Modeling endless fiber reinforced polymers in crashworthiness simulation

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Organic Sheets

- Endless fiber fabric (glass or carbon) in a thermoplastic matrix (e.g. PP, PA)
- Can be formed like a metal sheet at elevated temperatures
- Endless fiber fabric offers high stiffness and high strength in pre-defined directions

Courtesy of Kirchhoff Automotive: organic sheet component from R&D project

Motivation

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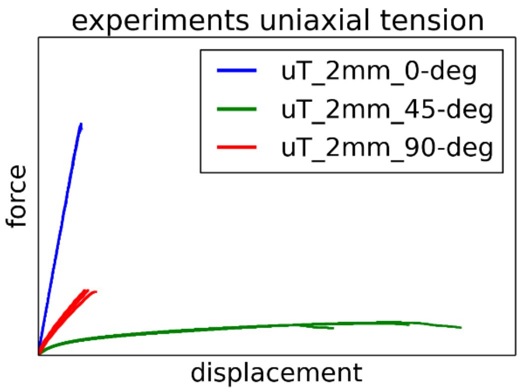
- However the modelling of the material behavior in misuse load cases and crashworthiness is challenging
- Material behavior of organic sheets is highly anisotropic in its initial condition (anisotropy of elasticity, plasticity and fracture)
- Material behavior can change locally from orthotropic to general ansiotropic behavior after thermoforming or after extensive deformation in crash



- Only an appropriate material model allows to fully exploit the potential of organic sheets in lightweight design of hybrid components
- Due to this challenges Ford R&A, Kirchhoff Automotive and MATFEM performed a first pilot project on crashworthiness simulation of organic sheets in 2014/15. Material model MF GenYld+CrachFEM was used as a development platform.

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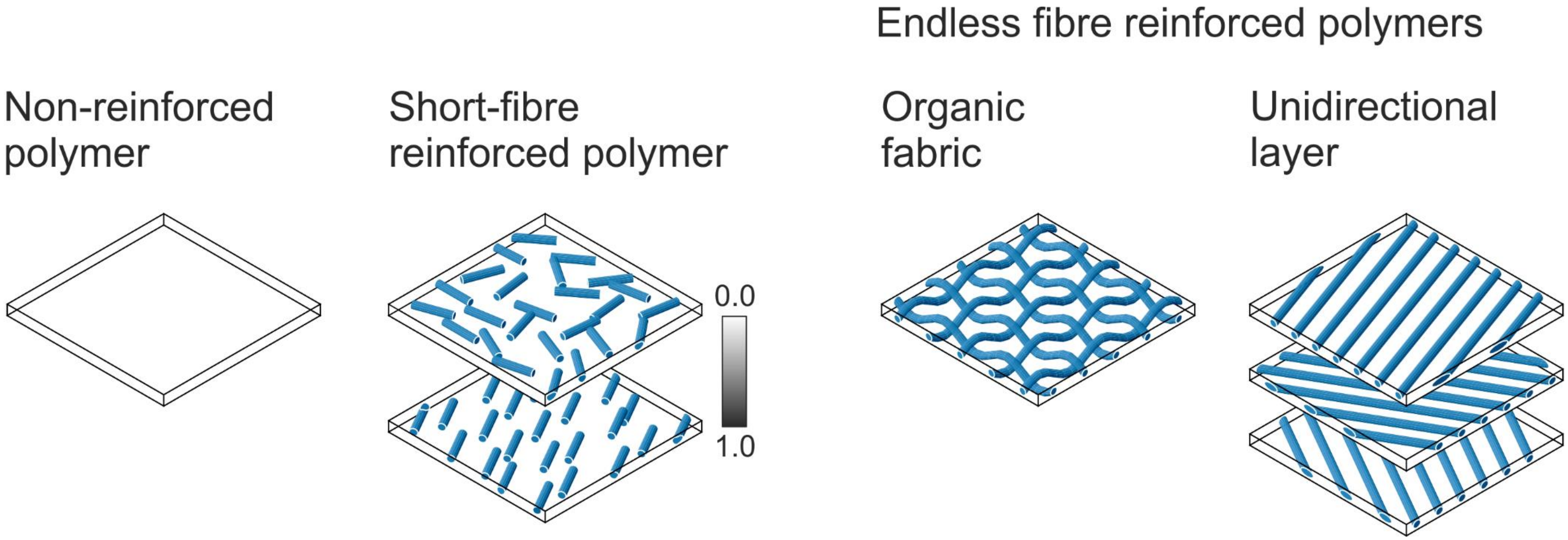
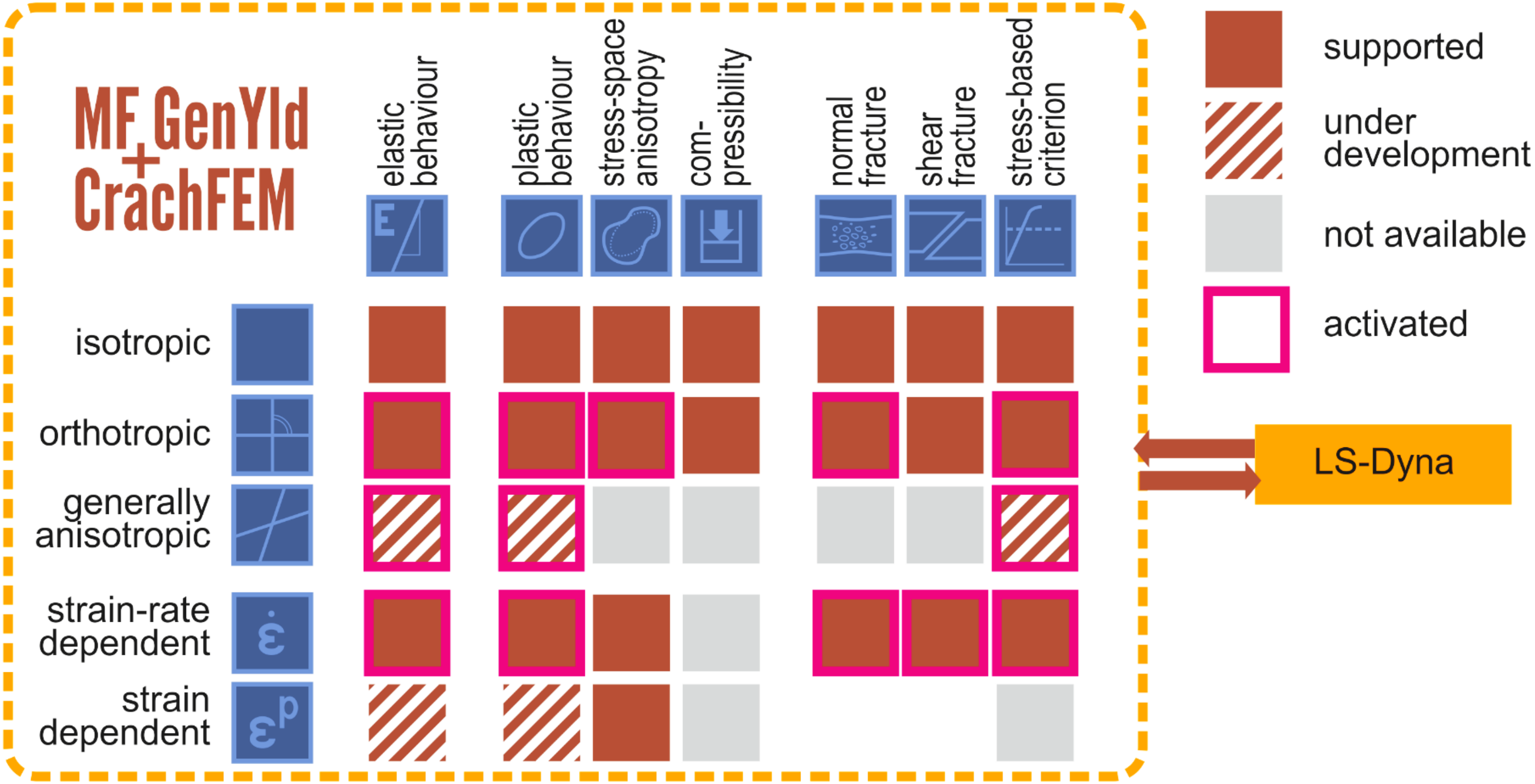
Different classes of polymers



