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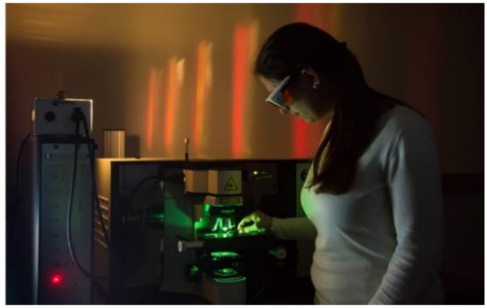

ON THE DETERMINATION OF SHEAR STRENGTH FROM TENSILE TESTS OF ±45° FIBER REINFORCED POLYMER LAMINATES

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ECCM21 – 21st European Conference on Composite Materials

02–05 July 2024, Nantes, France

Determination of shear strength *S*

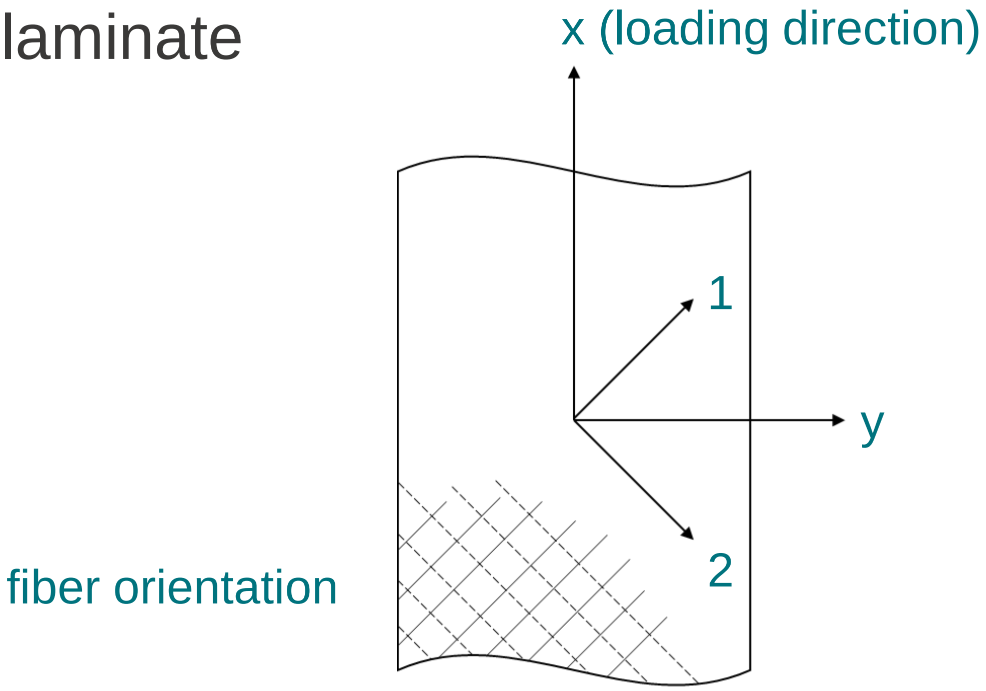
- Rail-shear test
- V-notched rail shear test
- ±45° tensile test
- Tube torsion test
- Off-axis tensile test
- Iosipescu test
- Shear frame test
- Biaxial tension-compression test

(Rail-shear test, V-notched rail shear test, ±45° tensile test, Tube torsion test: Standardized)

➔ Different test methods yield different values of *S*

±45° tensile test

- Quasi-static tensile test of symmetric ±45° laminate
- **ASTM D3518**, ISO 14129, EN 6031
- Non-linear stress-strain response
- Multi-axial stress state on ply level



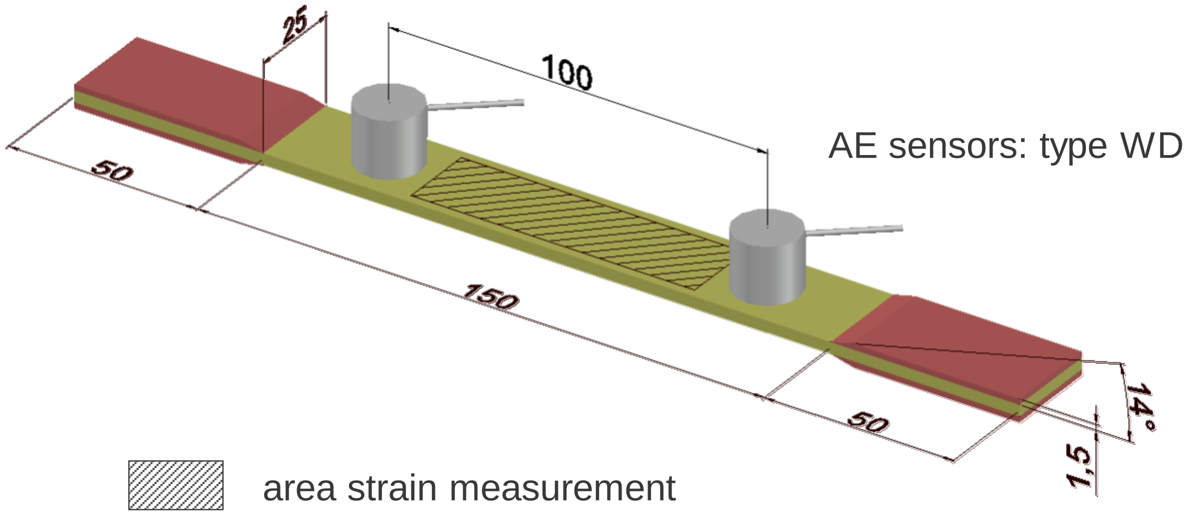
To be discussed…

- Does shear strength evaluated according to standards describe first-ply-failure (*FPF*)?
- What is the stress state on ply level? How significant is the influence of other stress components?

