KI-basierte Materialmodellierung für Holzwerkstoff
AI based Constitutive Modeling for Wood

Michael Kofler[1], Lukas Peyker[2], Mathias H. Luxner[2], and Heinz E. Pettermann[1*]

[1]Institute of Lightweight Design and Structural Biomechanics, TU Wien, 1060 Vienna, Austria.

[2]LUXNER Engineering ZT GmbH, 6460 Imst, Austria.

The funding of this project by *Land Tirol* is gratefully acknowledged

Blickpunkt Forschung - Nachhaltige Materialien und Werkstoffe, October 2025, TU Wien

Outline

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Motivation

... to foster ply wood in structural applications (automotive, aeronautics, etc.)

- renewable resource
- mechanical properties comparable to carbon composites

for better exploitation

$\rightarrow$ improved modeling and simulation tools

exceeding the linear elastic range

post peak response — load reserve OR catastrophic

for the prediction of the elasto-damage response of ply wood

Aims & Scope

- elasto-damage response of anisotropic materials
  - highly direction dependent
  - multiple, interacting damage mechanisms

- classical damage modeling strategies
  - closed-form constitutive laws
    - phenomenological (thus limited)
    - suitable for FEM implementation
  - homogenization
    - model of the resolved micro structure (RVE)
    - non-linear constitutive law cannot be deduced directly
    - FE^2 — extremely computer resource hungry

$\rightarrow$ **machine learning surrogate model**

train an ANN to learn the complex constitutive law

implement into FEM

Continuum Damage Mechanics

plane stress; Voigt notation with $\gamma_{xy} = 2\varepsilon_{xy}$

$$\boldsymbol{\sigma} = (\sigma_{xx}\ \sigma_{yy}\ \sigma_{xy})^{\mathrm{T}} \quad , \quad \boldsymbol{\varepsilon} = (\varepsilon_{xx}\ \varepsilon_{yy}\ \gamma_{xy})^{\mathrm{T}}$$

Hookes's law

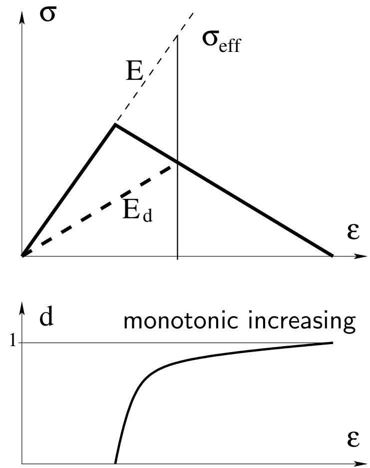
$$\boldsymbol{\sigma} = \mathbf{E}\boldsymbol{\varepsilon}$$

elasticity tensor

$$\mathbf{E} = \begin{pmatrix} E_{11} & E_{12} & 0 \\ E_{21} & E_{22} & 0 \\ 0 & 0 & E_{33} \end{pmatrix}$$

elasto-damage response

$$\boldsymbol{\sigma} = \mathbf{E_d}\boldsymbol{\varepsilon}, \quad \text{with} \quad \mathbf{E_d} = f(\mathbf{E}, \mathbf{d})$$



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Hashin Damage Model

damaged elasticity tensor, as implemented in ABAQUS

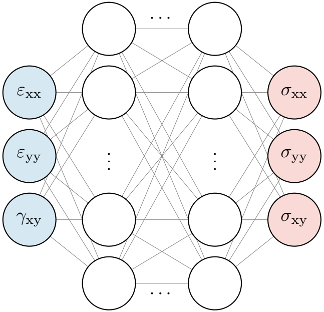
$$\mathbf{E}_{\mathbf{d}}^{(\mathrm{Hashin})} = f(\mathbf{E}, d_f^t, d_f^c, d_m^t, d_m^c, d_s)$$

damage initiation and evolution based on the failure modes

- fiber rupture in tension
- fiber buckling and kinking in compression
- matrix cracking under transverse tension and shearing
- matrix crushing under transverse compression and shearing