Modules for modelling of non-reinforced and fiber-reinforced polymers



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Pilot project on use of MF GenYld+CrachFEM

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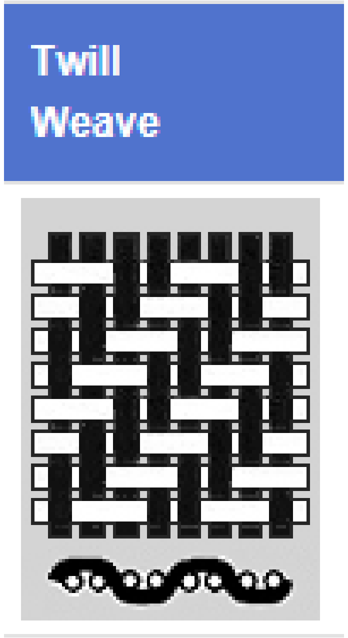
Material

- organic sheet with twill weave 80% / 20% in thickness of 2 mm
- for selected experiments (e.g. in-plane compression tests) also material in thickness of 4 mm was used
- all specimens have been conditioned prior to testing
- all specimens have been manufactured via milling



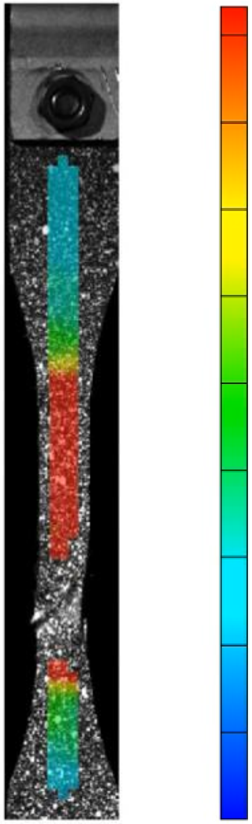
Source: BondLaminates

Test program

- organic sheet with twill weave 80% / 20% in thickness of 2 mm
- for selected experiments (e.g. in-plane compression tests) also material in thickness of 4 mm was used
- all specimens have been conditioned prior to testing
- all specimens have been manufactured via milling

[1] tests performed by Fundacion CIDAUT, Valladolid, Spain on behalf of Ford R&A/Kirchhoff/MATFEM

[2] tests performed by LFT at University Erlangen, Germany, on behalf of Ford R&A, Kirchhhoff and MATFEM

