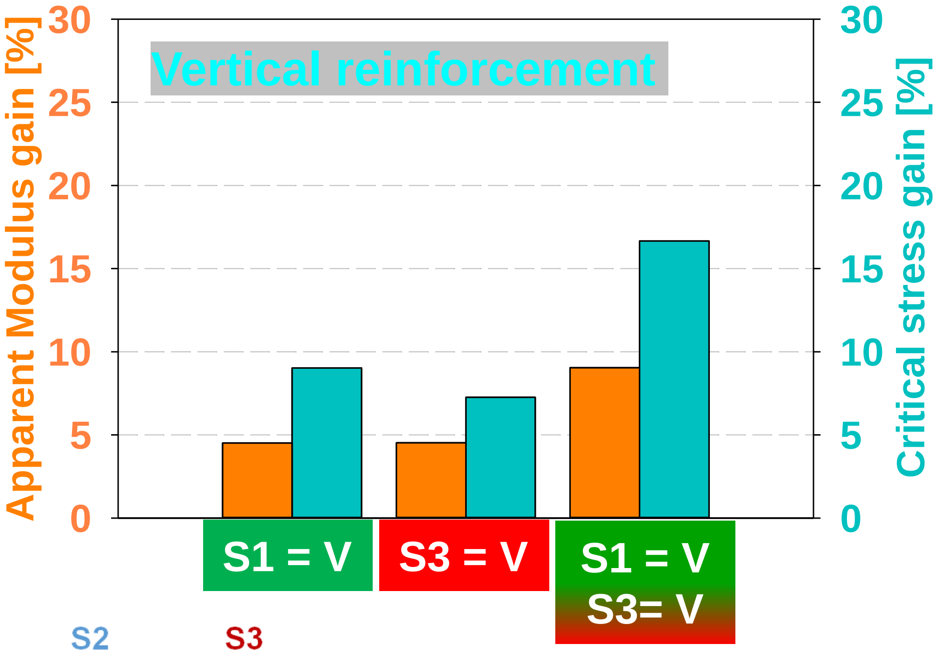
S2 = vertical

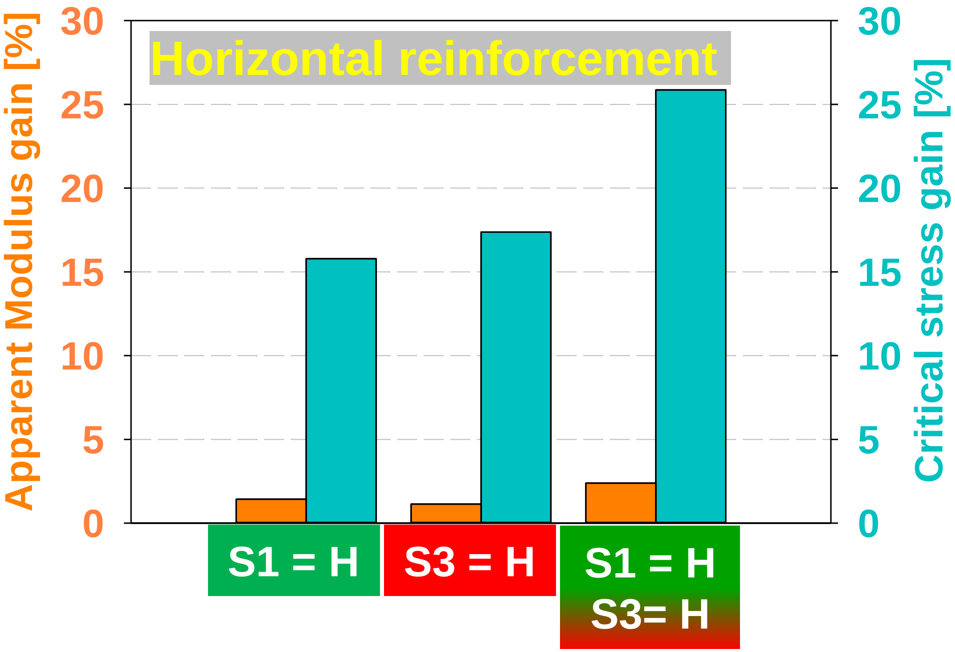

Vertical reinforcement
Apparent Modulus gain [%]
Critical stress gain [%]
30
25
20
15
10
5
0
S1 = V
S3 = V
S1 = V
S3= V