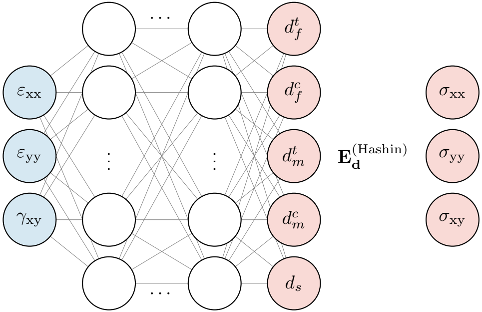
Neural Network Architecture (Single Ply)

network size: 4 layers with 64 neurons, ReLU activation function



$$f_\theta^\sigma : \mathbb{R}^3 \mapsto \mathbb{R}^3, \quad \boldsymbol{\varepsilon} \mapsto \boldsymbol{\sigma} = f_\theta^\sigma(\boldsymbol{\varepsilon})$$

stress mapping



$$f_\theta^d : \mathbb{R}^3 \mapsto \mathbb{R}^5, \quad \boldsymbol{\varepsilon} \mapsto \boldsymbol{d} = f_\theta^d(\boldsymbol{\varepsilon})$$

damage variable mapping

Neural Network Training

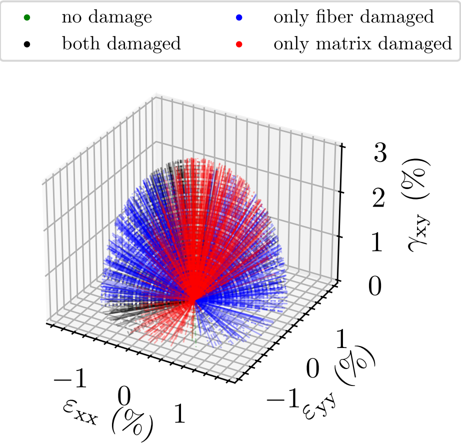
data base generation — FEM single element

1600 radial strain paths with 400 increments each

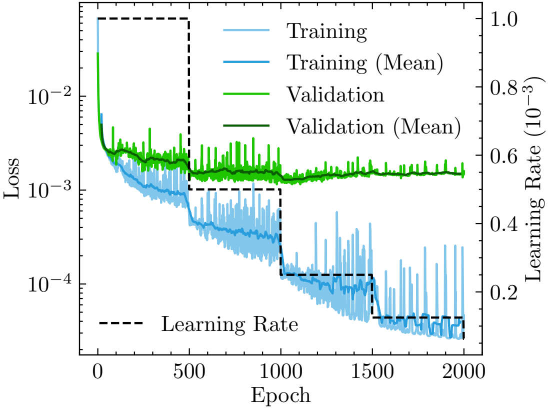
1200 used for training and 400 for validation

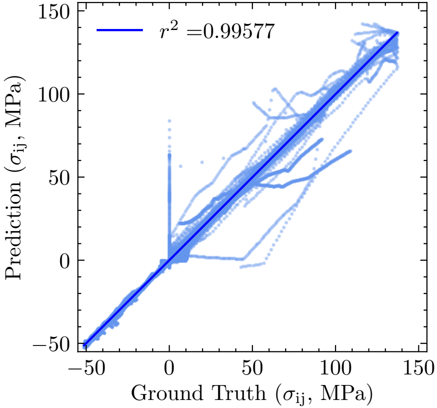
$$\arg\min_{\theta} \sum_{n=1}^{N} \sum_{m=1}^{M} \mathcal{L}\left(f_\theta\left(\varepsilon_{n,m}\right), \hat{d}_{n,m}\right)$$

N	... number of loading paths
M	... number of increments per path
$\mathcal{L}(\cdot,\cdot)$	... loss function
f_θ	... neural network output
$\varepsilon_{n,m}$	... input strain
$\hat{d}_{n,m}$	... Hashin damage variables
θ	... neural network parameters