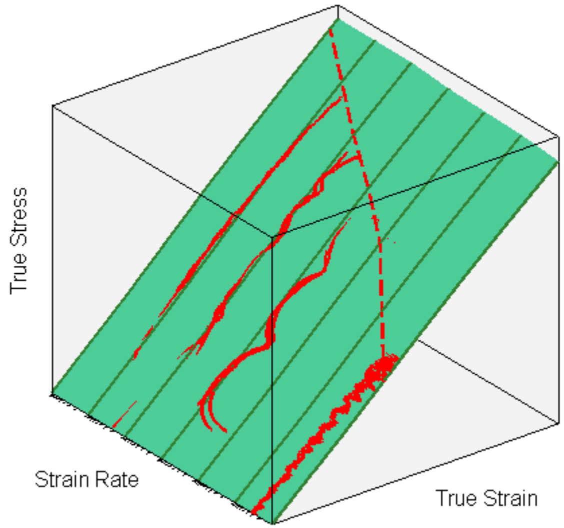


1st principal strain in quasi-static tensile test under 45 deg to main fiber direction (tests performed by Fundacion CIDAUT)

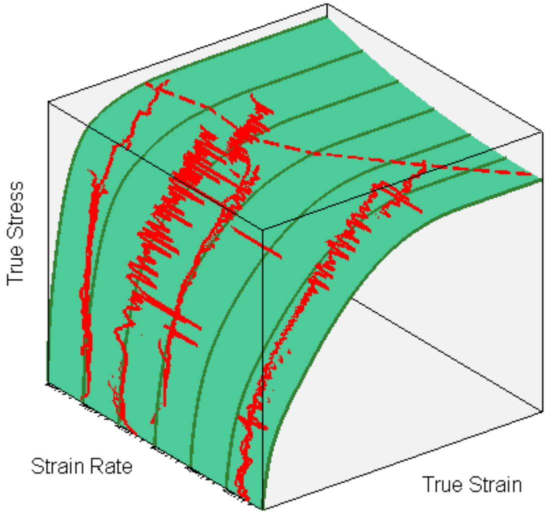
Source: automotive CAE Grand Challenge 2016, G. Oberhofer (Sp), H. Dell, M. Vogler, H. Gese

Material behavior as a function of strain rate

Material tests performed by Fundacion CIDAUT, Valladolid, Spain



- Material behavior dominated by glass fibers (80% of the fibers in 0°-direction)
- Linear elastic behavior at all speeds
- Strain rate independent elasticity
- High dependency of ultimate strength on strain rate; strength increases with strain rate



- Material behaviour dominated by matrix material
- Significant positive strain rate dependency of flow stress
- Decreasing fracture strain with increasing strain rate

Source: automotive CAE Grand Challenge 2016, G. Oberhofer (Sp), H. Dell, M. Vogler, H. Gese

Pilot project on use of MF GenYld+CrachFEM

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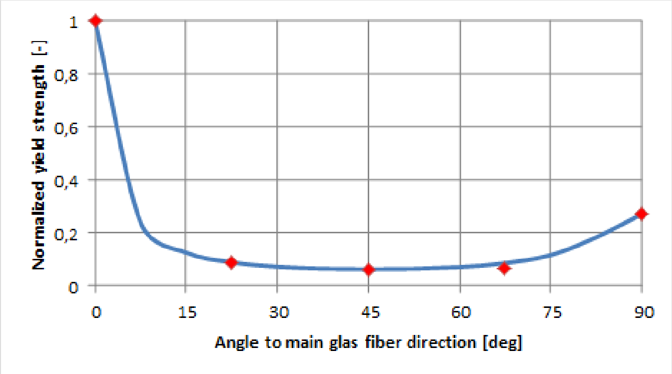
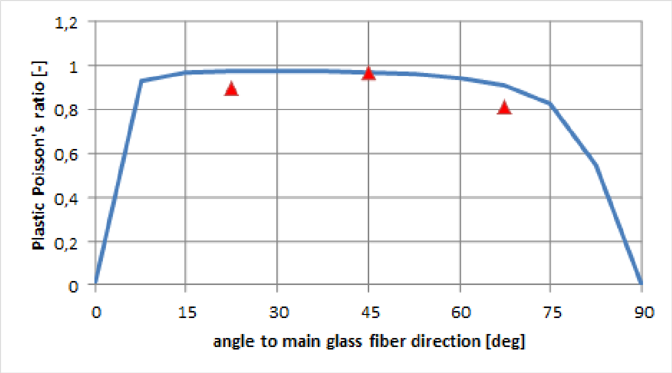
The following features of the material model have been used:

- orthotropic elasticity
- orthotropic plasticity (Hill-1948) with different orthotropy parameters for tensile regime (see graphs below) and compression regime
- anisotropic hardening (i.e. hardening is a function of stress state); different hardening in uniaxial compression and shear relative to uniaxial tension
- orthotropic strain based fracture for ductile normal fracture (strain rate dependent) in combination with stress dependent fracture for stronger fiber direction (currently still strain rate independent)





Source: automotive CAE Grand Challenge 2016, G. Oberhofer (Sp), H. Dell, M. Vogler, H. Gese