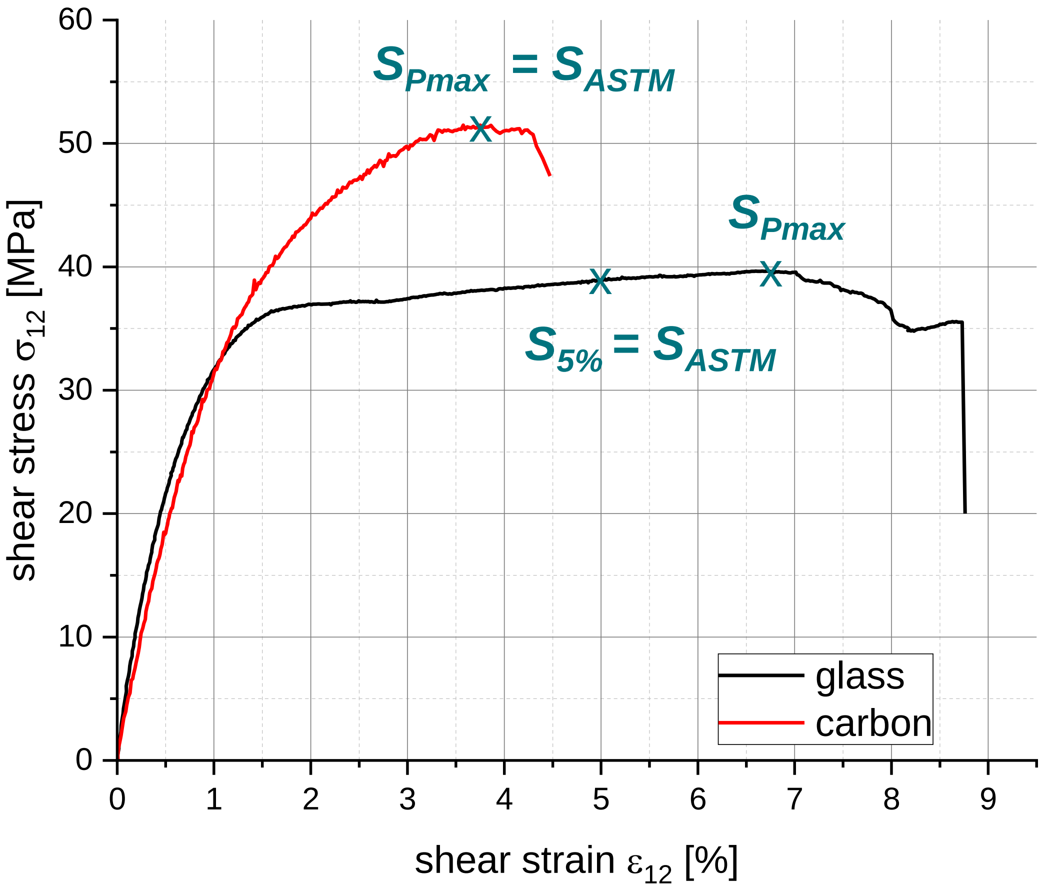
Material

- UD prepregs by Hexcel:
  - ➢ glass-epoxy: HexPly® M79-LT/25%/UD1200/G
  - ➢ carbon-epoxy: HexPly® M79/35%/UD600+2PES/CHS-50K

  } same matrix
- (+45/-45)$_s$ ➔ vacuum bagging process
  - total thickness:
    - ➢ glass-epoxy: 3.08 mm (ply thickness = 0.77 mm)
    - ➢ carbon-epoxy: 2.35 mm (ply thickness = 0.59 mm)
  - fiber volume fraction of ~ 60 %
- Quasi-static tensile tests:
  - cross-head speed = 2 mm/min
  - optical strain measurement
- Acoustic emission (AE) analysis
  - Detection of initial failure



Shear stress-strain behavior

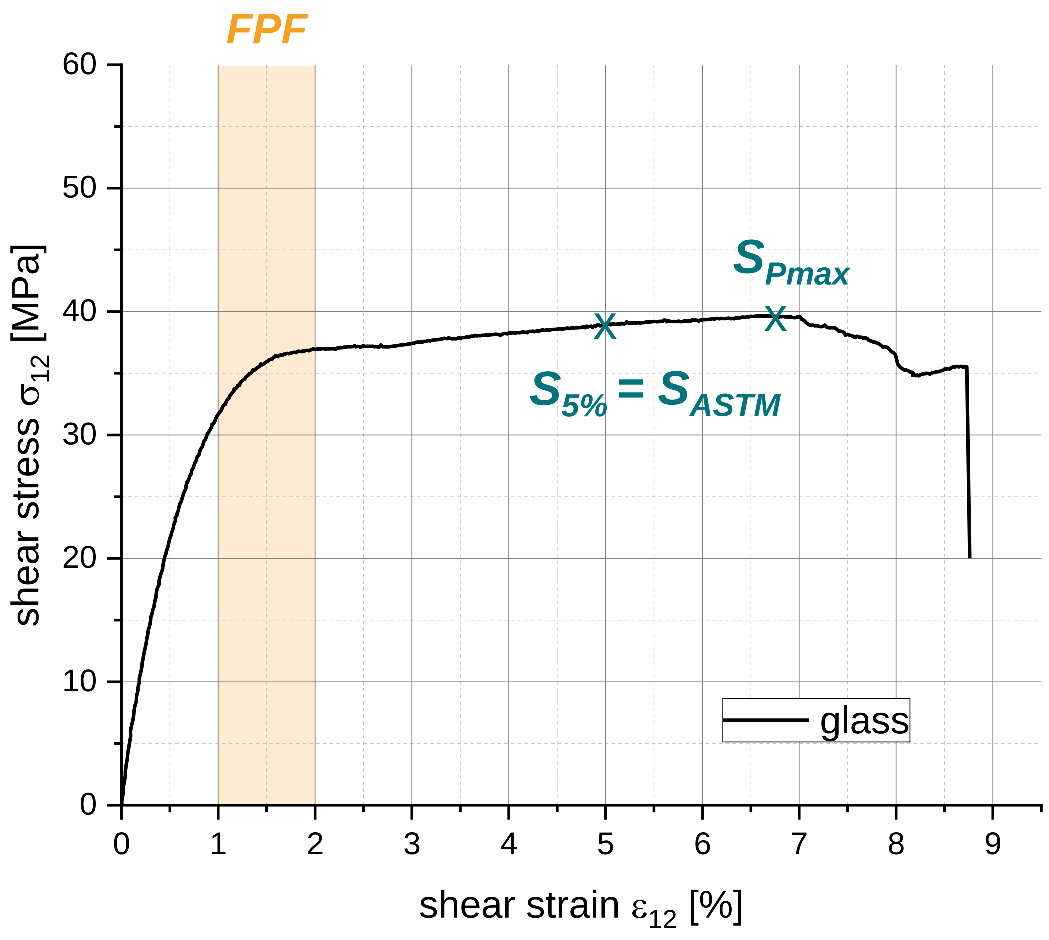


According to ASTM D3518:

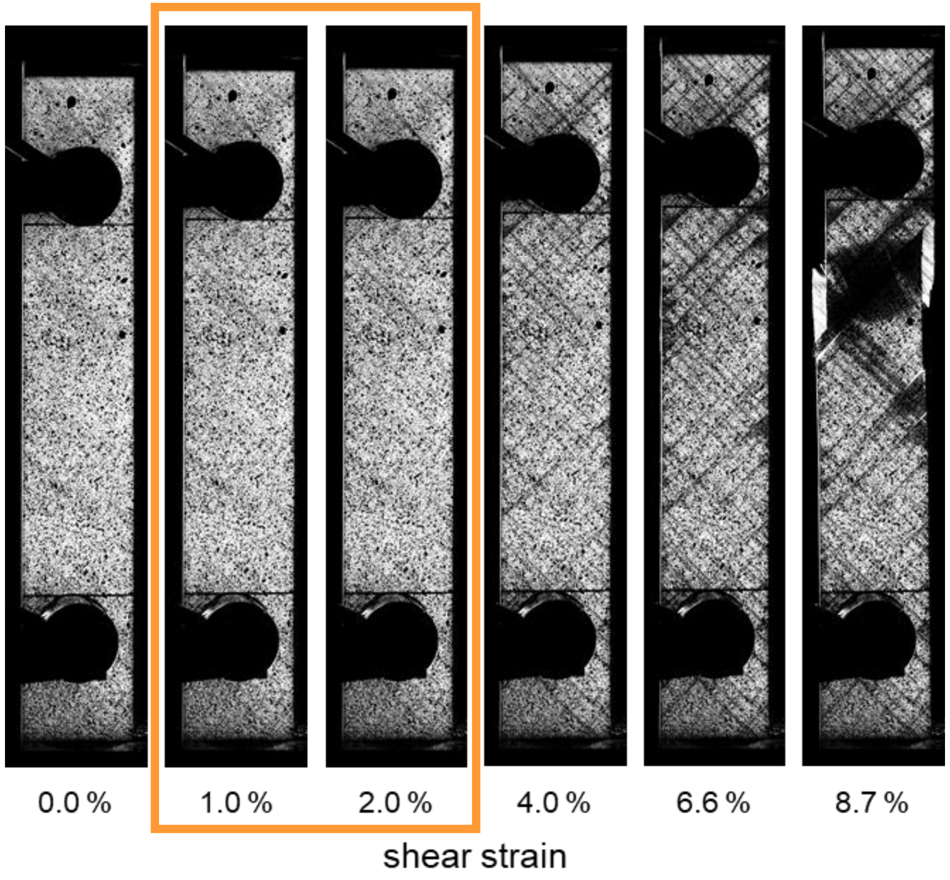
$$S_{ASTM} = min\begin{cases}\sigma_{12}\ at\ \varepsilon_{12} = 5\% \\ \sigma_{12}\ at\ P_{max}\end{cases}$$

