Engineering, Test & Technology
Boeing Research & Technology

Material characterization of composite materials with the help of multi scale methods:

an efficient and highly precise method for industrial application

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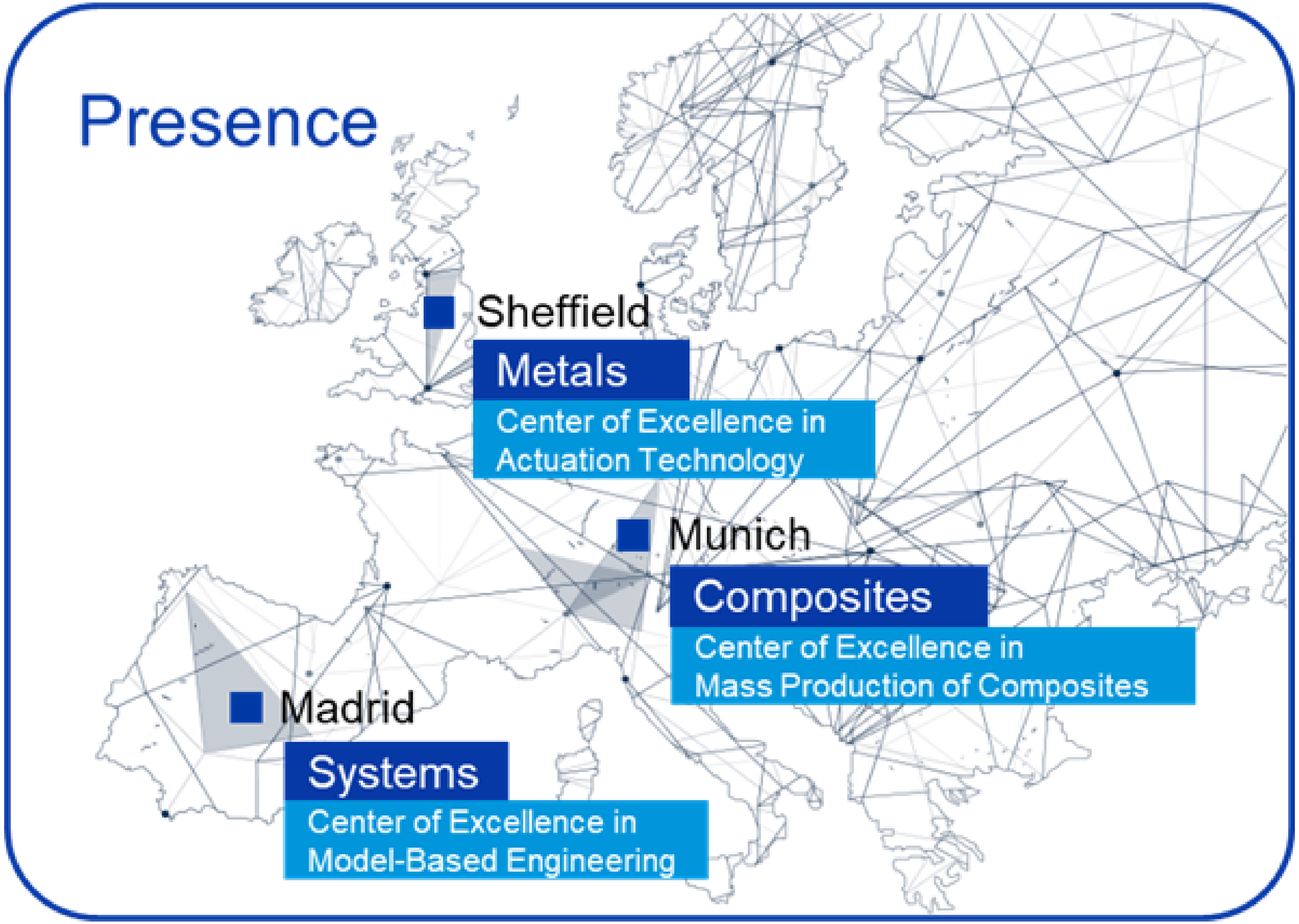
Boeing in Europe

Quick Overview

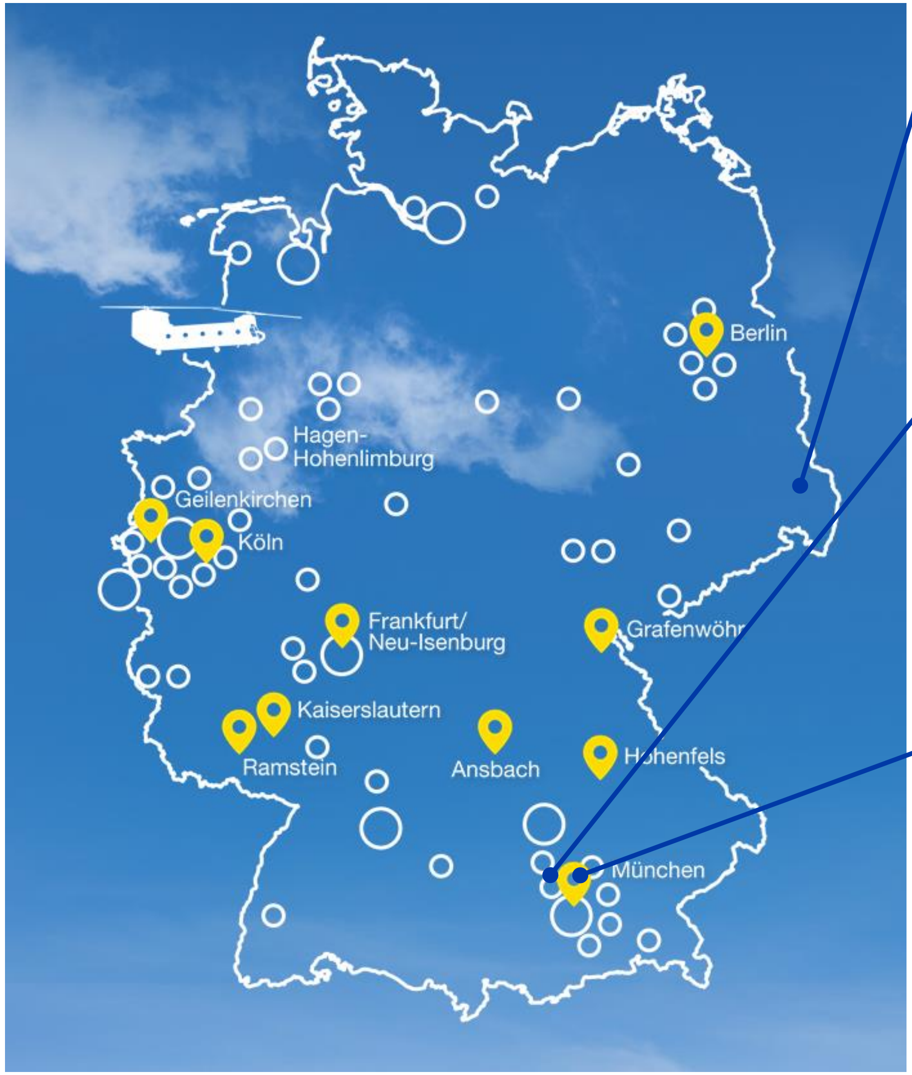
Boeing Research & Technology Europe



Project Partners

Quick Overview

Project Partners



Leichtbau-Zentrum Sachen

- Material test evaluation
- Analytical calculation methods
- Numerical simulations with Abaqus

ALTAIR Engineering

- Advanced numerical material methods
- Numerical simulations with OptiStruct/Radios

Boeing Research & Technology

- Material & failure models
- Analytical calculation methods
- Numerical simulations with MSC Nastran

Material Test Data

Ply based

Material Behaviour, Uniaxial Tests

Tension

ASTM D3039

Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials

Compression

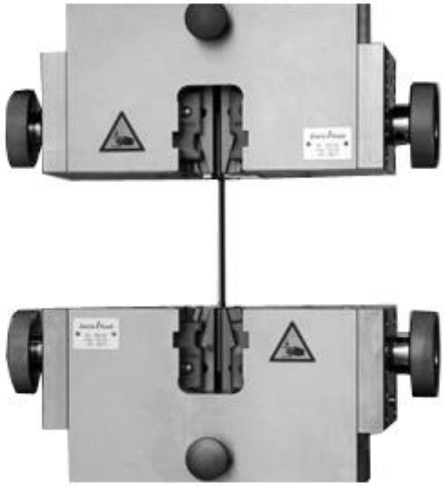
ASTM D 6641

Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture

Shear

ASTM D 5379

Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method

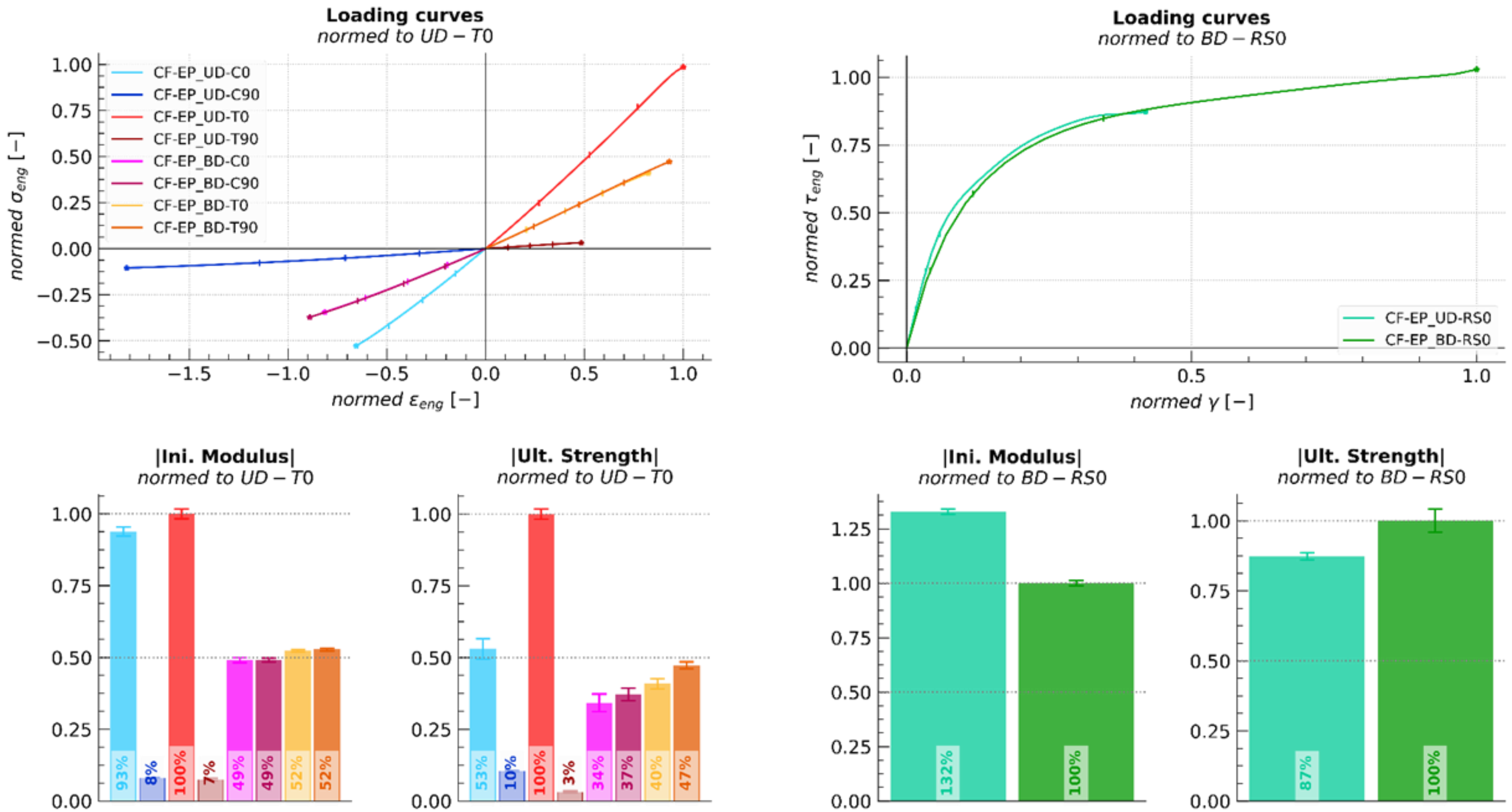


2x tension, 2x compression, 1x shear, 8 specimen, 3 temperatures, 3 batches

360 test results for one material

Nonlinearity on macro scale

Tension, Compression & Shear of UD and woven ply

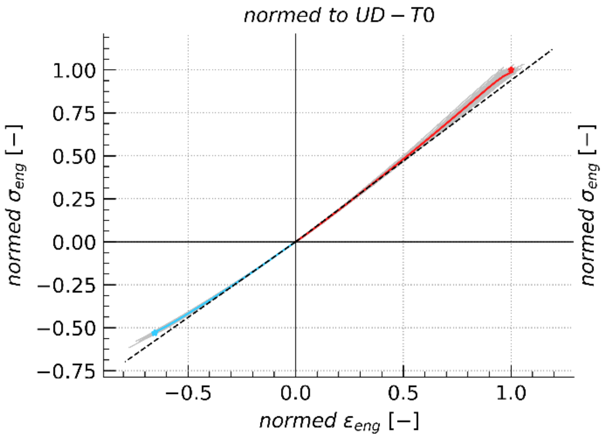


- UD ply: pronounced material asymmetry with progressive fiber tensile response
- BD ply: showing effects of internal reinforcement architecture in stiffness and strength
  - Comparing UD and woven response
  - Comparing Warp and Fill response