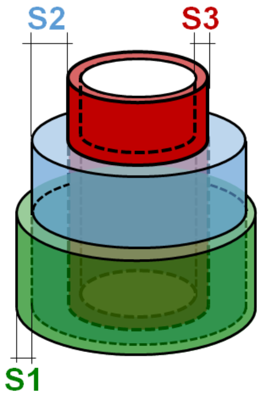

S2
S3
S1

S2 = vertical

+1.5%	+1.5%	+2.9%	**Volume fraction increase**	+3.3%	+3.3%	+6.0%

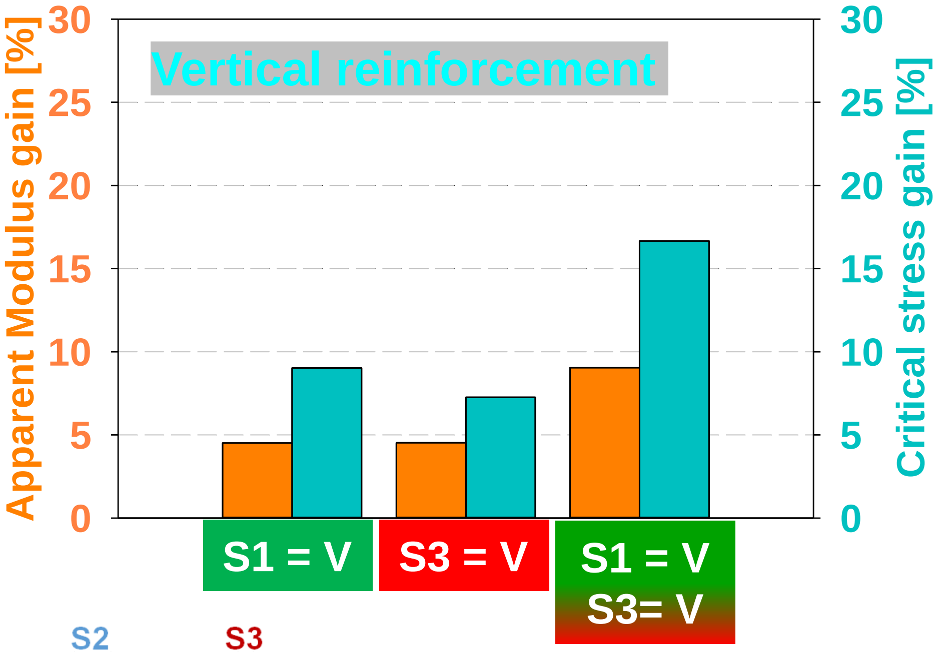


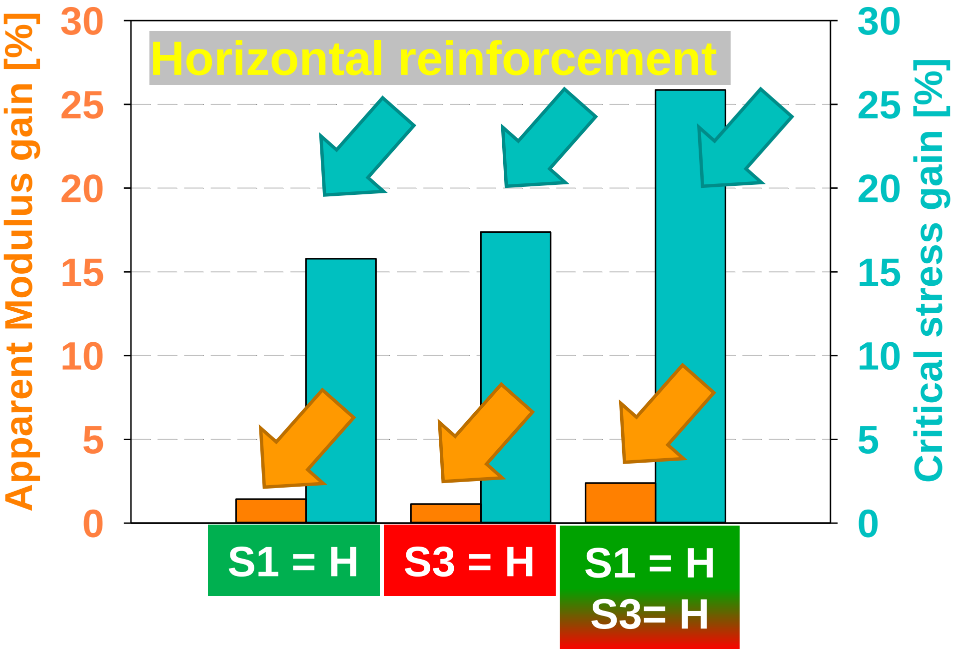


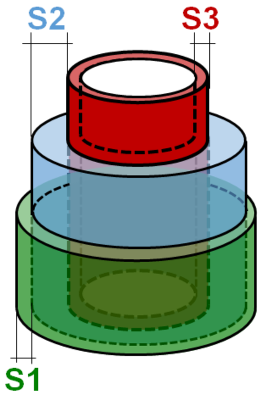


S2 = vertical

+1.5%	+1.5%	+2.9%	**Volume fraction increase**	+3.3%	+3.3%	+6.0%



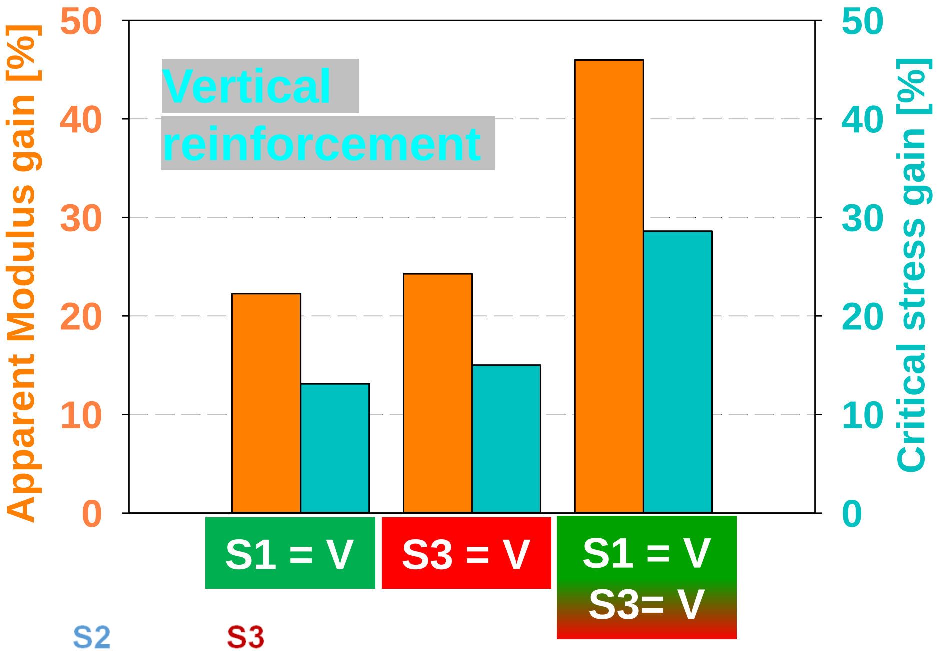


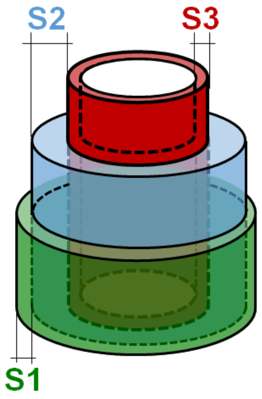


Horizontal reinforcement:

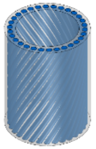
- Higher gain in critical stress than vertical reinforcement
- Decoupling Stiffness and buckling resistance

S2 = 30 degree

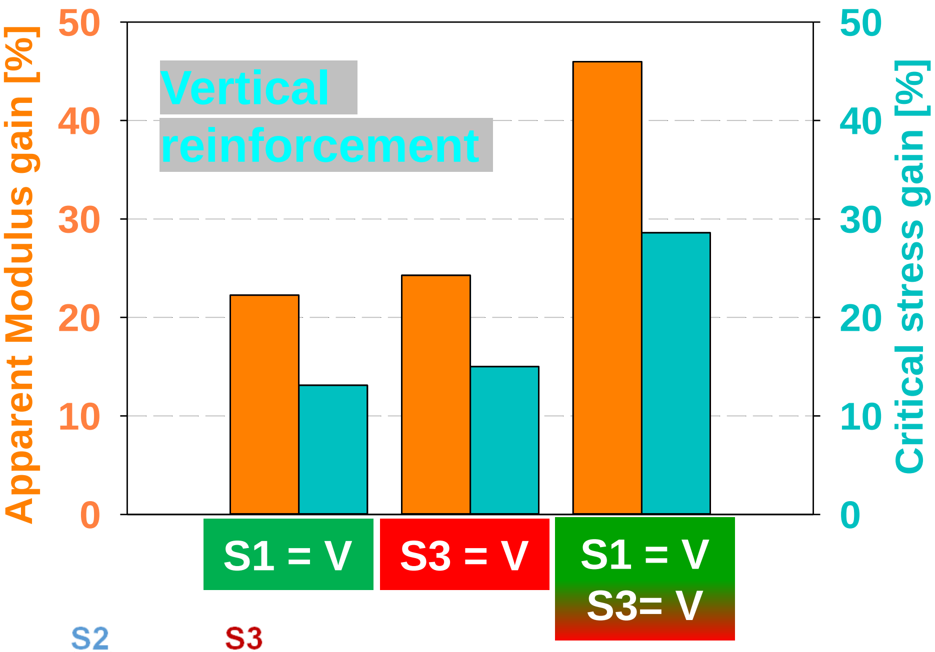

Apparent Modulus gain [%]
50
40
30
20
10
0
Critical stress gain [%]
50
40
30
20
10
0
Vertical reinforcement
S1 = V
S3 = V
S1 = V
S3= V

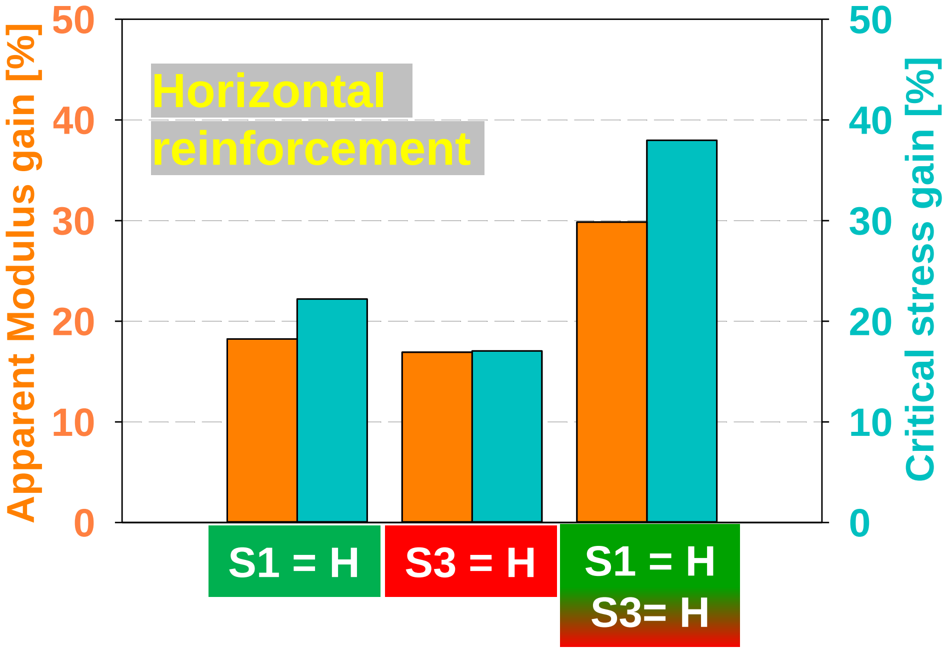

S2
S3
S1

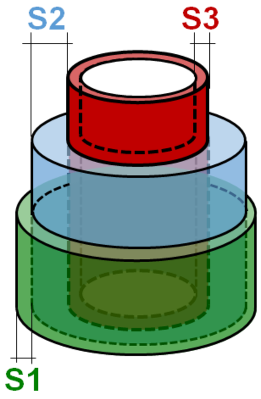
S2 = 30 degree



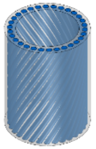
+1.5%	+1.5%	+2.9%	**Volume fraction increase**	+3.3%	+3.3%	+6.0%



