CHARACTERIZATION OF A POLYURETHANE ADHESIVE AND COMPARATIVE CALIBRATION OF DIFFERENT MATERIAL MODELS IN LS-DYNA

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Characterization and modelling of PU-adhesive
Agenda

- **Background info**
  - PU-adhesive basic data
- **Characterization experiments**
  - tests with steel sheet adherends
  - tests with thick adherends and adhesive bulk substance
  - tests with bulk specimens
- **Simulation**
  - cohesive zone modelling with *MAT-ARUP-ADHESIVE
  - elasto-plastic modelling with *MAT-TAPO
  - user-defined hyperelastic material model from IfM Kassel
- **Résumé and future perspective**

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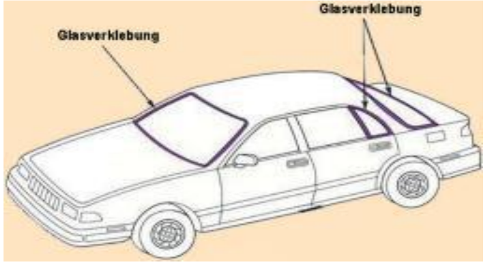
Characterization and modelling of PU-adhesive
PU-adhesive basic data

- **Polyurethane adhesive for semi-structural bonding in automotive industry**
  [from technical data sheet of manufacturer]
  - single component adhesive
  - very good adhesion, also after overburning, on electro coatings and OEM clearcoats
  - shear modulus > 8 MPa
  - lap shear strength (after 7 days, 23 °C / 50 % r.h.) > 8 MPa
  - elongation at break > 300 %

- application of PU-adhesives for light-weight multi-material structures,
  e.g. bonding of wind shields
  - ability to withstand large elastic deformations,
    including deformation mismatching of structural parts
  - typical layer thicknesses of 3-6 mm

    → exploitation of stiffness and strength potential
    → need for adequate modelling methods



Quelle: Chem. Unserer Zeit, 2008, 42, 92-101

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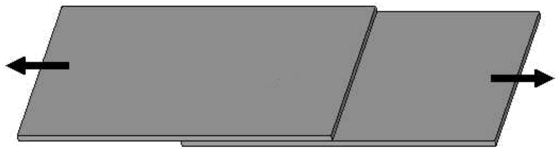
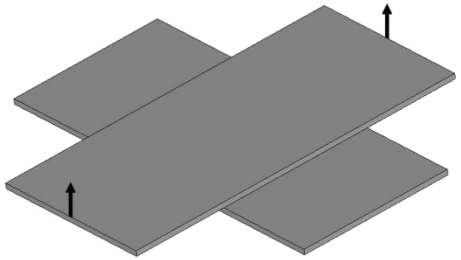
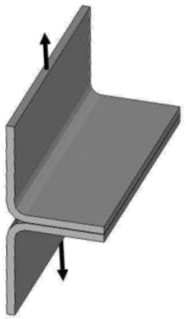
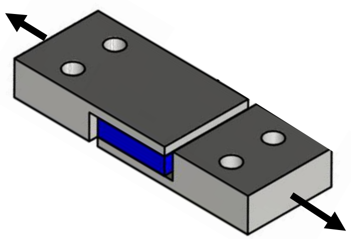
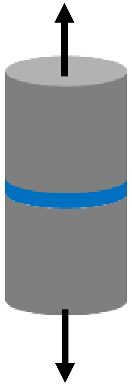
Characterization and modelling of PU-adhesive
Experimental characterization

- **steel sheet adherends**
  quasi-static loading
  - single lap shear, cross tension, peel

- **thick steel adherends**
  different loading speeds
  - thick adherend shear, butt-joint tension (full circular bond area)

- **adhesive substance flat tension**
  quasi-static loading

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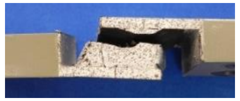
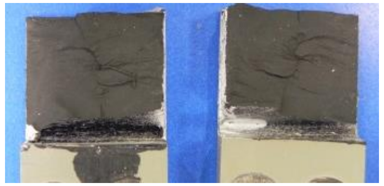
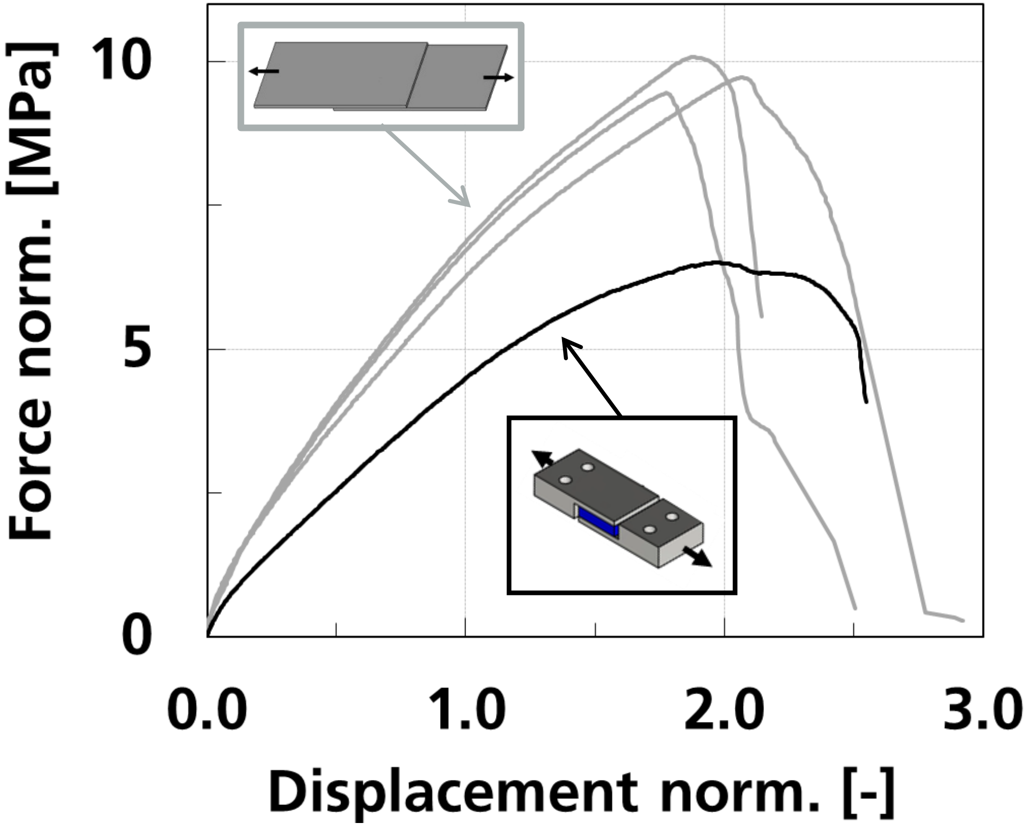
Characterization and modelling of PU-adhesive
Experimental characterization – shear

- **Comparison of different experimental tests in shear loading**
  single lap shear, quasi-static loading
  - steel sheet adherends (t_{steel} =1.5 mm), t_{adh} = 3.6 mm, A_{adh} = 16 x 45 mm²

  - "thick" steel adherends (t_{steel} =1.5 mm), t_{adh} = 5 mm, A_{adh} = 16 x 20 mm²







all diagrams: force normalized by adhesive bond area, displacement normalized by adhesive thickness

- ➢ all tests show cohesive failure
- ➢ plastic deformation of steel adherends in both test types
- ➢ **significantly higher normalized forces in steel sheet shear test**
- ➢ **strong influence of geometry (and possibly process parameters)**