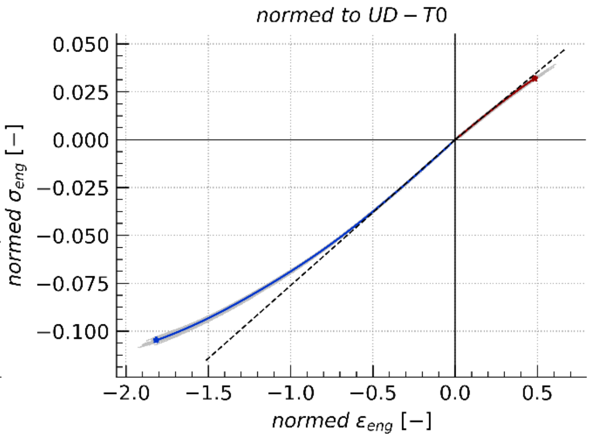
Nonlinearity on macro scale

Summary: Data for macro / micro mechanical models

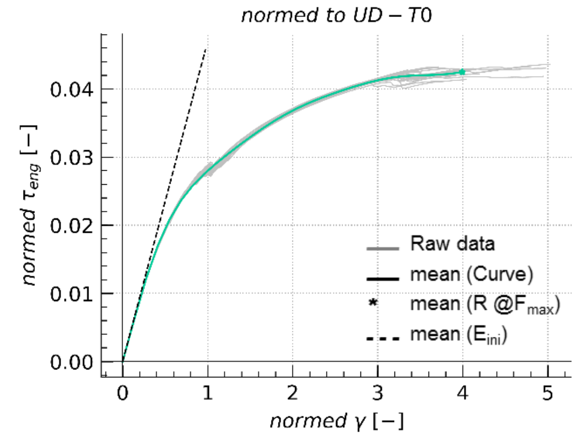
UD 0°



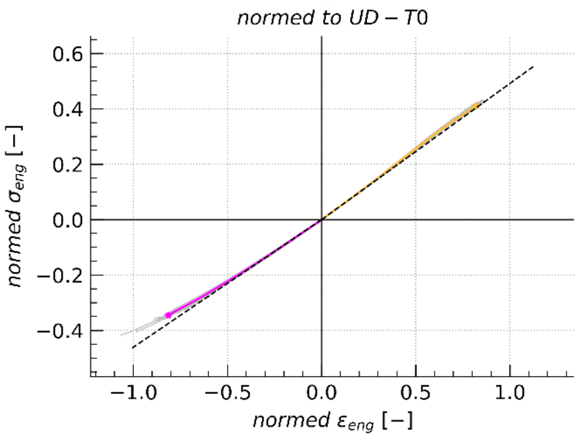
90°



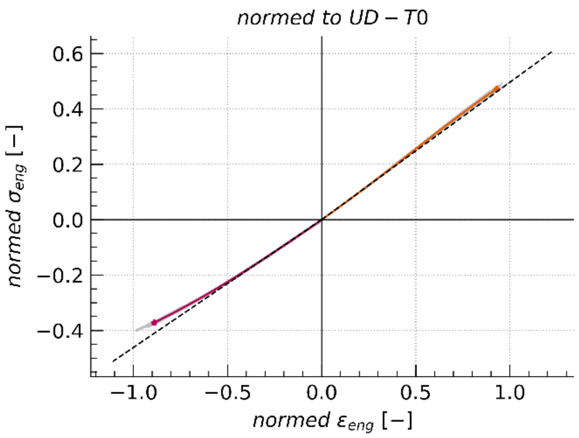
IPS



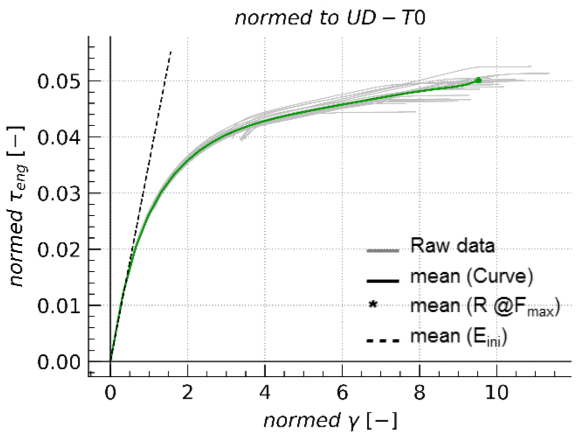
BD (woven) Warp



Fill



IPS



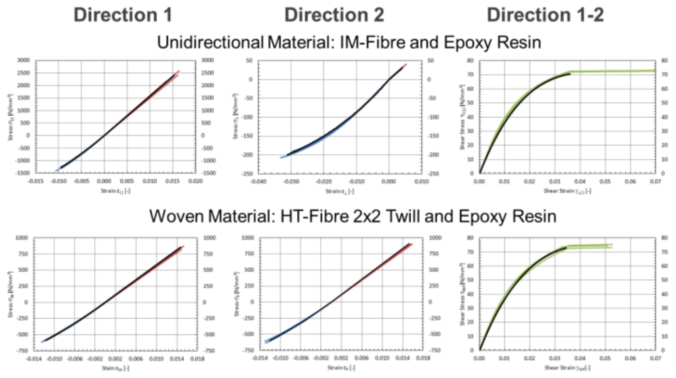
Examples of Numerical Simulations

Ply based CUNTZE-BOLD Material & Failure Model

CUNTZE-BOLD material & failure model

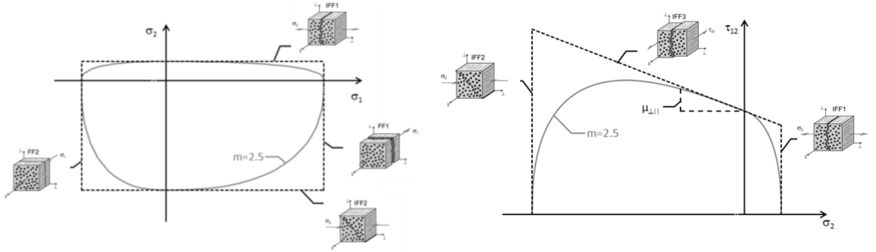
Pre-Failure: BOLD material model

- Formulation to describe stress-strain material behaviour with a single equation based on physical effects
- No additional test



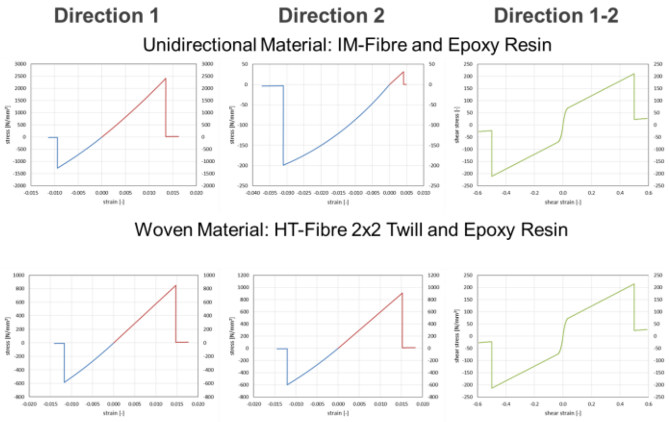
Failure: CUNTZE failure criteria

- State-of-the-art failure prediction based on failure modes and valid for unidirectional and woven materials
- No additional tests



Post-Failure: BOLD material model

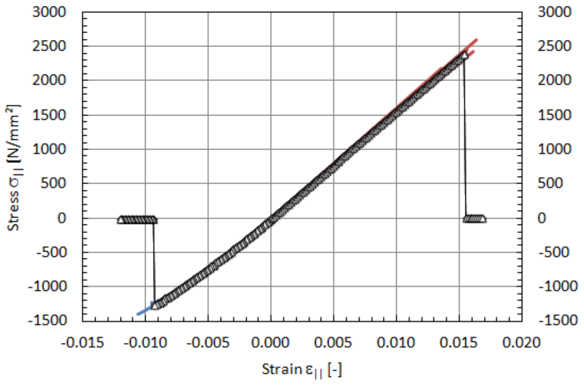
- Proper description after ply failure in laminate
- No additional tests

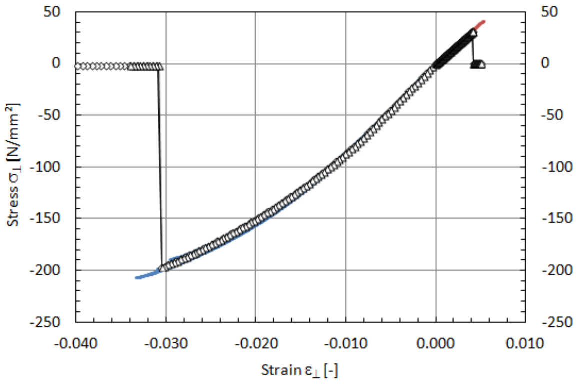


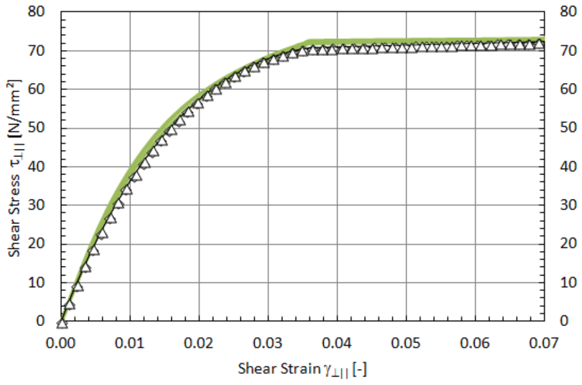
Example I: Single Element with single material under uniaxial loading

Direction 1 | Direction 2 | Direction 1-2

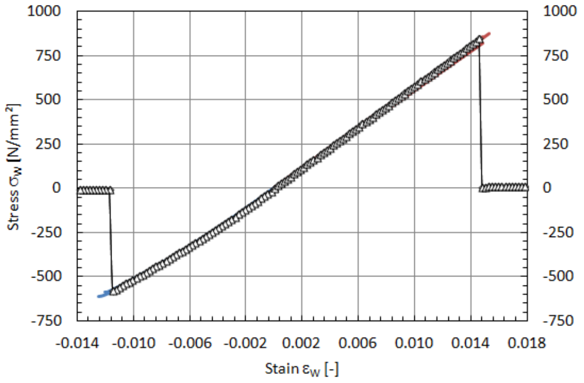
Unidirectional Material: IM-Fibre and Epoxy Resin

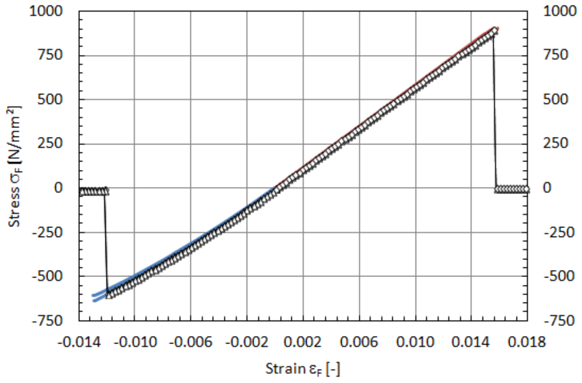


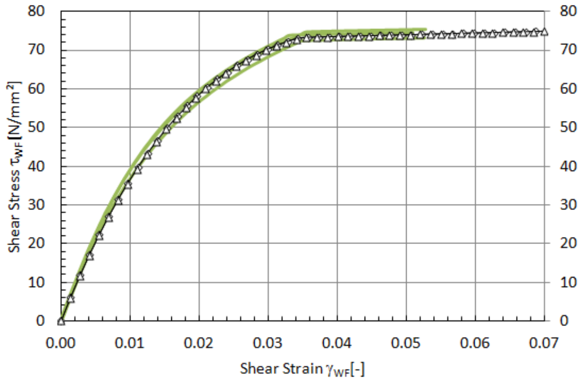




Woven Material: HT-Fibre 2x2 Twill and Epoxy Resin



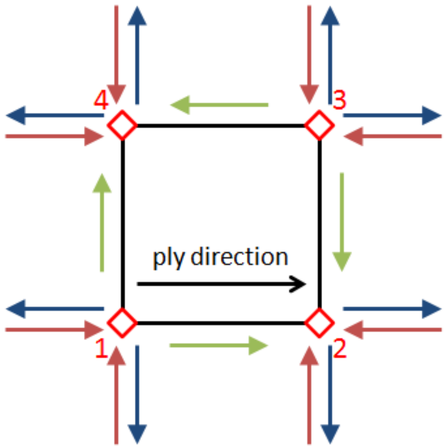


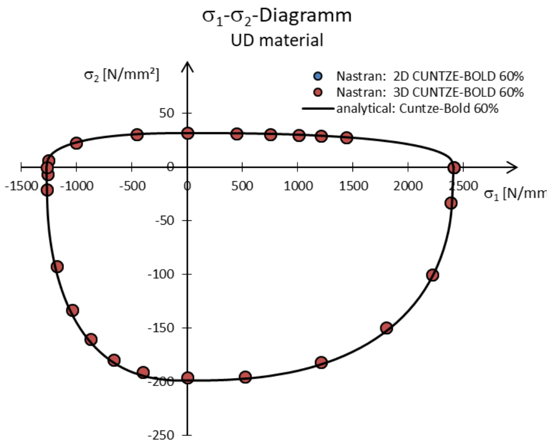


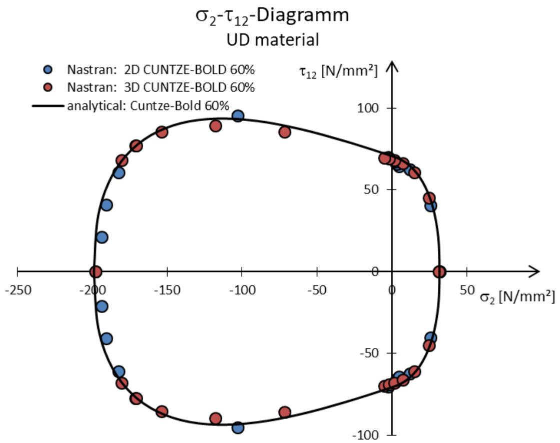
<u>Summary:</u> 2D (◇) and 3D (△) elements show recommended behaviour

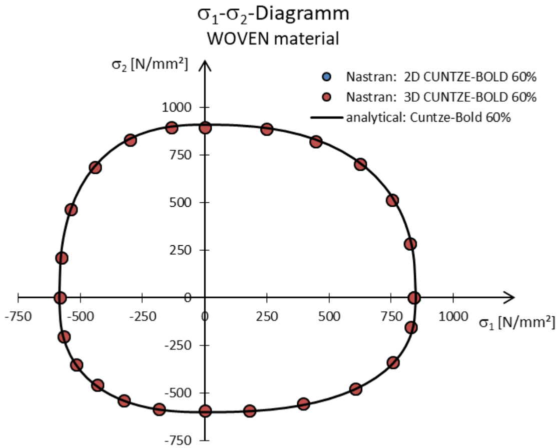
Example II: Single Element with single material under multi-axial loading