➔ different stress-strain behavior

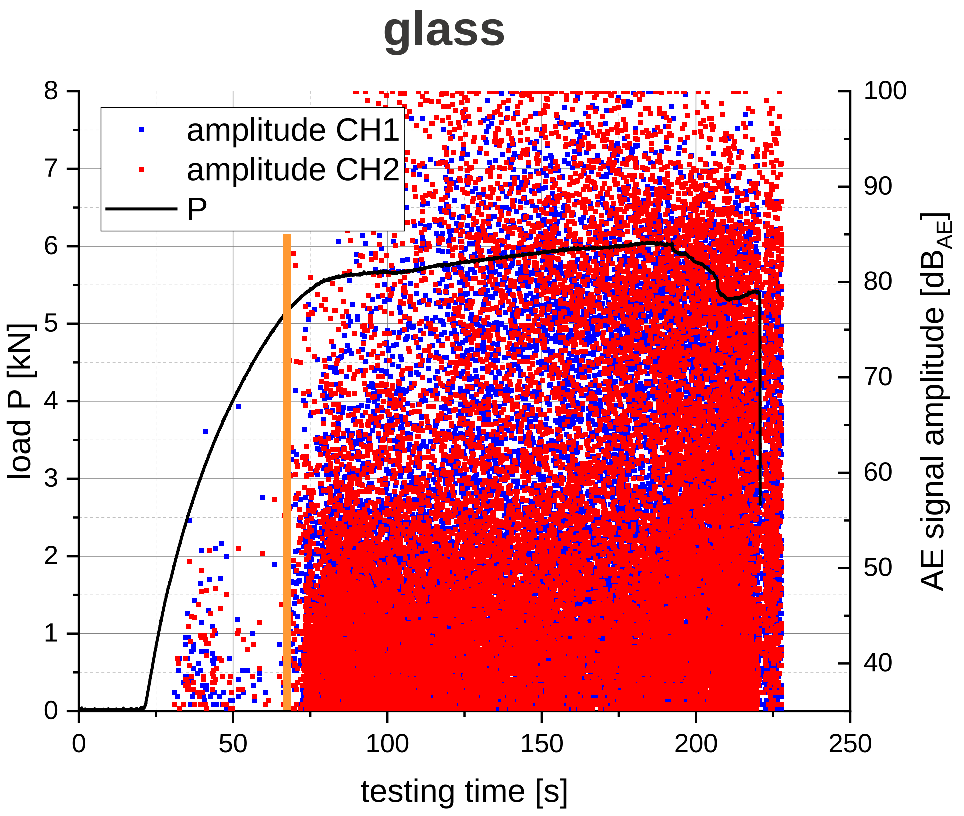
Shear stress-strain behavior

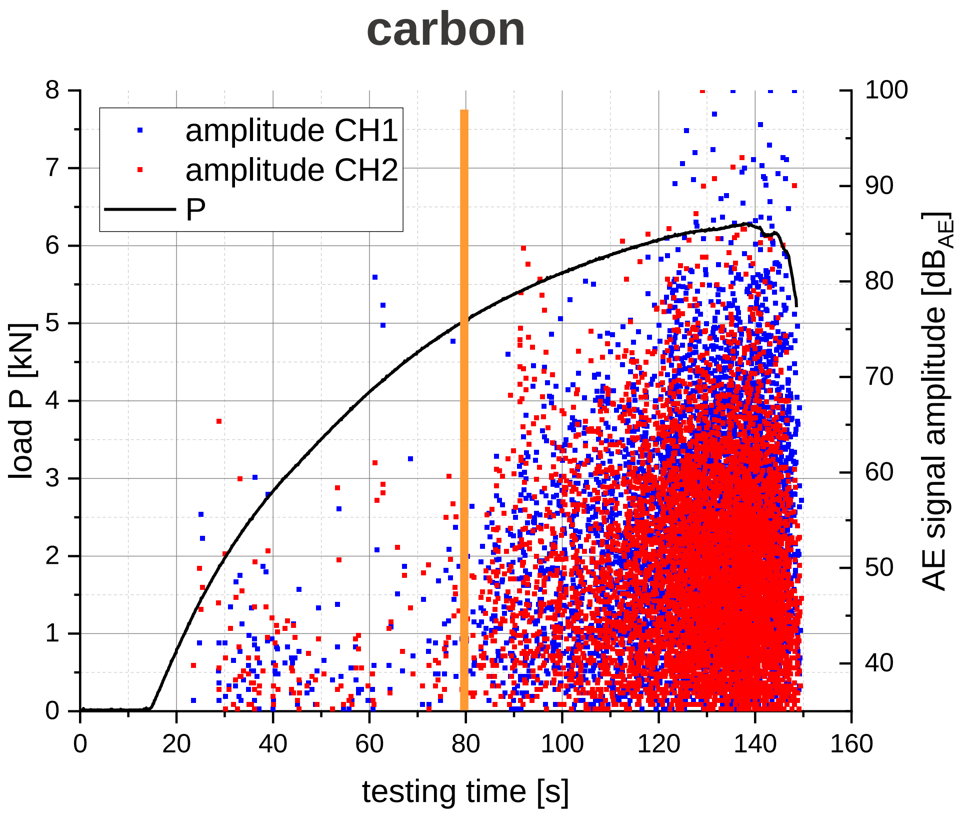


inter-fiber cracks



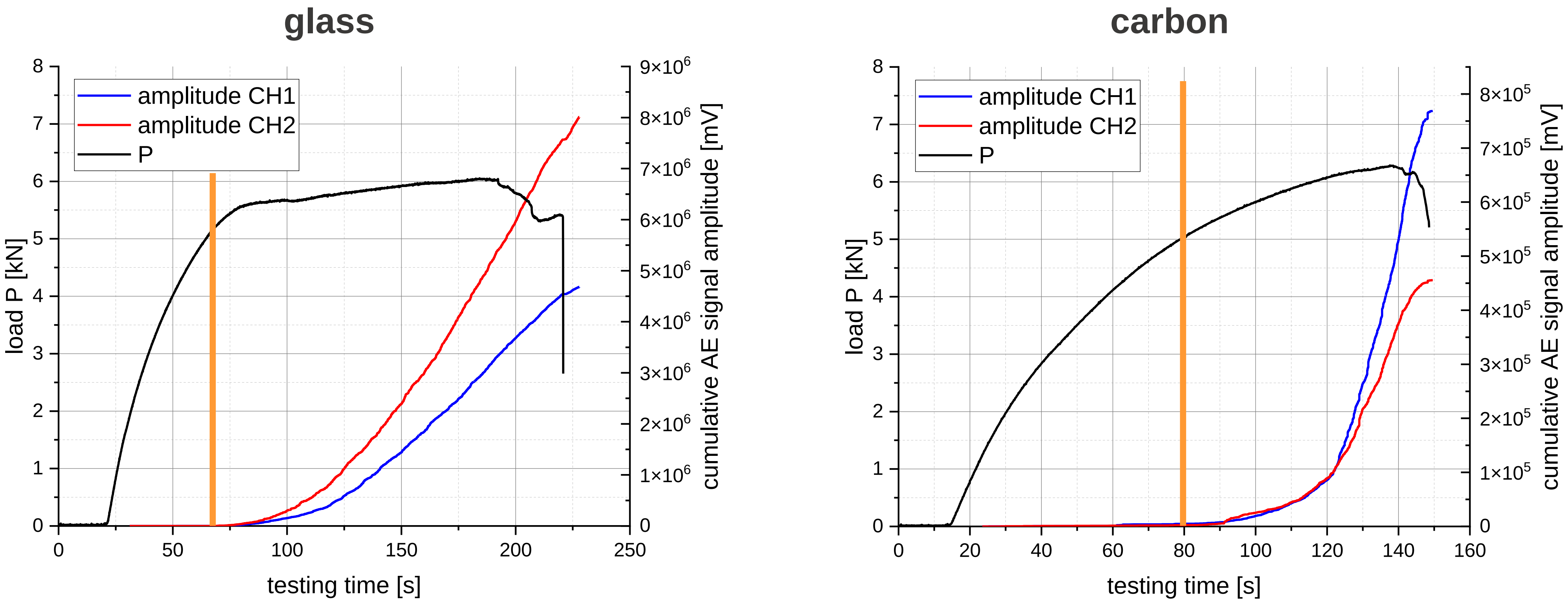
Shear stress-strain behavior – AE analysis