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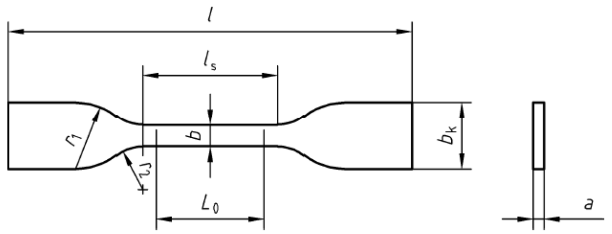
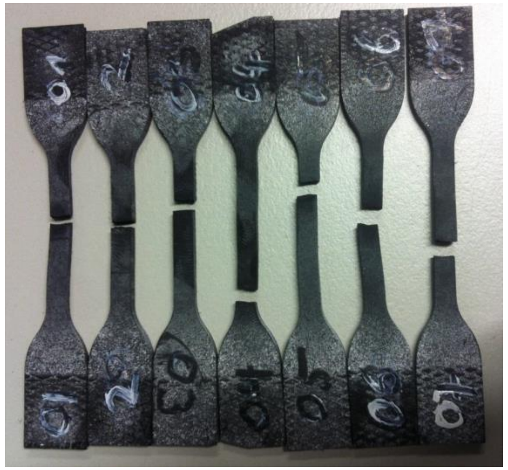
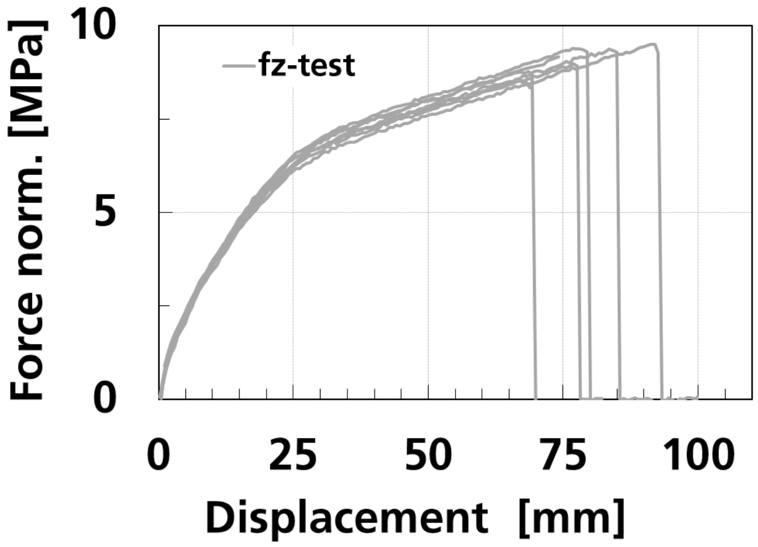
Characterization and modelling of PU-adhesive
Experimental characterization – substance flat tension

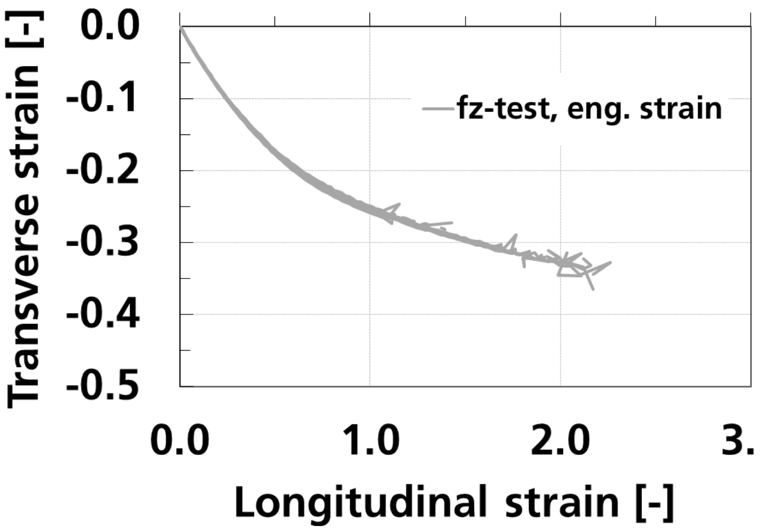
- **adhesive substance flat tension test**
  quasi-static loading, Aramis strain measurement
  - elastic modulus ca. 22 MPa
  - nearly incompressible
  - more than 200 % elongation before fracture



L_0 = 20 mm, L_S = 28 mm, b = 4 mm, a = 2.2 mm,
(free deformation length = 45 mm, $L_{0,transv}$ = 3 mm)







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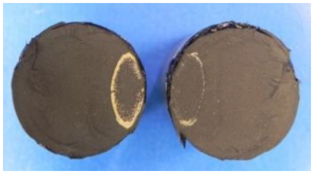
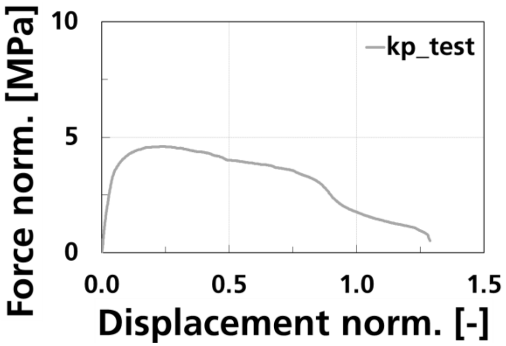
Characterization and modelling of PU-adhesive

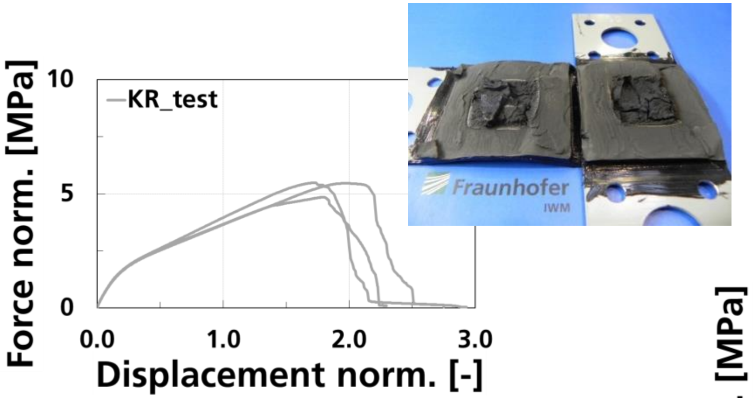
Experimental characterization – tension with lateral constraint and peel

- **butt-joint tension with steel adherend**
  quasi-static loading, full circular bonding area
  - t_{adh} = 4 mm, ø 20 mm

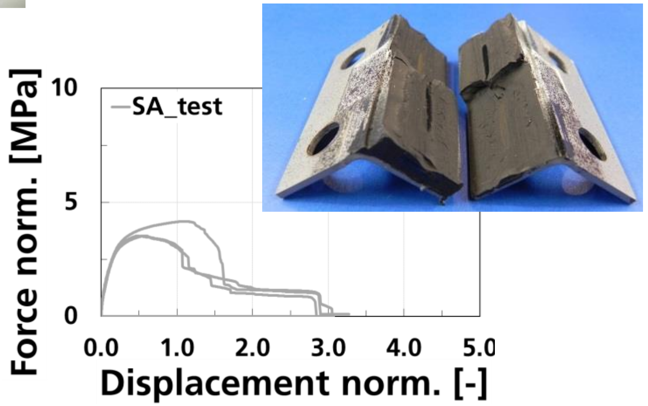




- **cross tension with steel sheet adherend**
  quasi-static loading
  - adhesive: $b*l*t_{adh}$ = 50*50*4 mm³
    steel sheet: t = 1.5 mm