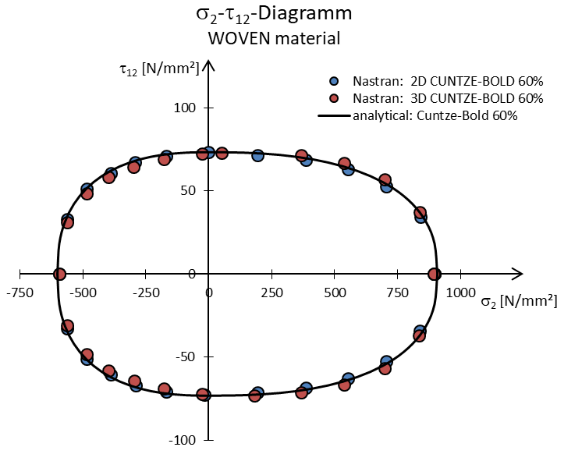
Displacement Based











Advantage

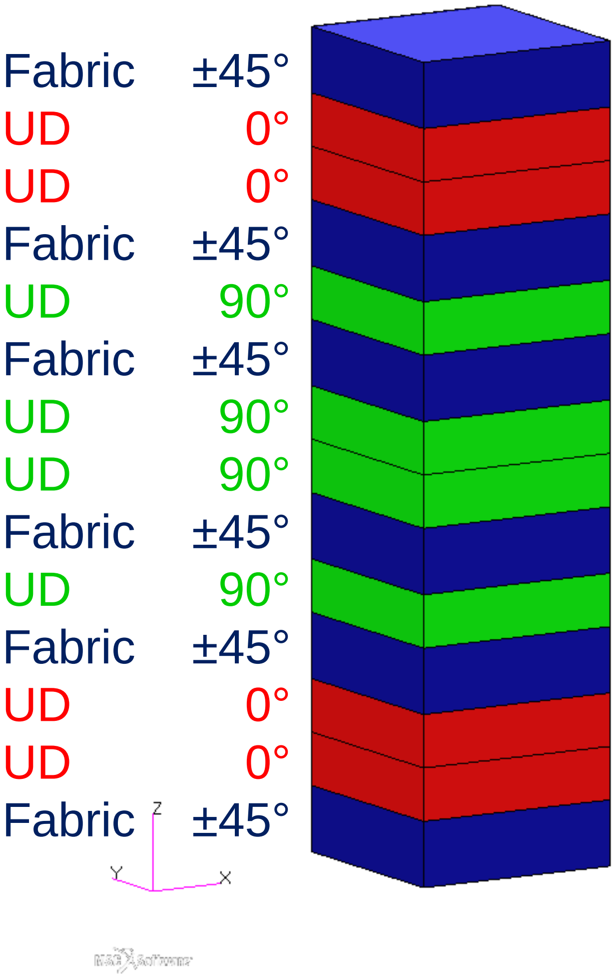
- Clear stress state

Challenge

- High number of combinati
- Enforced displacements

Example III: Layup with different materials under combined loading

Layup



Model Description

3D Hex8 Elements

One Element per Ply

One Layer per Element

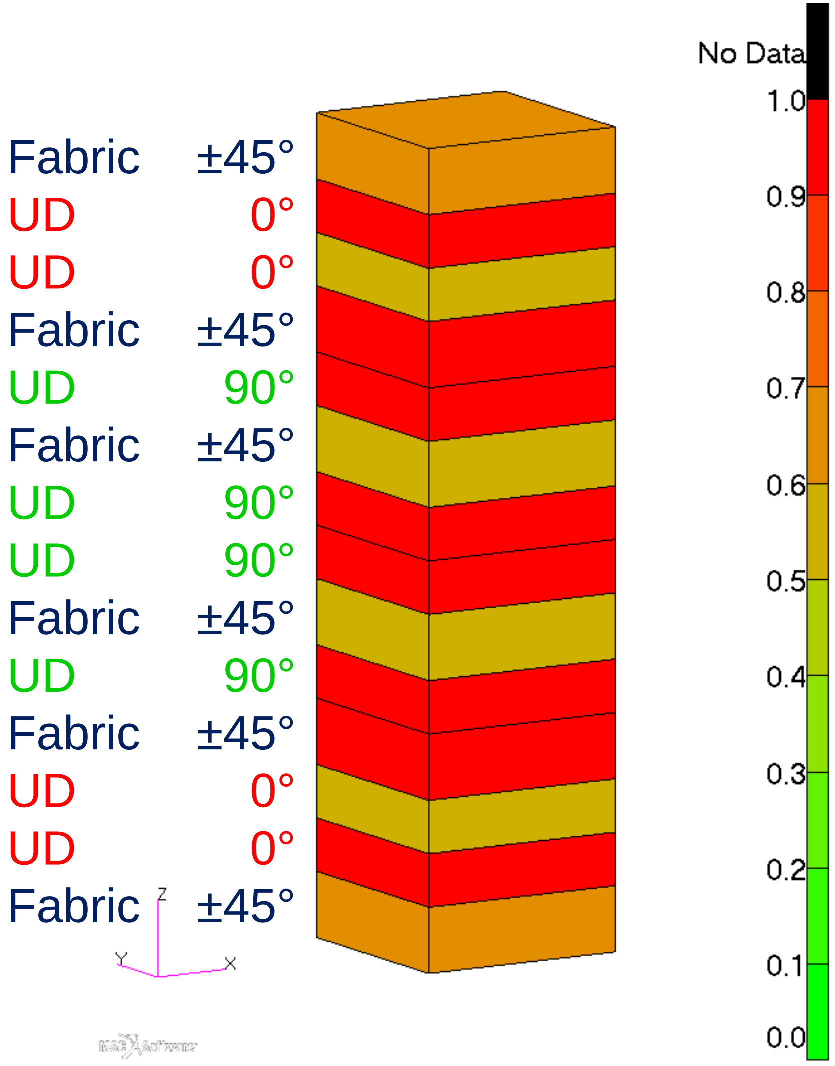
Displacement Loading

- Tension
- Compression

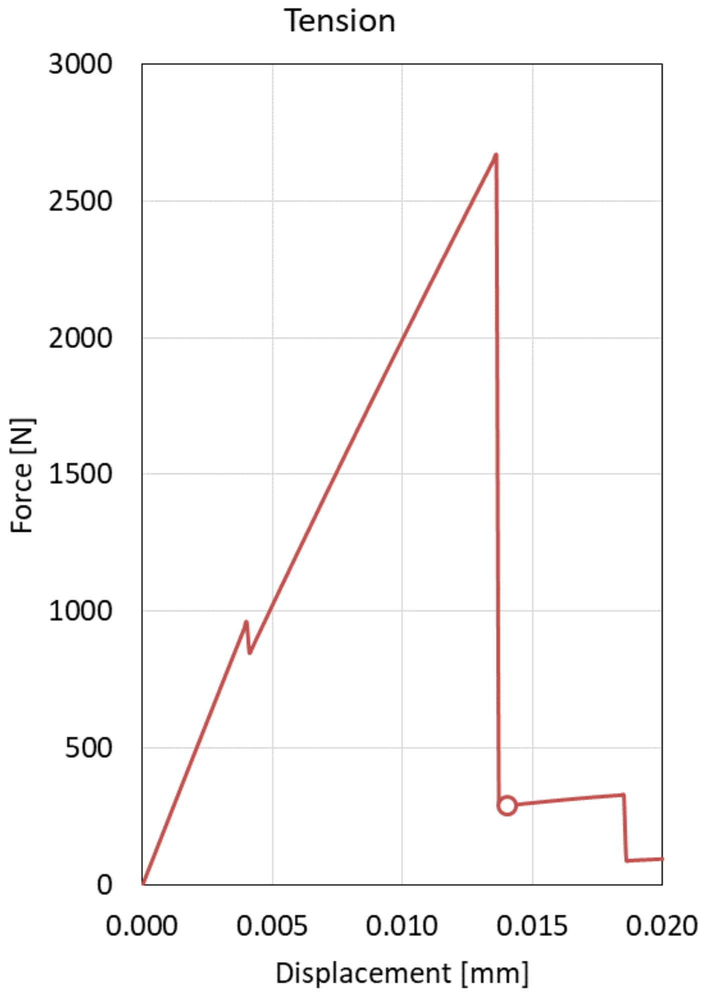
Displacement applied via Rigid Body Element (RBE) with only coupling in load direction

Example III: Layup with different materials under combined loading

Total Damage



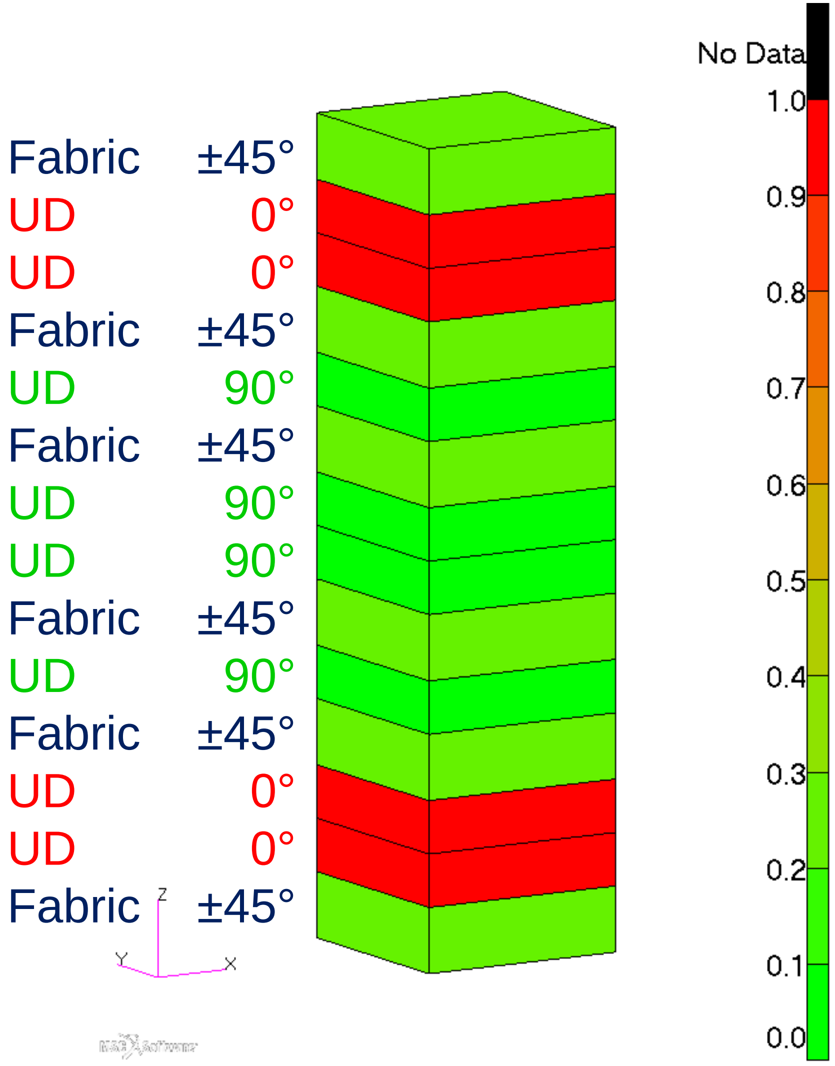
Load: Tension

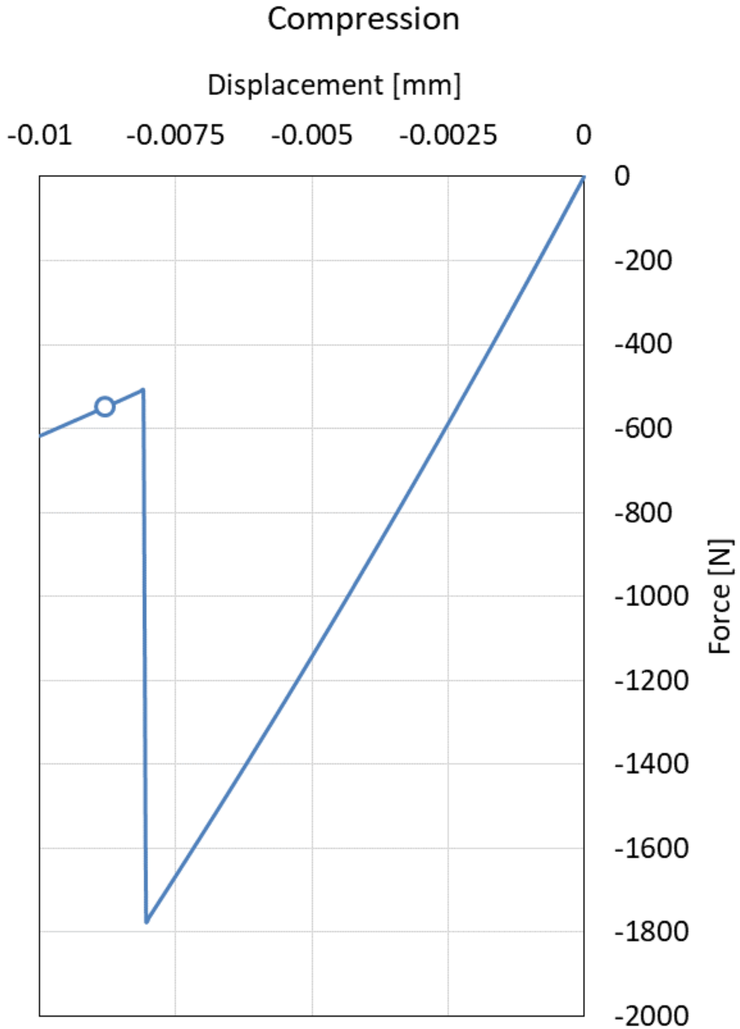


Example III: Layup with different materials under combined loading

Total Damage

Load: Compression



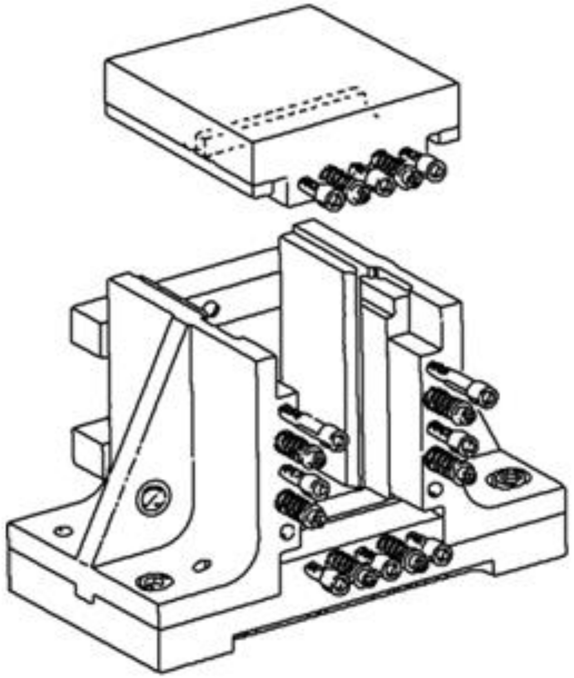


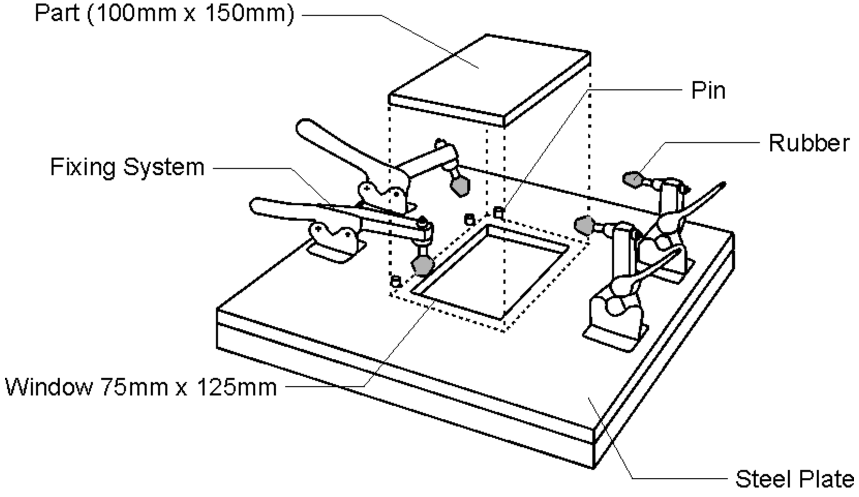
Example IV: Compression after Impact Model