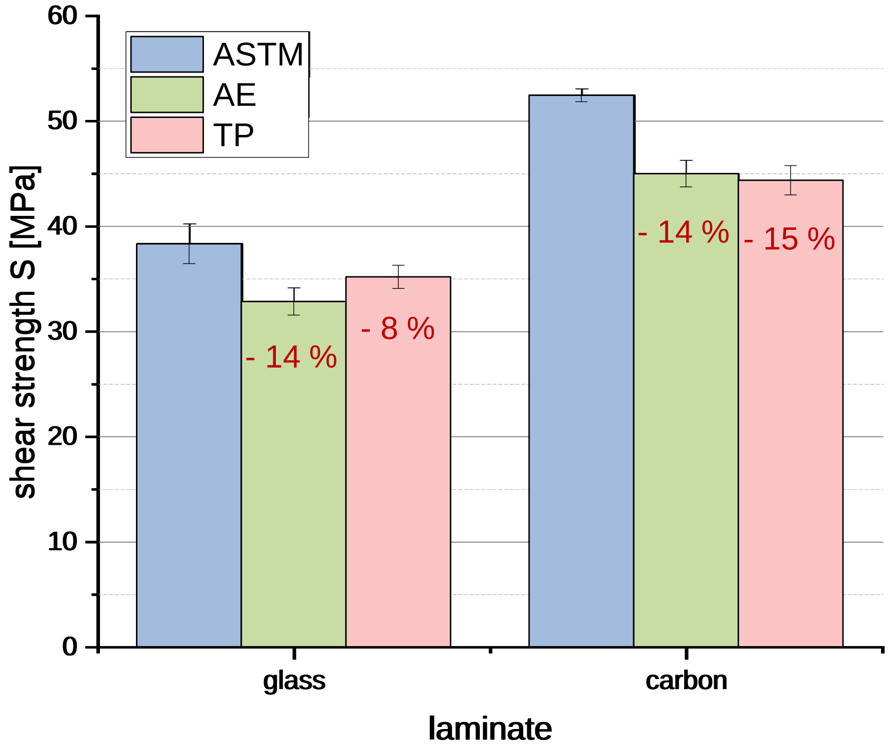
increased AE activity ➔ inter-fiber cracks ➔ ***FPF***

Shear stress-strain behavior – AE analysis



increased AE activity ➔ inter-fiber cracks ➔ ***FPF***

Evaluation of shear strength *S*

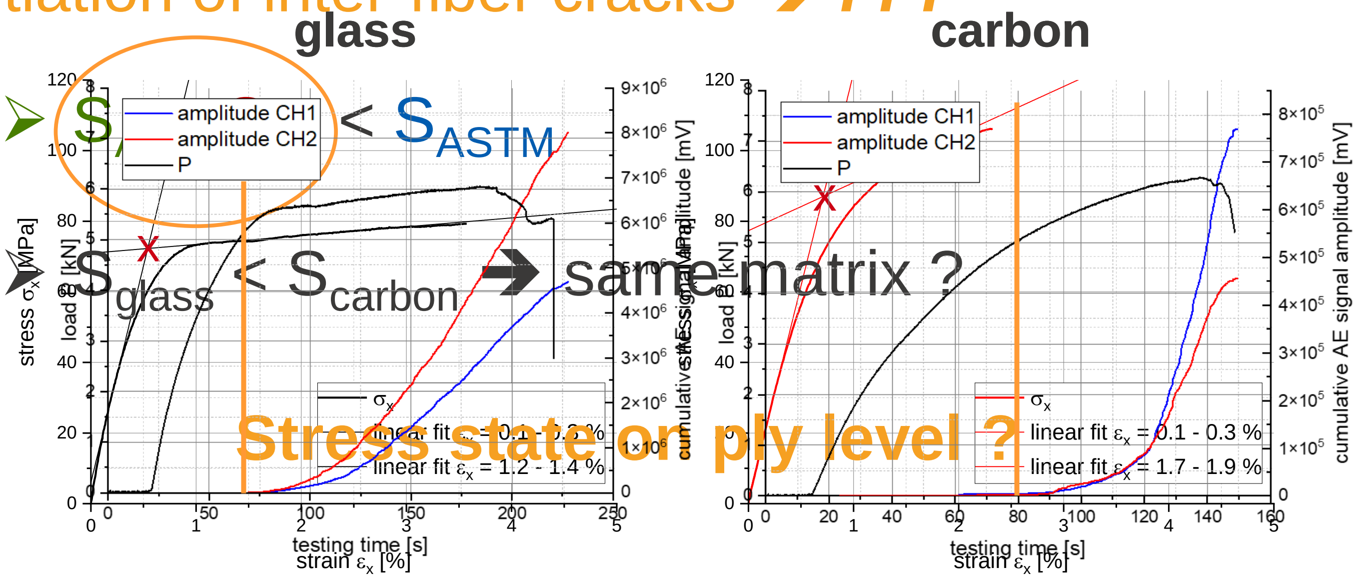


glass: 10 specimens
carbon: 6 specimens

- ASTM D3518
- Increased AE activity
- Transition point (ASTM D3039)

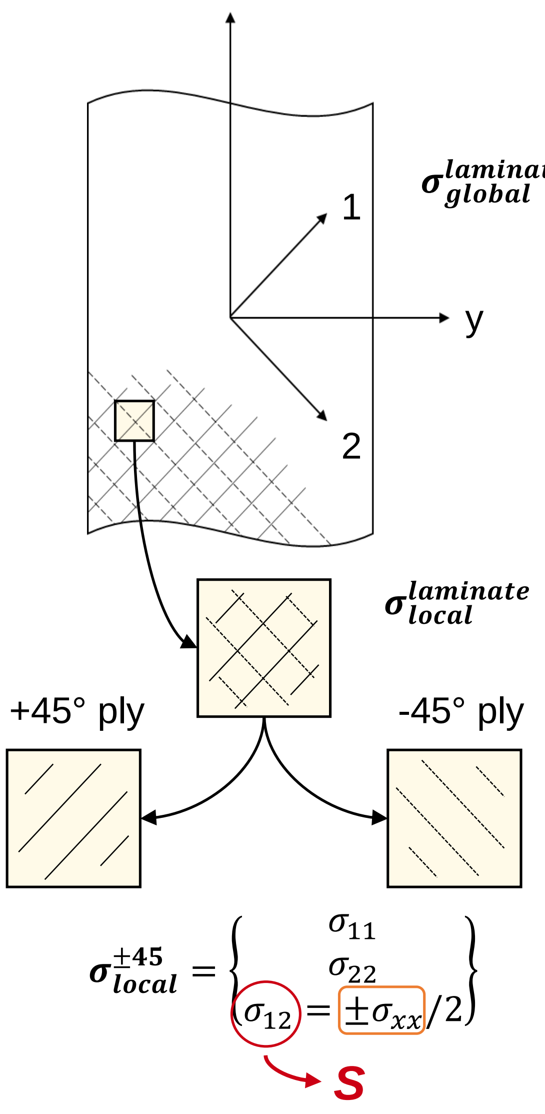
initiation of inter-fiber cracks ➔ *FPF*

- $S_{AE} < S_{ASTM}$
- $S_{glass} < S_{carbon}$ ➔ same matrix ?