- **peel test with steel sheet adherend**
  quasi-static loading
  - adhesive: $b*l*t_{adh}$ = 50*18*4 mm³
    steel sheet: t = 1.5 mm



all diagrams: force normalized by adhesive bond area, displacement normalized by adhesive thickness

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Characterization and modelling of PU-adhesive
Modelling – cohesive zone model

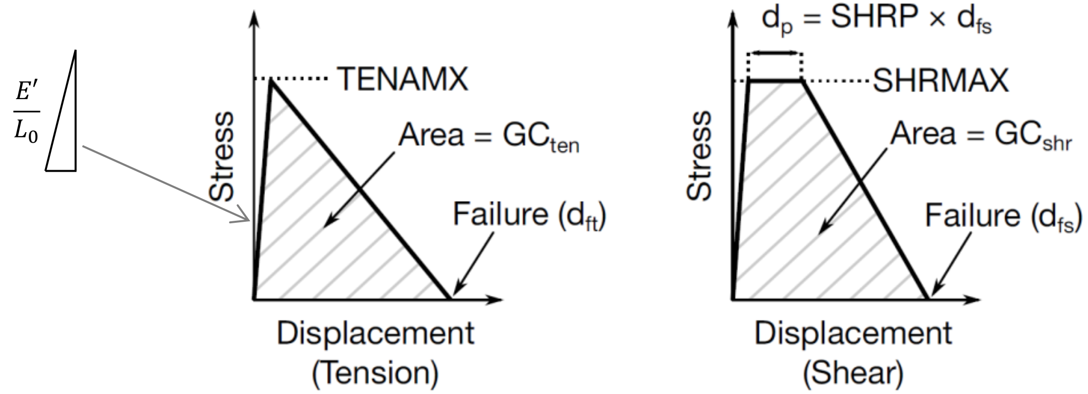
- ***MAT_ARUP_ADHESIVE (*MAT_169)**
  (from LS-DYNA handbook)
  - traction-separation laws for shear and tension
  - elastic stiffness affected by initial thickness (L_0) stiffness modulus E' in tension (deformation constraint by stiff adherends)

$$E' = \frac{E(1-\nu)}{(1-2\nu)(1+\nu)}$$

  - yield and failure surfaces are treated as a power-law combination of direct tension and shear across the bond

$$\left(\frac{\sigma}{\sigma_{max}}\right)^{PWRT} + \left(\frac{\tau}{\tau_{max} - SHT\_SL \times \sigma}\right)^{PWRS} = 1.0$$

  - parameter calibration:
    - input: elastic modulus E and poisson ratio ν
    - TENMAX / SHRMAX define yield stress
    - GCTEN / GCSHR and SHRP define damage behavior and failure



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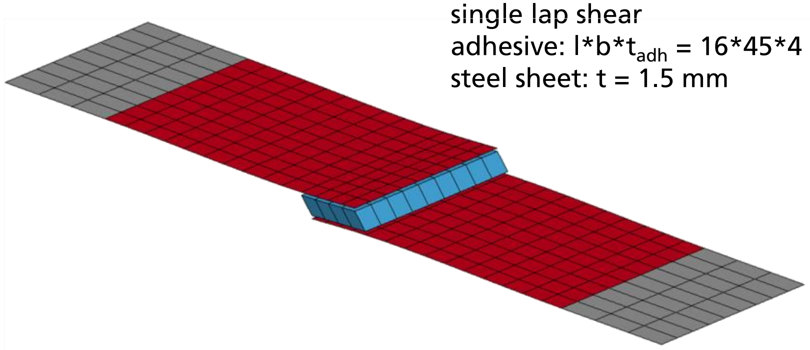
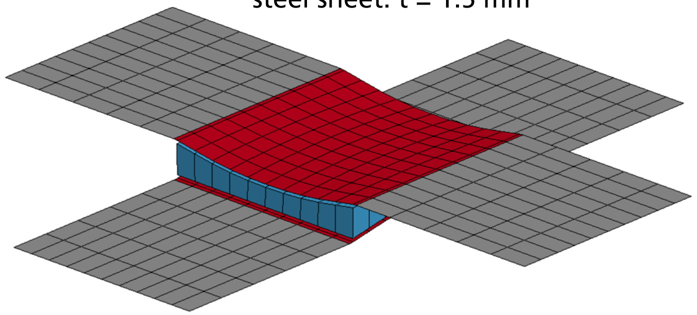
Characterization and modelling of PU-adhesive
Modelling – cohesive zone model

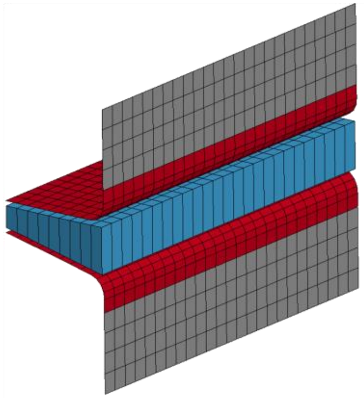
- **Mesh and modelling info**
  - adhesive (blue): *MAT_169, Elform=2, *L*e ca. 5 mm / 1-2 mm
  - steel sheet adherends: shells, Elform=16, red: *MAT_024 (calibrated elasto-plastic deformation behvior), grey: *MAT_rigid
  - *CONTACT_TIED_SHELL_EDGE_TO_SURFACE_CONSTRAINED_OFFSET (Slave=part_kleb, Master=part_stahl)



single lap shear
adhesive: $l*b*t_{adh}$ = 16*45*4 mm³
steel sheet: t = 1.5 mm



cross tension
adhesive: $b*l*t_{adh}$ = 50*50*4 mm³
steel sheet: t = 1.5 mm



peel
adhesive: $b*l*t_{adh}$ = 50*18*4 mm³
steel sheet: t = 1.5 mm

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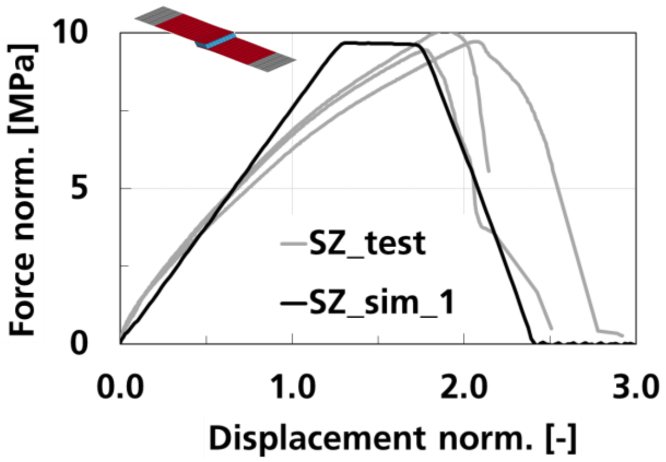
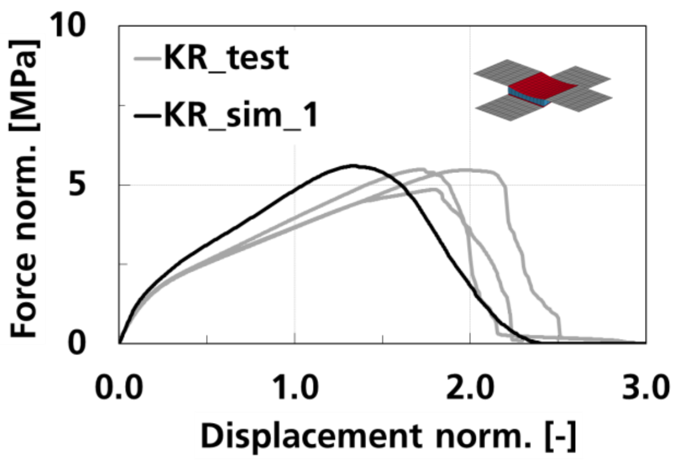
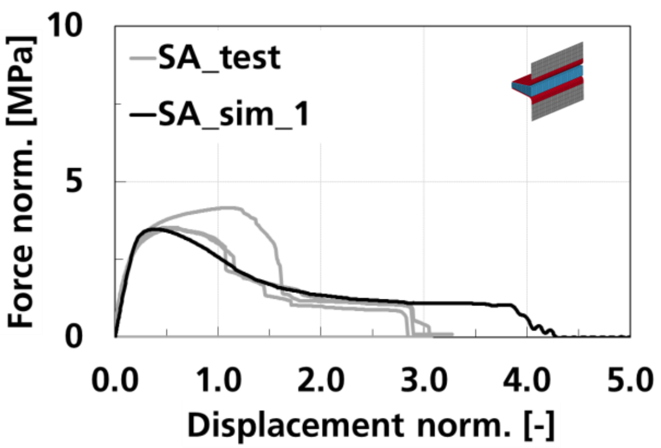
Characterization and modelling of PU-adhesive
Modelling – cohesive zone model

