PORSCHE

Modelling of Adhesively Bonded Joints with *MAT252 and *MAT_ADD_COHESIVE for Practical Applications

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Motivation

Modelling and FE-calculation of structural adhesive joints for the crash analysis are characterised by:

- Reliable computation of the stresses in the adhesive layer
- Description of the failure
- Capture the strain rate dependent material properties
- Efficiency with regard to the computation time (no influence on critical time step size)
- Simple and unique identification of the material- and failure parameters

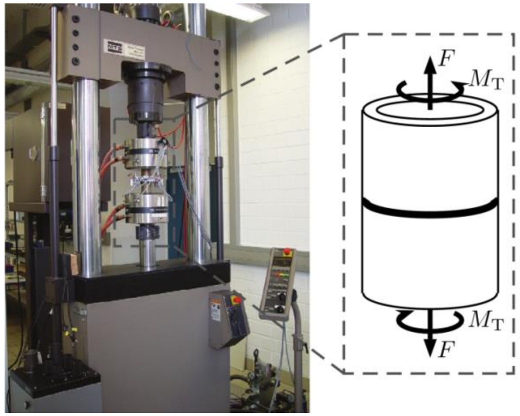
Outline

- Non-associated elasto-viscoplastic material model (*MAT252 since LS-DYNA R7.1.1) for rubber-toughened adhesive polymeres
- Verification by means of basic tests
- Modelling approaches for the adhesive joint
- Formulation*MAT_ADD_COHESIVE (LS-DYNA R7.1.1) for interface elements (ELFORM 19 and 20)
- Comparison of *MAT252 (TAPO-model) with *MAT169 (ARUP-model)
- Validation by means of component-like specimens

Basic tests of adhesively bonded joints

Characterisation of the elastoplastic behaviour of the structural adhesive:

Bluntly glued steel tube specimen (DIN EN 14869-1)

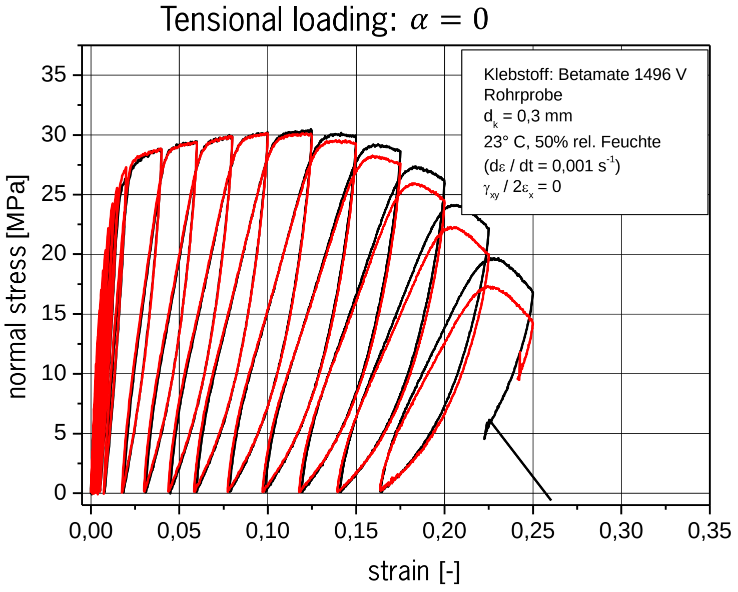


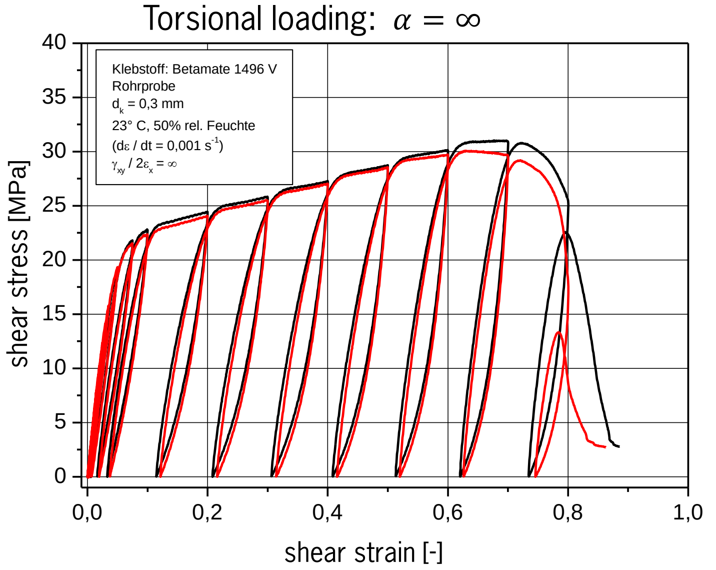
[Schlimmer / Report of P676 FOSTA, 2007]

Torsion-, tension- and combined-loading-tests as well as tests with loading and unloading

Tensional and torsional loadings are characterised: $\alpha = \dfrac{|\gamma_{xy}|}{2\,\varepsilon_{xx}}$

Average testing speed: 2.0e-4 mm/s





Yield functions of the TOUGHENED-ADHESIVE-POLYMERE-MODEL *MAT252

Yield conditions of the **T**OUGHENED-**A**DHESIVE-**PO**LYMERE-MODEL (TAPO available since LS-DYNA R7.1.1):

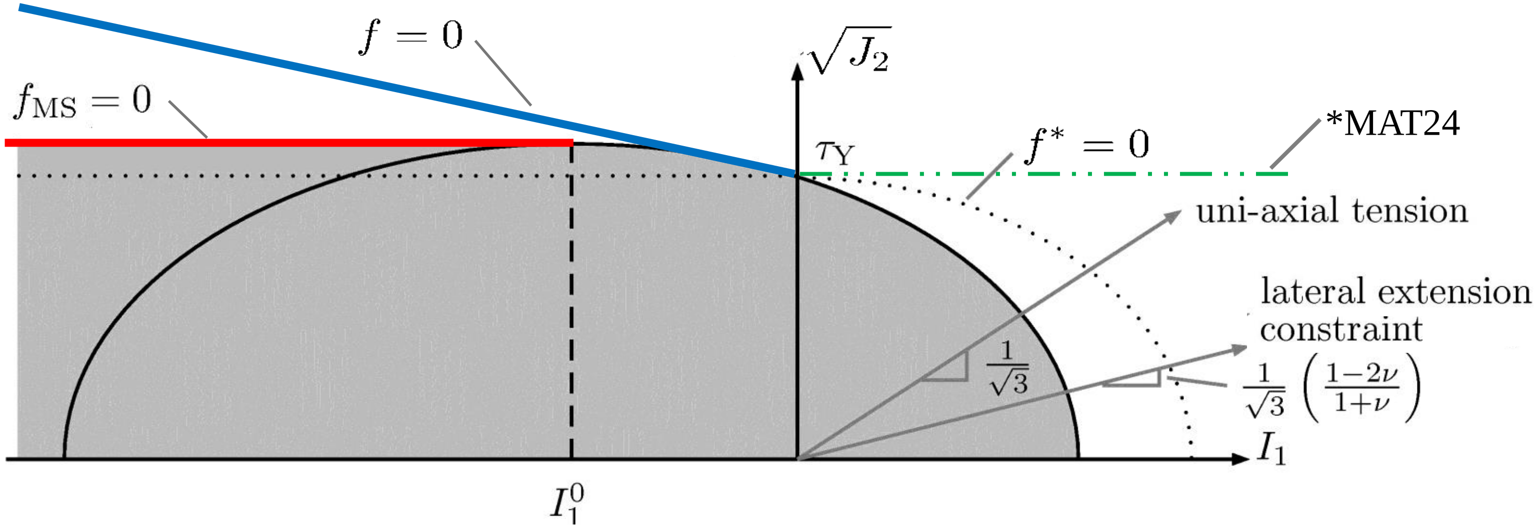
In the domain of pressure, the elliptic yield function is replaced by DRUCKER & PRAGER-criterion (FLG=1)

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

No pressure tests available, then von MISES-yield condition (FLG=2) starting from vertex:

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

Conservative estimation of the pressure-shear strength!



Consideration of the micro friction for pressure $I_1 < 0$ is performed by formative hardening:
[Yee and Pearson / J. Mat. Science, 1986]

$$a_1 := \hat{a}_1(r) \qquad \dot{a}_1 := a_{H1}\dot{r} \quad \wedge \quad a_1(r) \geq 0$$

Non-associated flow rule

Flow rule of the **T**OUGHENED-**A**DHESIVE-**PO**LYMERE-MODEL (TAPO-model)

$$\dot{\boldsymbol{\varepsilon}}^{\mathrm{pl}} = \lambda \frac{\partial f^*}{\partial \boldsymbol{\sigma}} = \frac{\lambda}{(1-D)^2}\left(\boldsymbol{\sigma}^{\mathrm{D}} + \frac{2}{3} a_2^* \langle I_1 \rangle \, \mathbf{1}\right)$$

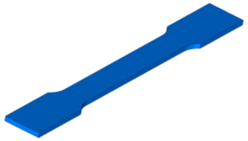
depends on elliptic plastic potential:

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

to reduce the plastic dilatation by means of an additional parameter a_2^* .