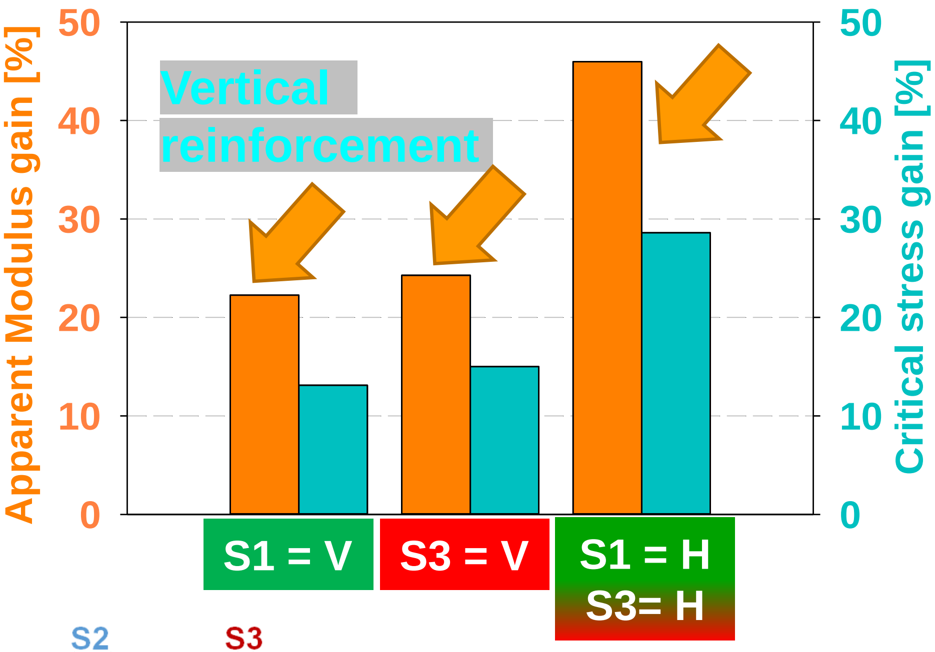


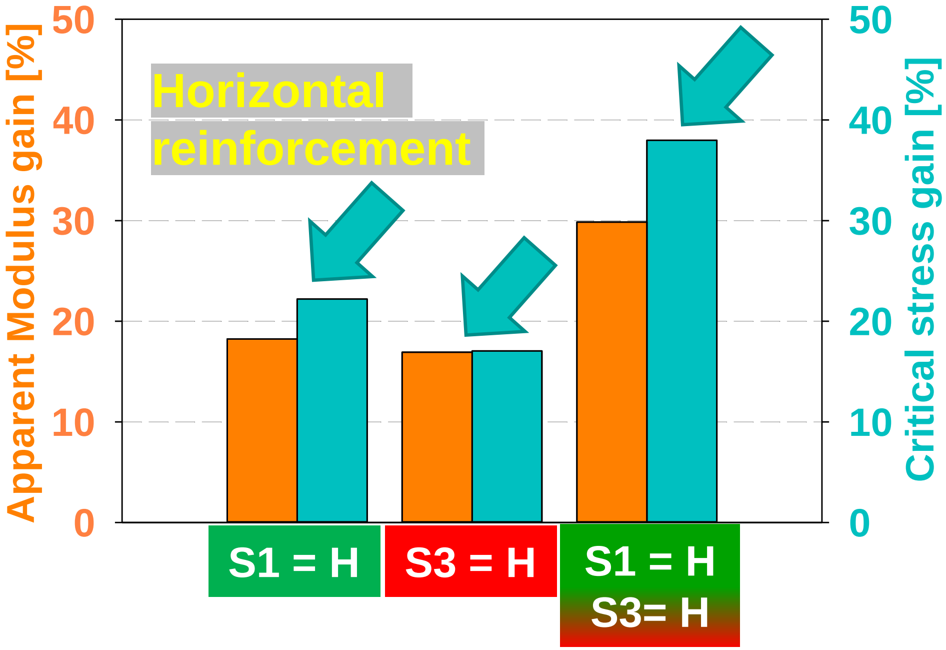


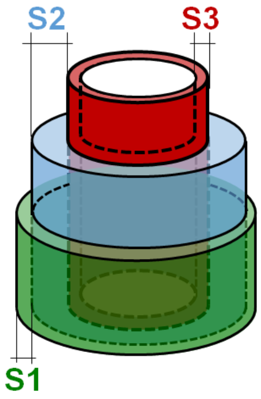
S2 = 30 degree



+1.5%	+1.5%	+2.9%	**Volume fraction increase**	+3.3%	+3.3%	+6.0%







Vertical reinforcement:

- Higher gain in apparent modulus

Horizontal reinforcement:

- Higher gain in critical stress
- Block rotation

3D printing multilayer composites

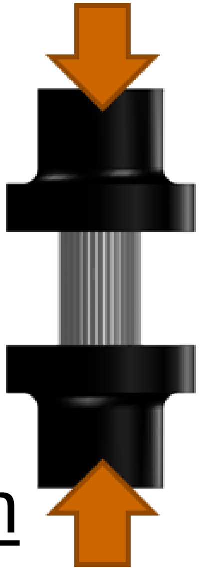
Sample production through **polyjet printing**