Stress state on ply level ?

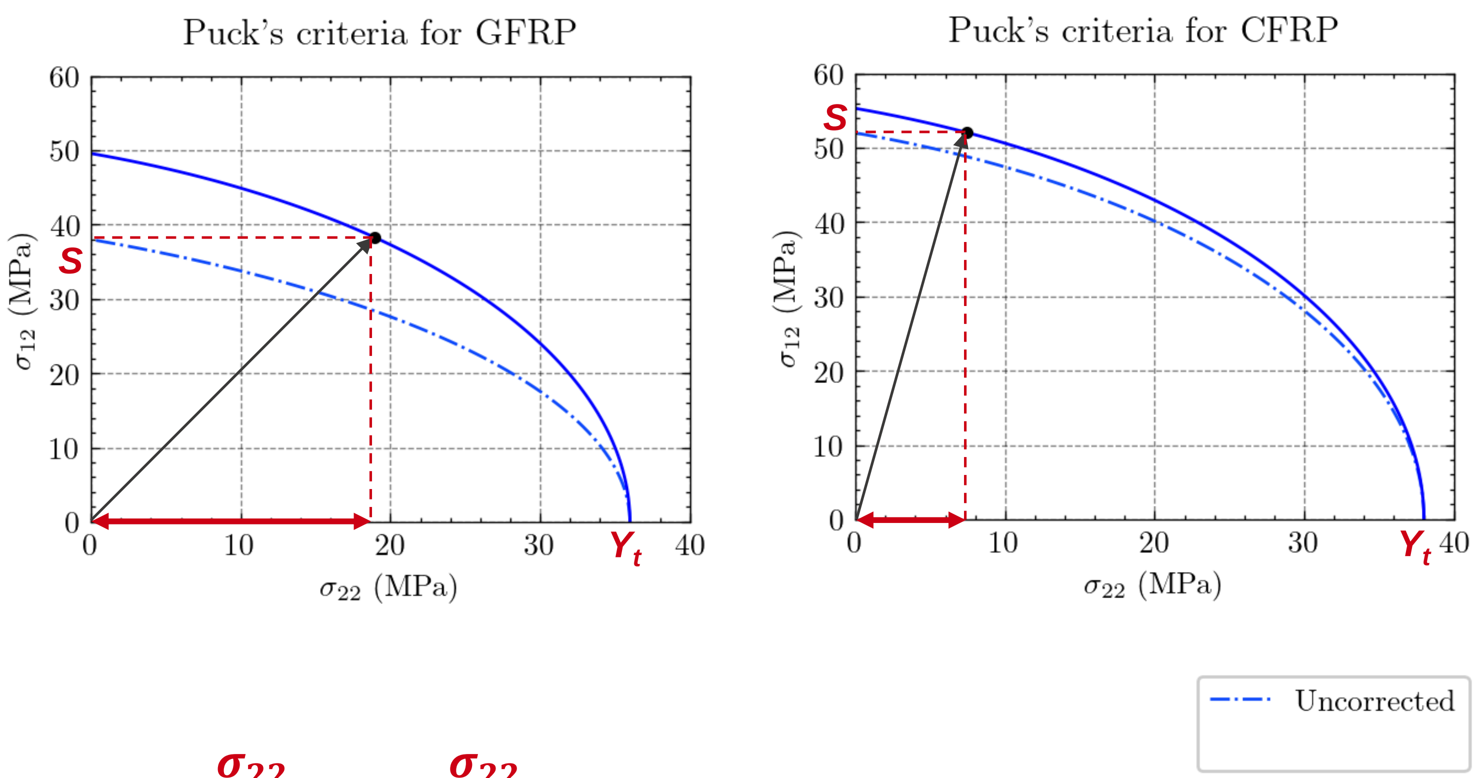
Stress state on ply level



$$\sigma^{laminate}_{global} = \begin{Bmatrix} \sigma_{xx} \\ 0 \\ 0 \end{Bmatrix}$$