Identification of parameter a_2^* :

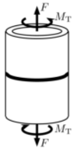
- From uni-axial tension test with measurements of axial and transversal strain

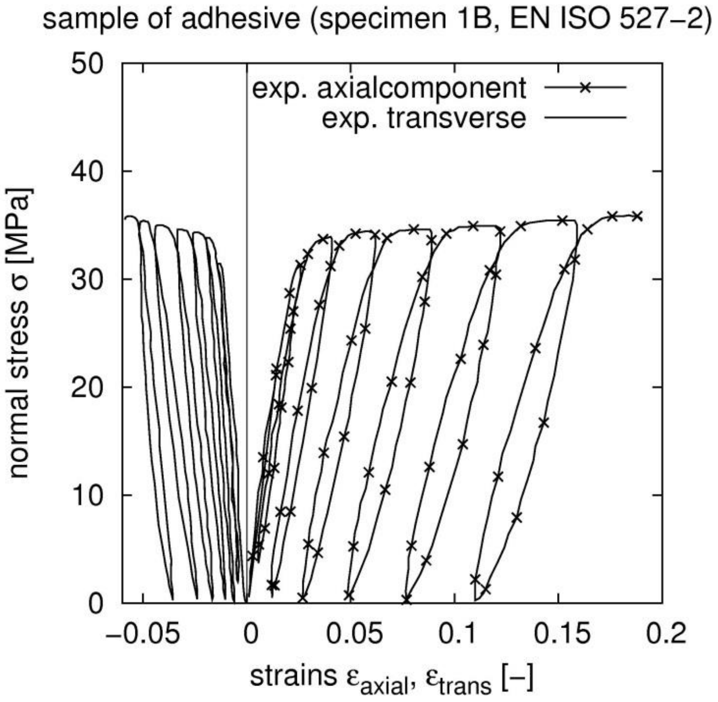


$$a_2^* = \frac{1-2\nu^*}{2(1+\nu^*)}$$

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

- From tests of bluntly glued steel tube specimen under tensile and combined tensile-shear loadings
→ inverse parameter identification with LS-OPT





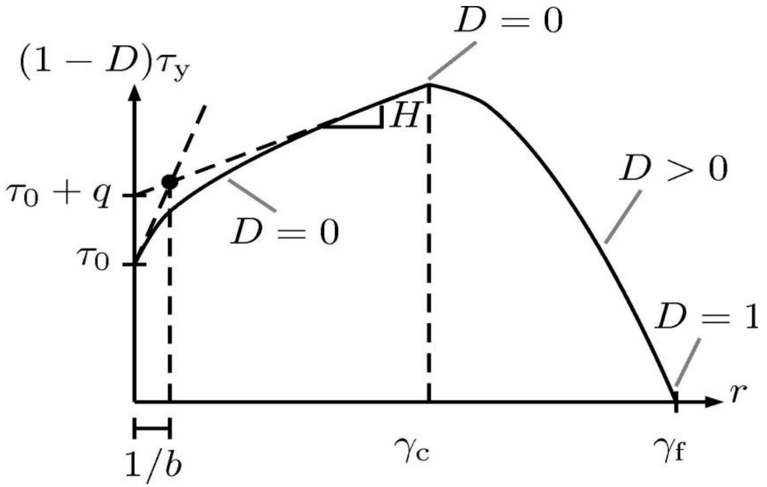
Material hardening and strain rate dependency of the yield stress

Definition of the plastic arclength is based on then EUKLIDEAN norm:

$$\dot{\gamma}_{\mathrm{v}} := \sqrt{2\,\dot{\boldsymbol{\varepsilon}}_{\mathrm{pl}} \cdot \dot{\boldsymbol{\varepsilon}}_{\mathrm{pl}}} = \sqrt{2}\lambda\sqrt{\frac{\partial f^*}{\partial \boldsymbol{\sigma}} \cdot \frac{\partial f^*}{\partial \boldsymbol{\sigma}}}$$

Damaged hardening variable is introduced because of thermodynamic consistency:
[Lemaitre: A Course on Damage Mechanics, 1992]

$$\dot{r} := (1 - D)\,\dot{\gamma}_{\mathrm{v}}$$



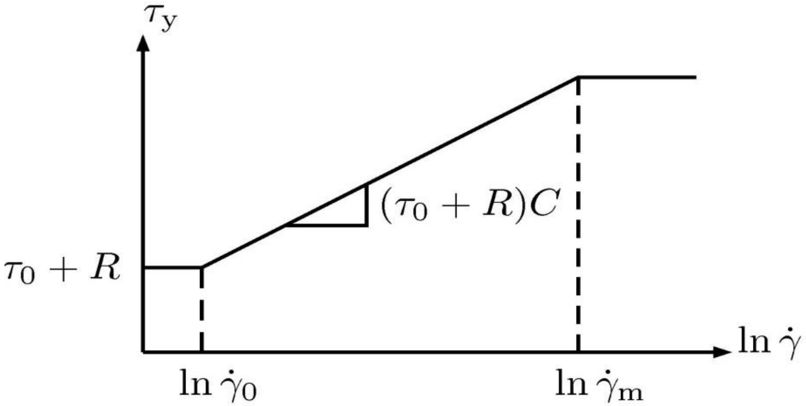
Standard (analytical approach):
Isotropic hardening stress depends on plastic deformation:

$$R = q[1 - \exp(-b\,r)] + H\,r$$

Rate dependent yield shear stress τ_{Y} of the I_1-J_2-plasticity model is according to modified JOHNSON & COOK model:

$$\tau_{\mathrm{Y}} = (\tau_0 + R)\left[1 + C\left(\left\langle \ln\frac{\dot{\gamma}}{\dot{\gamma}_0}\right\rangle - \left\langle \ln\frac{\dot{\gamma}}{\dot{\gamma}_{\mathrm{m}}}\right\rangle\right)\right]$$

$$\dot{\gamma} := \sqrt{2\dot{\boldsymbol{\varepsilon}} \cdot \dot{\boldsymbol{\varepsilon}}}$$



Identification of $C, \dot{\gamma}_0, \dot{\gamma}_{\mathrm{m}}$ with testing rate dependent data*

*) M. Brede, IFAM, FhG Bremen, Report of P676, FOSTA, 2007

Material hardening and strain rate dependency of the yield stress

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$$\dot{\gamma}_{\mathrm{v}} := \sqrt{2\,\dot{\boldsymbol{\varepsilon}}_{\mathrm{pl}} \cdot \dot{\boldsymbol{\varepsilon}}_{\mathrm{pl}}} = \sqrt{2}\lambda\sqrt{\frac{\partial\, f^*}{\partial \boldsymbol{\sigma}} \cdot \frac{\partial\, f^*}{\partial \boldsymbol{\sigma}}}$$

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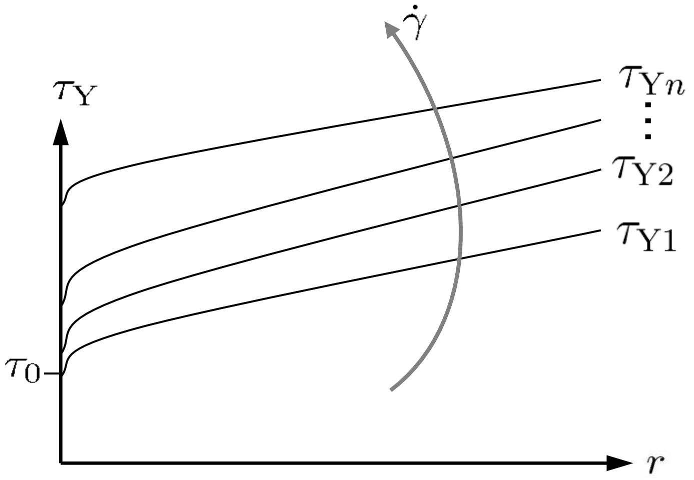


Alternative (tabulated input):
Definition of the rate dependent yield shear stress

$$\tau_{\mathrm{Y}} = \begin{cases} \tau_{\mathrm{Y}1} & , \mathrm{LCSS{=}Load\ Curve\ ID} \\ \tau_{\mathrm{Y}n}(\dot{\gamma}) & , \mathrm{LCSS{=}Table\ ID} \end{cases}$$

identically to *MAT24 with table formulation *TABLE and curve formulation *CURVE is possible.