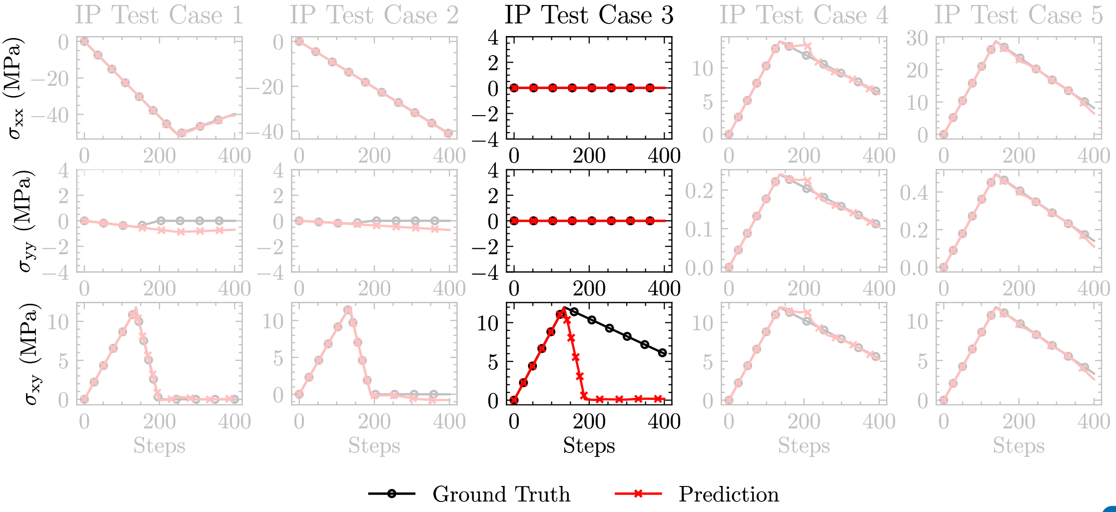


Neural Network Training





Comparison around Simple Shear: Stresses



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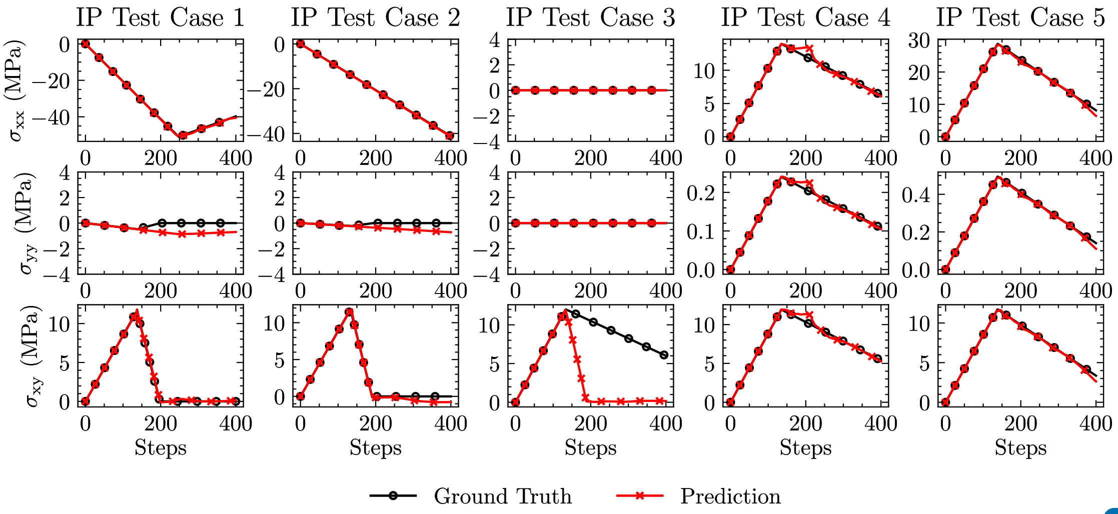
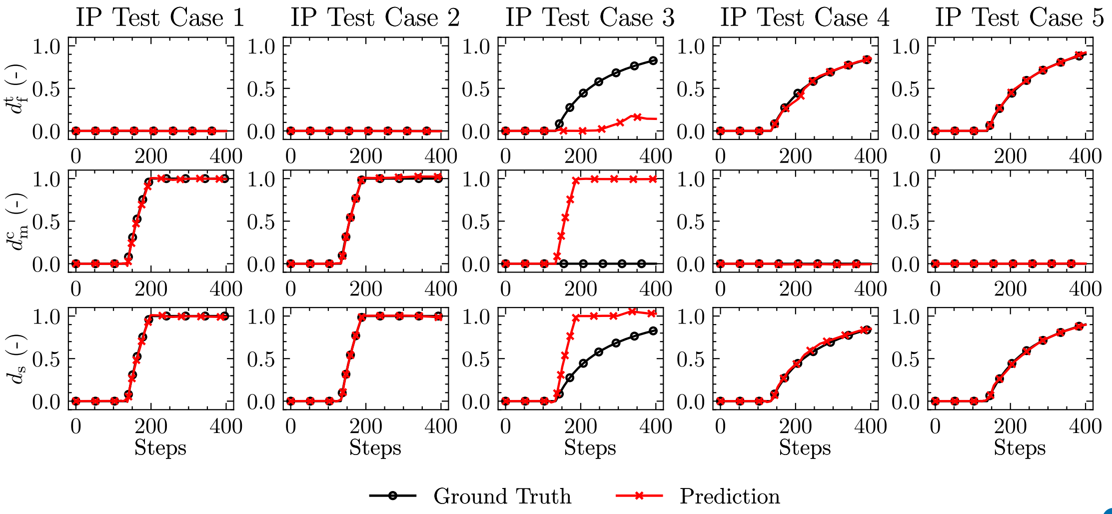