→ **Fibers: 2.47 GPa**

→ **Matrix: 45.1 MPa**

→ **$E_{fibers}/E_{matrix} \cong 55$**

Large strain mechanical tests: **compression**



Only configuration with **S1+S3**

Test preload: 2 N

Test speed: $5e^{-4}$ s^{-1}

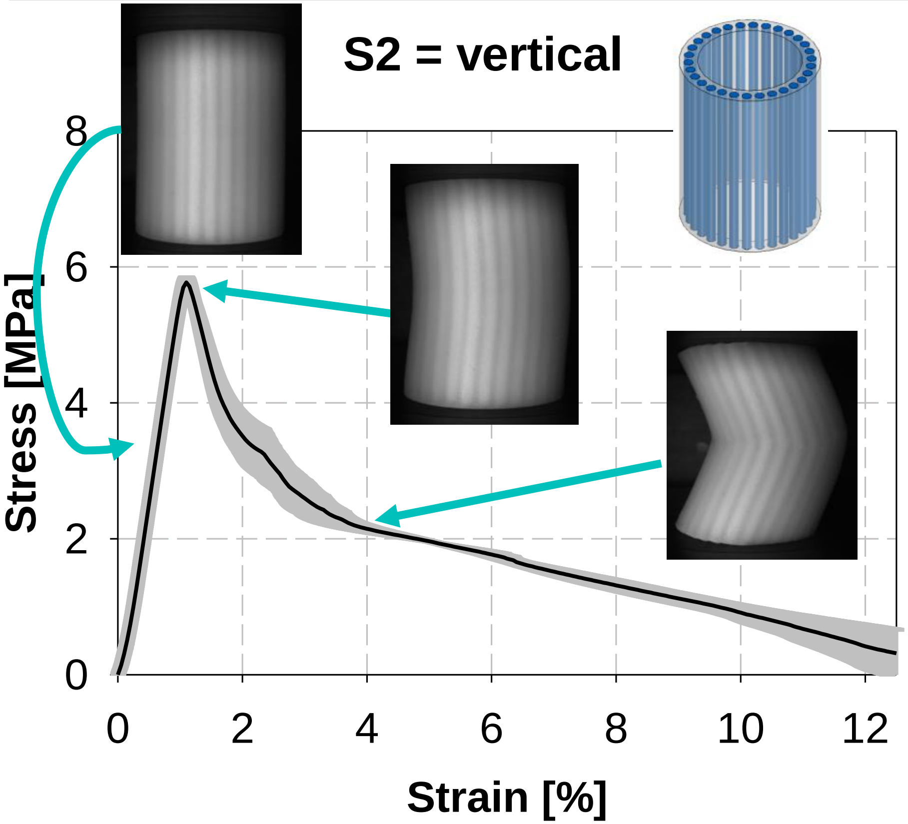
Reference configuration

→ **Only S2 layer**

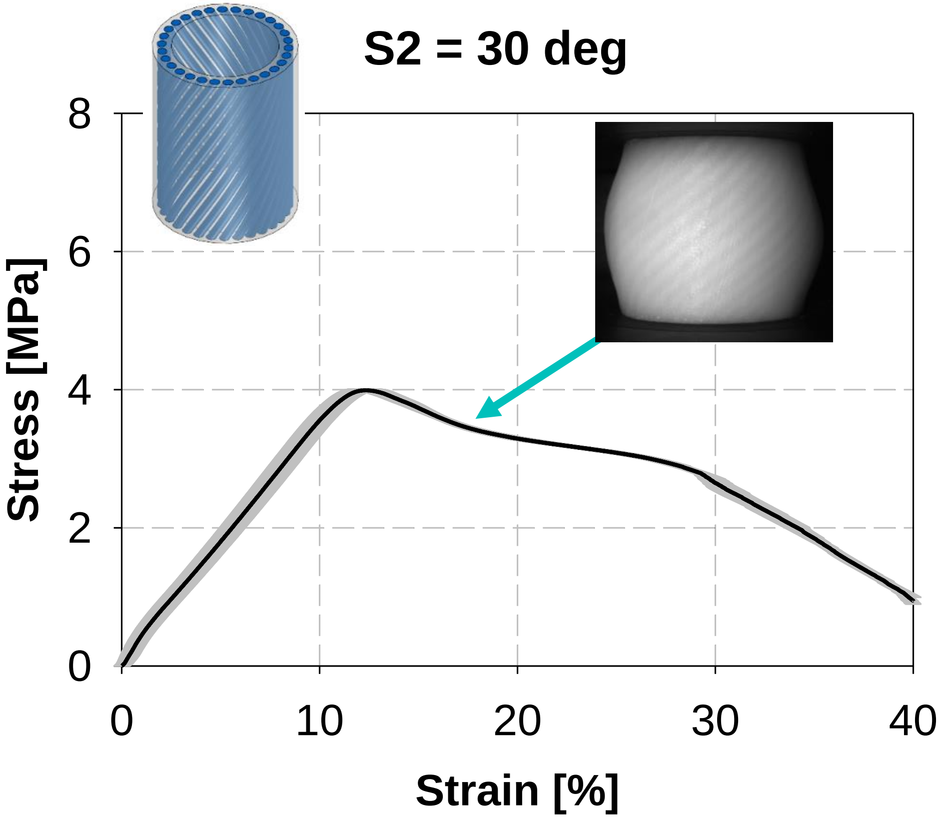
Critical stress gain

Post-buckling behavior

Mechanical tests: results



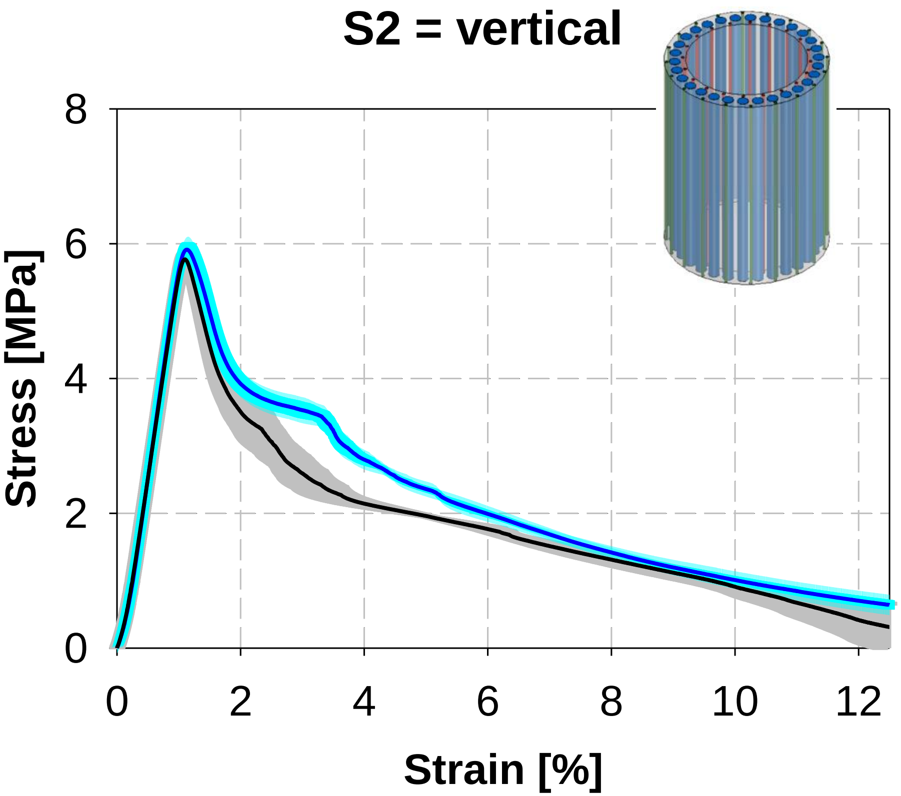
S2 = vertical

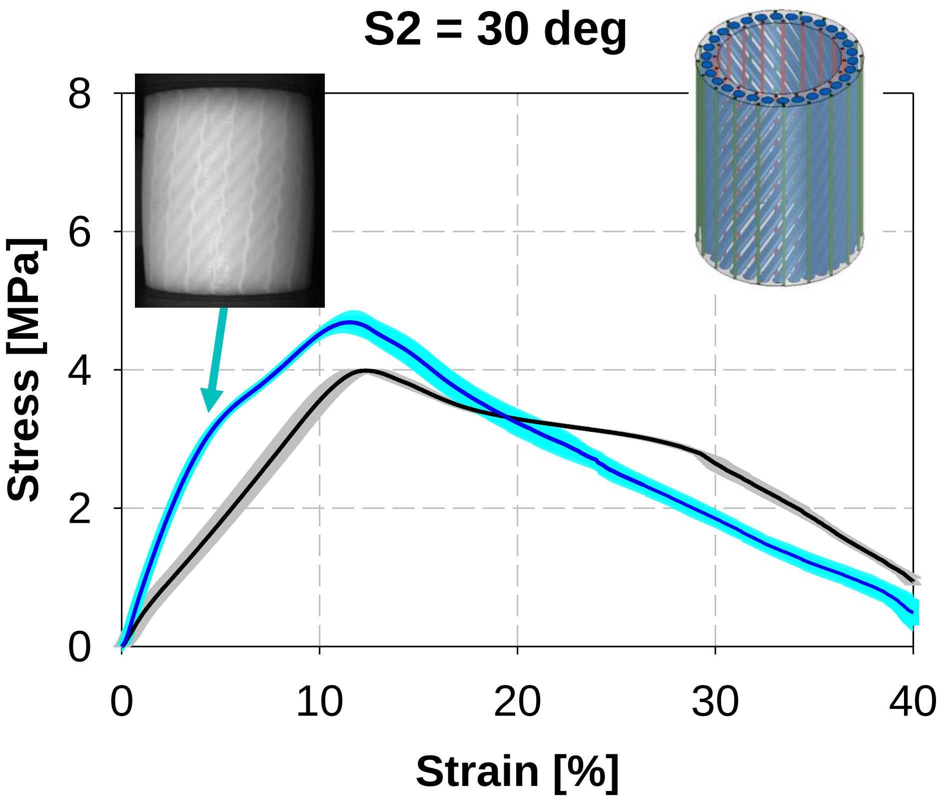


S2 = 30 deg

▨ **No reinforcements**

Mechanical tests: results