Pilot project on use of MF GenYld+CrachFEM

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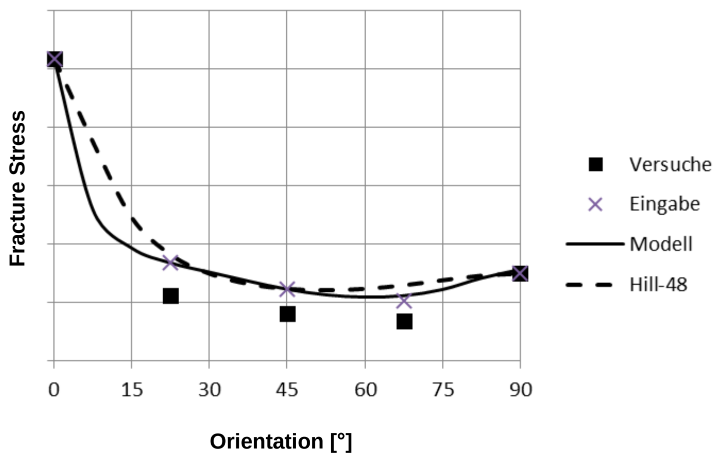
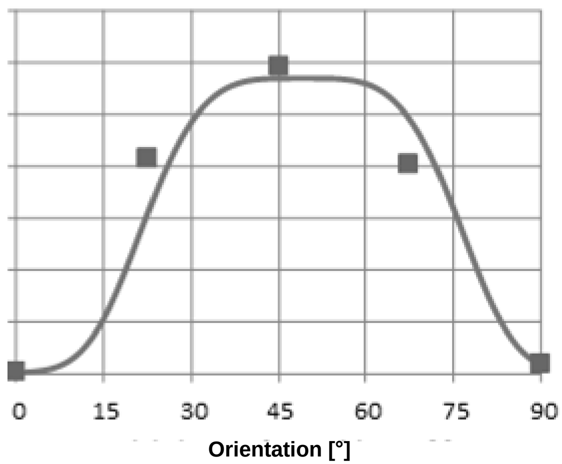
The following features of the material model have been used:

- orthotropic strain based fracture for ductile normal fracture (strain rate dependent) in combination with stress dependent fracture for stronger fiber direction (strain rate dependent)

Tension

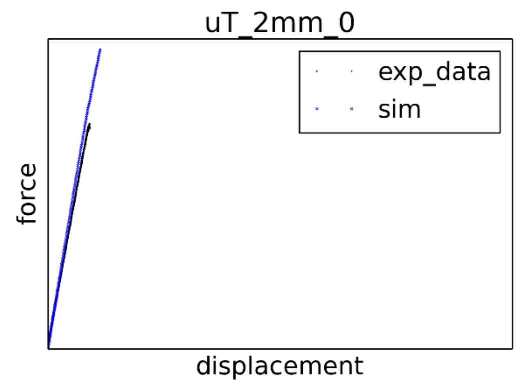


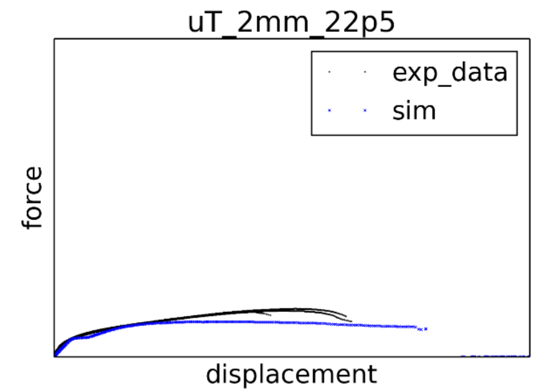


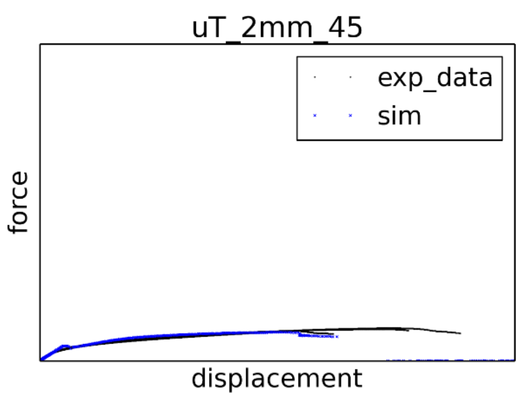
Behavior is different for compression

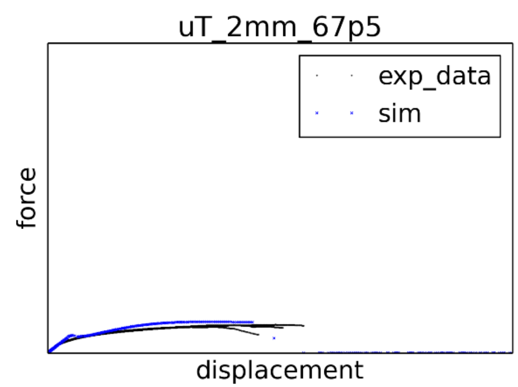
Prediction of quasi-static uniaxial tensile tests under 0° / 22.5° / 45° / 67.5° / 90° (material thickness: 2mm)