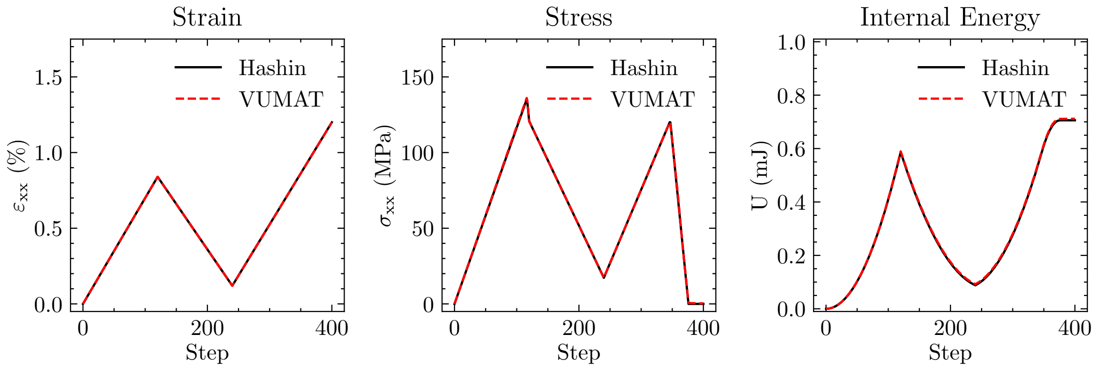
Comparison: Damage Variables



FEM Implementation — VUMAT

enforce damage mechanics principles — monotonic rising damage variables

loading–unloading–reloading sequence



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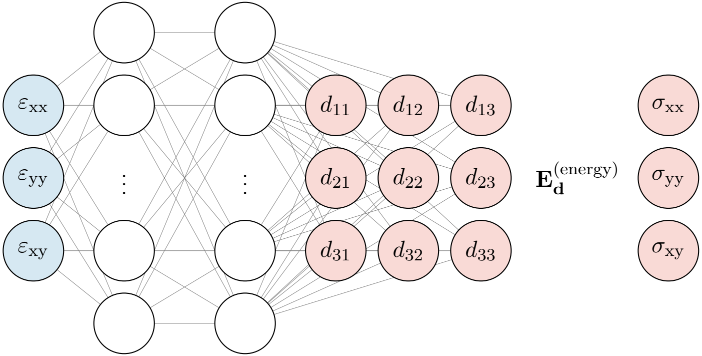
Network Architecture for Ply Wood