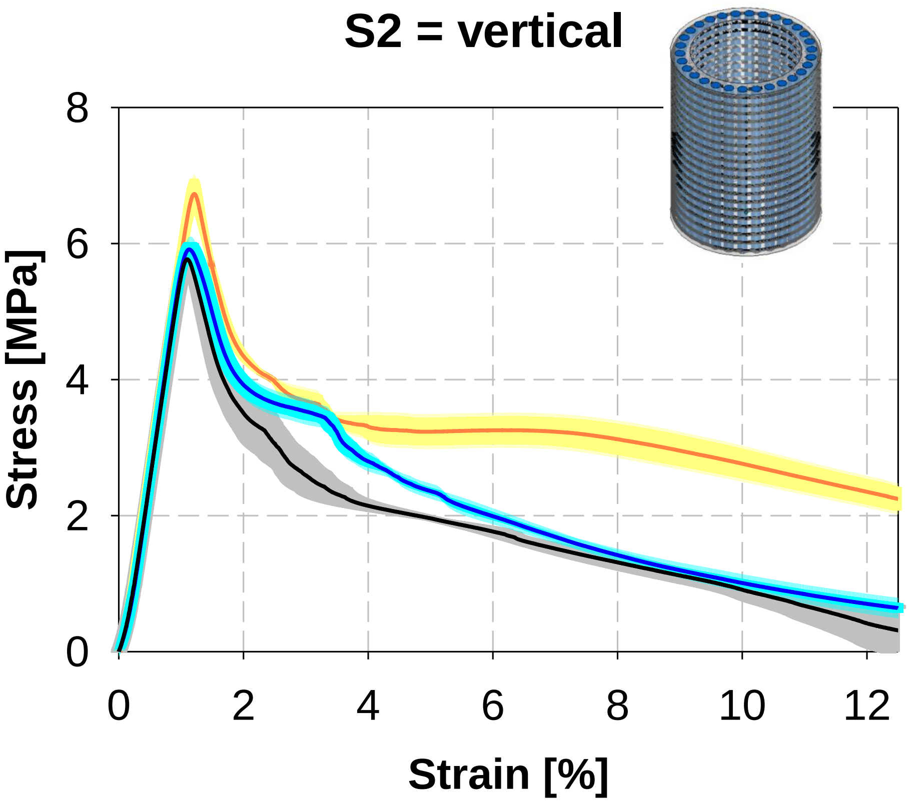


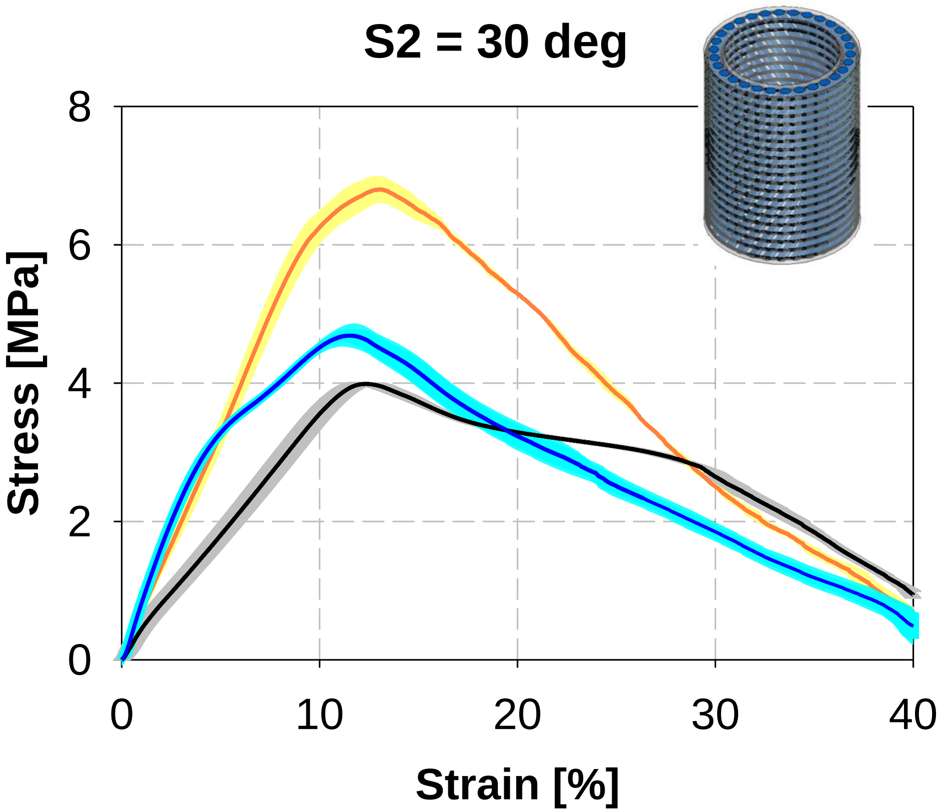


▬ **No reinforcements**

▬ **Vertical reinforcements**

Mechanical tests: results



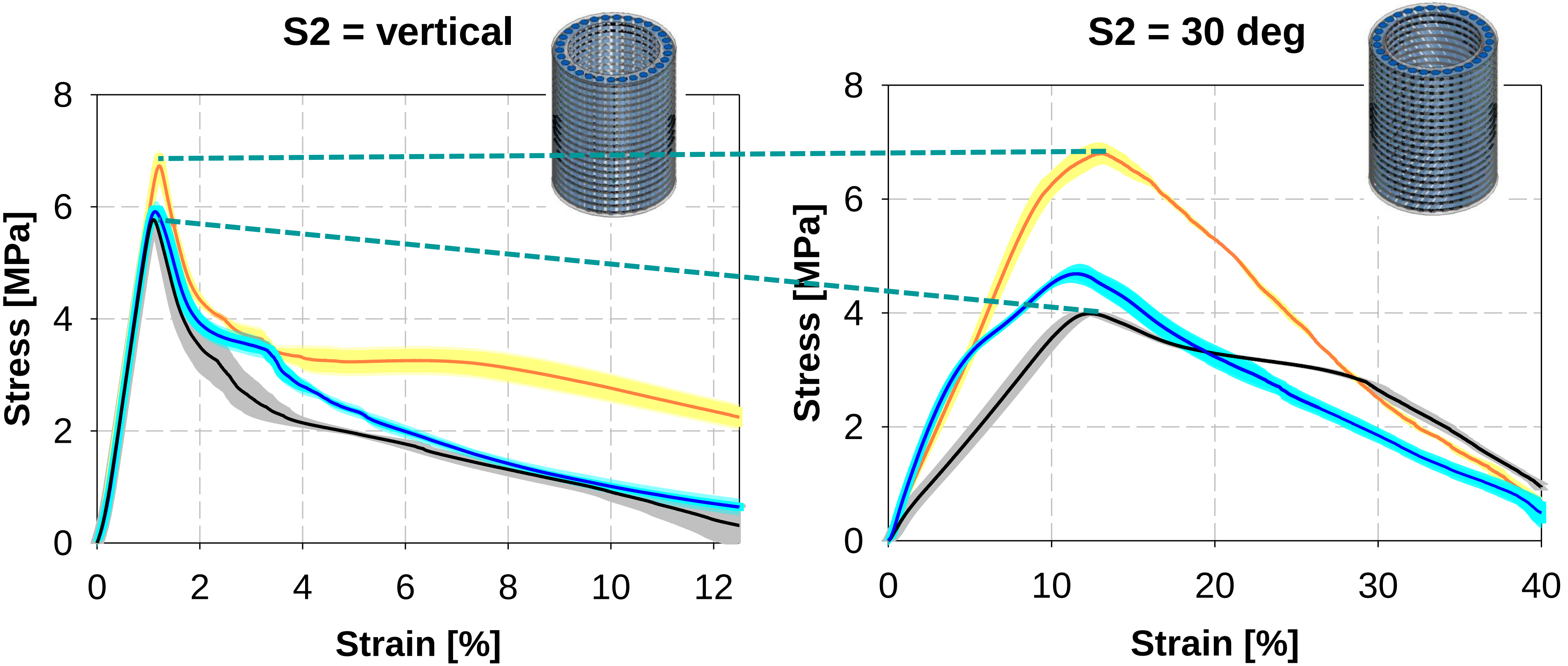


▬ **No reinforcements**

▬ **Vertical reinforcements**

▬ **Horizontal reinforcements**

Mechanical tests: results



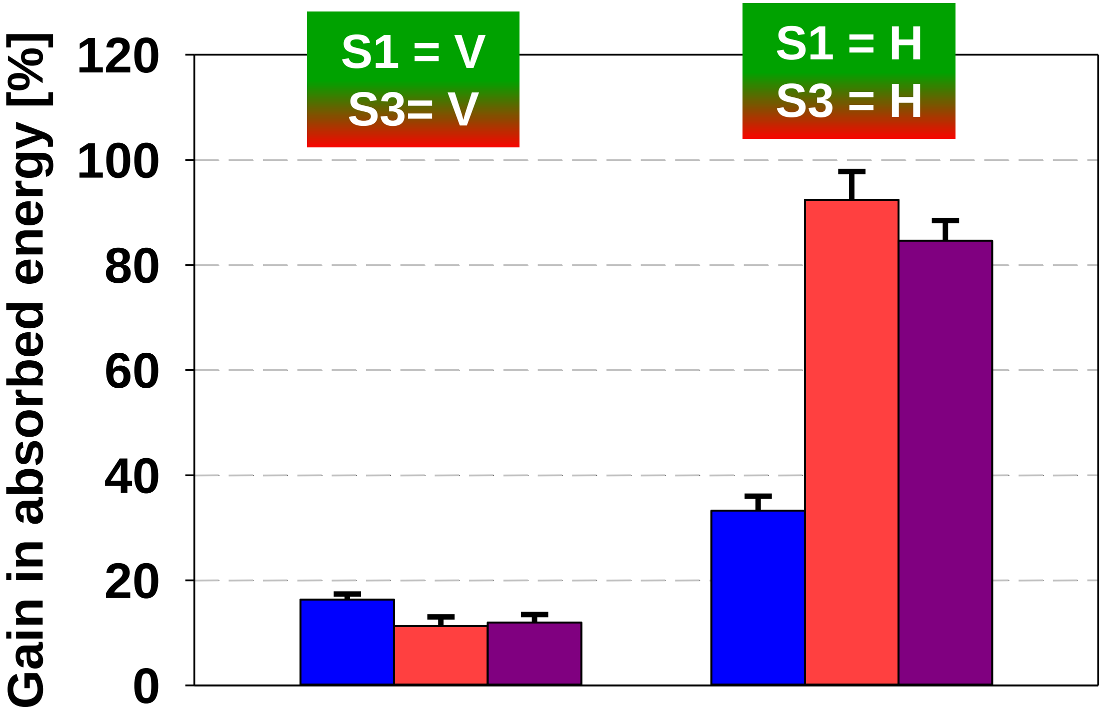
No reinforcements

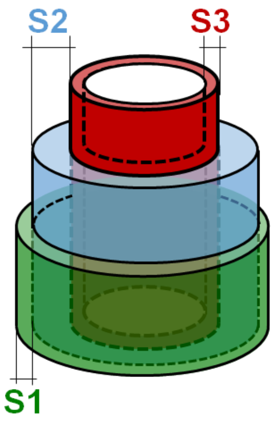
Vertical reinforcements

Horizontal reinforcements

Horizontal reinforcement of S2 = 30 deg → same stress peak than vertical S2

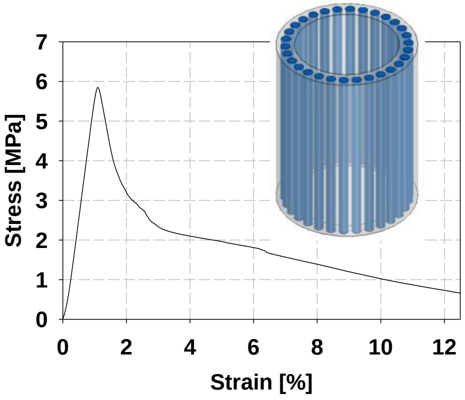