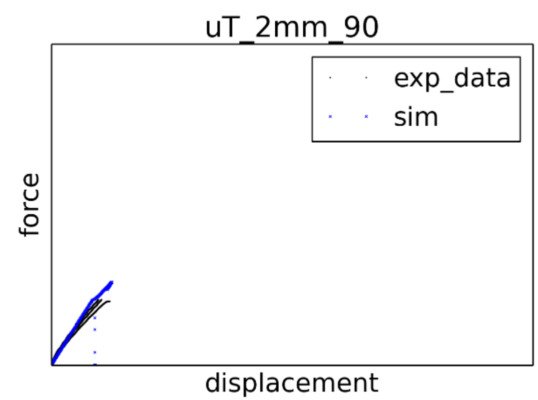
Shell discretization
Element size 2 mm





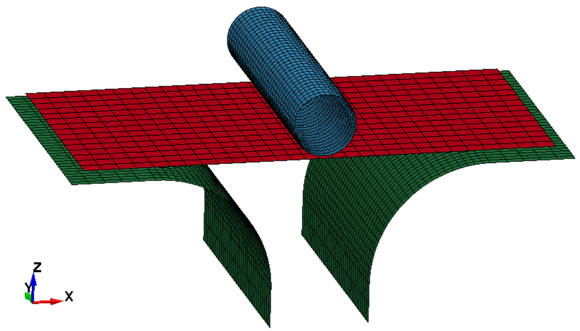




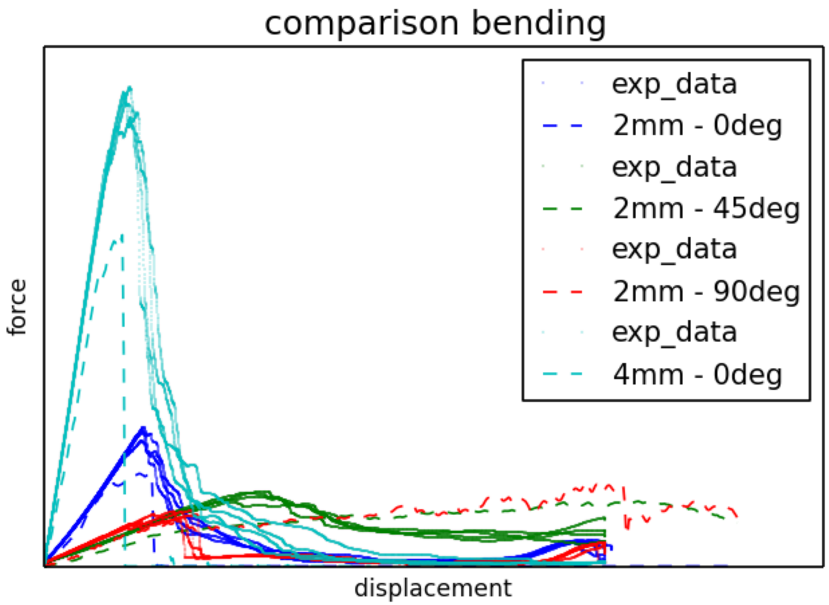


Source: automotive CAE Grand Challenge 2016, G. Oberhofer (Sp), H. Dell, M. Vogler, H. Gese

Prediction of 3-point bending tests under 0° / 45° / 90° (thickness 2mm) and under 0° (thickness: 4mm)



Shell discretization
Element size 1.7-2 mm



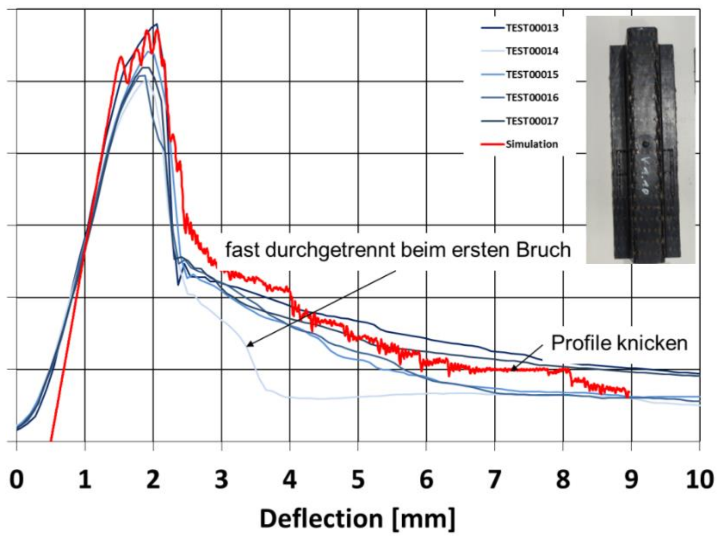
- Good prediction of elastic orthotropy and orthotropic plastic yielding for uniaxial tension and 3-point-bending
- Good prediction of fracture in the two main fiber directions
- Satisfactory prediction of strain hardening and onset of fracture in ductile directions

Source: automotive CAE Grand Challenge 2016, G. Oberhofer (Sp), H. Dell, M. Vogler, H. Gese

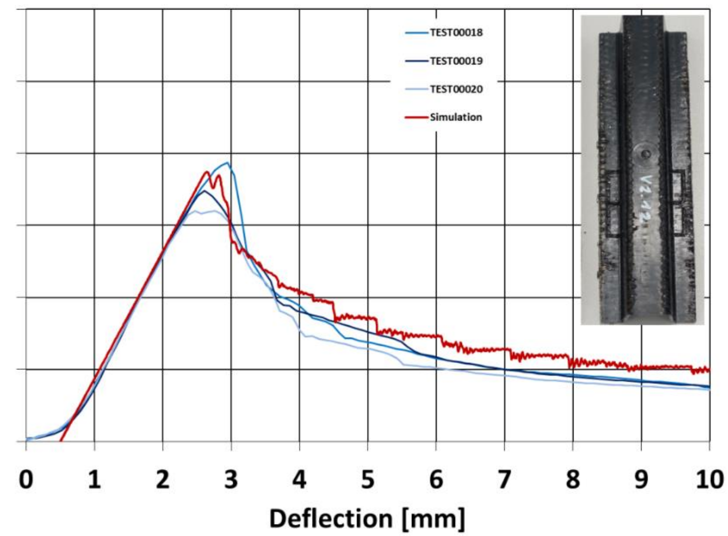
Simulation of generic components (hat profile)