Parameters $\tau_0, q, b, H, C, \dot{\gamma}_0, \dot{\gamma}_{\mathrm{m}}$ of modified JOHNSON & COOK ansatz are not needed anymore.

Damage and failure of the adhesive layer

Development of the effective stress $\boldsymbol{\sigma}^{\mathrm{eff}} = \dfrac{\boldsymbol{\sigma}}{\psi}$ according to RABOTNOV in yield condition is performed by means of the continuity $\psi = 1 - D$

Evolution equation for damage as a function of the plastification:

$$\dot{D} = n \left\langle \frac{r - \gamma_{\mathrm{c}}}{\gamma_{\mathrm{f}} - \gamma_{\mathrm{c}}} \right\rangle^{n-1} \frac{\dot{r}}{\gamma_{\mathrm{f}} - \gamma_{\mathrm{c}}}$$

Empirical approach for damage:
[Lemaitre / J. Eng. Mater. Tech., 1985]

$$D = \left\langle \frac{r - \gamma_{\mathrm{c}}}{\gamma_{\mathrm{f}} - \gamma_{\mathrm{c}}} \right\rangle^{n}$$

Fracture strain γ_{f} (shear resp. tensile fracture) depends on the loading.

Measure of the loading is the triaxiality $T := \sigma_{\mathrm{m}}/\sigma_{\mathrm{eq}}$, which influences the fracture strain according to JOHNSON & COOK model:

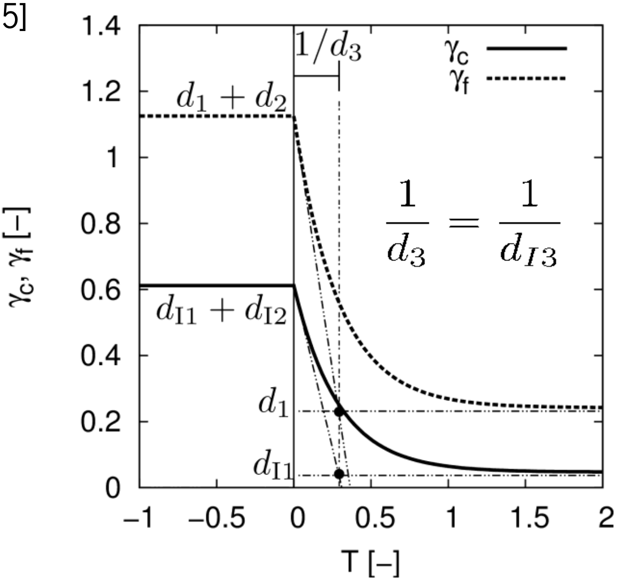
$$\gamma_{\mathrm{f}} = [d_1 + d_2\, \exp(-d_3 \langle T \rangle)] \left(1 + d_4 \left\langle \ln \frac{\dot{\gamma}}{\dot{\gamma}_0} \right\rangle\right)$$

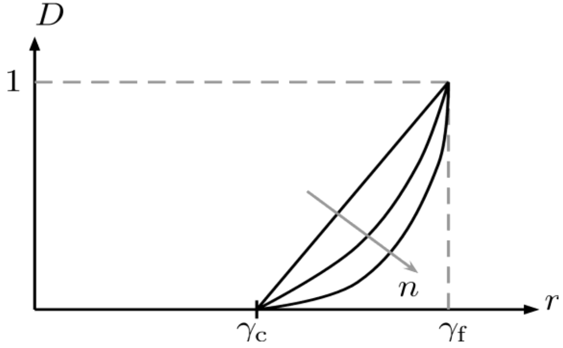
Multiaxiality of the fracture strain
[Rice und Tracy / J. Mech. Phys. Solids, 1969]

Critical strain γ_{c} shall be proportional to the failure strain γ_{f}:

$$\gamma_{\mathrm{c}} = [d_{\mathrm{I1}} + d_{\mathrm{I2}}\, \exp(-d_3 \langle T \rangle)] \left(1 + d_4 \left\langle \ln \frac{\dot{\gamma}}{\dot{\gamma}_0} \right\rangle\right)$$

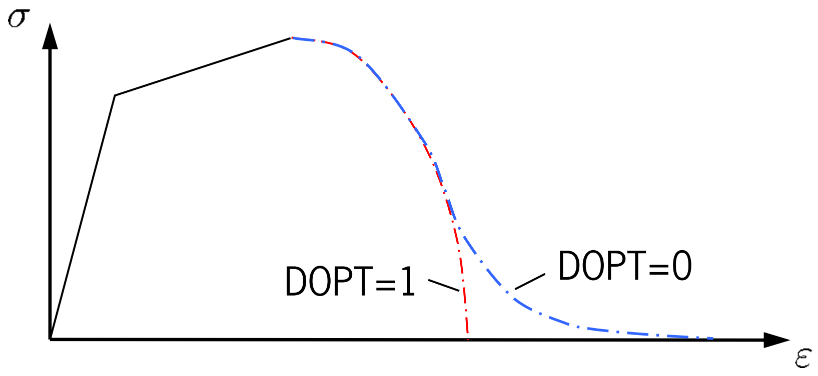
Damage evolution $\dot{D} > 0$ takes place above the defect inducing strain $r \geq \gamma_{\mathrm{c}}$.



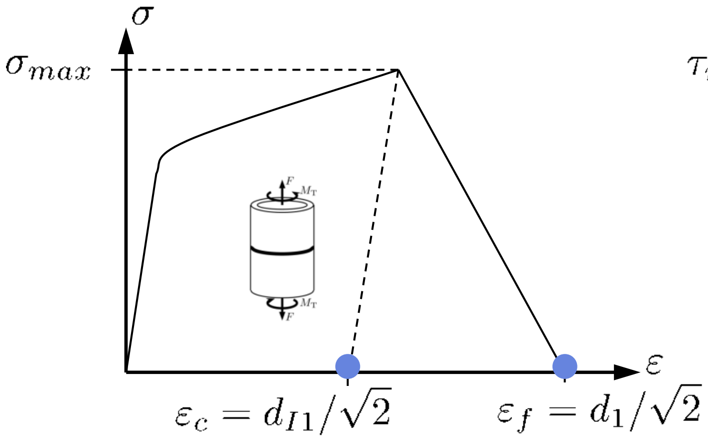


Damage and failure of the adhesive layer

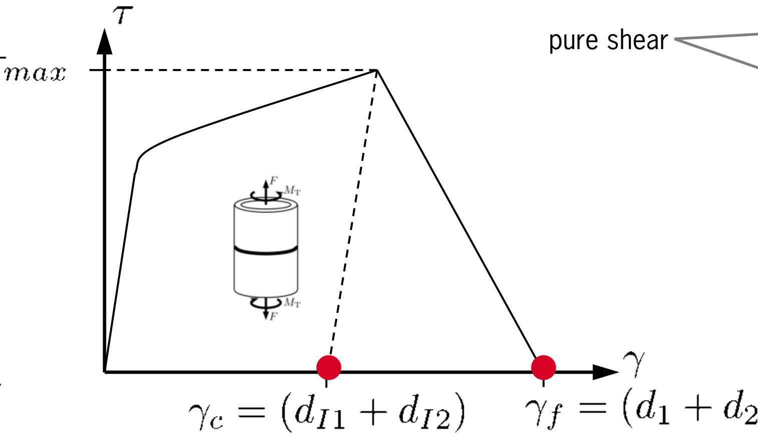
Two damage models are available: DOPT=0 with turning point or DOPT=1 without turning point



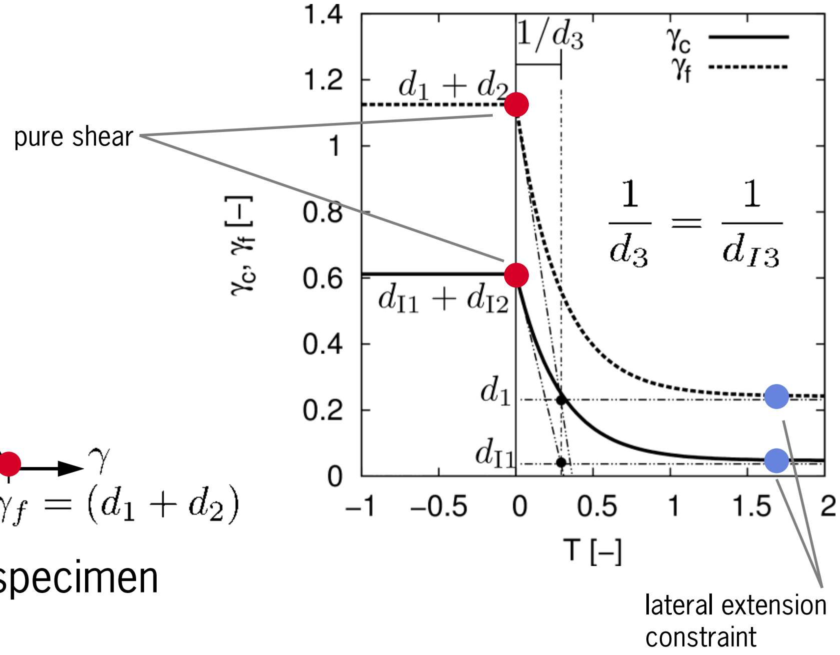
Simple identification of the JOHNSON & COOK parameters:



Blunty glued steel tube specimen
with tensional loading

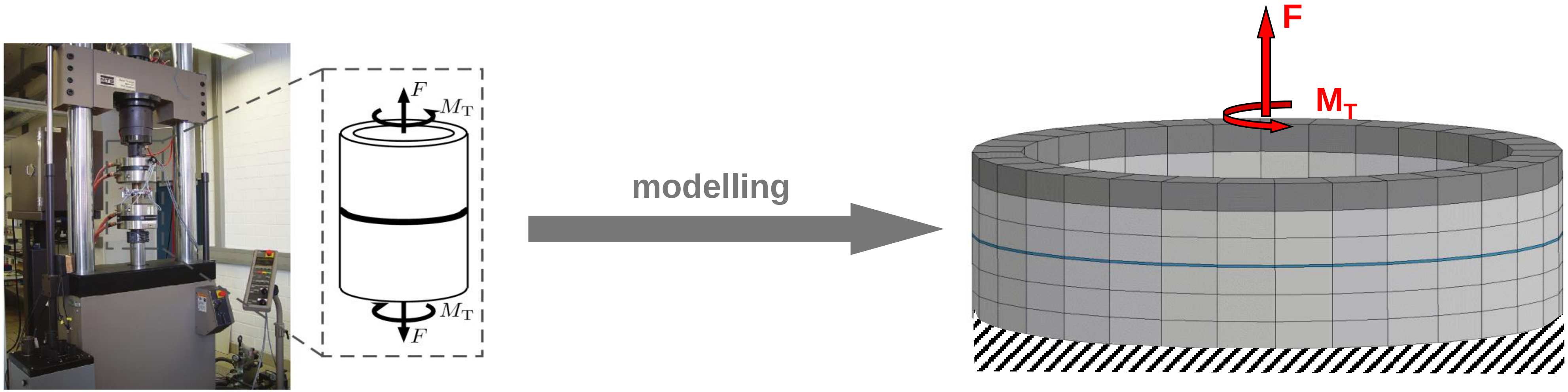


Blunty glued steel tube specimen
with torsional loading



Simulation of the basic tests for verification

Bluntly glued steel tube specimen (DIN EN 14869-1)

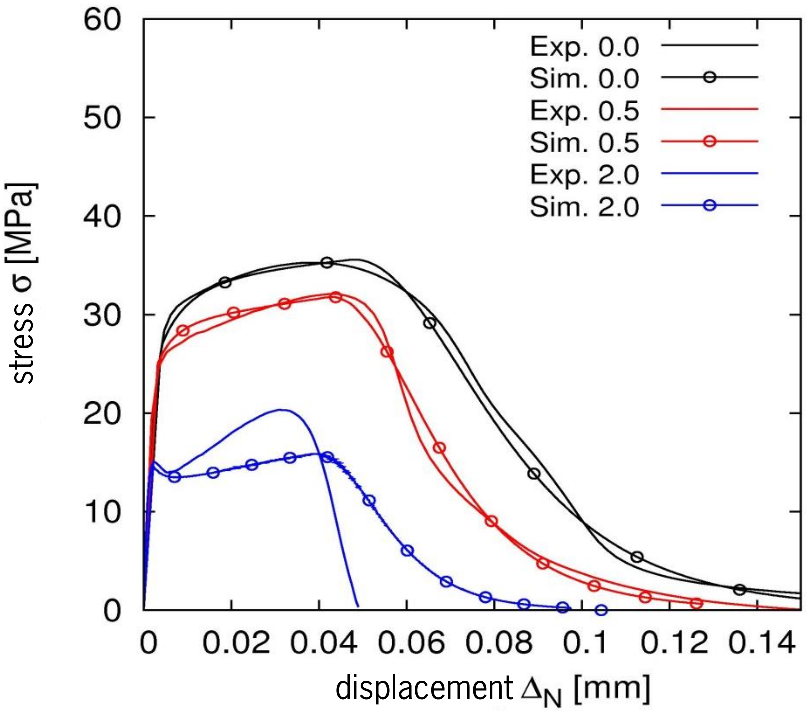


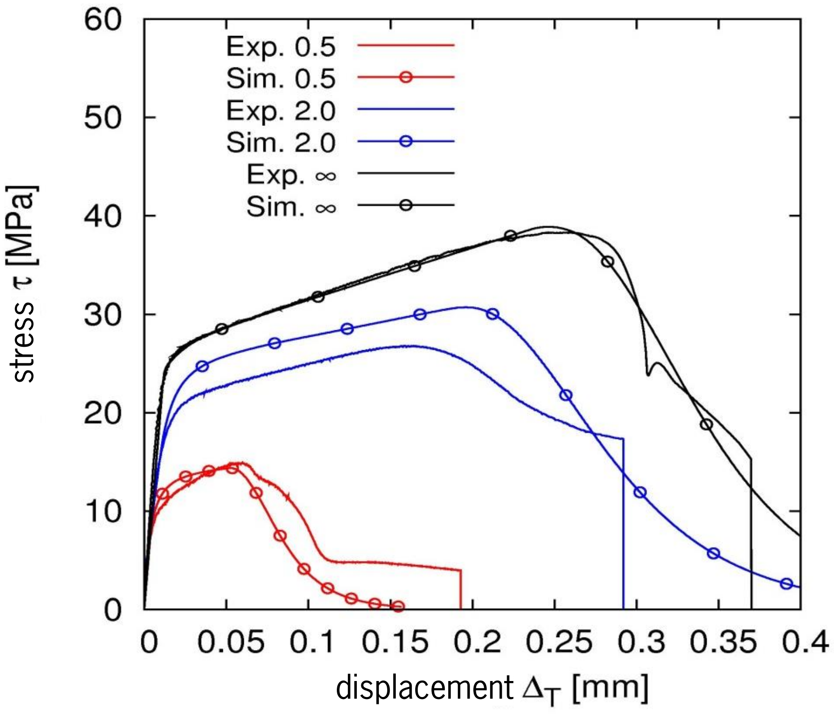
[Schlimmer / Report of P676 FOSTA, 2007]

- Discretization of adhesive layer is done by 1 solid element in direction of thickness $d_k = 0.2\ \mathrm{mm}$
- Average testing speed: $v = 2 \cdot 10^{-4}\ \mathrm{mm/s}$
- Identification of the material parameters for the elastic-plastic domain including damage and failure is done by means of optimisation software LS-OPT
- 6 quasi-static tests of the bluntly glued steel tube specimen provide the data for the identification

Simulation of the basic tests

Comparisons of experiment* and simulation of the steel tube test:





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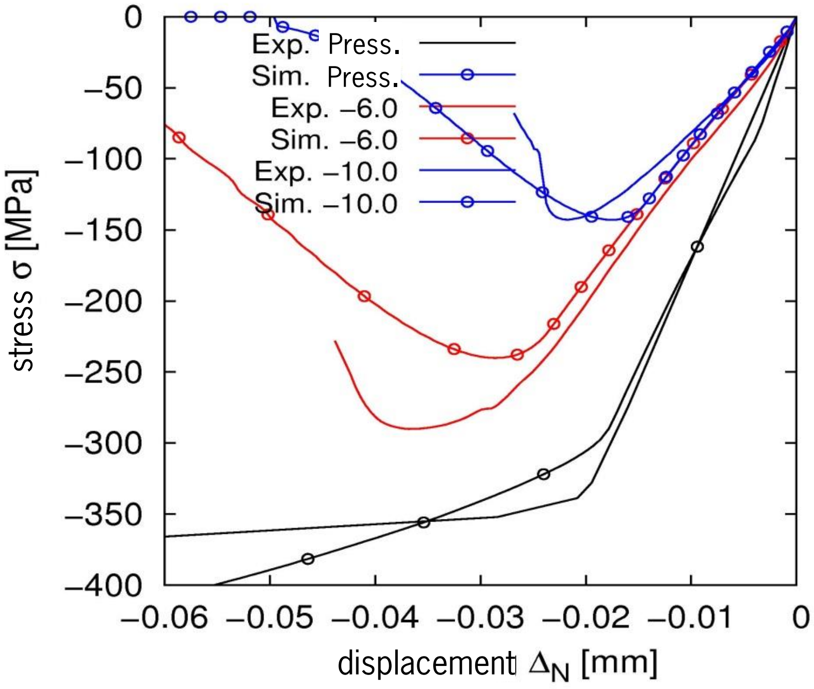
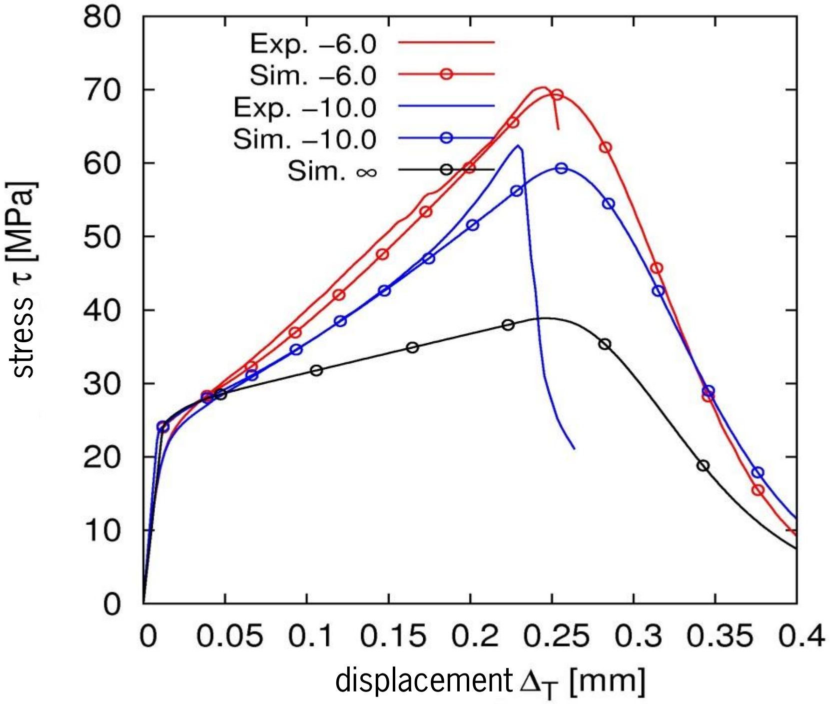
*) M. Schlimmer, C. Barthel, IfW, University of Kassel, Report of P676, FOSTA, 2007

Simulation of the basic tests – cont.

Comparisons of experiment* and simulation of the steel tube test under pressure and torsion:



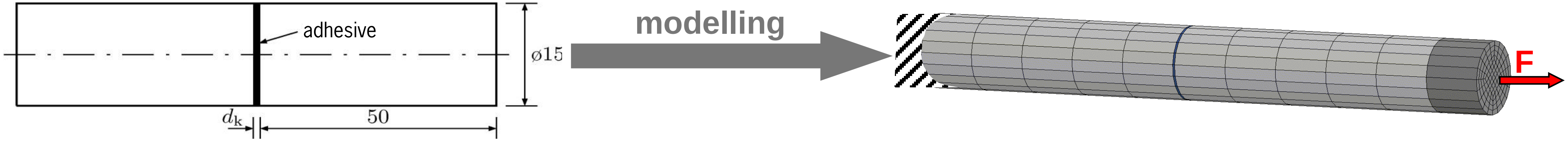


- Static steel tube tests are suitable for the identification of the material parameters for plastic hardening and damage
- TAPO-model captures the basic phenomenological properties of the rubber-toughened adhesive polymere

*) M. Schlimmer, C. Barthel, IfW, Universität Kassel, Forschungsbericht zu P676, FOSTA, 2007

Simulation of the basic tests for verification

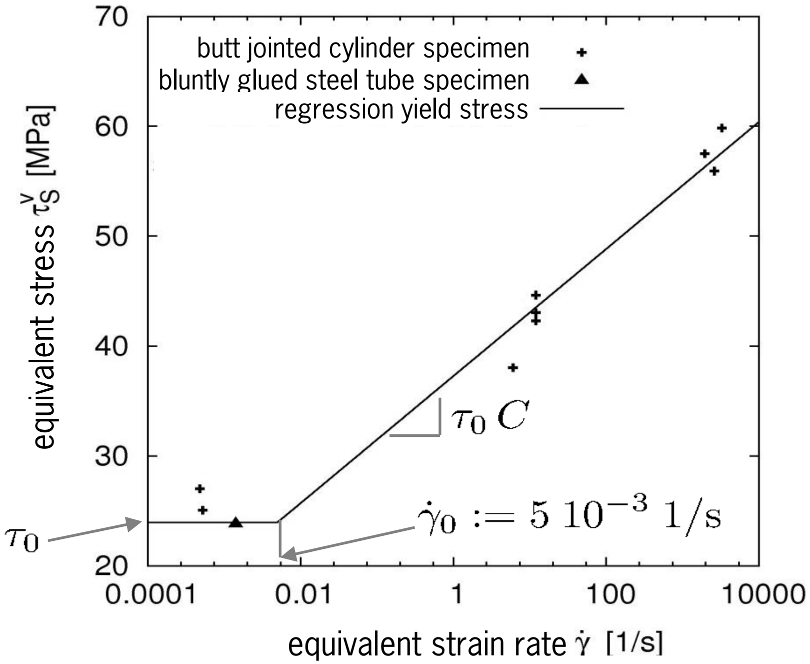
Dynamic tests of the butt jointed steel cylinder specimen*



- Discretization of adhesive layer with 1 solid element in direction of thickness $d_\mathrm{k} = 0.4\ \mathrm{mm}$
- Testing speeds at the specimen: $\dot{\Delta}_\mathrm{v} = 8.0\,10^{-5},\ 3.4,\ 740\ [\mathrm{mm/s}]$

Identification of the strain rate dependent material parameters

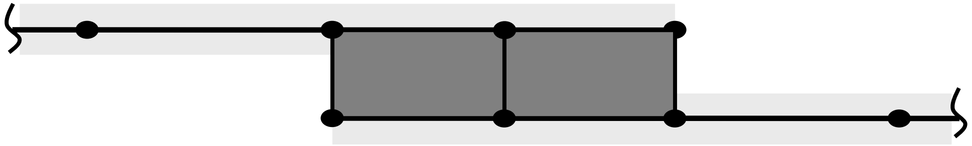
- equivalent stress: $\tau_\mathrm{S}^\mathrm{v} := \sqrt{J_2 + \frac{1}{\sqrt{3}} a_1 \tau_0 I_1 + \frac{1}{3} a_2 I_1^2}$
- equivalent shear strain rate: $\dot{\gamma} = \sqrt{2\,\dot{\boldsymbol{\varepsilon}} \cdot \dot{\boldsymbol{\varepsilon}}}$
- determination of C: $\tau_\mathrm{S}^\mathrm{v} = \tau_0 + \tau_0\, C\, \left\langle \ln \frac{\dot{\gamma}}{\dot{\gamma}_0} \right\rangle$



*) M. Brede, IFAM, FhG Bremen, Report of P676, FOSTA, 2007

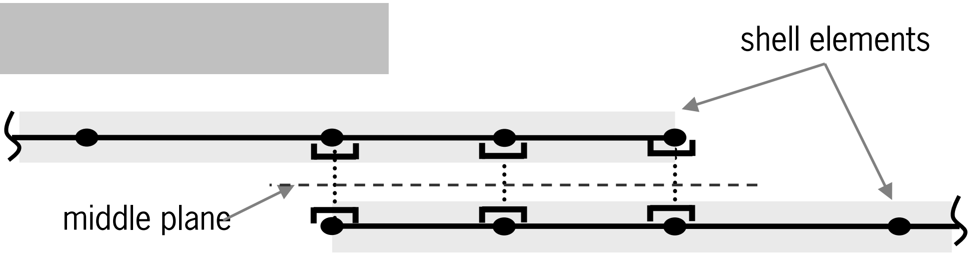
Modelling approaches of the adhesive joint

kinematics



solid elements ELFORM 1 and 2

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{13} & \varepsilon_{23} & \varepsilon_{33} \end{bmatrix}$$



interface elements ELFORM 19 and 20

$$\boldsymbol{\Delta} = \begin{bmatrix} \Delta_{\mathrm{T1}} \\ \Delta_{\mathrm{T2}} \\ \Delta_{\mathrm{N}} \end{bmatrix} \qquad \Delta_{\mathrm{T}} = |\boldsymbol{\Delta}_{\mathrm{T}}|$$

material models

3D-continuum

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{11} & \tau_{12} & \tau_{13} \\ \tau_{21} & \sigma_{22} & \tau_{23} \\ \tau_{13} & \tau_{23} & \sigma_{33} \end{bmatrix}$$

compounded model

$$\mathbf{t} = \begin{bmatrix} t_{\mathrm{T1}} \\ t_{\mathrm{T2}} \\ t_{\mathrm{N}} \end{bmatrix} \qquad \tau = |\mathbf{t}_{\mathrm{T}}|$$