- **Comparison of experimental results with simulation from different parameter sets**
  - experimental results (grey line)
  - calibration with sheet adherend specimens (parameter set 1) (black line)







all diagrams: force normalized by adhesive bond area, displacement normalized by adhesive thickness

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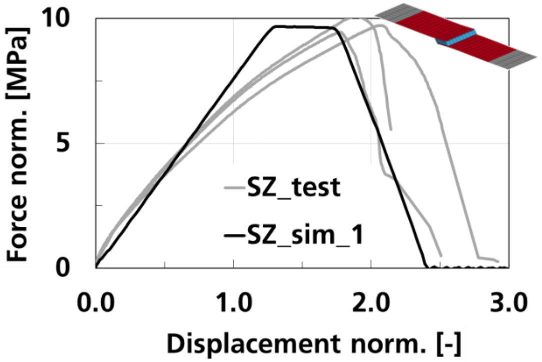
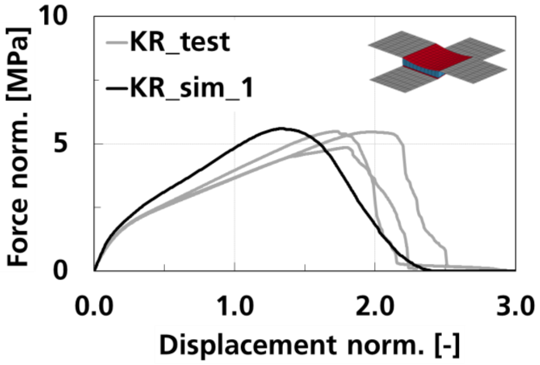
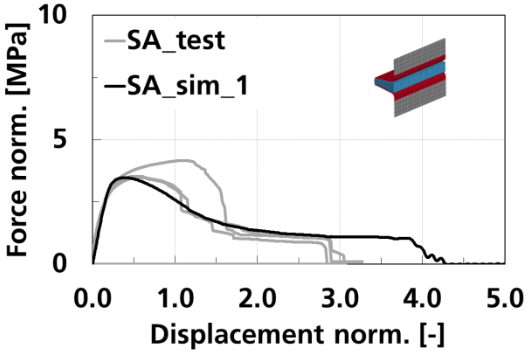
Characterization and modelling of PU-adhesive

Modelling – cohesive zone model

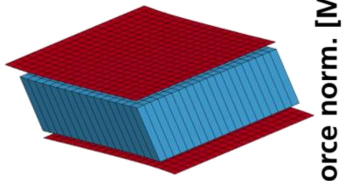
- **Comparison of experimental results with simulation from different parameter sets**
  - experimental results
  - calibration with sheet adherend specimens (parameter set 1)

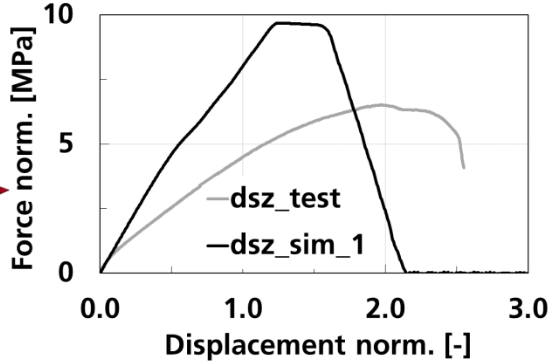


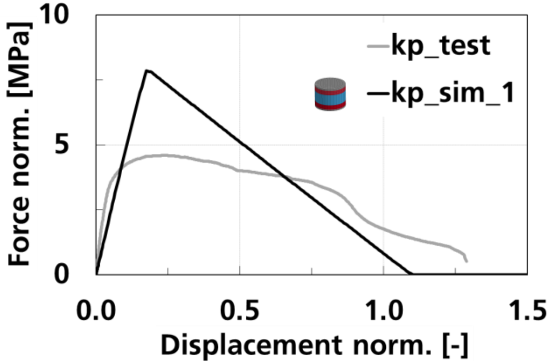


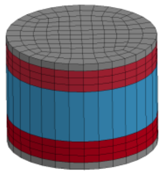


thick adherend shear
adhesive:
$l*b*t_{adh}$ = 16*20*5 mm³
steel (in bond region):
t = 1.5 mm









butt-joint tension
r = 10 mm,
adhesive:
t_{adh} = 4 mm

all diagrams: force normalized by adhesive bond area, displacement normalized by adhesive thickness

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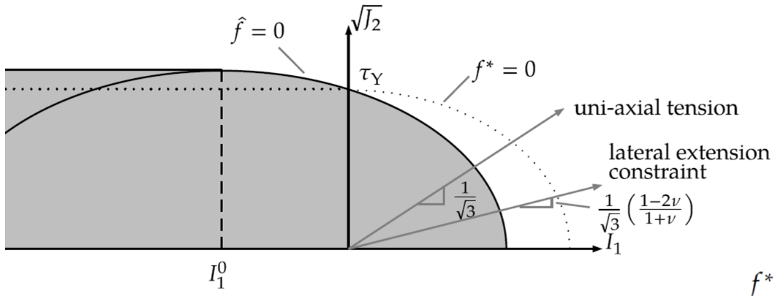
Characterization and modelling of PU-adhesive
Modelling – 3D elasto-plastic material model

- ***MAT_TOUGHENED_ADHESIVE_POLYMER (TAPO, *MAT_252)**
  (from LS-Dyna handbook & Burbulla et al., 10th European LS-Dyna Conference, 2015)
  - non-associated, elasto-viscoplastic material model for crash optimized high-strength adhesives under combined shear and tensile loading
  - (rate-dependent) yield strength τ_Y with non-linear hardening contribution *R* $\quad \tau_Y = (\tau_0 + R) \qquad R = q[1 - \exp(-br)] + Hr$
  - softening due to damage, rate-dependency, and constitutive description for mechanical behavior under compression



yield function $\hat{f}$ and plastic flow potential f^*

$$\hat{f} := \frac{J_2}{(1-D)^2} + \frac{a_2}{3}\left\langle \frac{I_1}{1-D} + \frac{\sqrt{3}a_1\tau_0}{2a_2} \right\rangle^2 - \left(\tau_Y^2 + \frac{a_1^2\tau_0^2}{4a_2}\right) = 0$$