- Results for quasi-static axial laoding

glass fiber 80% along /20% transverse



glass fiber 20% along/80% transverse



- Good prediction of elastic orthotropy and orthotropic plastic yielding for uniaxial tension and 3-point-bending
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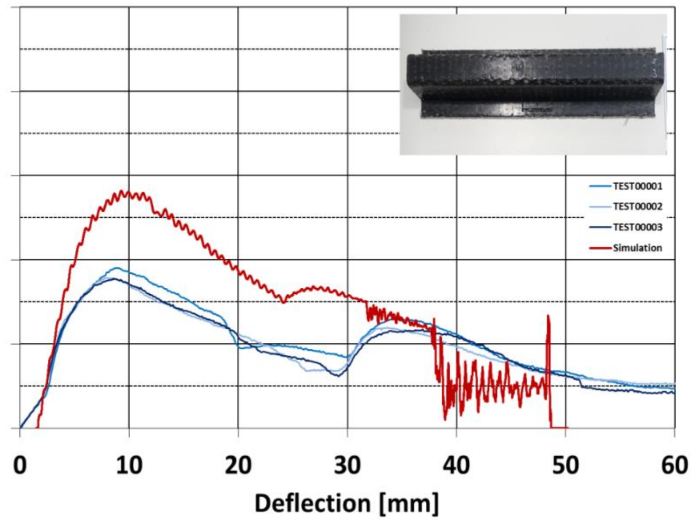
Source: automotive CAE Grand Challenge 2016, G. Oberhofer (Sp), H. Dell, M. Vogler, H. Gese

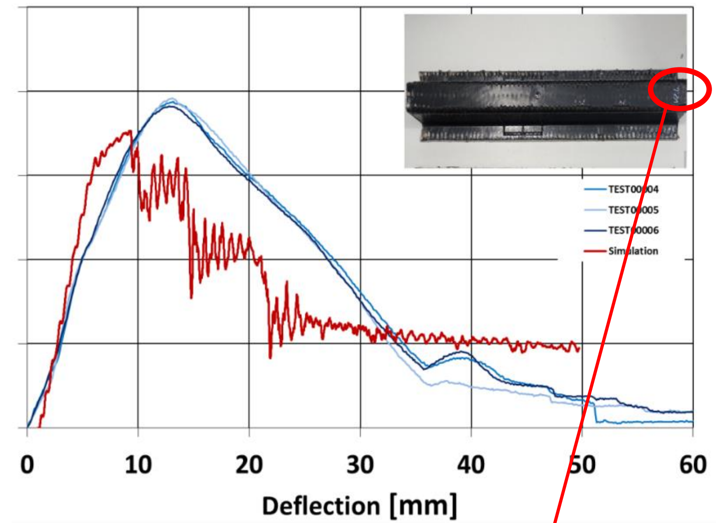
Simulation of generic components (hat profile)

▶ Results for quasi-static bending laoding

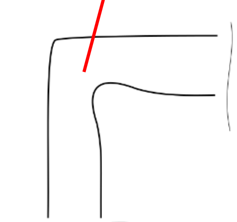
glass fiber 80% along /20% transverse



glass fiber 20% along/80% transverse



▶ Lateral bending of hat profile walls very sensitive to geometry:



Source: automotive CAE Grand Challenge 2016, G. Oberhofer (Sp), H. Dell, M. Vogler, H. Gese

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Features under development for organic sheets

MATFEM

The following features are under development in MF GenYld+CrachFEM:

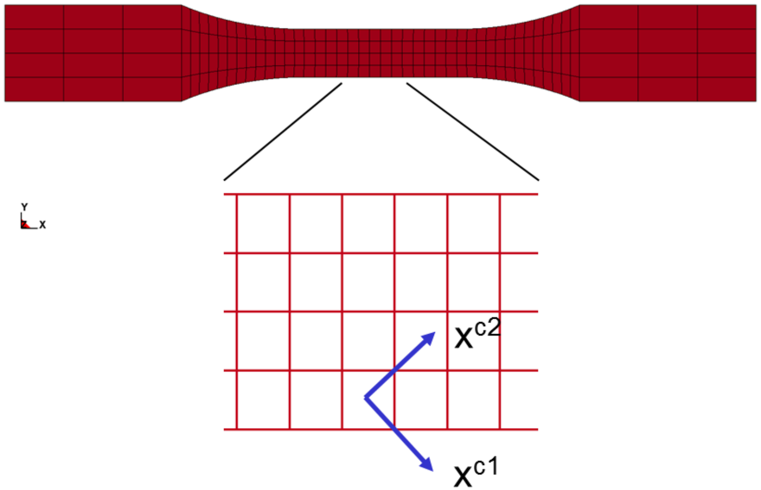
- General anisotropy of elasticity and plasticity either based on
  - Superposition of two or multiple transversely-isotropic components or
  - Structural tensors (implementation according to Ph.D. thesis of M. Vogler)
- Strain dependent evolution of plastic yield locus (allows for different strain hardening in different orientations to main fiber directions and change of Lankford parameter with increasing plastic strain)
- Stress based failure (1-dimensional) for main fiber direction should be strain rate dependent