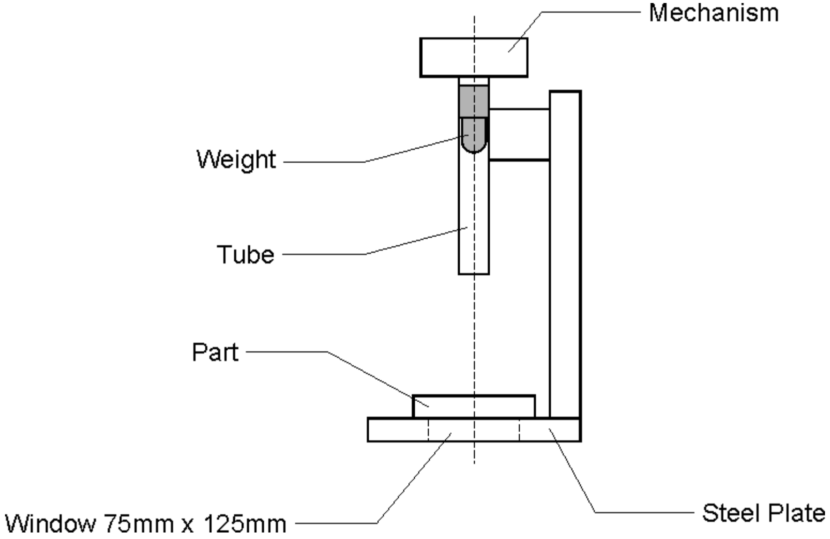
Compression After Impact

Different Energies

- Typical 25J to 50J
- Two different weights
- Corresponding height

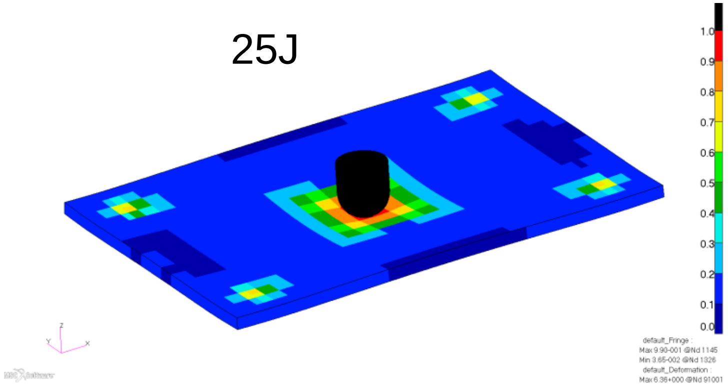


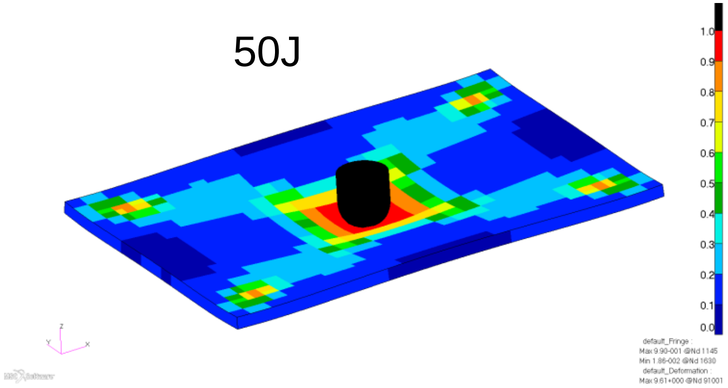




Example IV: Compression after Impact Model

Impact: ANALYSIS=NLTRANS





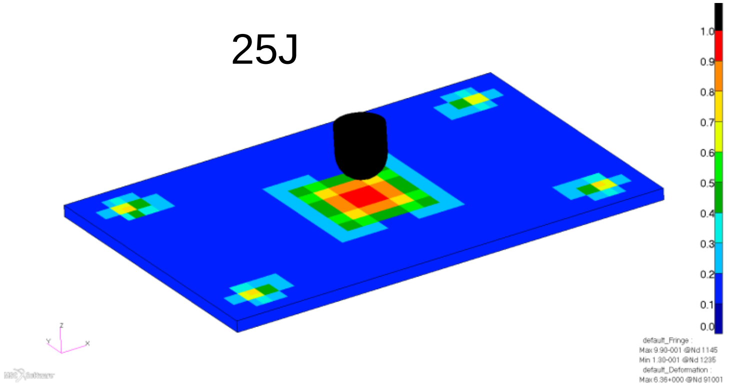
Compression: ANALYSIS=NLSTAT

Example IV: Compression after Impact Model

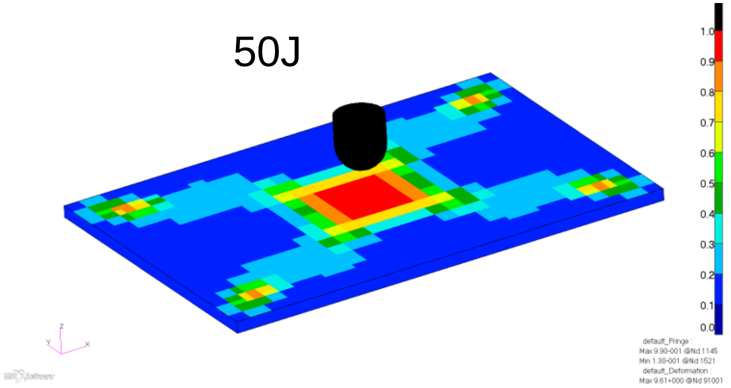
Impact: ANALYSIS=NLTRANS

Compression: ANALYSIS=NLSTAT

25J



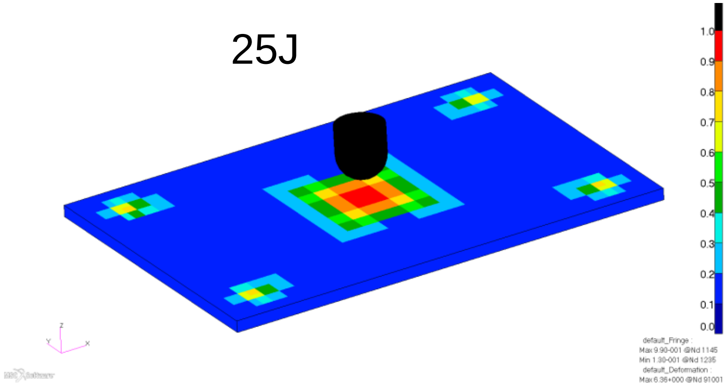
50J



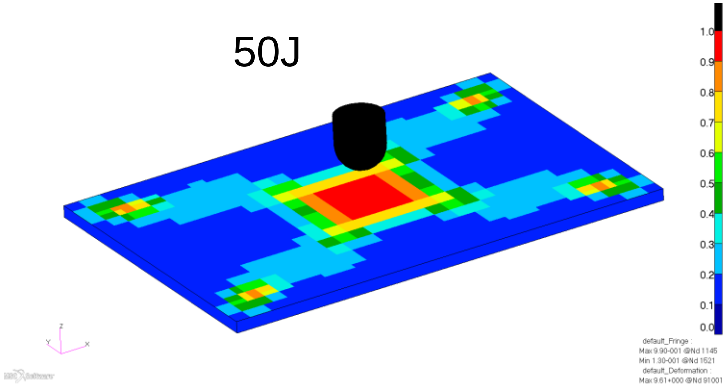
Example IV: Compression after Impact Model

Impact: ANALYSIS=NLTRANS

25J

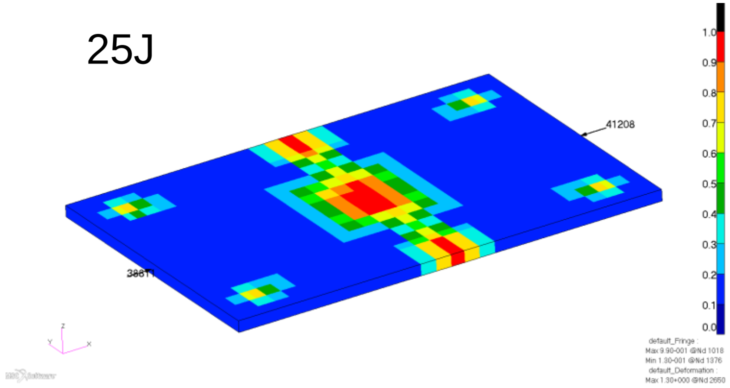


50J

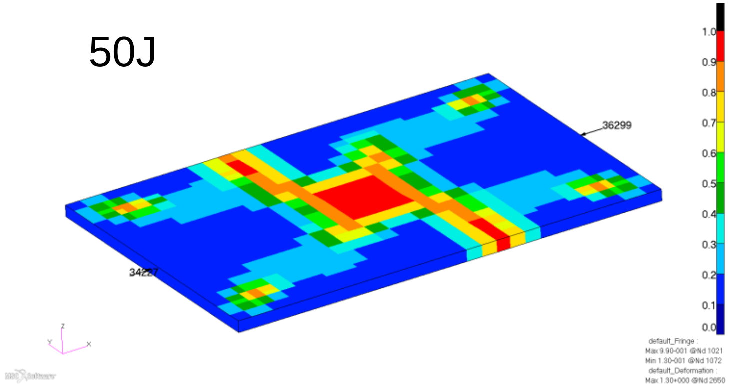


Compression: ANALYSIS=NLSTAT

25J

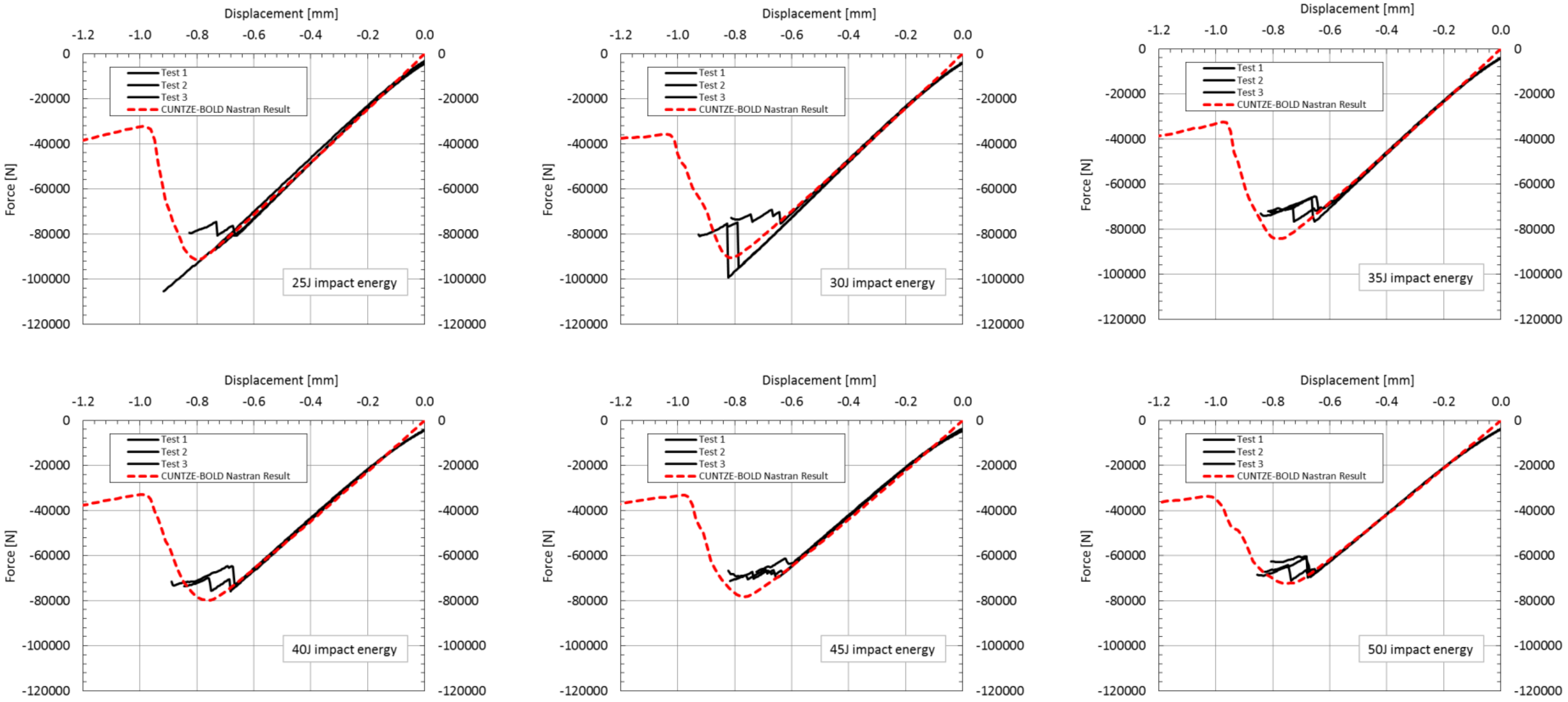


50J



Example IV: Compression after Impact Model

Force-Displacement Diagram: Test vs. Numerical Simulation



Good correlation between test and numerical simulation

BUT: What about deviations in fibre volume content?

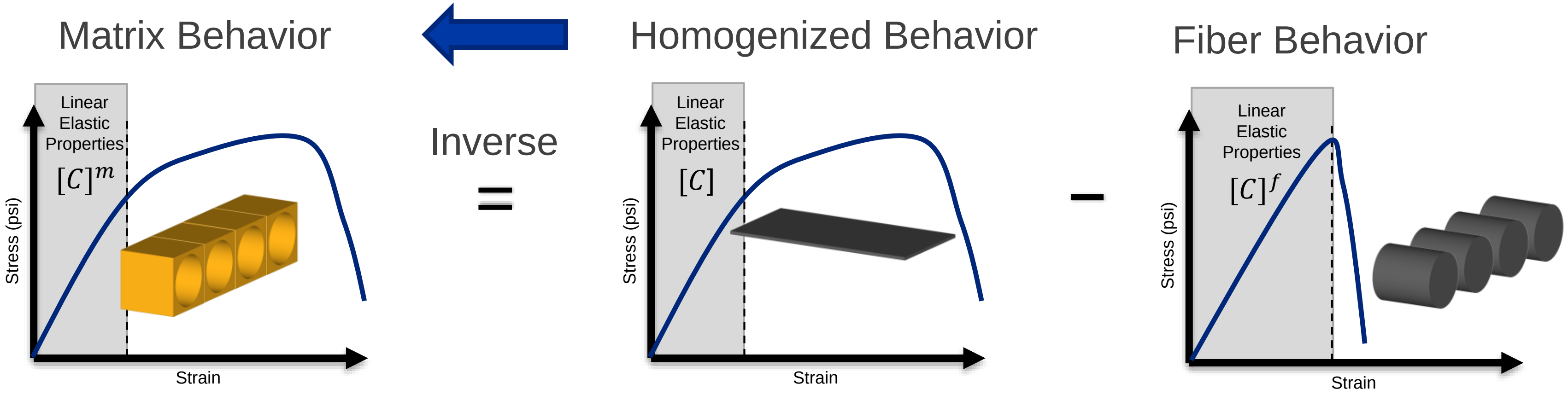
Industrial Use of Multiscale Designer

Altair

Multiscale Designer

Step 1:

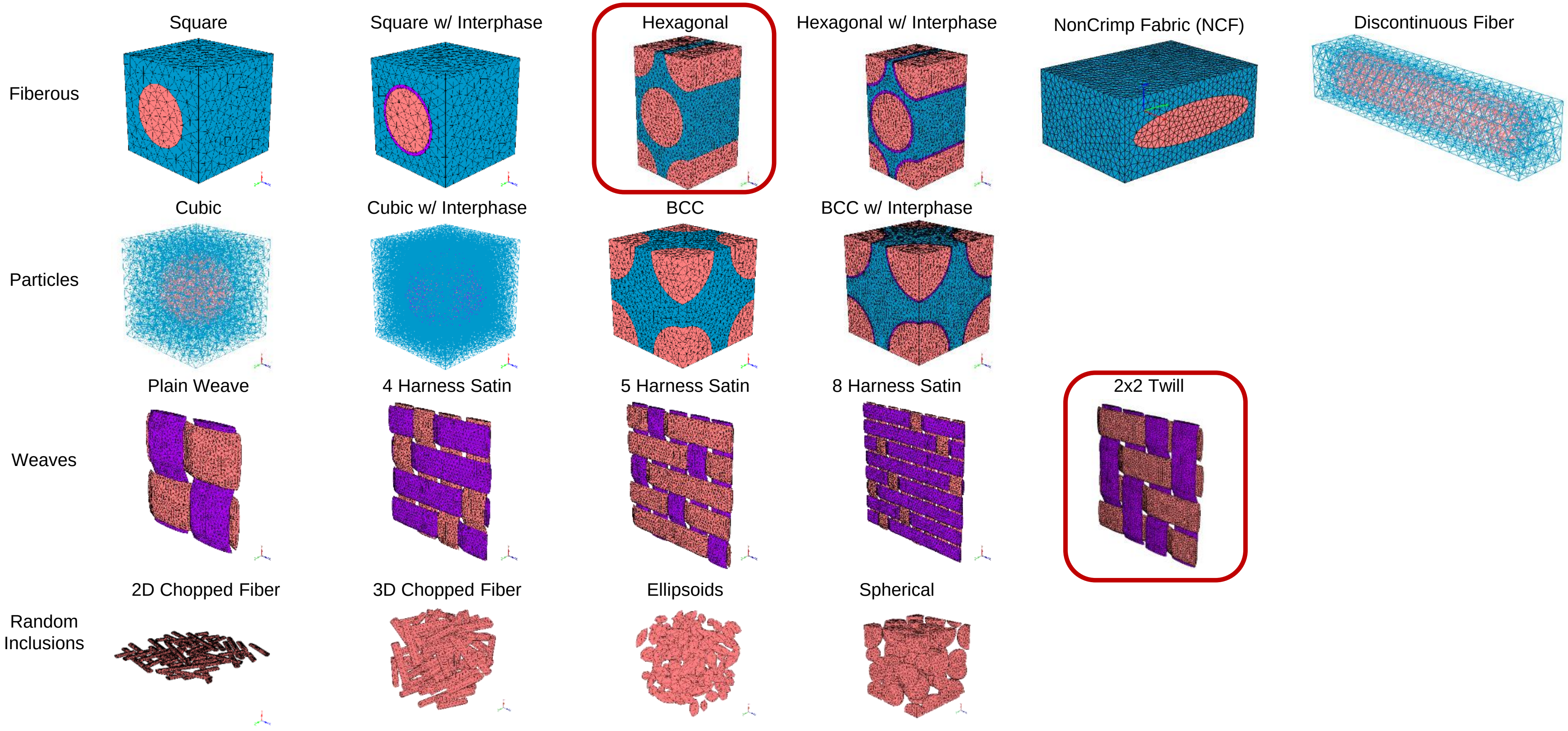
- Inverse Characterization
  - From homogenized ply and fiber behavior to matrix behavior with known fiber volume fraction



- All test results can be used
  - Tension
  - Compression
  - shear

Multiscale Designer

Parametric Unit Cell Library



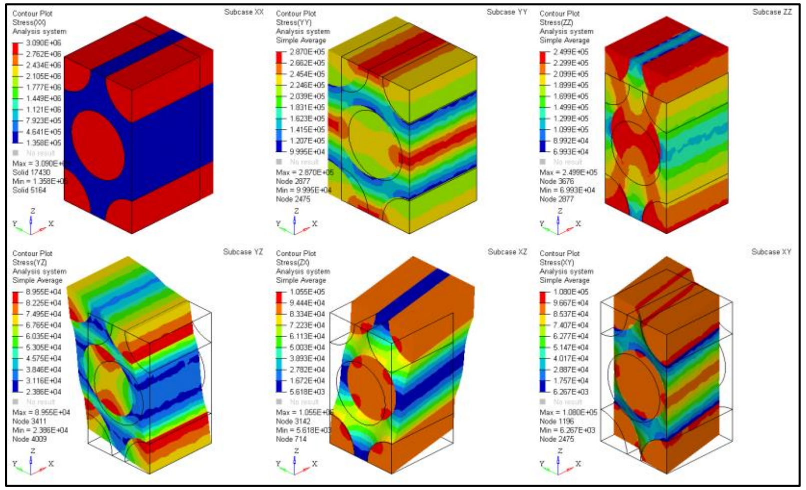
Multiscale Designer

Determining Homogenized Engineering Constant

- The 21 independent engineering constants that define the anisotropic stiffness matrix are determined by placing a specimen of material under 6 different strain boundary conditions within the linear elastic regime.

- Boundary conditions

BC1	$\varepsilon_1 = 1$	$\varepsilon_2 = \varepsilon_3 = \gamma_{12} = \gamma_{23} = \gamma_{13} = 0$
BC2	$\varepsilon_2 = 1$	$\varepsilon_1 = \varepsilon_3 = \gamma_{12} = \gamma_{23} = \gamma_{13} = 0$
BC3	$\varepsilon_3 = 1$	$\varepsilon_1 = \varepsilon_2 = \gamma_{12} = \gamma_{23} = \gamma_{13} = 0$
BC4	$\gamma_{12} = 1$	$\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \gamma_{23} = \gamma_{13} = 0$
BC5	$\gamma_{23} = 1$	$\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \gamma_{12} = \gamma_{13} = 0$
BC6	$\gamma_{13} = 1$	$\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \gamma_{12} = \gamma_{23} = 0$



Multiscale Designer

Boundary Condition #1

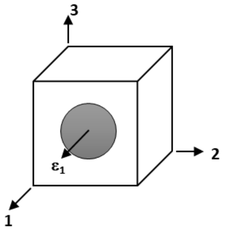
$\bar{\varepsilon}_1 = 1 \qquad \bar{\varepsilon}_2 = \bar{\varepsilon}_3 = \bar{\gamma}_{12} = \bar{\gamma}_{23} = \bar{\gamma}_{13} = 0$

$$\begin{Bmatrix} \bar{\sigma}_1 \\ \bar{\sigma}_2 \\ \bar{\sigma}_3 \\ \bar{\tau}_{12} \\ \bar{\tau}_{23} \\ \bar{\tau}_{13} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{Bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

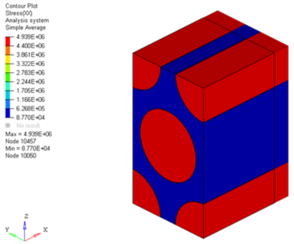
$C_{11} = \bar{\sigma}_1, C_{21} = \bar{\sigma}_2, C_{31} = \bar{\sigma}_3, C_{41} = \bar{\tau}_{12}, C_{51} = \bar{\tau}_{23}, C_{61} = \bar{\tau}_{13}$

where;

$\bar{\sigma}_1 = \frac{\int \sigma_1 dv}{\int dv} \qquad \bar{\sigma}_2 = \frac{\int \sigma_2 dv}{\int dv}$ etc…



σ_1 under ε_1



Boundary Condition #2

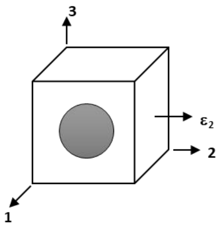
$\bar{\varepsilon}_2 = 1 \qquad \bar{\varepsilon}_1 = \bar{\varepsilon}_3 = \bar{\gamma}_{12} = \bar{\gamma}_{23} = \bar{\gamma}_{13} = 0$

$$\begin{Bmatrix} \bar{\sigma}_1 \\ \bar{\sigma}_2 \\ \bar{\sigma}_3 \\ \bar{\tau}_{12} \\ \bar{\tau}_{23} \\ \bar{\tau}_{13} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{Bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

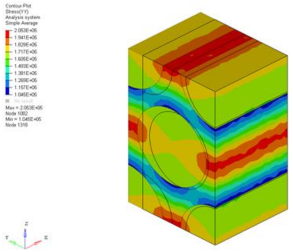
$C_{12} = \bar{\sigma}_1, C_{22} = \bar{\sigma}_2, C_{32} = \bar{\sigma}_3, C_{42} = \bar{\tau}_{12}, C_{52} = \bar{\tau}_{23}, C_{62} = \bar{\tau}_{13}$

where;

$\bar{\sigma}_1 = \frac{\int \sigma_1 dv}{\int dv} \qquad \bar{\sigma}_2 = \frac{\int \sigma_2 dv}{\int dv}$ etc…



σ_2 under ε_2



Boundary Condition #4

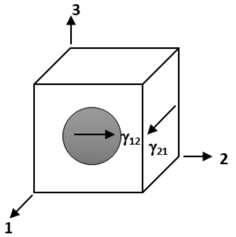
$\bar{\gamma}_{12} = 1 \qquad \bar{\varepsilon}_1 = \bar{\varepsilon}_2 = \bar{\varepsilon}_3 = \bar{\gamma}_{23} = \bar{\gamma}_{13} = 0$

$$\begin{Bmatrix} \bar{\sigma}_1 \\ \bar{\sigma}_2 \\ \bar{\sigma}_3 \\ \bar{\tau}_{12} \\ \bar{\tau}_{23} \\ \bar{\tau}_{13} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{Bmatrix}$$

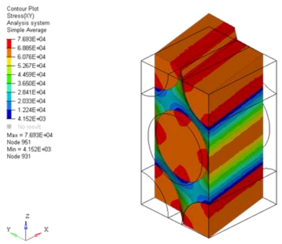
$C_{14} = \bar{\sigma}_1, C_{24} = \bar{\sigma}_2, C_{34} = \bar{\sigma}_3, C_{44} = \bar{\tau}_{12}, C_{54} = \bar{\tau}_{23}, C_{64} = \bar{\tau}_{13}$

where;

$\bar{\sigma}_1 = \frac{\int \sigma_1 dv}{\int dv} \qquad \bar{\sigma}_2 = \frac{\int \sigma_2 dv}{\int dv}$ etc…



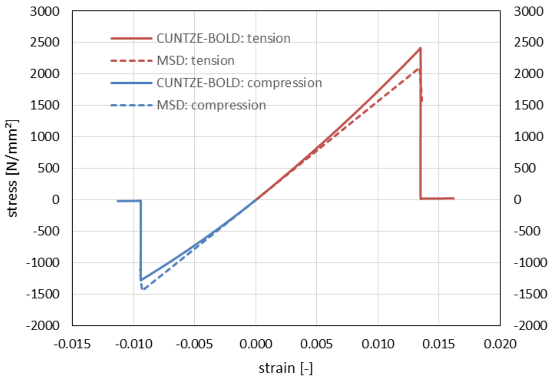
τ_{12} under γ_{12}

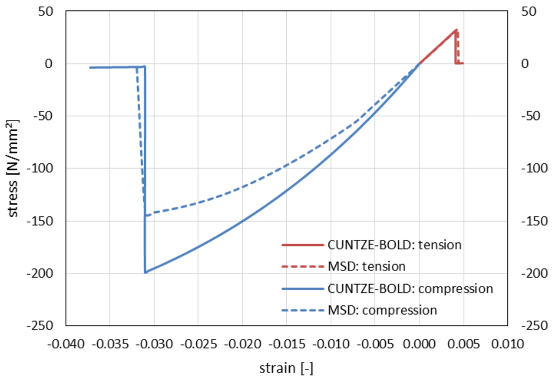


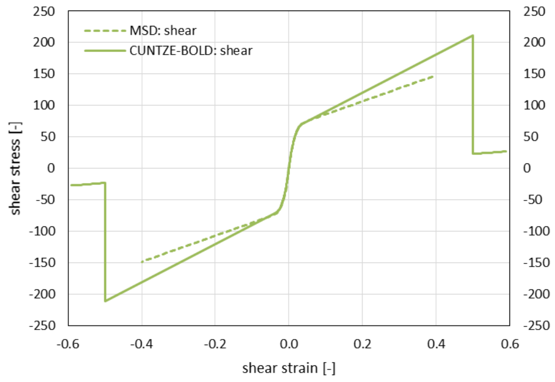
Multiscale Designer: Comparison Test vs. Multiscale Designer

Direction 1 | Direction 2 | Direction 1-2

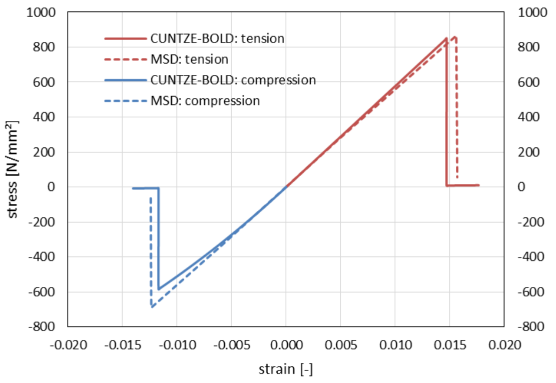
Unidirectional Material: IM-Fibre and Epoxy Resin

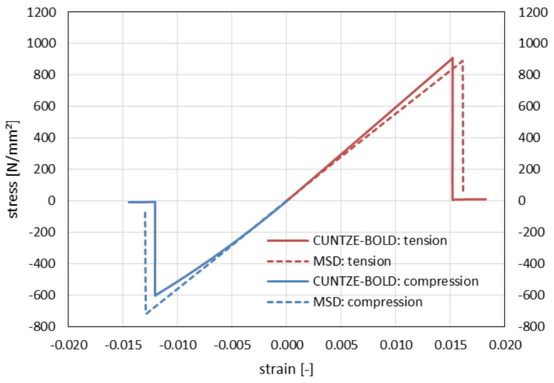


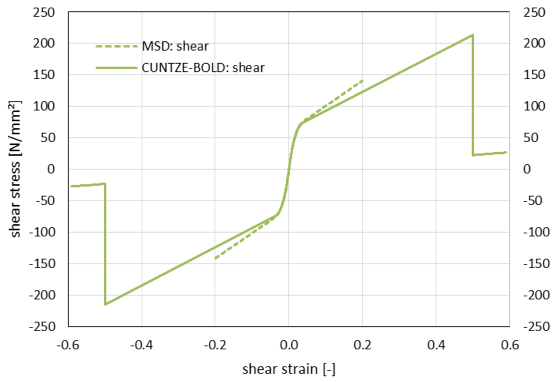




Woven Material: HT-Fibre 2x2 Twill and Epoxy Resin





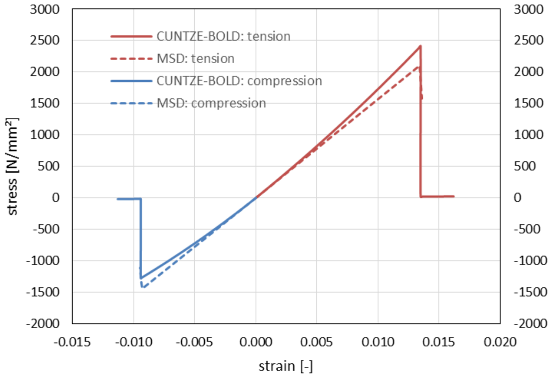


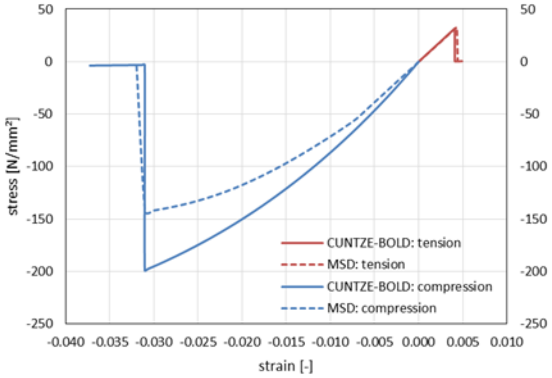
Conclusion: modification of residual stiffness in shear in CUNTZE-BOLD material & failure model