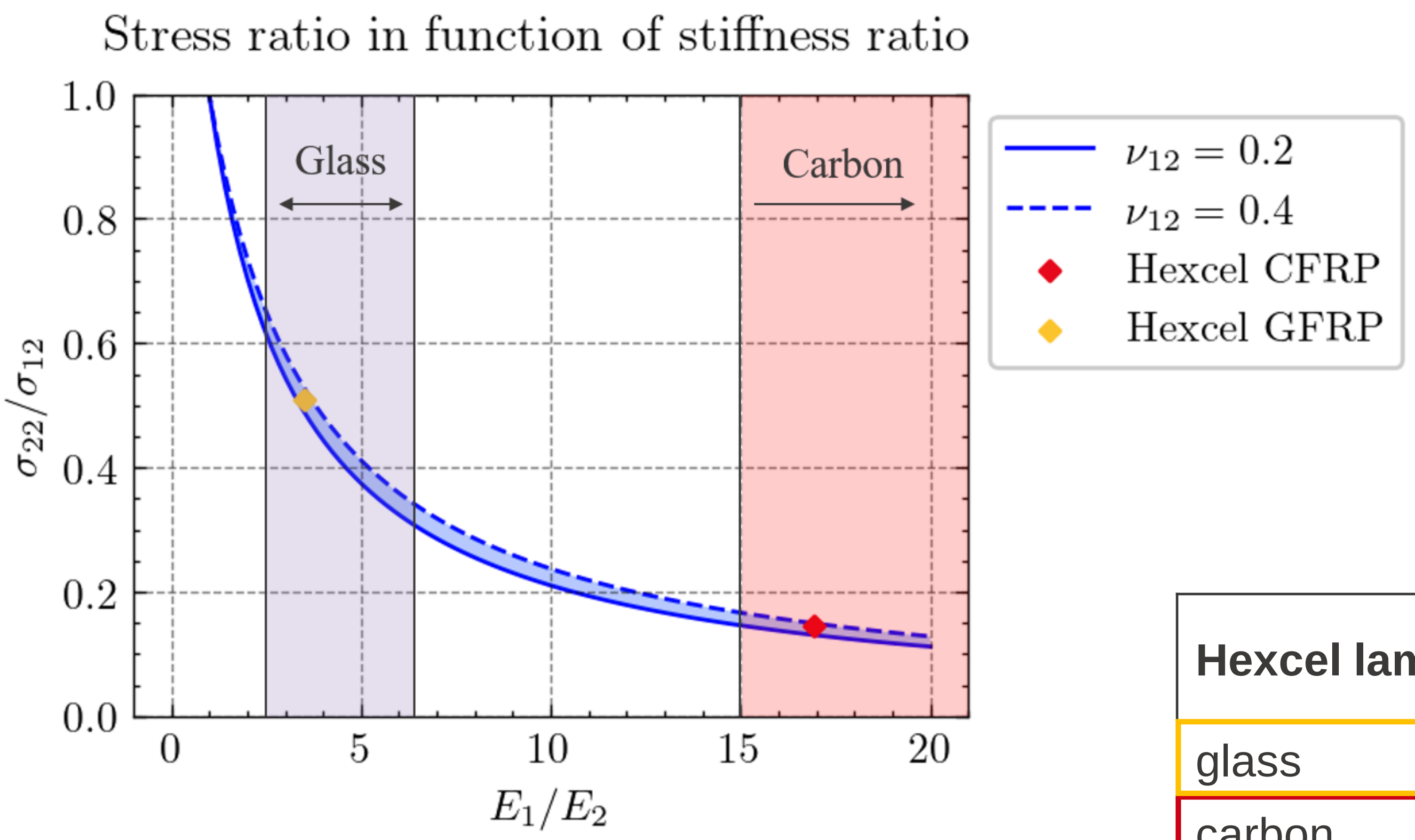
$$\sigma^{laminate}_{local} = \begin{Bmatrix} \sigma_{xx}/2 \\ \sigma_{xx}/2 \\ \sigma_{xx}/2 \end{Bmatrix}$$

$$\sigma^{\pm 45}_{local} = \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} = \pm\sigma_{xx}/2 \end{Bmatrix}$$



$$\frac{\sigma_{22}}{\sigma_{12}}_{glass} > \frac{\sigma_{22}}{\sigma_{12}}_{carbon}$$

Why are the stress ratios so different?



Laminate theory:

$$\frac{\sigma_{22}}{\sigma_{12}} = 2.\frac{1+\nu_{12}}{\frac{E_1}{E_2}+1+2\nu_{12}}$$

Hexcel laminate	$\frac{E_1}{E_2}$	$\frac{\sigma_{22}}{\sigma_{12}}$	ν_{12}
glass	3.524	0.526	0.296
carbon	16.917	0.145	0.351

Stress state on ply level mainly depends on ratio E_1/E_2

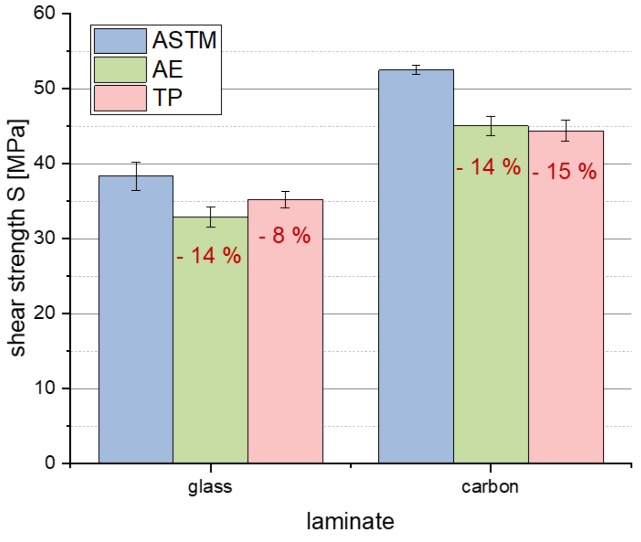
Quasi-static tensile tests

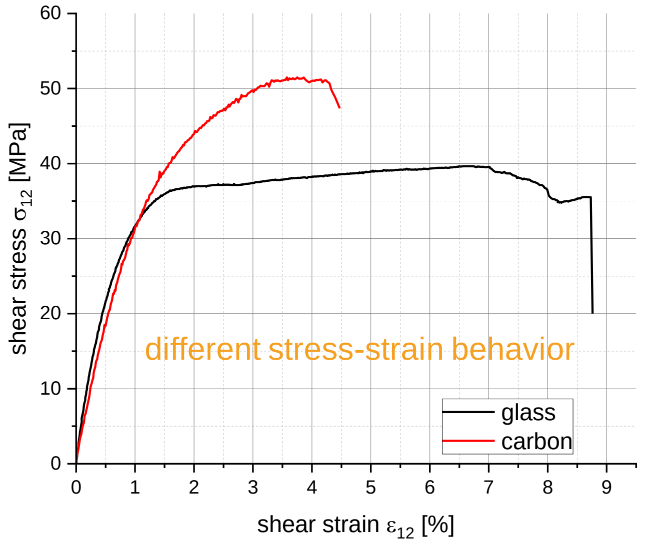
Conclusion

- Quasi-static tensile tests on ±45° laminates (ASTM D3518) ➔ ***S***
  - glass-epoxy
  - carbon-epoxy

➢ Does shear strength evaluated according to standards describe first-ply-failure (*FPF*)?

- S_{ASTM} ≠ *FPF (initiation of inter-fiber cracks)* ➔ S_{AE} / S_{TP}
- S_{glass} < S_{carbon} ➔ same matrix ?