Post-buckling behavior: S2 = vertical

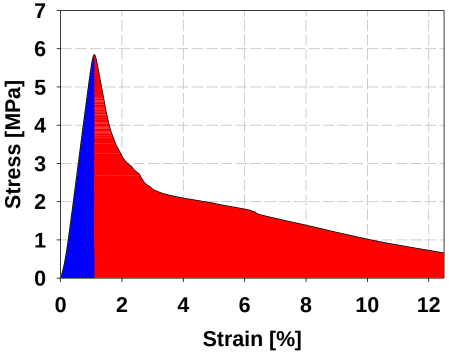


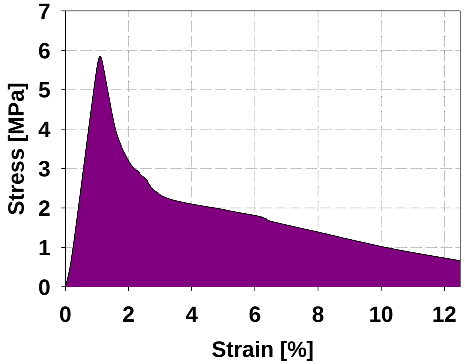


Energy gain =

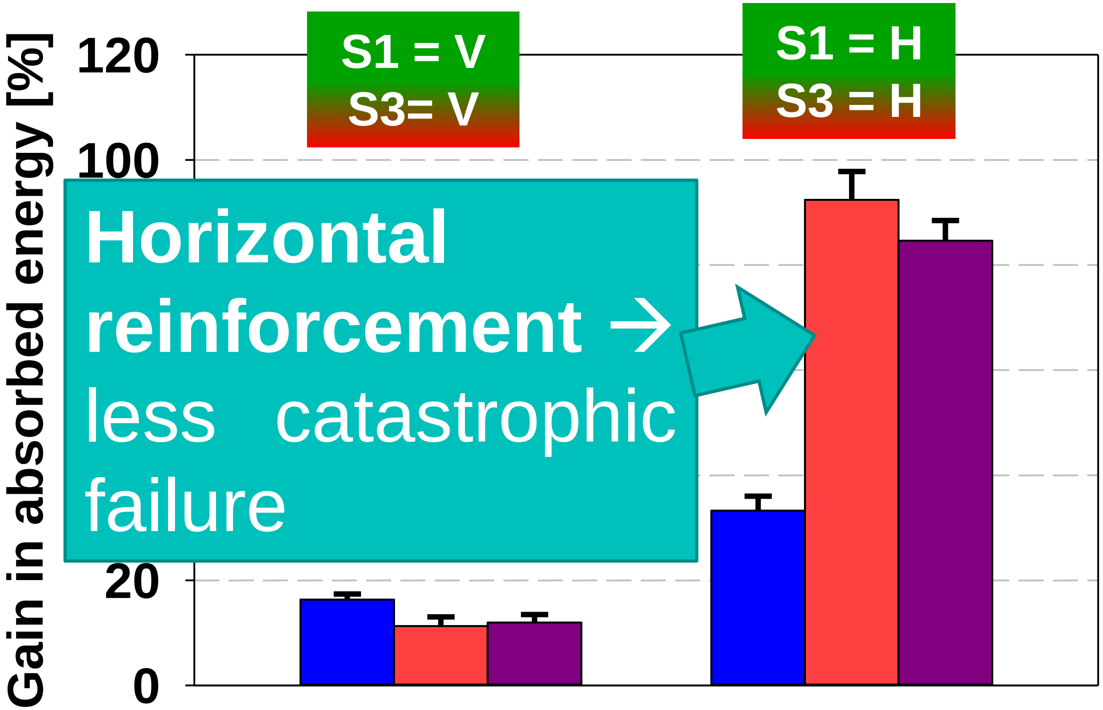
$$100 \cdot \frac{E_{sample} - E_{ref}}{E_{ref}}$$



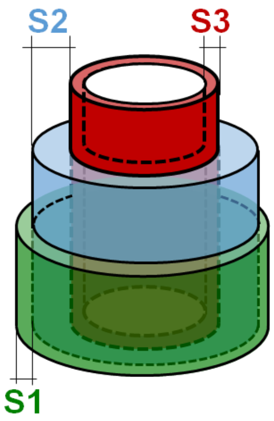




Post-buckling behavior: S2 = vertical

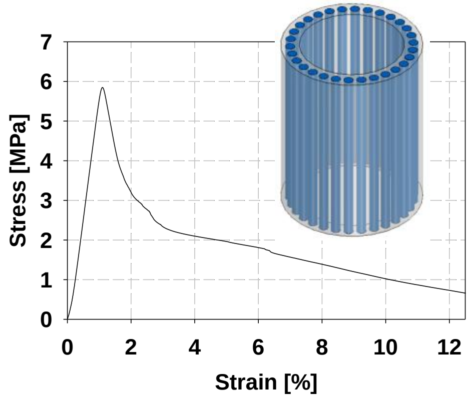


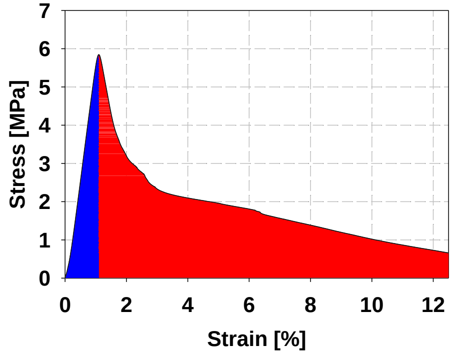
Horizontal reinforcement → less catastrophic failure

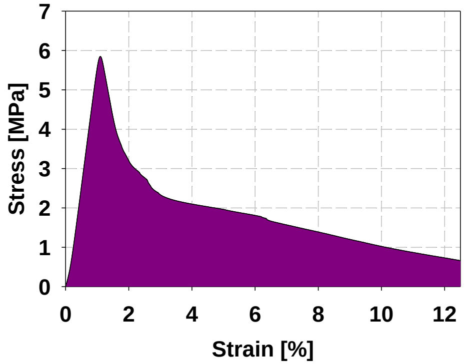


Energy gain =

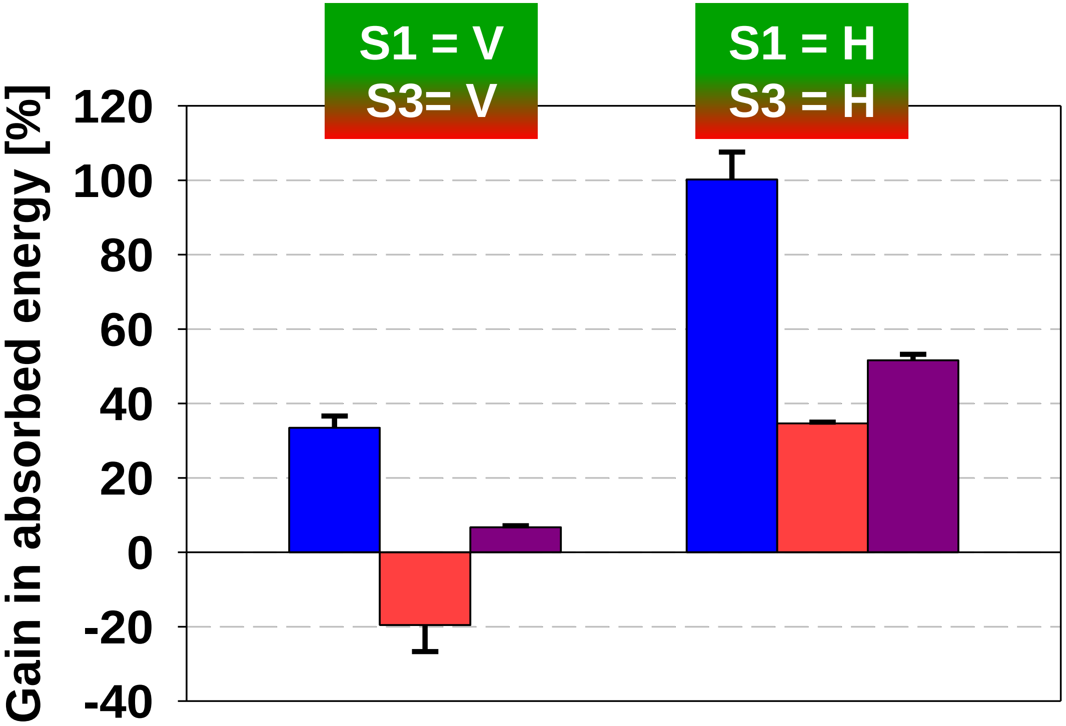
$$100 \cdot \frac{E_{sample} - E_{ref}}{E_{ref}}$$