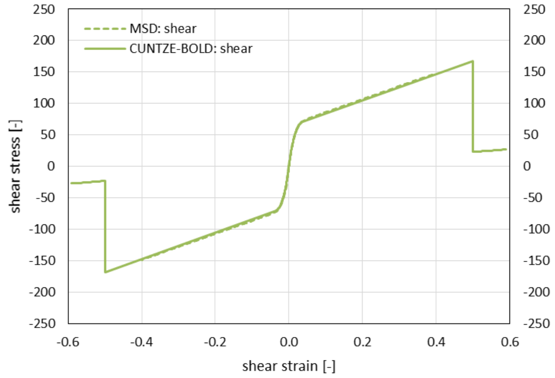
Multiscale Designer: Comparison Test vs. Multiscale Designer

Direction 1 | Direction 2 | Direction 1-2

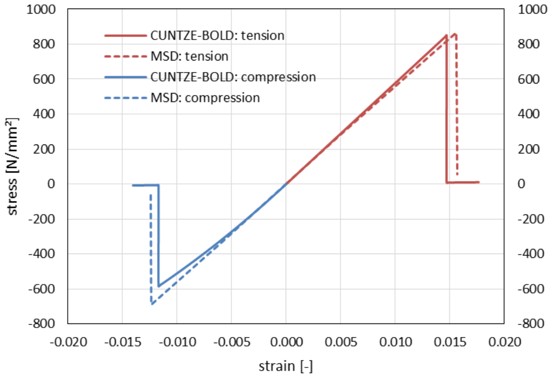
Unidirectional Material: IM-Fibre and Epoxy Resin

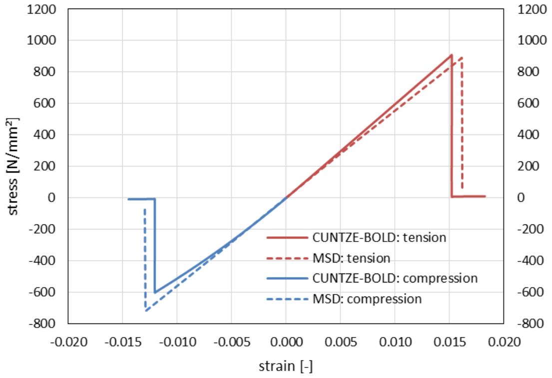


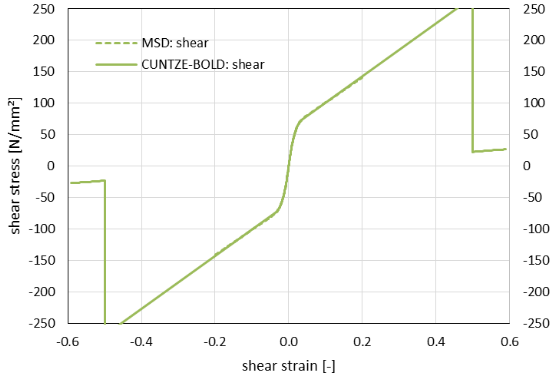




Woven Material: HT-Fibre 2x2 Twill and Epoxy Resin

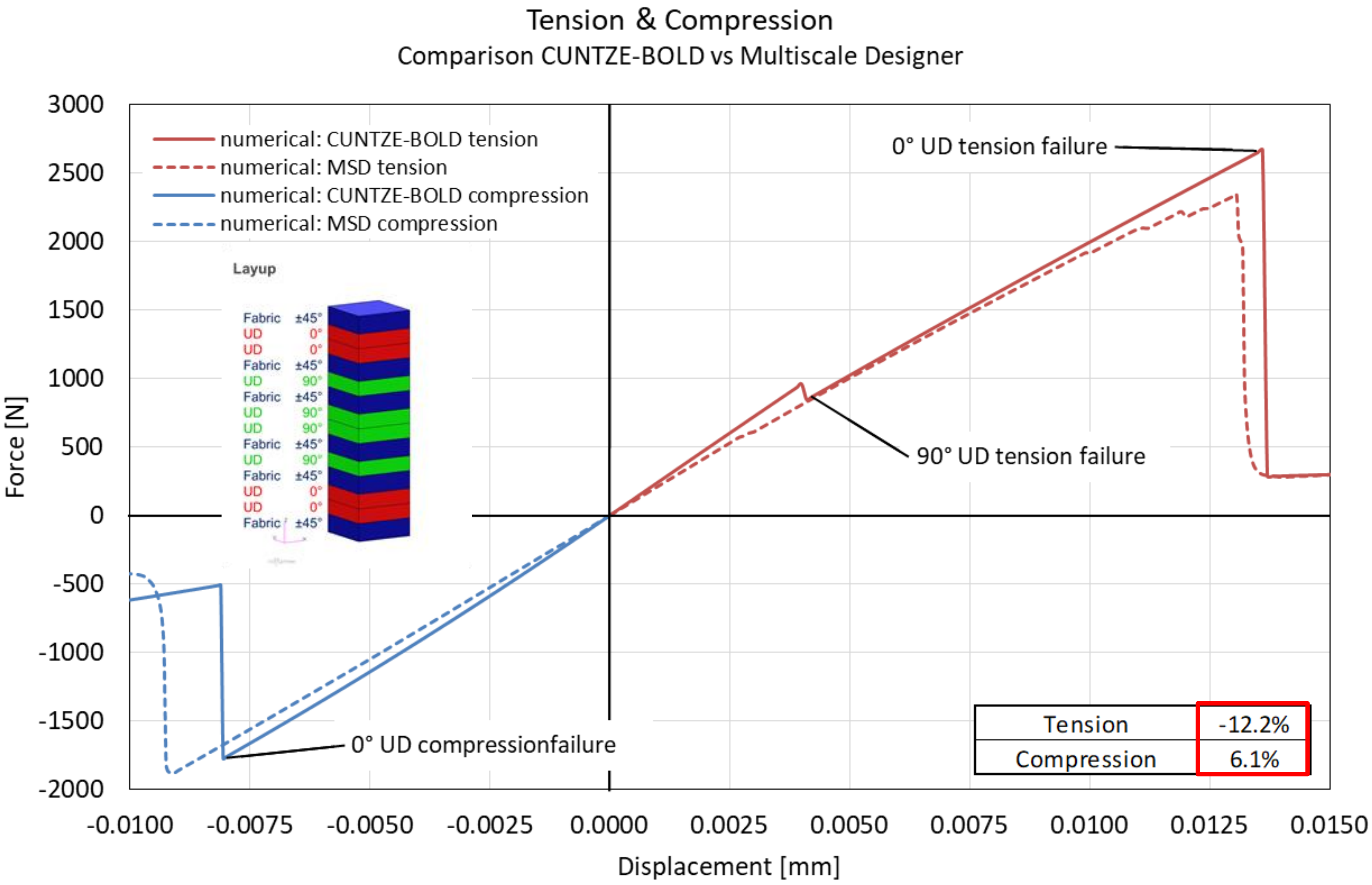






Conclusion: modification of residual stiffness in shear in CUNTZE-BOLD material & failure model

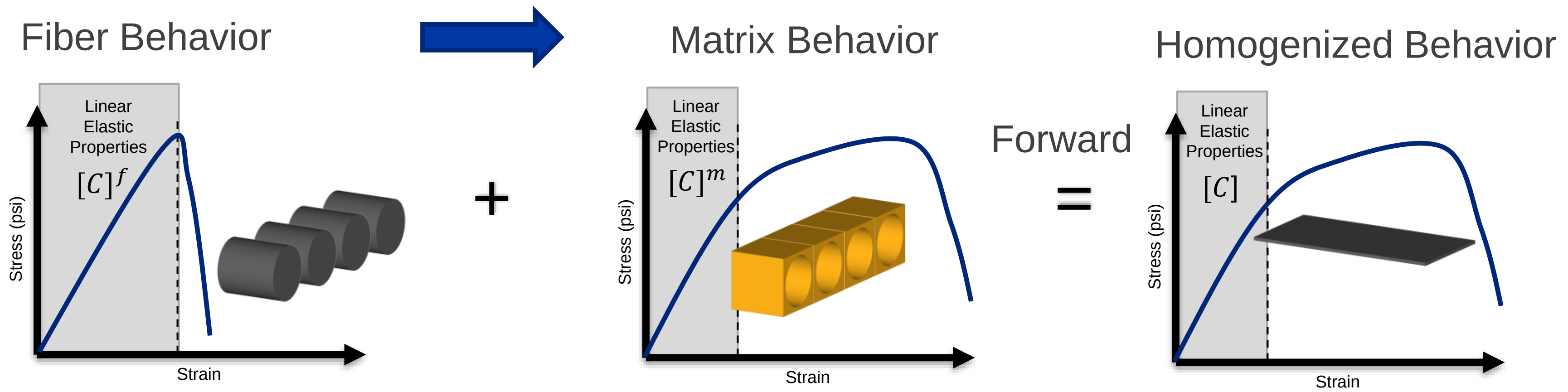
Example III: Layup with different materials under combined loading



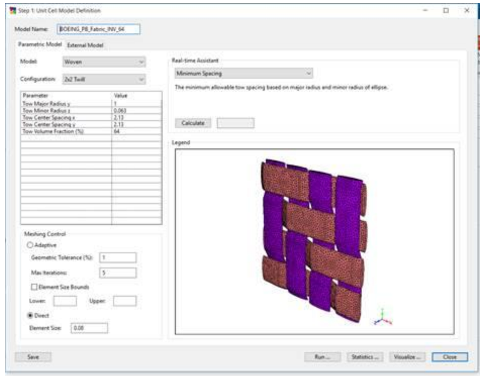
Multiscale Designer

Step 2:

- Forward Characterization: From matrix and fiber behavior to homogenized ply behavior with <u>different fiber volume fraction</u> (±5%)



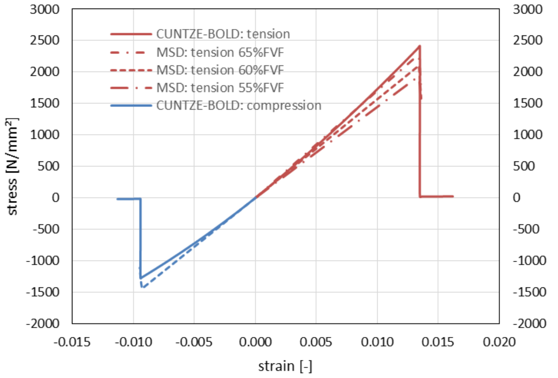
- All stress-strain curves can be predicted
  - Tension
  - Compression
  - shear

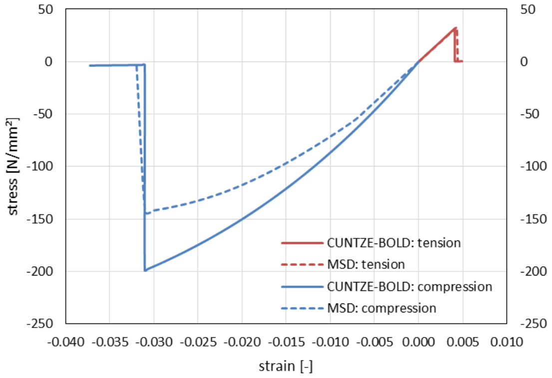


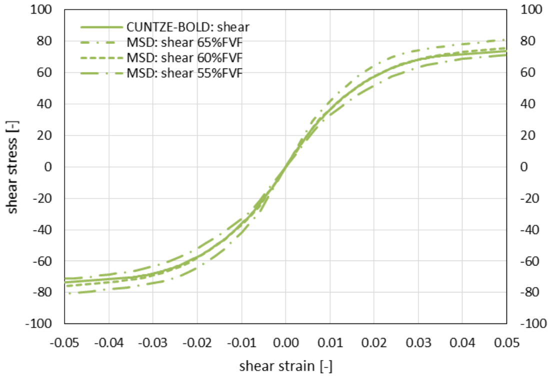
Multiscale Designer: Comparison of different fiber volume fraction

Direction 1 | Direction 2 | Direction 1-2

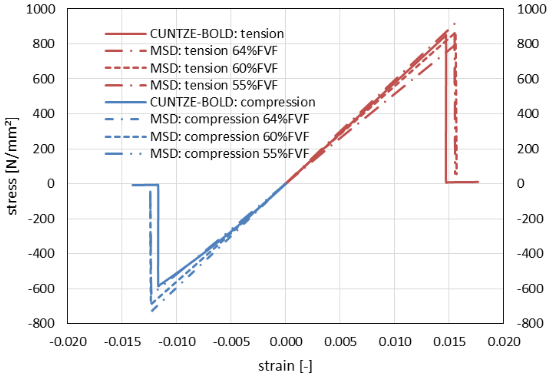
Unidirectional Material: IM-Fibre and Epoxy Resin

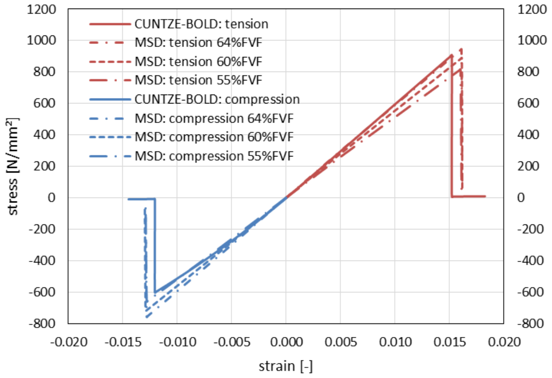


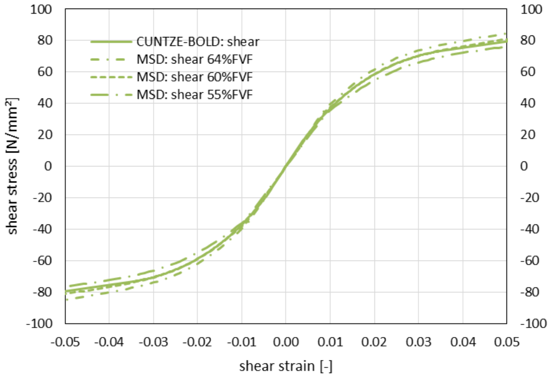




Woven Material: HT-Fibre 2x2 Twill and Epoxy Resin







Summary: changes in material behaviour can be evaluated

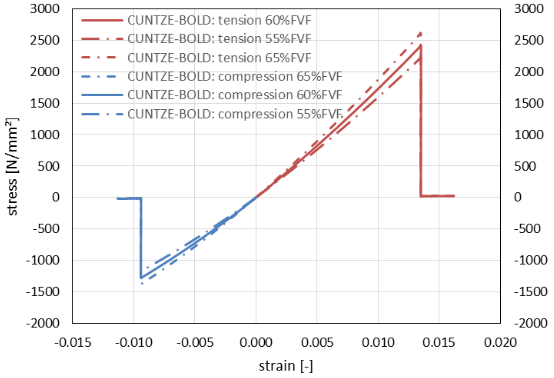
Application of Multiscale Designer Results