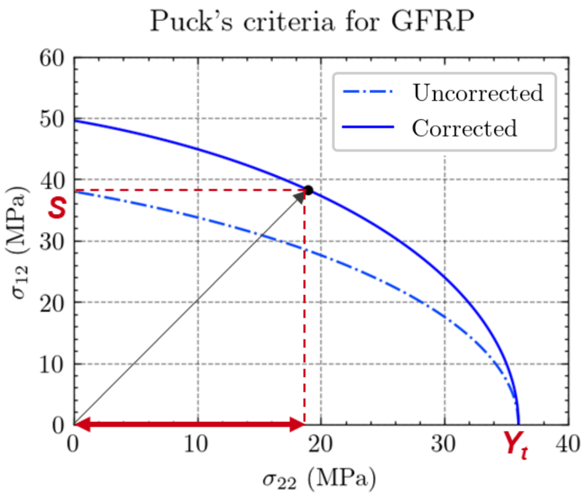


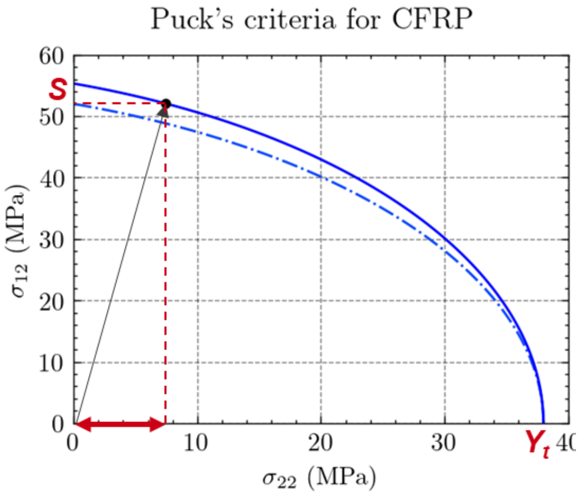
Conclusion

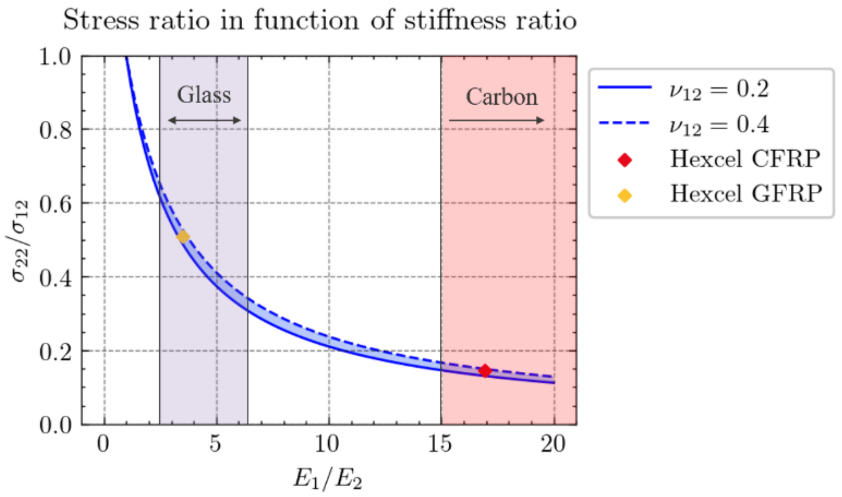
- Quasi-static tensile tests on ±45° laminates (ASTM D3518) ➔ ***S***
  - glass-epoxy
  - carbon-epoxy

➢ What is the stress state on ply level? How significant is the influence of other stress components?
  - Shear $\boldsymbol{\sigma_{12}}$ + transverse tension $\boldsymbol{\sigma_{22}}$ (glass > carbon)
  - Stress state on ply level mainly depends on ratio $\boldsymbol{E_1/E_2}$

➔ different stress-strain behavior, $S_{glass} < S_{carbon}$







Part of this work has been performed within the COMET-project *Consideration of local microstructure in the lifetime assessment of long and continuous fibre reinforced polymers* (project-no.: VII-3.03) at the Polymer Competence Center Leoben GmbH (PCCL, Austria) within the framework of the COMET program of the Federal Ministry for Transport, Innovation and Technology and the Federal Ministry for Digital and Economic Affairs with contributions by Montanuniversität Leoben (Chair of Designing Plastics and Composite Materials, Chair of Materials Science and Testing of Polymers) and MAGNA Powertrain Engineering Center Steyr GmbH CO KG. The PCCL is funded by the Austrian Government and the State Governments of Styria, Lower Austria and Upper Austria.

Thank you for your attention!

Why are the stress ratios so different?

$$\begin{Bmatrix} \boldsymbol{n} \\ \boldsymbol{m} \end{Bmatrix} = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} \\ \boldsymbol{B} & \boldsymbol{D} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\varepsilon_0} \\ \boldsymbol{\kappa_0} \end{Bmatrix} \longrightarrow \mathbf{n} = \begin{Bmatrix} n_x \\ 0 \\ 0 \end{Bmatrix} \longrightarrow \begin{matrix} \mathbf{B} = [0] \\ \boldsymbol{\varepsilon_0} = \mathbf{A}^{-1}.\boldsymbol{n} \end{matrix}$$

Ply k:

$$\boldsymbol{\sigma}^{k}_{global} = \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} = [\overline{Q}]_k . \boldsymbol{\varepsilon_0}$$

$$\boldsymbol{\sigma}^{k}_{local} = \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} = [\mathbf{T}]_k^{-1} \boldsymbol{\sigma}^{k}_{global}$$

$$\boldsymbol{\varepsilon}^{k}_{local} = [\boldsymbol{R}].[\mathbf{T}]_k.[\boldsymbol{R}]^{-1} \ \boldsymbol{\varepsilon}^{k}_{global}$$

Transformation
from global to local

→ Closed form equations for the +45° layer:

$$\sigma^{+45°}_{local} = \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix}$$

$$\sigma_{22} = \frac{n_x}{4t} \cdot \frac{1 + \nu_{12}}{\frac{E_1}{E_2} + 1 + 2\nu_{12}} \qquad \sigma_{12} = \frac{n_x}{8t}$$

t ply thickness