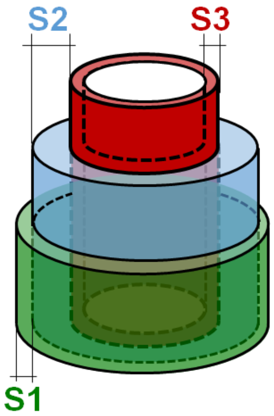






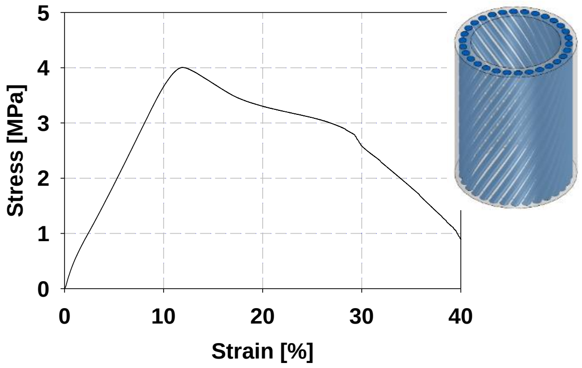
Post-buckling behavior: S2 = 30 deg

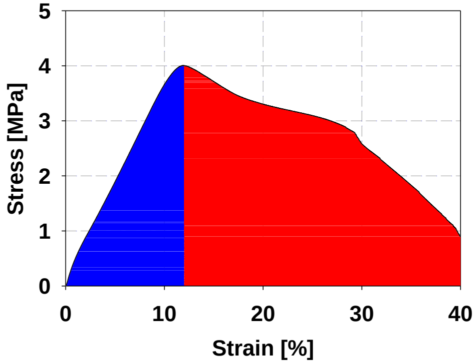


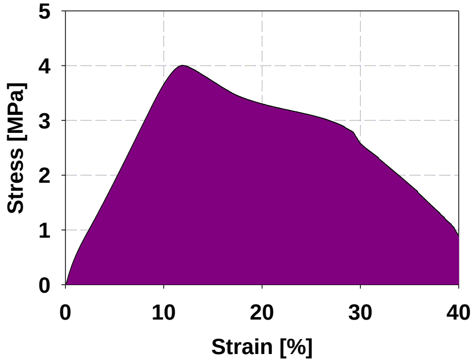


Energy gain =

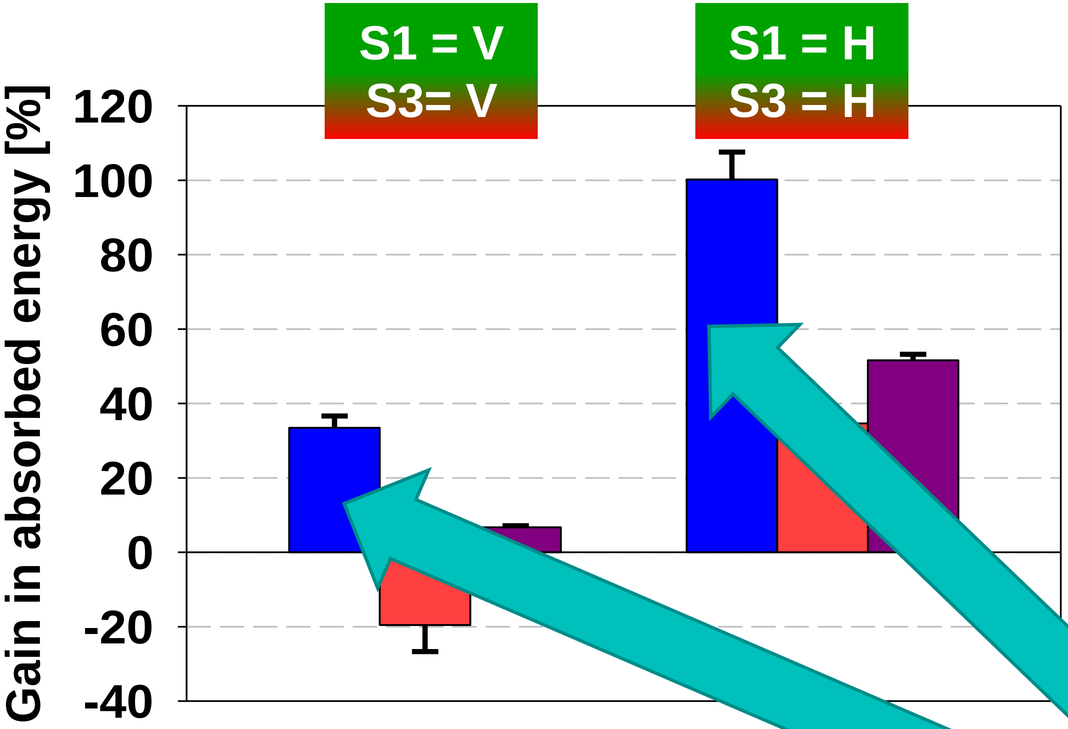
$$100 \cdot \frac{E_{sample} - E_{ref}}{E_{ref}}$$

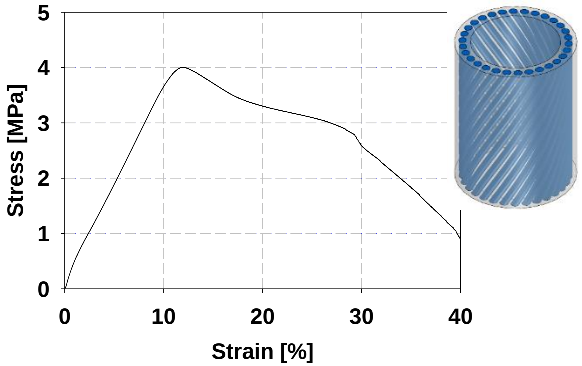


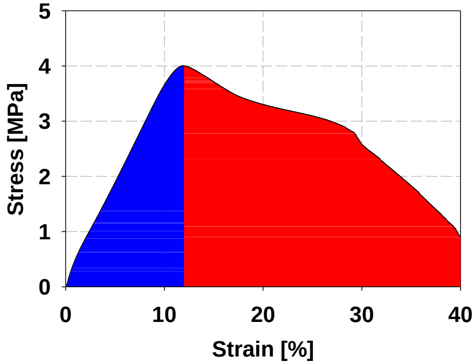


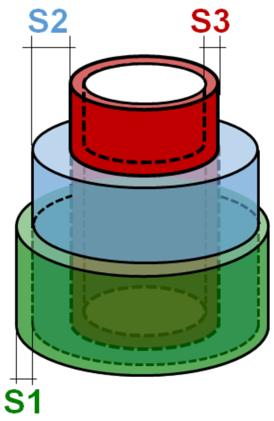


Post-buckling behavior: S2 = 30 deg







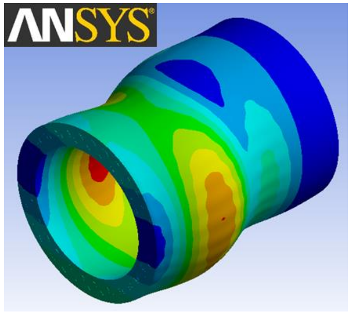


Energy gain =

$$100 \cdot \frac{E_{sample} - E_{ref}}{E_{ref}}$$

For S2 = 30 deg energy absorbed gained mostly **before buckling**

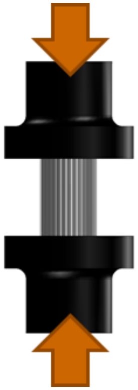
Conclusion



Simulations

- **Reinforcements =** efficient material arrangement
  - Avoid structure stiffening
  - Enhances buckling resistance

+



Experiments

- Development of **samples with same trend** of simulations
- **Reinforcements = less catastrophic failure**

=

- **Minimal increase of volume fraction** of stiff phase
- **Significant toughening** of the structure