network size: 4 layers with 64 neurons, ReLU activation function



$$f_\theta^D : \mathbb{R}^3 \to \mathbb{R}^{3\times 3} \quad \boldsymbol{\varepsilon} \mapsto \boldsymbol{D} = f_\theta^D(\boldsymbol{\varepsilon}); \quad \mathbf{E}_{\mathbf{d}}^{(\text{energy})} = (\mathbf{I} - \mathbf{D})\ \mathbf{E}\ (\mathbf{I} - \mathbf{D})^{\mathrm{T}}$$

Neural Network Training

data base generation for the (homogenized) ply wood response — as before
training on the stresses
damage variables not known explicitly; but deduced by the ANN

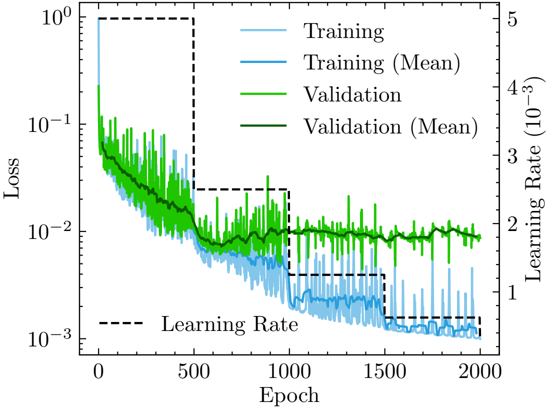
$$\arg\min_{\theta} \sum_{n=1}^{N} \sum_{m=1}^{M} \mathcal{L}\left(\boldsymbol{\sigma}_{n,m}, \hat{\boldsymbol{\sigma}}_{n,m}\right)$$

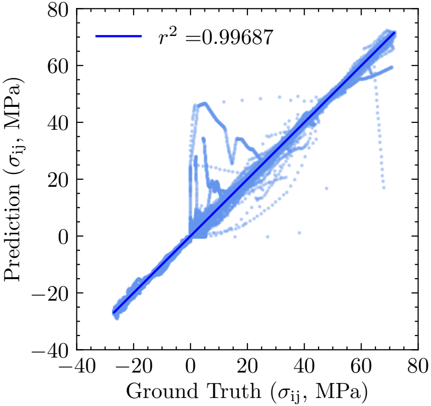
with

$$\boldsymbol{\sigma}_{n,m} = \left(\mathbf{I} - \mathbf{D}\right) \mathbf{E} \left(\mathbf{I} - \mathbf{D}\right)^T \boldsymbol{\varepsilon}_{n,m}$$

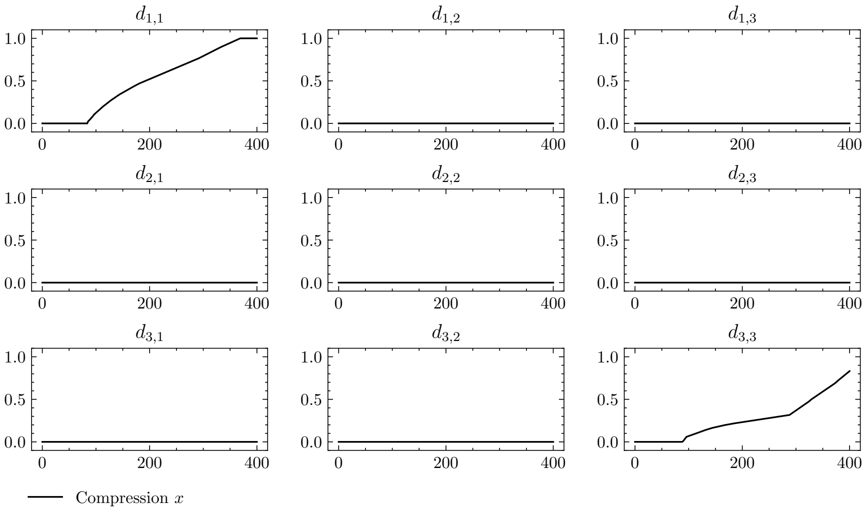
$$\boldsymbol{\sigma}_{n,m} = \left(\mathbf{I} - f_\theta^D\left(\boldsymbol{\varepsilon}_{n,m}\right)\right) \mathbf{E} \left(\mathbf{I} - f_\theta^D\left(\boldsymbol{\varepsilon}_{n,m}\right)\right)^T \boldsymbol{\varepsilon}_{n,m}$$