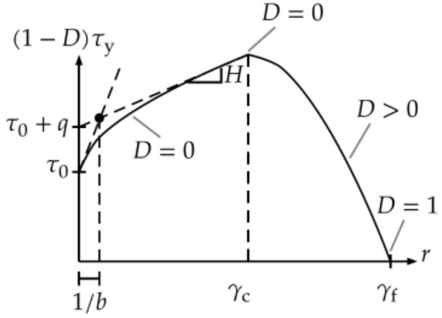
yield function $\hat{f}$ with first invariant of the stress tensor I_1 and second invariant of the stress deviator J_2

$$I_1 = \operatorname{tr}\sigma \qquad J_2 = (1/2)\operatorname{tr}(\mathbf{s})^2$$

$$f^* := \frac{J_2}{(1-D)^2} + \frac{a_2^*}{3}\left\langle \frac{I_1}{1-D} \right\rangle^2 - \tau_Y^2 \qquad a_2^* = \frac{1-2\nu^*}{2(1+\nu^*)}$$

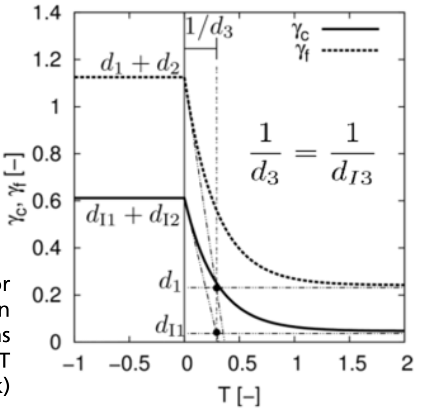
plastic potential f^* with parameter a^*_2 to influence plastic dilatation, to be identified from uni-axial tension test

$$\nu^* = -\frac{\dot{\varepsilon}^{pl}_{trans}}{\dot{\varepsilon}^{pl}_{axial}}$$



effective yield strenght τ_Y vs. effective damage plastic strain *r*

threshold strains for damage initiation and rupture as function of triaxiality T (Johnson & Cook)



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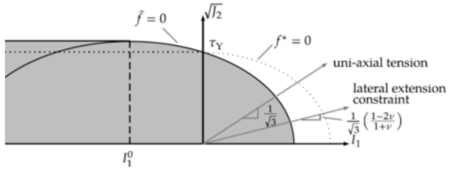
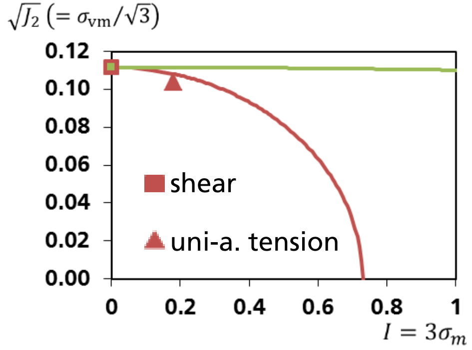
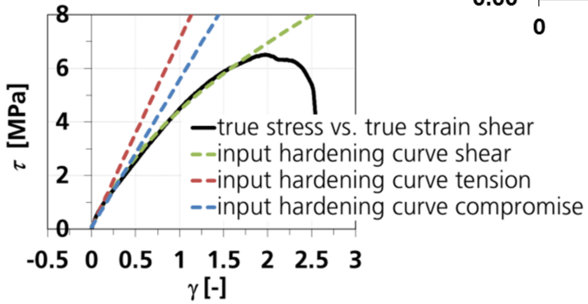
Characterization and modelling of PU-adhesive
Modelling – 3D elasto-plastic material model

- ***MAT-TAPO parameter calibration for deformation behavior**
  - elliptical yield function form directly from experimental results: yield stress in shear loading and uni-axial tensile loading
    - no additional data from compression or mixed-mode shear-tension tests available → $I^0{}_1 = 0$ ($a_{10} = 0$)
    - *difficulty*: large elastic deformation capacity of the PU adhesive
      → low ratio of elastic modulus to material strength → instability problems
      ➔ unrealistic high elastic modulus & low yield stress levels
  - input E = 1000 MPa, ν = 0.49 (→ G = 335 MPa)
    yield function ellipse with τ_0 = 0.1116 MPa (shear) and σ_0 = 0.15 MPa (uni-a. tension)
    - *difficulty*: very flat ellipse shape (green line) needed to reproduce deformation behavior in butt-joint tension test
      → this results in early localization in uni-axial tension
    - *difficulty*: hardening behavior from shear test does not fit deformation behavior in uni-axial tensile loading → compromise hardening input
    - ➔ either uni-axial tension or shear and constrained tension deformation can be reproduced







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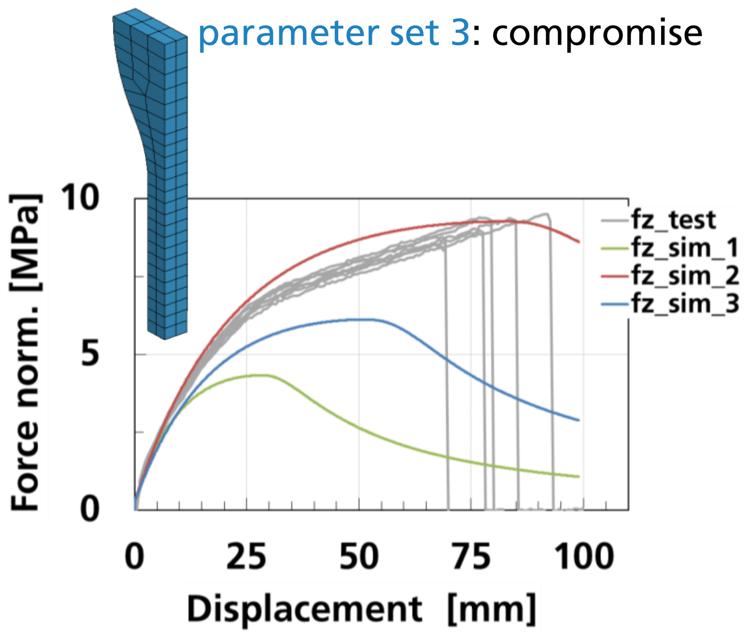
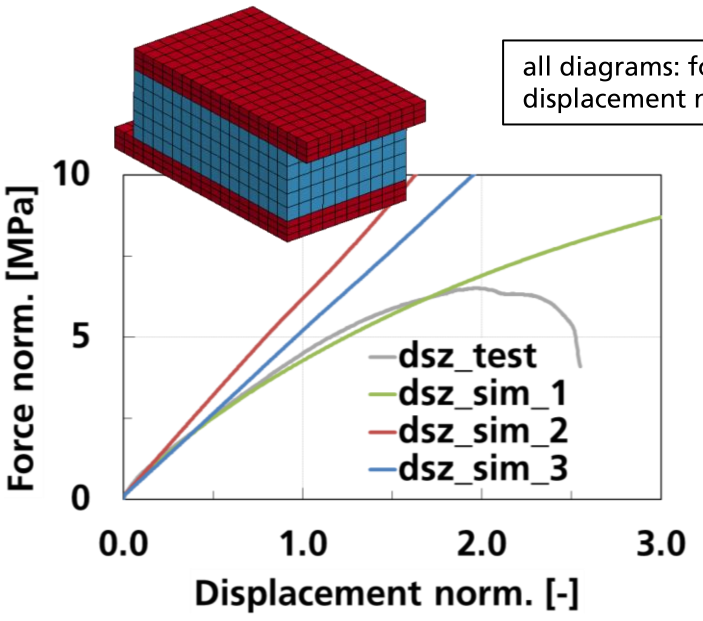
Characterization and modelling of PU-adhesive