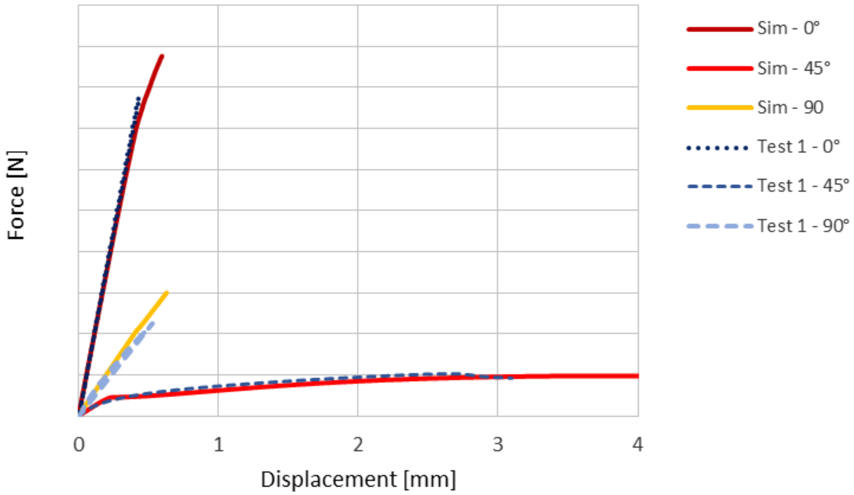
Features under development for organic sheets

MATFEM

Superpositioning of two transversal-isotropic representations

Validation of superposition method for initially orthogonal fabric (example without failure criterion)

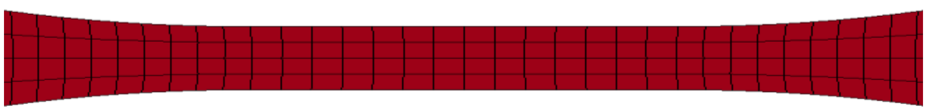


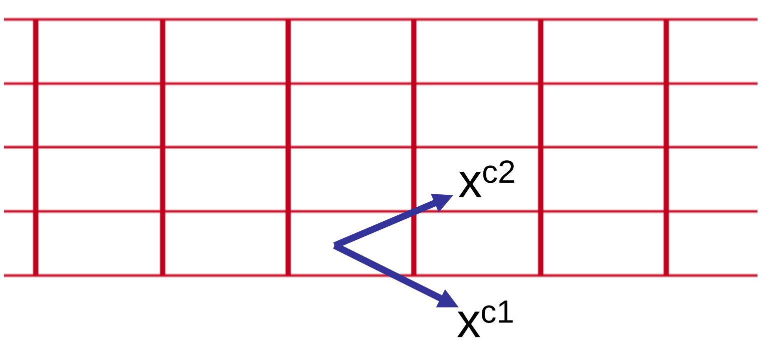


- Perfect prediction of behavior in different orientations to main fiber direction
- Very robust method; low CPU time
- However identification of material parameters is challenging

Superpositioning of two transversal-isotropic representations

Orientation of x-axes of both material coordinate systems after simulation of uniaxial tension in 45° direction



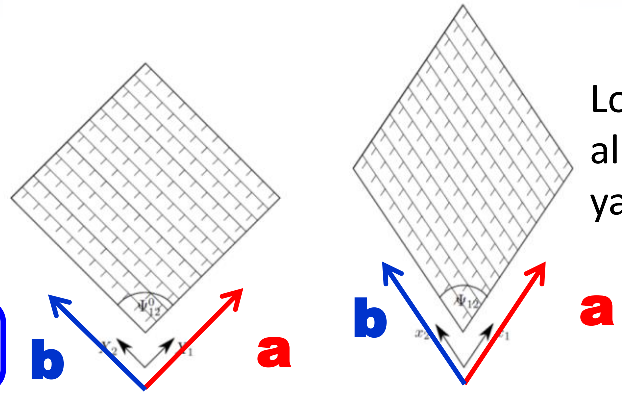


- Relative rotation of x-axes x^{c1} and x^{c2} ; final angle smaller than 90 deg
- Superposition of two or multiple transversely-isotropic material components can also be used for modeling of fabrics with initially non-orthogonal pattern

Structural tensor approach according to

Ph.D. thesis of Matthias Vogler

$\mathrm{B} = \mathrm{b} \otimes \mathrm{b}$



Loading induced alignment of the yarns

$\mathrm{A} = \mathrm{a} \otimes \mathrm{a}$

➡ a and b not necessarily perpendicular to each other! a $\not\perp$ b

➡ Monoclinic material behavior (not orthotropic anymore)!