Acknowledgements

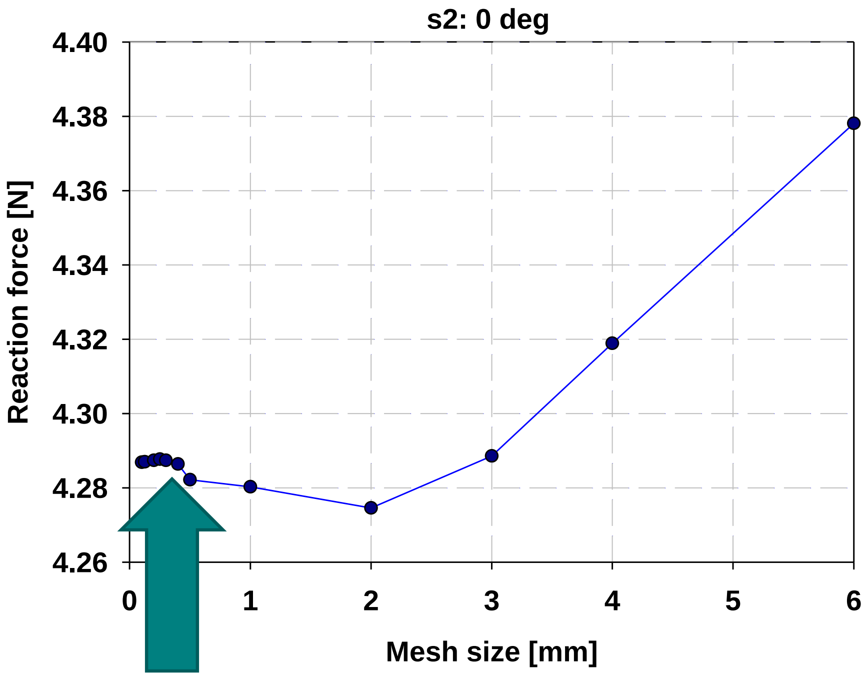
Thank you for your kind attention

Question time

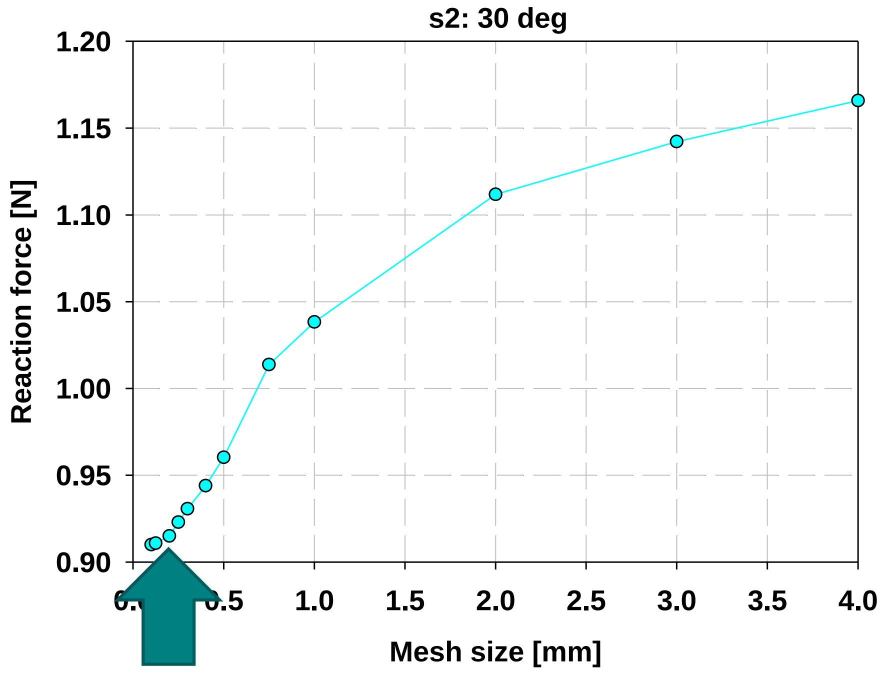
We would like to kindly acknowledge **Thierry Marchal** and **Thomas Dalberto**, from Ansys Belgium for providing free licences in the framework of an academic collaboration

Appendix 1.1 : Mesh convergence

- **s2 = 0 deg,** s1 = s3 = no reinforcement;
- **s2 = 30 deg,** s1 = s3 = no reinforcement;



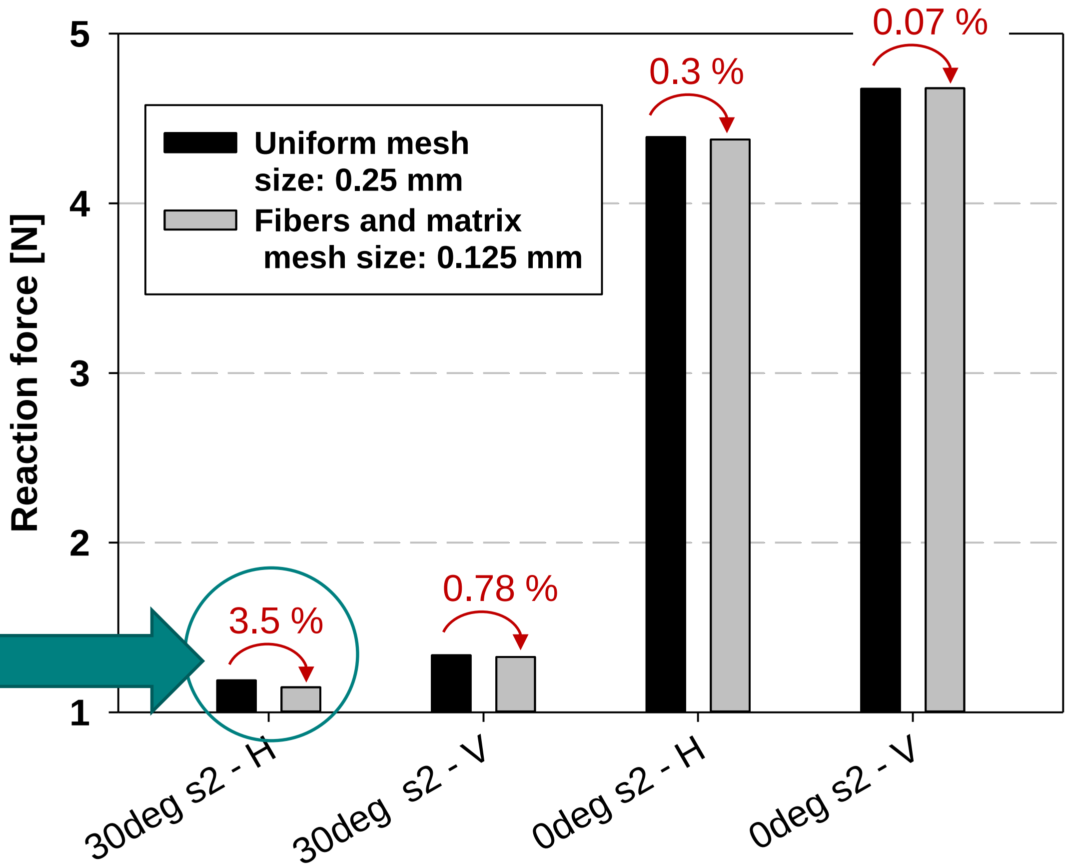
Easier convergence: starting from mesh size 0.5 mm, values are very similar (difference with more refine result = 0.1%)



Convergence reached at 0.25 mm mesh size (difference with more refine result = 0.55%)

Appendix 1.2 : Mesh convergence

- **s2 = 30 deg,** s1 = s3 = H;
- **s2 = 30 deg,** s1 = s3 = V;
- **s2 = 0 deg,** s1 = s3 = H;
- **s2 = 0 deg,** s1 = s3 = V;



Not as low as the other configurations: we keep a uniform mesh of 0.25 mm anyway to speed up computational time

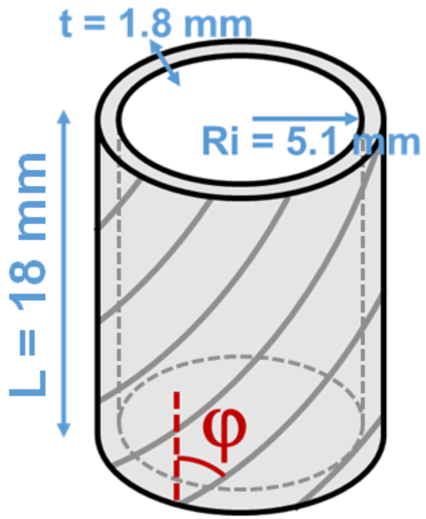
Appendix 2: Fiber dimensions

Simulations		S2 = 0 deg	S2 = 30 deg
No reinforcement		0.9295 mm	0.8693 mm
Equivalent configurations	H - int + ext	1.0191 mm	0.9484 mm
	H - ext	0.9804 mm	0.9124 mm
	H - int	0.9702 mm	0.9029 mm
	V - int + ext	0.9733 mm	0.9058 mm
	V - ext	0.9517 mm	0.8856 mm
	V - int	0.9517 mm	0.8856 mm

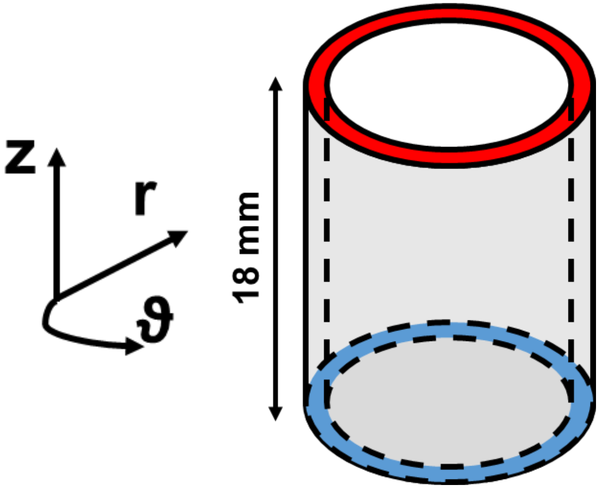
Reinforcement fibers diameter = **0.25 mm**

Constant volume fraction

Experiments: Dimension x 3



Appendix 3: Boundary conditions



🟦
$U_r = 0$
$U_\vartheta = 0$
$U_z = 0$

🟥
$U_r = 0$
U_ϑ = free
$U_z = -1.8e-3$ mm
→ $\varepsilon_z = -0.1$ %

Mesh

- Tetraedric mesh, average mesh size = 0.25 mm;
- Element number = 1 M

Performed analysis

- Static structural analysis → effective Young Modulus;
- Linear buckling analyis → critical buckling load.