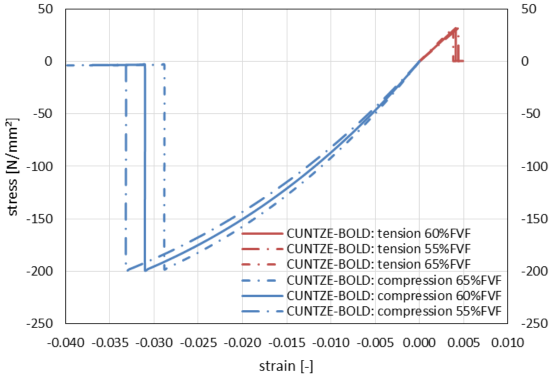
Numerical Simulation with CUNTZE-BOLD Material & Failure Model

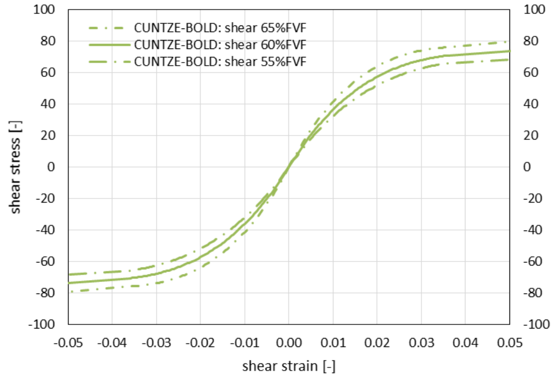
CUNTZE-BOLD material & failure model with different fiber volume fractions

Direction 1 | Direction 2 | Direction 1-2

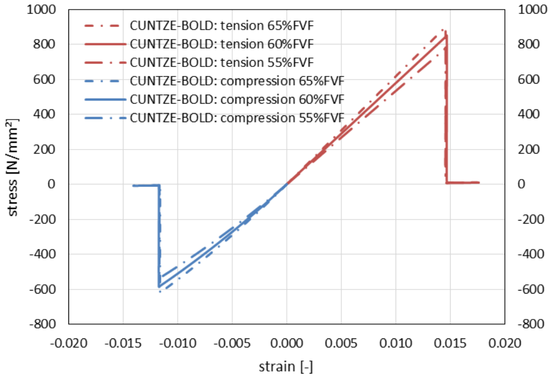
Unidirectional Material: IM-Fibre and Epoxy Resin

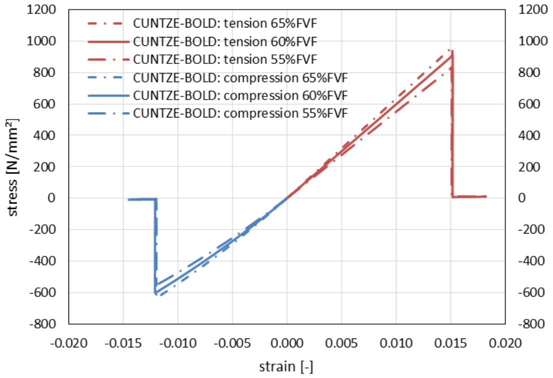


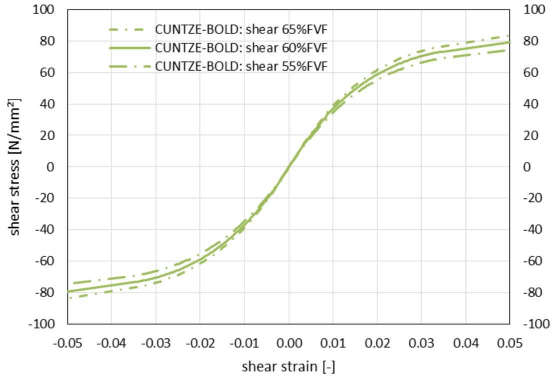




Woven Material: HT-Fibre 2x2 Twill and Epoxy Resin

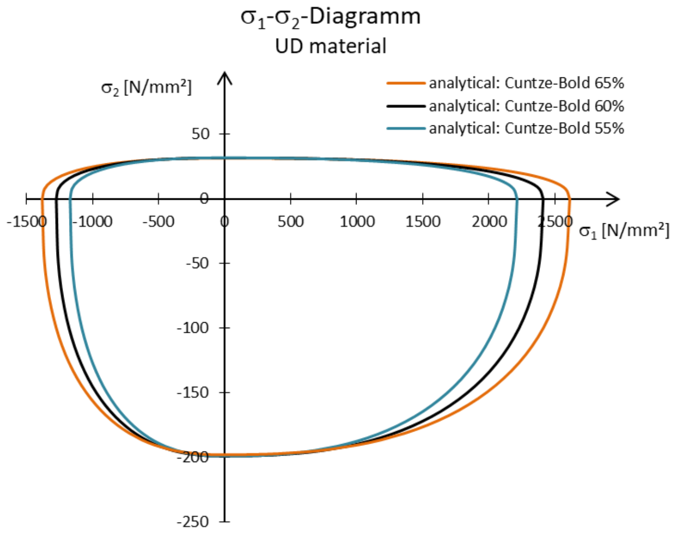


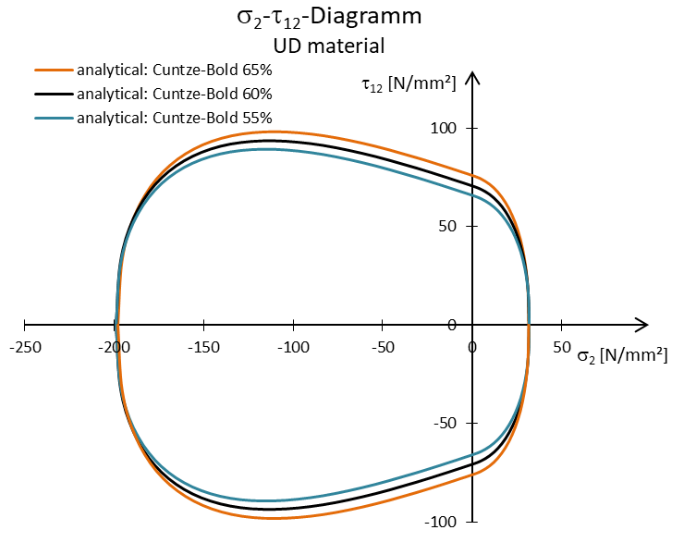


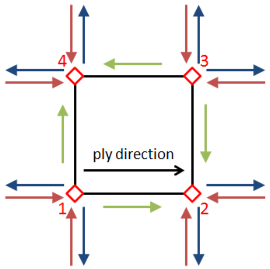


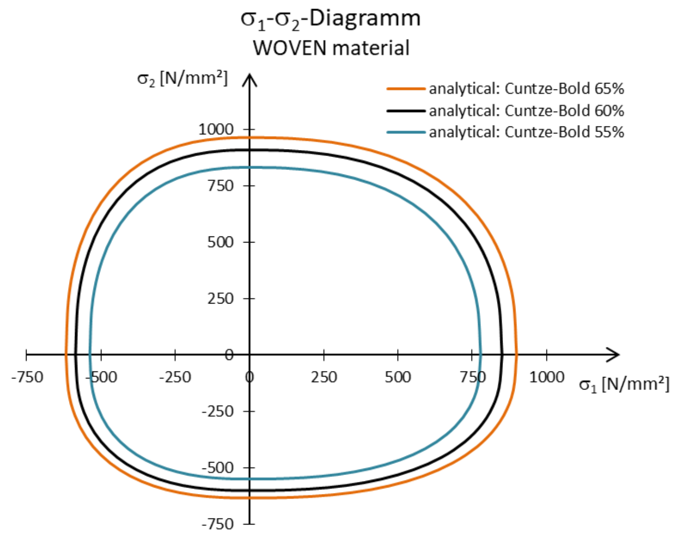
<u>Summary:</u> changes in material behaviour can be evaluated

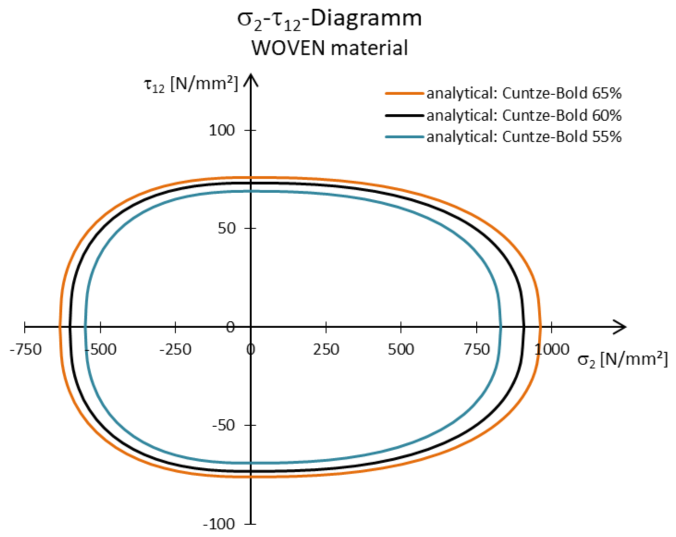
Example II: Single Element with single material under multi-axial loading