model accuracy ←

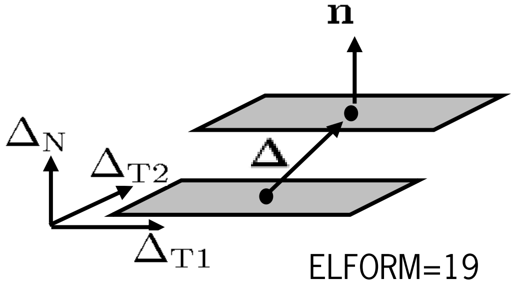
→ computational efficiency

Formulation *MAT_ADD_COHESIVE for the interface element

$$\boldsymbol{\Delta} = \begin{bmatrix} \Delta_{\mathrm{T1}} \\ \Delta_{\mathrm{T2}} \\ \Delta_{\mathrm{N}} \end{bmatrix} \quad \text{with assumption of the state of strain:} \quad \boldsymbol{\varepsilon}_{\mathrm{qD}} := \begin{bmatrix} 0 & 0 & \varepsilon_{13} \\ 0 & 0 & \varepsilon_{23} \\ \varepsilon_{13} & \varepsilon_{23} & \varepsilon_{33} \end{bmatrix}$$

strain rate

$$\dot{\boldsymbol{\varepsilon}}_{\mathrm{qD}} = \begin{bmatrix} 0 & 0 & \frac{1}{2}\left(\frac{\dot{\Delta}_{\mathrm{T1}}}{d_{\mathrm{k}}+\Delta_{\mathrm{N}}}\right) \\ 0 & 0 & \frac{1}{2}\left(\frac{\dot{\Delta}_{\mathrm{T2}}}{d_{\mathrm{k}}+\Delta_{\mathrm{N}}}\right) \\ \frac{1}{2}\left(\frac{\dot{\Delta}_{\mathrm{T1}}}{d_{\mathrm{k}}+\Delta_{\mathrm{N}}}\right) & \frac{1}{2}\left(\frac{\dot{\Delta}_{\mathrm{T2}}}{d_{\mathrm{k}}+\Delta_{\mathrm{N}}}\right) & \frac{\dot{\Delta}_{3}}{d_{\mathrm{k}}+\Delta_{\mathrm{N}}} \end{bmatrix}$$



TAPO-continuum model resp. all classic solid models in LS-DYNA

$$\boldsymbol{\sigma}_{\mathrm{qD}} = \begin{bmatrix} \sigma_{11} & 0 & \tau_{13} \\ 0 & \sigma_{22} & \tau_{23} \\ \tau_{13} & \tau_{23} & \sigma_{33} \end{bmatrix}$$

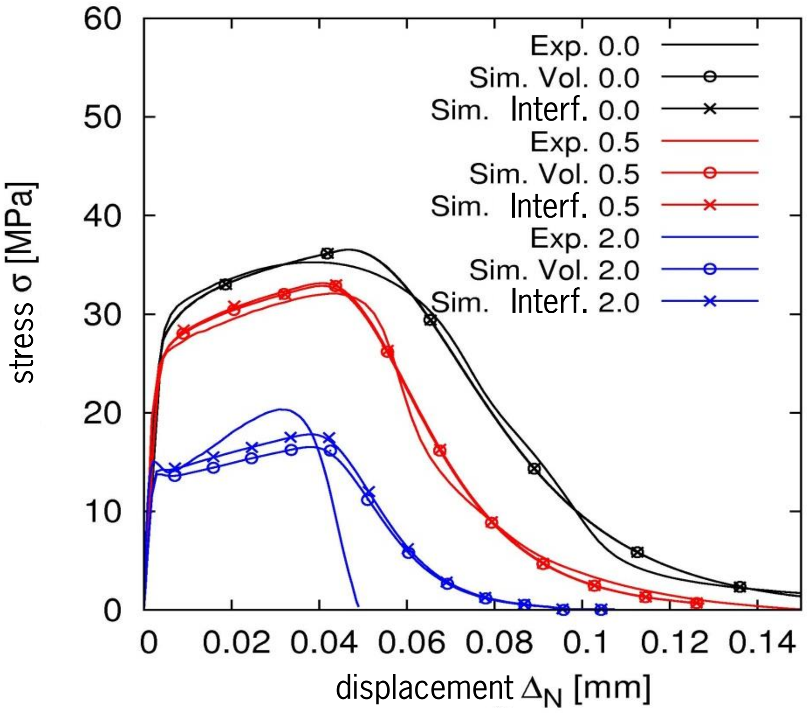
back substitution for traction vector by means of CAUCHY-theorem

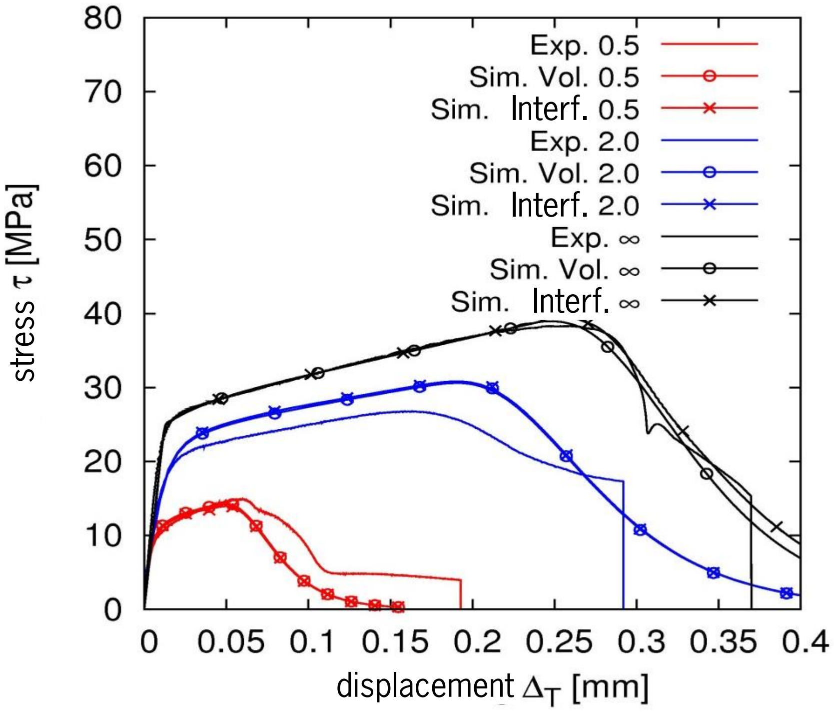
$$\mathbf{t} = \begin{bmatrix} t_{\mathrm{T1}} \\ t_{\mathrm{T2}} \\ t_{\mathrm{N}} \end{bmatrix} = \begin{bmatrix} \tau_{13} \\ \tau_{23} \\ \sigma_{33} \end{bmatrix} = \boldsymbol{\sigma}_{\mathrm{qD}}\,\mathbf{n}$$

$(\cdot)_{\mathrm{qD}}$: adhesive layer with lateral extension constraint

Formulation *MAT_ADD_COHESIVE for the interface element

Comparison between simulations with solid and interface elements as well as the experiment*
by means of the steel tube test





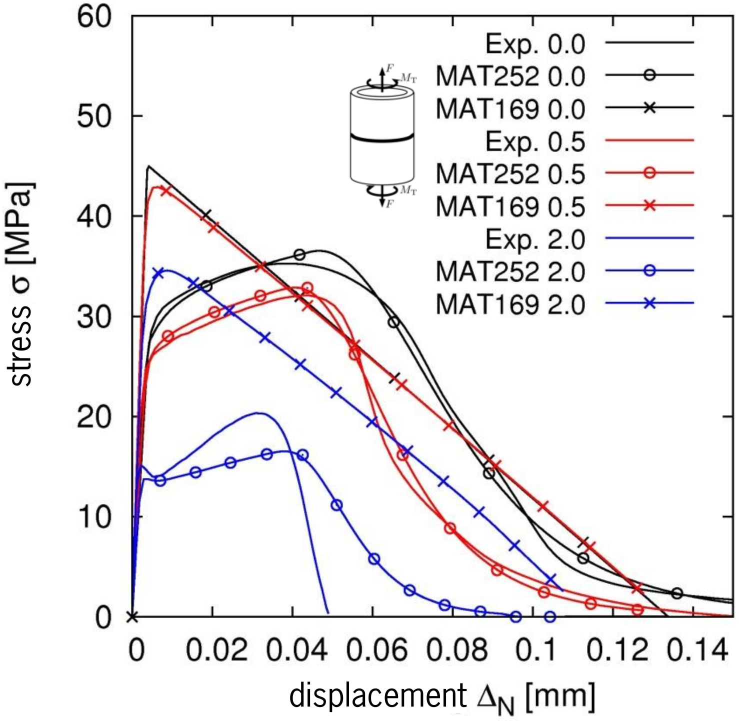
Advantages of the method:

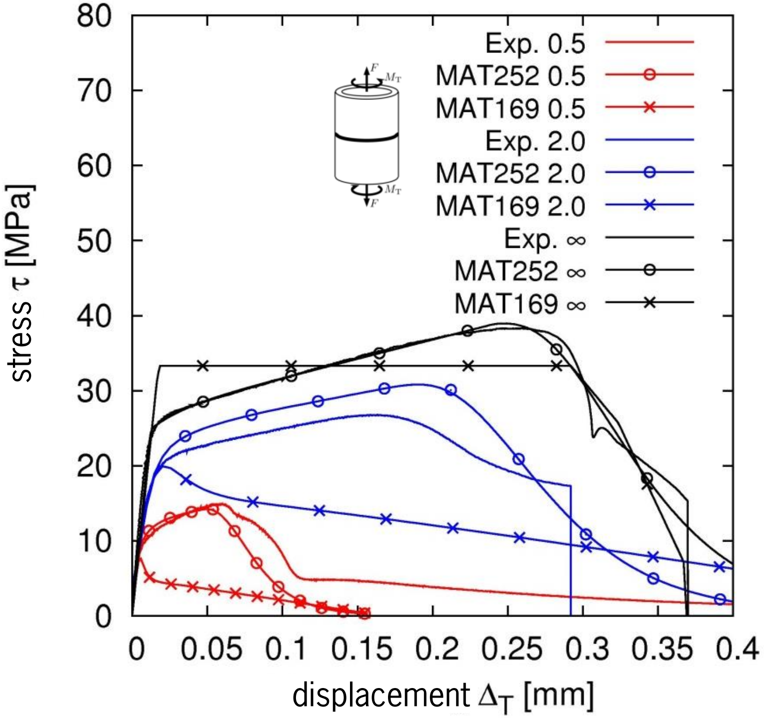
- Renewed parameter identification is not necessary.
- Higher computational efficiency is achieded with interface element ELFORM=19 at quasi identical model accuracy.

*) M. Schlimmer, C. Barthel, IfW, University of Kassel, Report of P676, FOSTA, 2007

*MAT252 versus *MAT169

Comparison between simulations with *MAT252 (TAPO-model) and *MAT169 (ARUP-model)





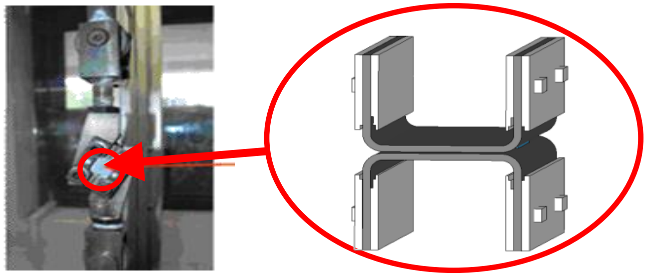
- Number of material parameters: *MAT252 #15 versus *MAT169 #9
- No dissipation at *MAT169
- Damage criterion:
  - *MAT252 strain based
  - *MAT169 stress based

***MAT**	# of elements	initial added mass [%]	total added mass [%]
252 & MAT_ADD_COHESIVE	39609	2,33	2,37
169	39609	45,05	44,95

Added mass in computation of the complete vehicle structure

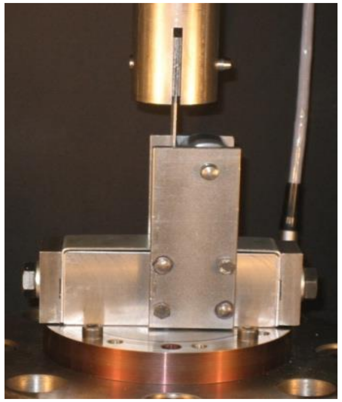
Validation of the TAPO-model by means of component-like specimens