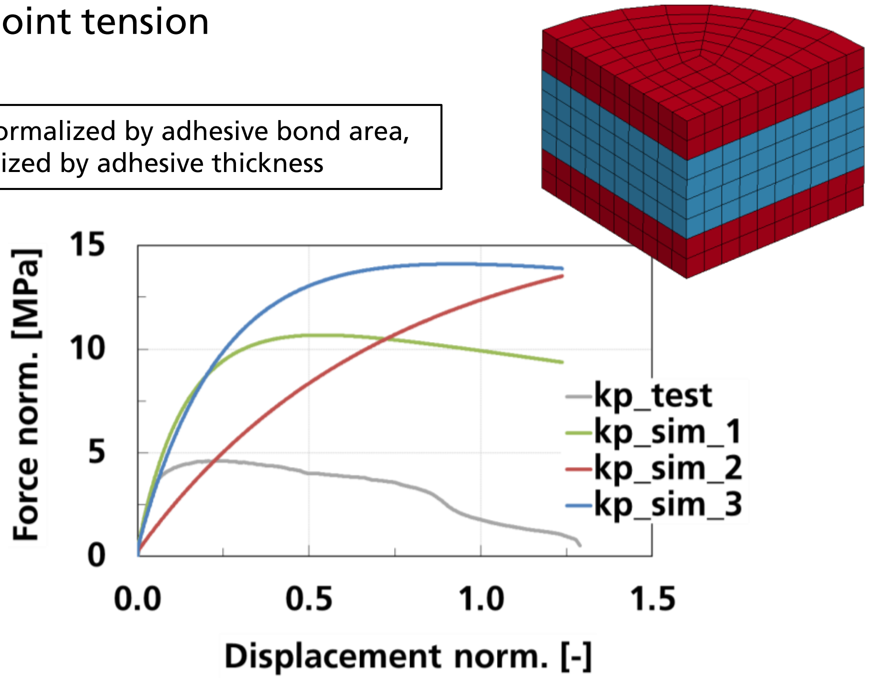
Modelling – 3D elasto-plastic material model

- ***MAT-TAPO parameter calibration for deformation behavior**
  - adhesive (blue): *MAT_252, Elform=1, *Le* = 1 mm; steel adherends (red): *MAT_024, Elform=2
  - parameter set 1: to reproduce shear and butt-joint tension → trade-off for uni-axial tension
  - parameter set 2: to reproduce uni-axial tension → trade-off for shear and butt-joint tension
  - parameter set 3: compromise

all diagrams: force normalized by adhesive bond area, displacement normalized by adhesive thickness







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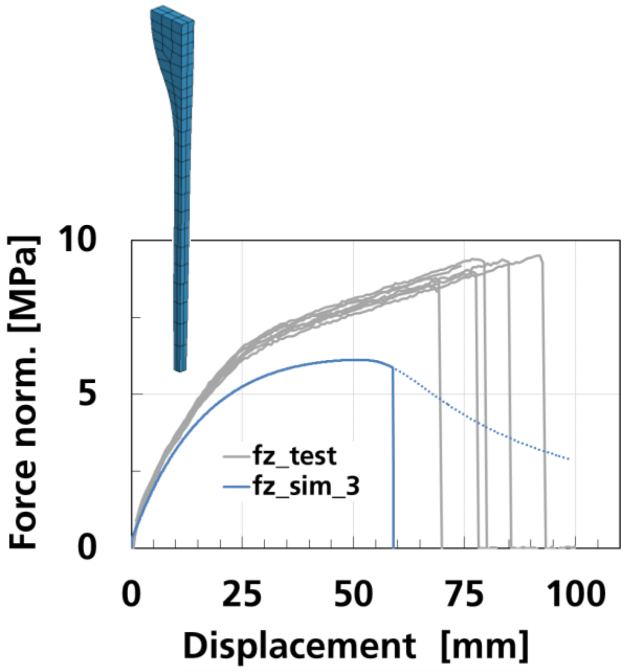
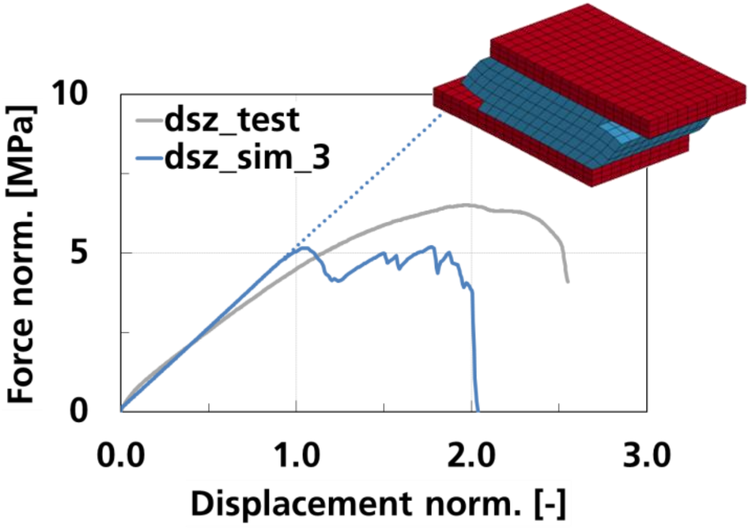
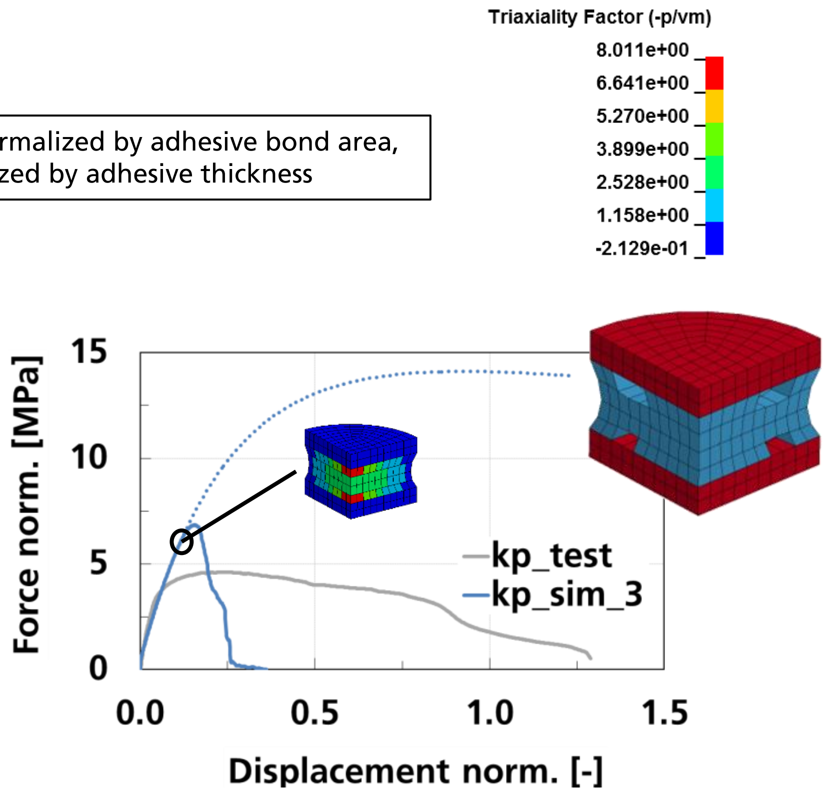
Characterization and modelling of PU-adhesive
Modelling – 3D elasto-plastic material model

- *MAT-TAPO parameter calibration for failure behavior
  - paramter set 3: compromise in deformation behavior
  - damage initiation and failure curves

all diagrams: force normalized by adhesive bond area, displacement normalized by adhesive thickness







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Characterization and modelling of PU-adhesive