Neural Network Training





Damage Tensor for Various Test Cases



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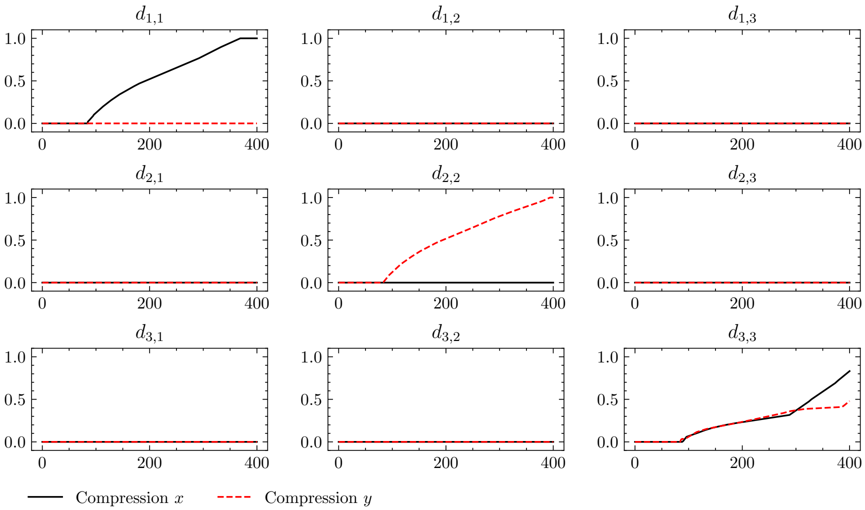

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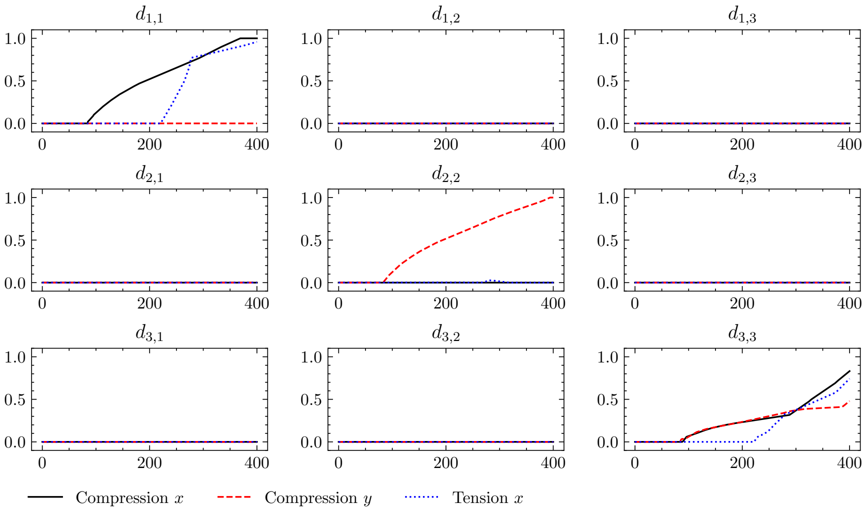