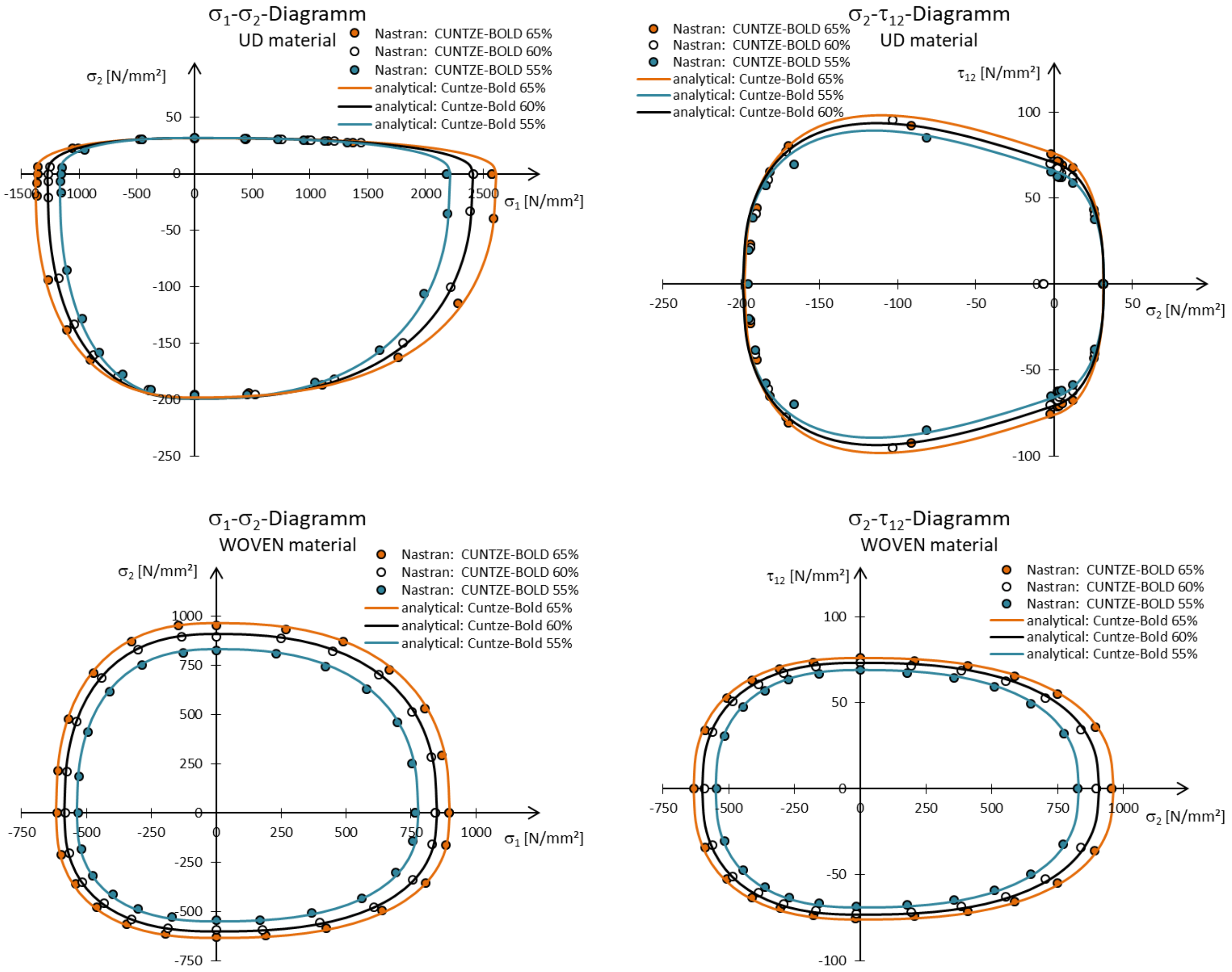


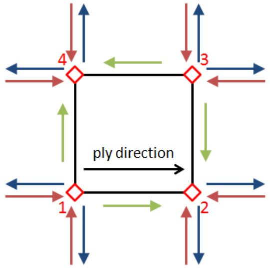






Example II: Single Element with single material under multi-axial loading

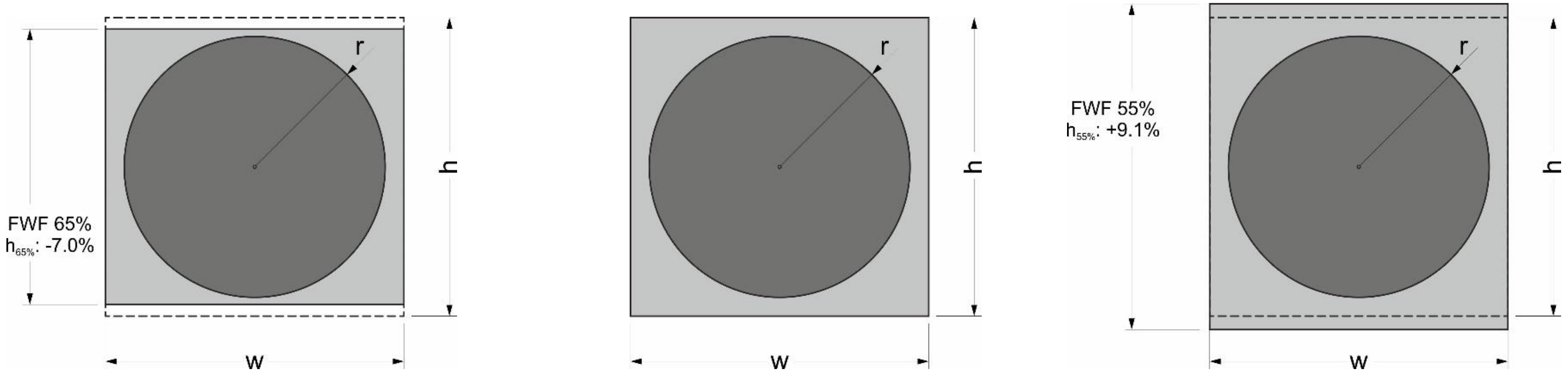




Variation in Fiber Volume Fraction

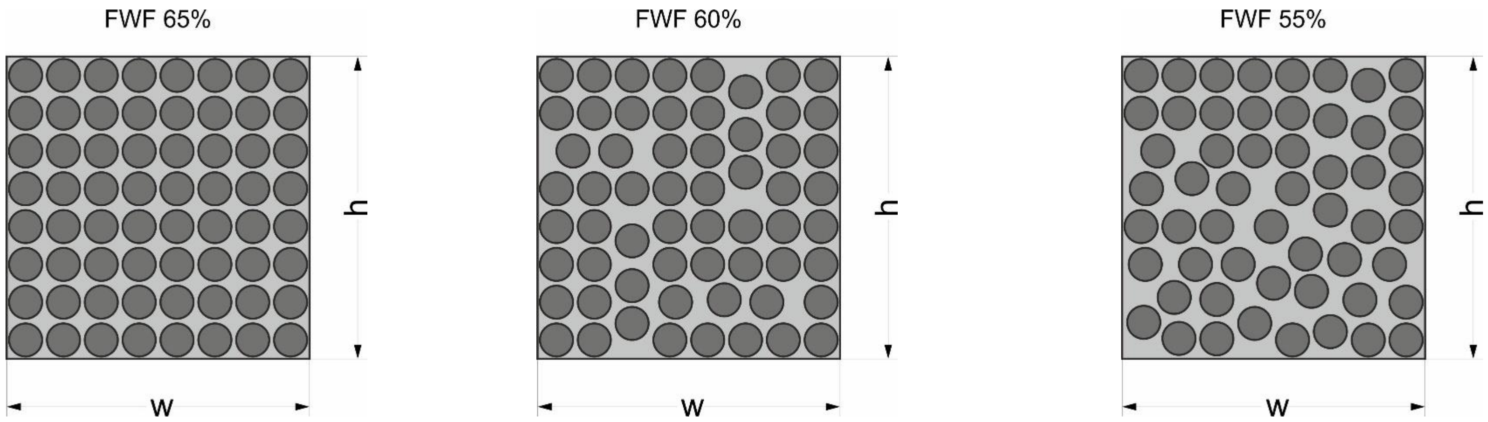
Method 1

- Contant fiber volume   Changed total dimension



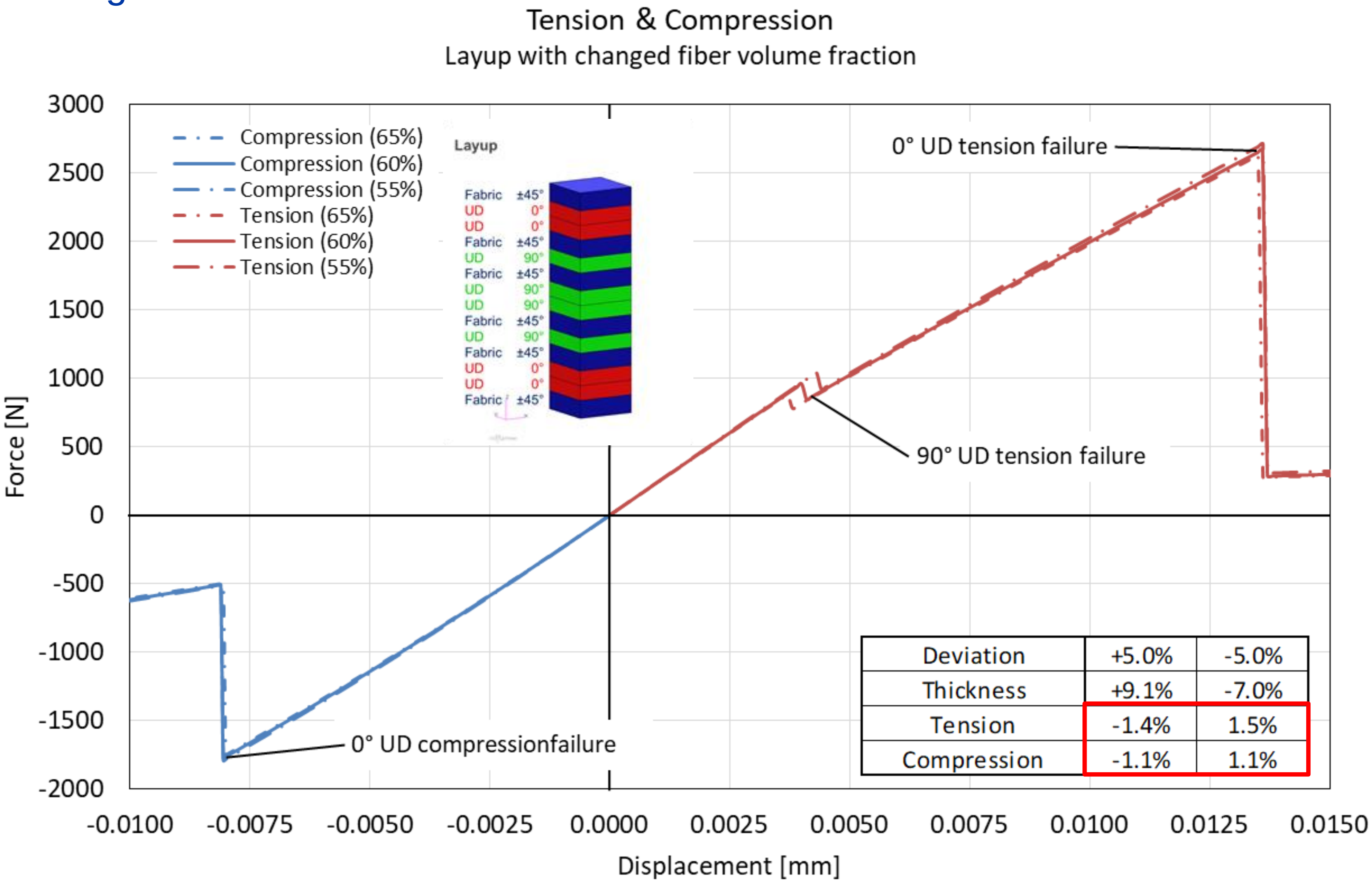
Method 2

- Changed fiber volume   Constant total dimensions



Example III: Layup with different materials under combined loading

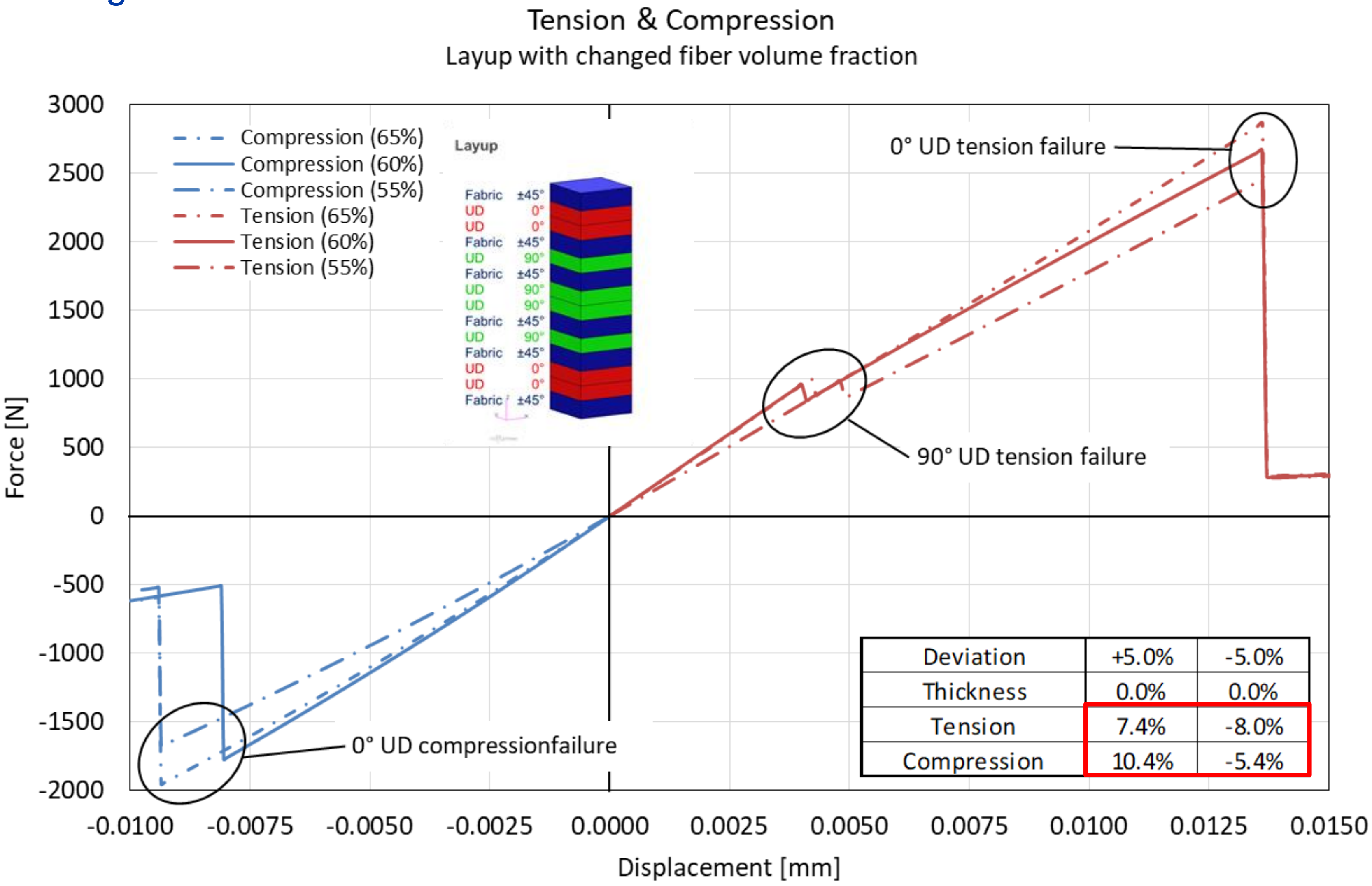
Changed total dimensions



Deviation	+5.0%	-5.0%
Thickness	+9.1%	-7.0%
Tension	-1.4%	1.5%
Compression	-1.1%	1.1%

Example III: Layup with different materials under combined loading

Changed total dimensions

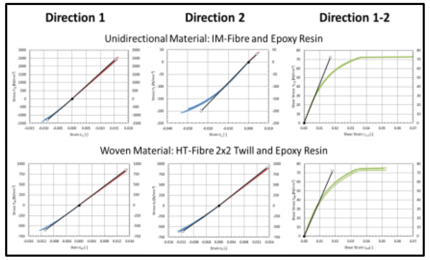


Deviation	+5.0%	-5.0%
Thickness	0.0%	0.0%
Tension	7.4%	-8.0%
Compression	10.4%	-5.4%

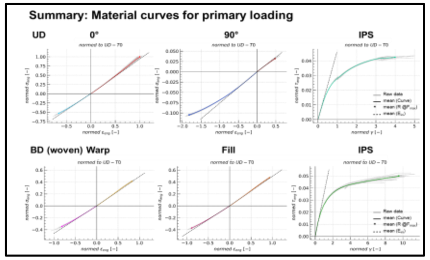
Summary & Conclusion

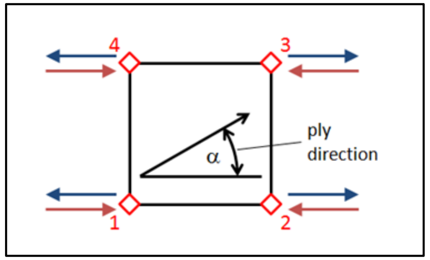
Summary & Conclusion

PAST		FUTURE

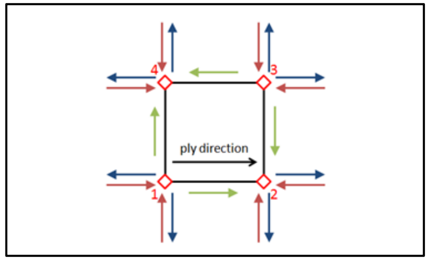


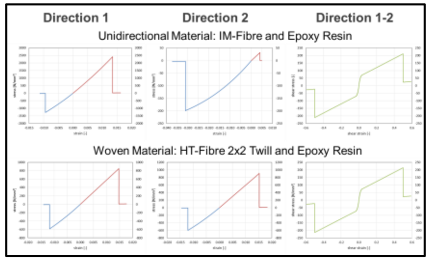
From hand evaluation to **automated evaluation**



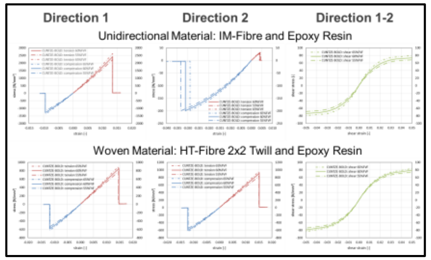


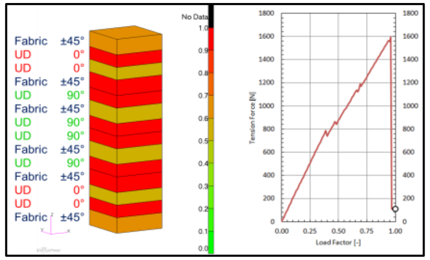
From turned layup to **real biaxiale loading**



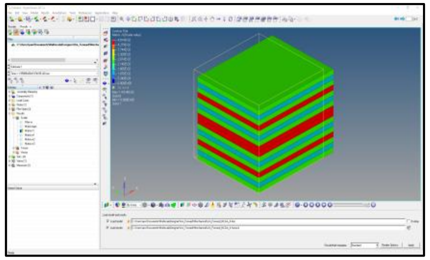


From single fiber volume to **stochastic distribution**





From hand evaluation to **automated evaluation**



Summary & Conclusion

Different approaches can be combined to predict the material behavior

- Ply based methods based on CUNTZE-BOLD
- Micro scale methods based on Multiscale Designer

Advantages for Composite Simulations in Industrial Applications

- Prediction of deviations
- Highly efficient
- Fast

Conclusion

- Still some challenges to describe the material behavior in depth
- Engineering judgement of experienced experts are necessary
- Composite material characterization with the help of multi scale methods is possible when combining different methods

Thank you.
Questions?