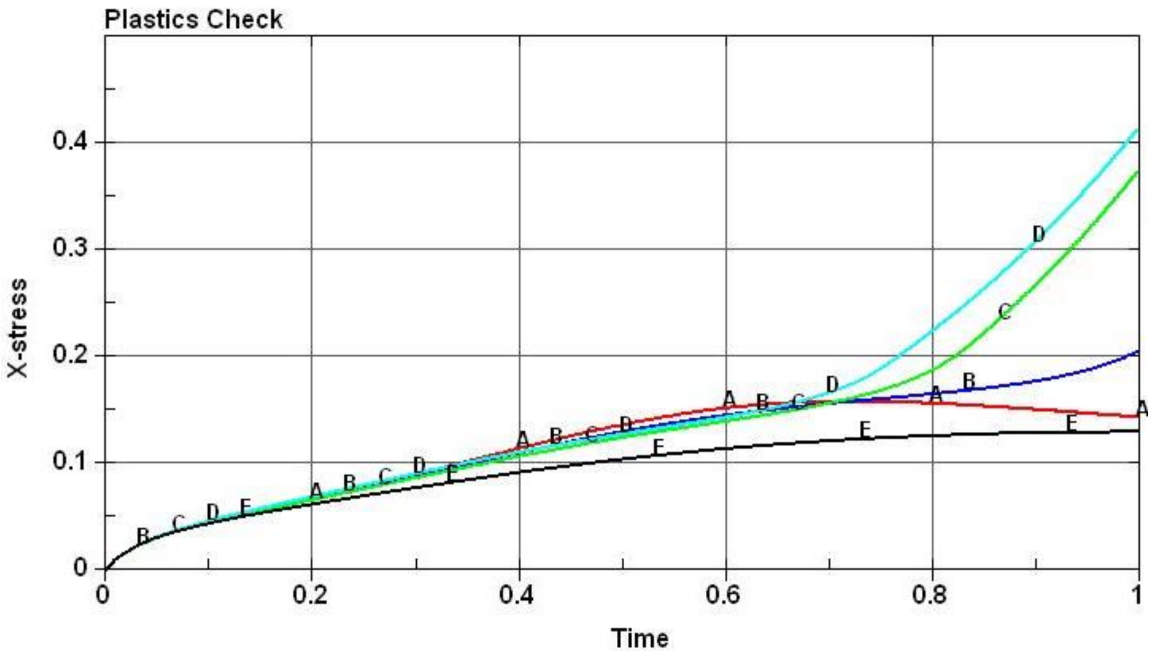
$$f = \hat{f}(\boldsymbol{\sigma}, \bar{\varepsilon}^p, \mathbf{A}, \mathbf{B}) = \alpha_1 I_1 + \alpha_2 I_2 + \alpha_3 I_3 + \underline{\alpha_7 I_7} - 1$$

- Mixed Invariant $I_7 := \underline{\mathrm{tr}\left[\mathrm{AB}\left(\boldsymbol{\sigma}^{\mathrm{pind}}\right)^2\right]}$ has to be regarded in the yield surface formulation and in the elasticity law
- Additional anisotropy parameter $\underline{\alpha_7}$

  … which physical meaning?

  … how to determine?

Structural tensor approach according to Ph.D. thesis of Matthias Vogler



$$f = \alpha_1 I_1 + \alpha_2 I_2 + \alpha_3 I_3 + \underline{\alpha_7 I_7} - 1$$

- Model can describe non-orthotropic alignment of yarns in loading direction
- Model can describe stress increase for higher rotations of fabric by stress invariant I_7
- Model can describe initially non-orthotropic fabrics
- CPU time still to be improved

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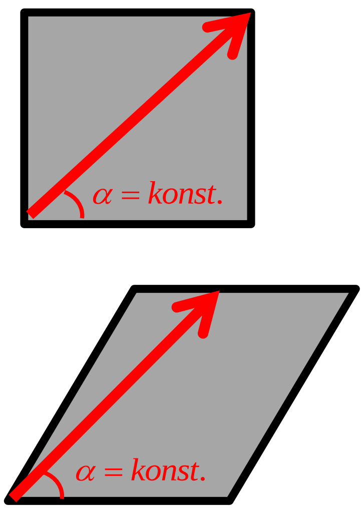
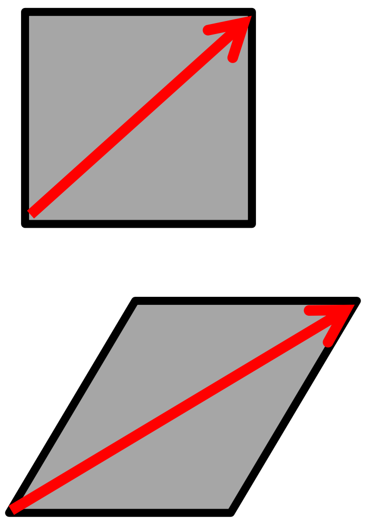
Tracking of main fiber directions during large plastic deformations

Method 1
fixed angle between
element axis and fiber direction



- not precise in shear
- only one direction can be tracked

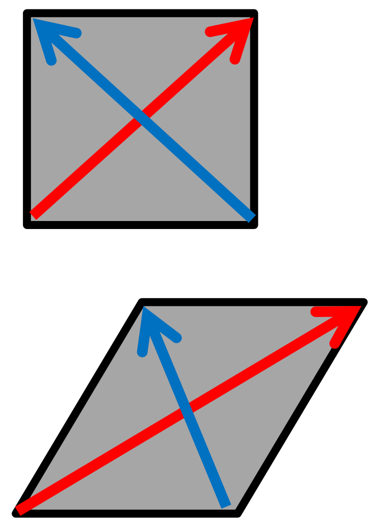
Method 2
shape functions



$$a_i = x_{iI} N_I^A$$
$$b_i = x_{iI} N_I^B$$
$$n^1 = \frac{a}{|a|}$$
$$n^3 = \frac{a \times b}{|a \times b|}$$
$$n^2 = n^3 \times n^1$$

- better
- only one direction can be tracked

Method 3
deformation gradient



$$a = F\ a^0$$
$$b = F\ b^0$$
$$n^1 = \frac{a}{|a|}$$
$$n^2 = \frac{b}{|b|}$$

- precise
- Multiple directions can be tracked

Thank you for your attention!