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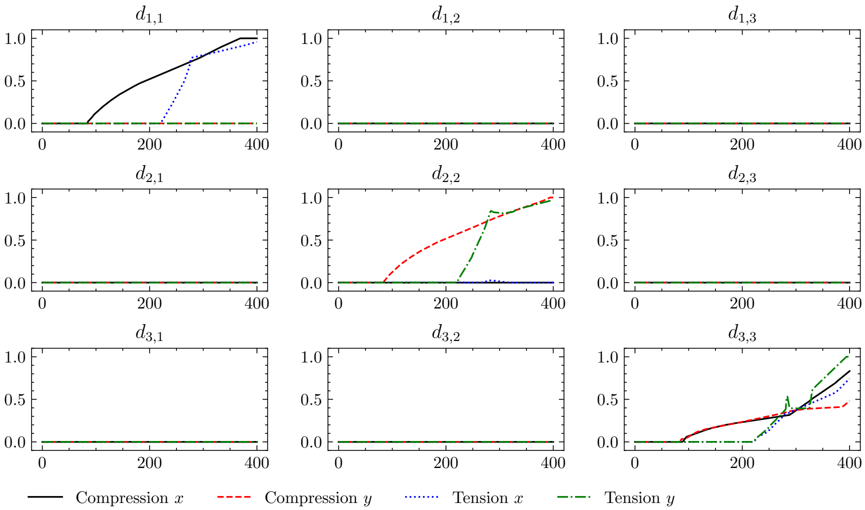

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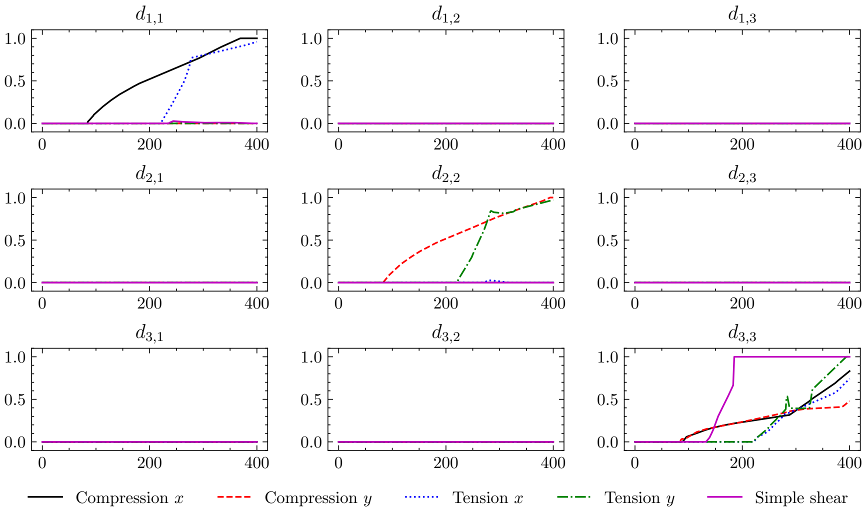

Discussion of the Damage Tensor

- $4th$ order damage tensor is formulated
  evolution is deduced
  for which there is no explicit expression
- diagonal damage tensor
  because of 0/90 layup
  expected to be non-symmetric for general cases

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Summary

ILSB LUXNER ENGINEERING ZT GMBH

- machine learning / AI methods to predict the elasto-damage response of anisotropic materials as wood, ply wood, and composites
- reproduce an existing continuum damage model for a single ply / veneer
- implement the ANN as constitutive law into FEM
- apply damage mechanics principles to capture unloading and reloading

- predict homogenized ply wood response for which there is no closed form
- extract the evolution of the implicit damage tensor

work in progress

- further verification on ply wood
- investigate response to non-radial strain loading
- application to structural analyses with non-uniform mesh size

Hashin Damaged Elasticity Tensor

$$\mathbf{E}_{\mathbf{d}}^{(\mathrm{Hashin})} = \frac{1}{\Delta} \begin{pmatrix} (1-d_f)E_x & (1-d_f)(1-d_m)\nu_{yx}E_x & 0 \\ (1-d_f)(1-d_m)\nu_{xy}E_y & (1-d_m)E_y & 0 \\ 0 & 0 & (1-d_s)G_{xy}\Delta \end{pmatrix}$$

with $\Delta = 1-(1-d_f)(1-d_m)\nu_{xy}\nu_{yx}$.