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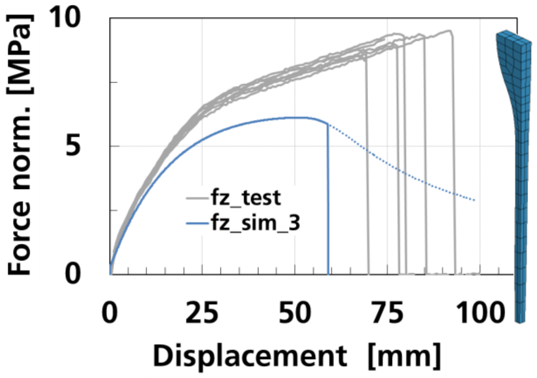

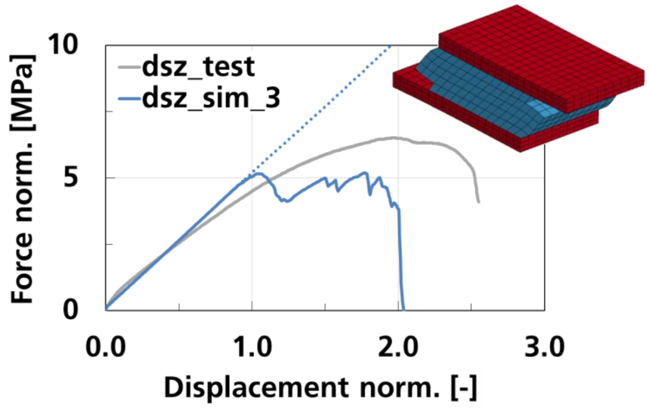

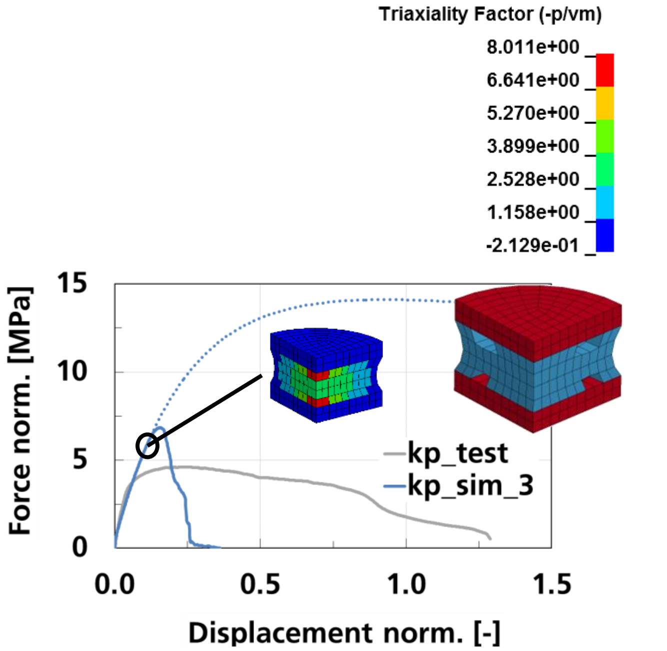

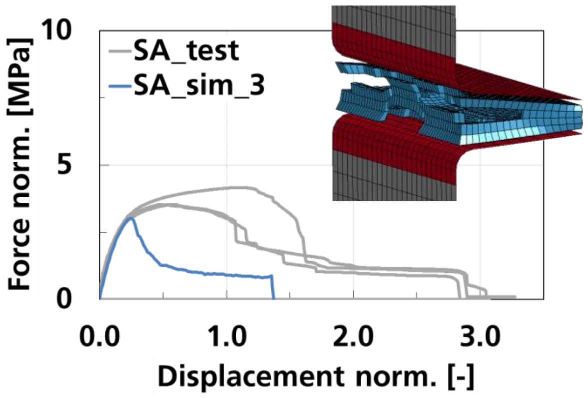

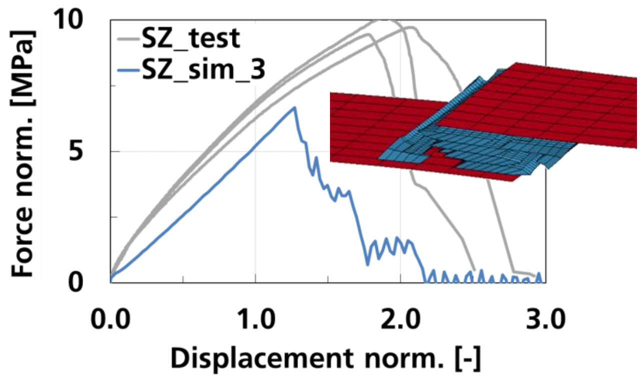

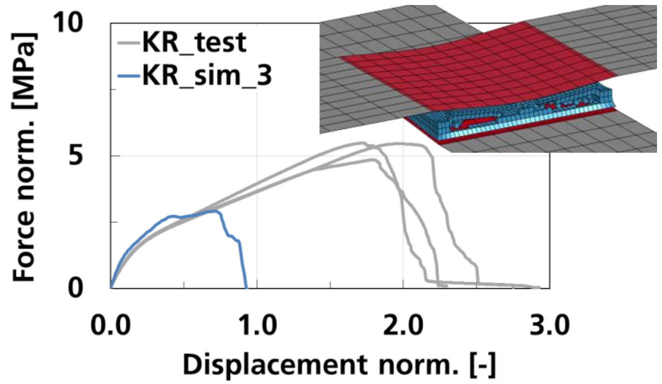

all diagrams: force normalized by adhesive bond area, displacement normalized by adhesive thickness

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Characterization and modelling of PU-adhesive
Modelling – 3D hyperelastic material model

UNI KASSEL VERSITÄT
Prof. Dr.-Ing. A.Matzenmiller
Dipl.-Ing. A. Nelson

- **hyperelastic user-defined material model by IfM (*)**
  - deviatoric-volumetric split $\bar{\mathbf{F}} = J^{-1/3}\mathbf{F}$ $\quad J = \det(\mathbf{F}) = \sqrt{\det(\mathbf{C})}$ $\quad \bar{\mathbf{B}} = \bar{\mathbf{F}} \cdot \bar{\mathbf{F}}^{\mathsf{T}} = J^{-2/3}\mathbf{F} \cdot \mathbf{F}^{\mathsf{T}}$
  - strain energy density function

$$W(\mathbf{B}) = \underbrace{\frac{1}{2}c_{10}(I_{\bar{\mathbf{B}}} - 3) + \frac{1}{2}c_{01}(II_{\bar{\mathbf{B}}} - 3)}_{W^{\text{iso}}} + \underbrace{K(J - 1 - \ln J)}_{W^{\text{vol}}}$$

MOONEY-RIVELIN model [from **]

  - resulting stress-strain relationship

$$\mathbf{T} = \frac{1}{J}\left(\left(c_{10} + c_{01} I_{\bar{\mathbf{B}}}\right)\bar{\mathbf{B}}^{\mathsf{D}} - c_{01}\left(\bar{\mathbf{B}}^2\right)^{\mathsf{D}}\right) + \frac{1}{J}K(J-1)\mathbf{1}$$

3 deformation parameters

  - continuum damage mechanics
    energy based failure model

$$D^{\text{iso}} = \left\langle \frac{W^{\text{iso}}(I_{\bar{\mathbf{B}}}, II_{\bar{\mathbf{B}}}) - W^{\text{iso}}_{\text{fl}}}{W^{\text{iso}}_{\text{fc}} - W^{\text{iso}}_{\text{fl}}} \right\rangle \quad D^{\text{vol}} = \left\langle \frac{W^{\text{vol}}(J) - W^{\text{vol}}_{\text{fl}}}{W^{\text{vol}}_{\text{fc}} - W^{\text{vol}}_{\text{fl}}} \right\rangle \quad \mathbf{T} = (1 - D)(\mathbf{T}^{\text{iso}} + \mathbf{T}^{\text{vol}}) \quad D = \max[D^{\text{iso}}, D^{\text{vol}}]$$

3 damage initiation parameters,
3 failure parameters

* Nelson, A., Matzenmiller, „Modelling and finite element analysis of cavitation and isochoric failure of hypereleastic adhesives“, proc.10th Conf. on Constitutive Models for Rubber (ECCMR X), 357-363, 2017.

** Miehe, C., „Computation of isotropic tensor functions“, Communications in Numerical Methods in Engineering, 9:889-896, 1993.

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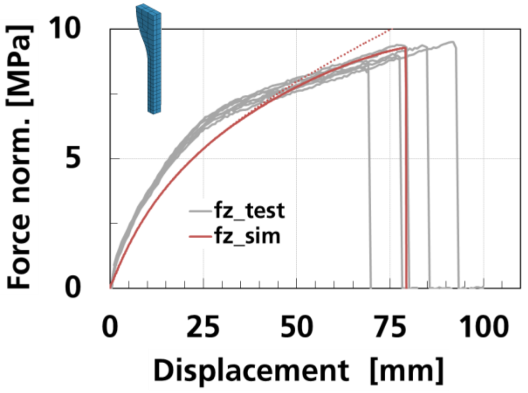
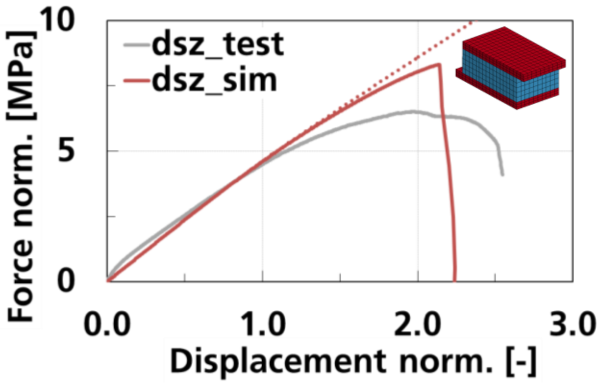
Characterization and modelling of PU-adhesive

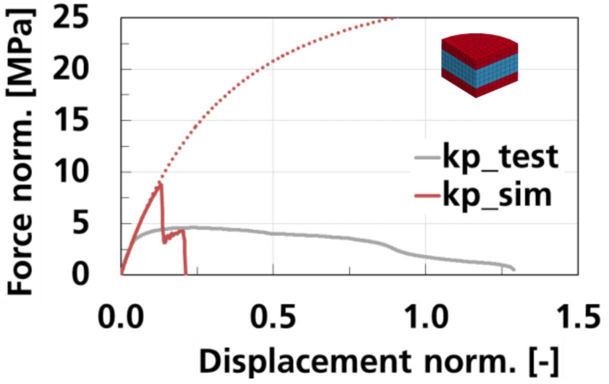
Modelling – 3D hyperelastic material model

- **hyperelastic user-defined material model by ifm**
  - parameter calibration for deformation and failure behavior

all diagrams: force normalized by adhesive bond area, displacement normalized by adhesive thickness







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Characterization and modelling of PU-adhesive
Résumé

- **experimental characterization**
  - similar loading conditions may lead to different results
    - shear strength from sheet adherend tests ca. 1.5 times higher than from „thick" adherend tests
    - → strong influence of geometry, smaller specimens tend to have stronger influence of notch effects
    - influence of adhesive bonding process must be taken into account
- **material models**
  - cohesive zone modelling with *MAT-ARUP
    - acceptable agreement with experimental results, simple calibration procedure, elastic deformation represented
  - MAT-TAPO
    - not suited for large elastic deformations,
      differences in deformation behavior in shear and tension are not covered,
      damage and failure behavior not very well represented especially in butt-joint loading
  - hyperelastic MAT-user-defined by IfM
    - deformation behavior well represented, including unloading; damage and failure behavior: different models still tested

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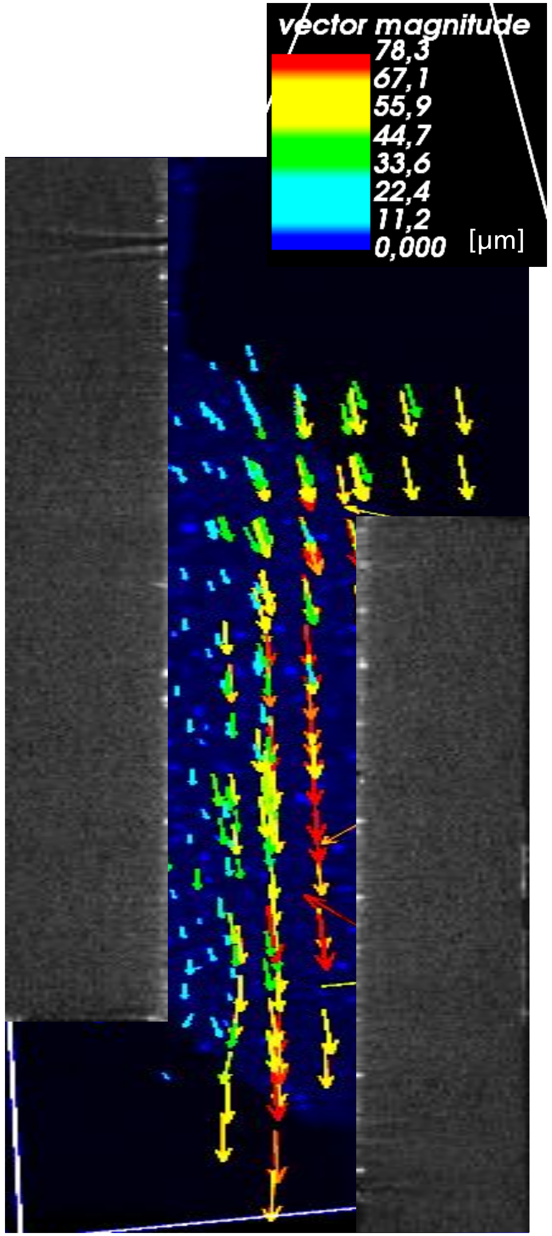
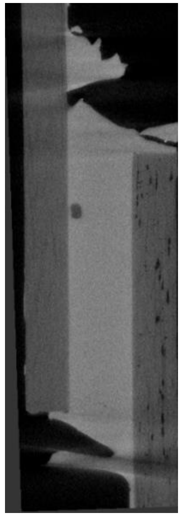
Characterization and modelling of PU-adhesive
Future perspective

- **parameter calibration based on DVC 3D-strain field analysis**
  (joint Fraunhofer IWM & IMWS research project)
  - 3D strain field analysis of PU-adhesive layer for advanced material model calibration by CT-measurement and digital volume correlation (DVC) method

example of **displacement vector analysis in shear test** (different specimen)



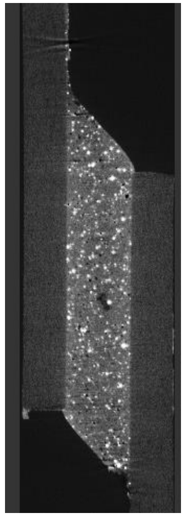
CT-scan picture of single lap shear test with **pure PU-adhesive**



\+ possibility of 3D displacement and strain field analysis in the adhesive layer by DVC

contrasting particles added

− influence on mechanical properties



CT-scan picture of single lap shear test with **PU-adhesive containing small amount of contrast particles**

DVC analysis

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