KS2-specimen



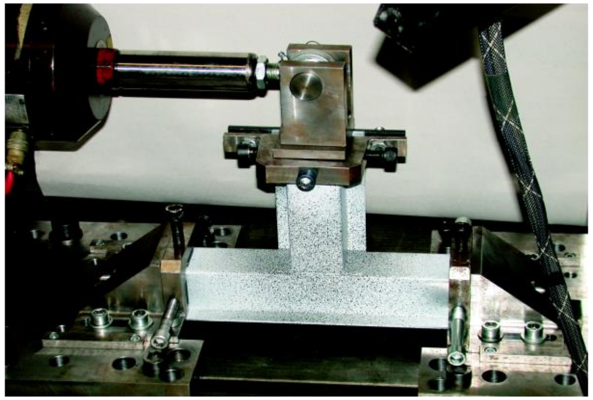
LWF, Paderborn

Peel-Shear-Test



IfM, Kassel

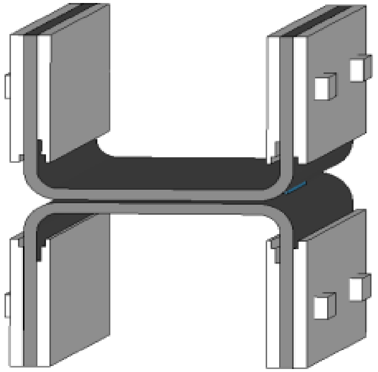
T-intersection



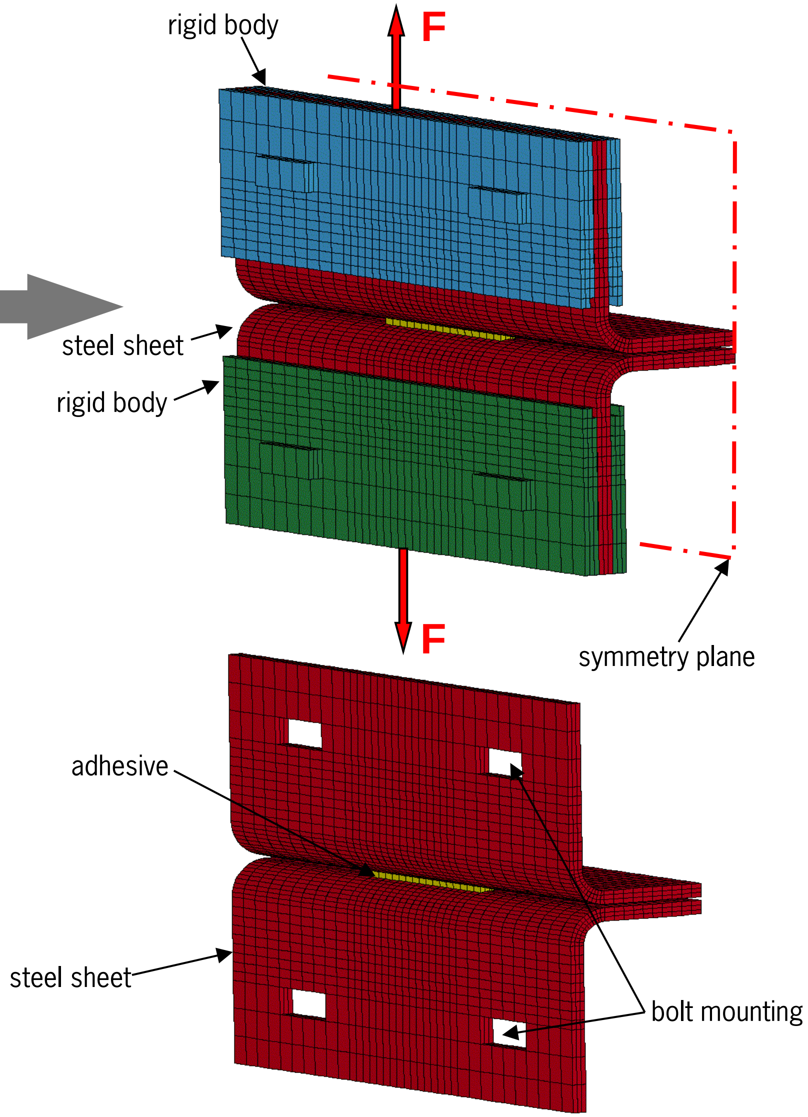
LWF, Paderborn

Validation by means of KS2-test

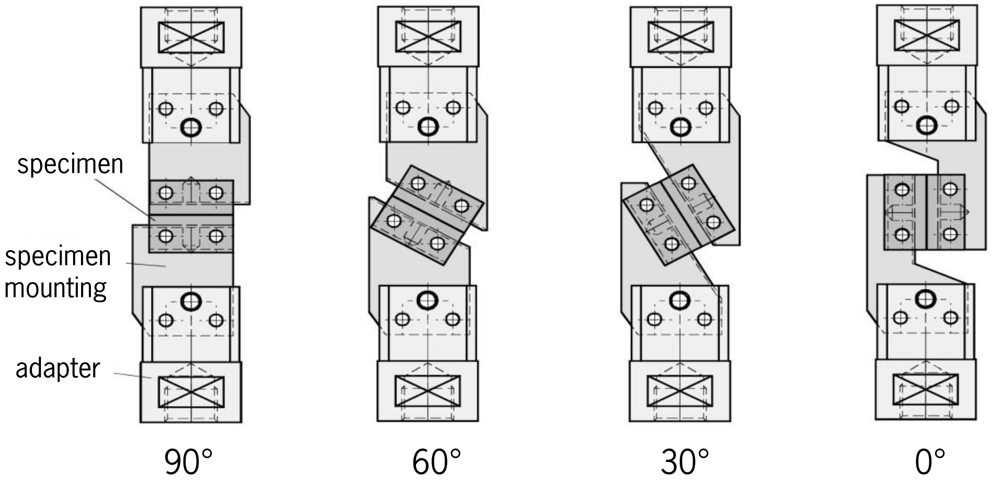
FE-model of the KS2-specimen*



modelling

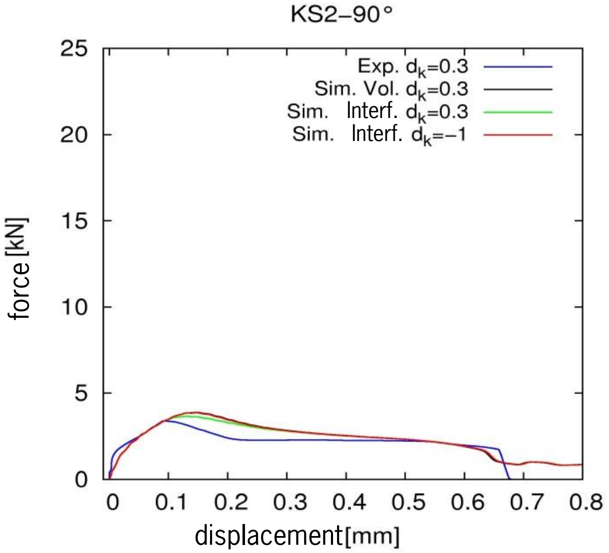


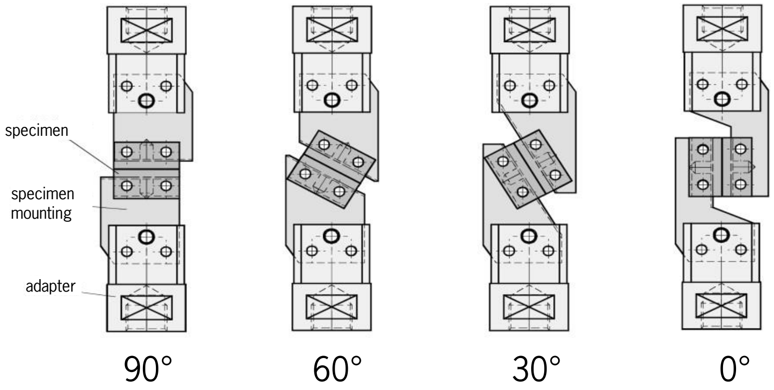
combined tension-shear loadings

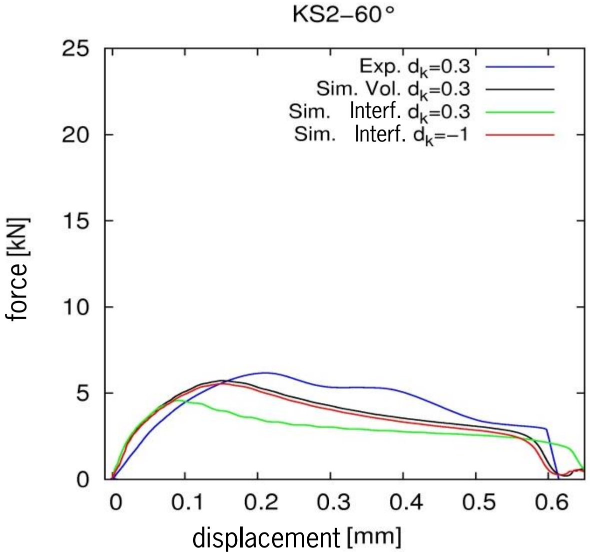


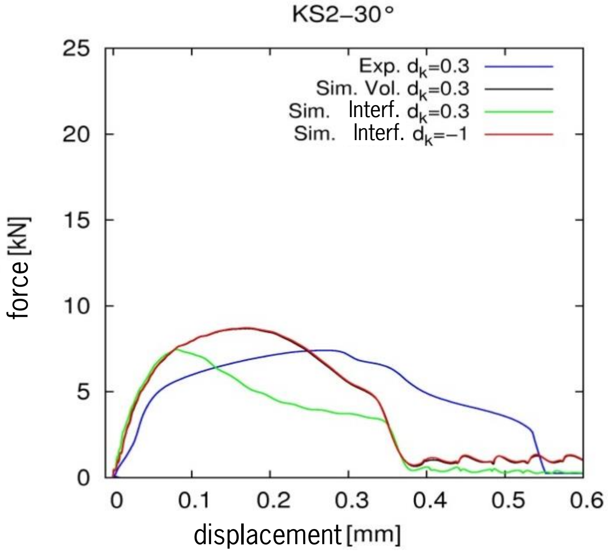
*) O. Hahn, M. Wißling, LWF, University of Paderborn, Report of P676, FOSTA, 2007

Validation by means of KS2-specimen (nom. v = 10 mm/min)

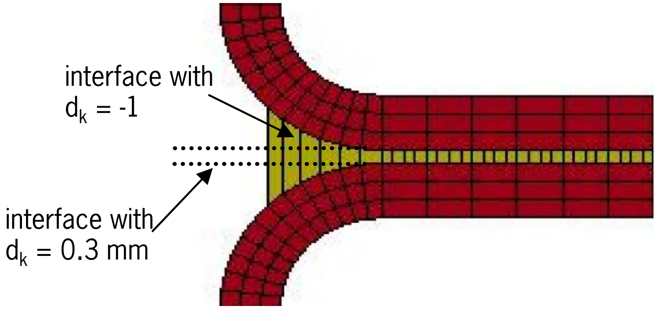


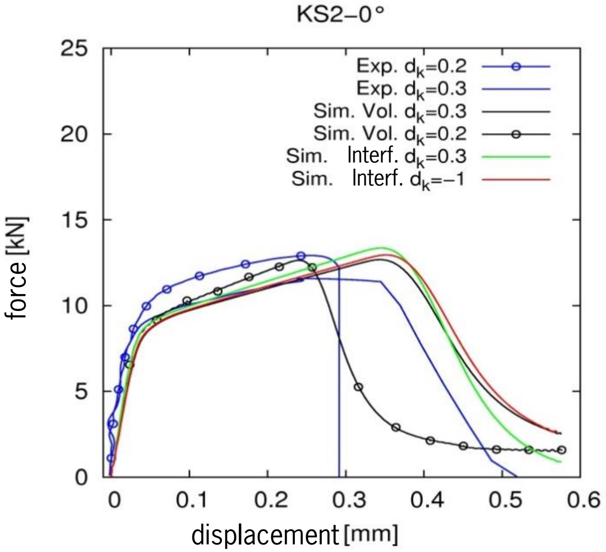




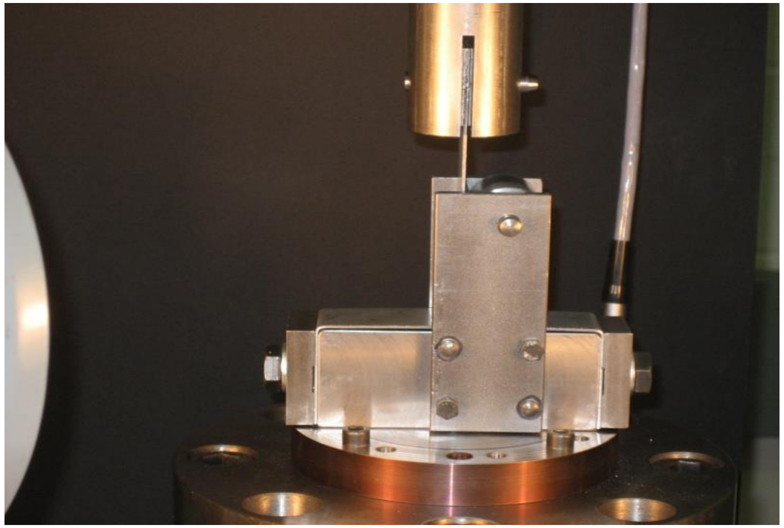


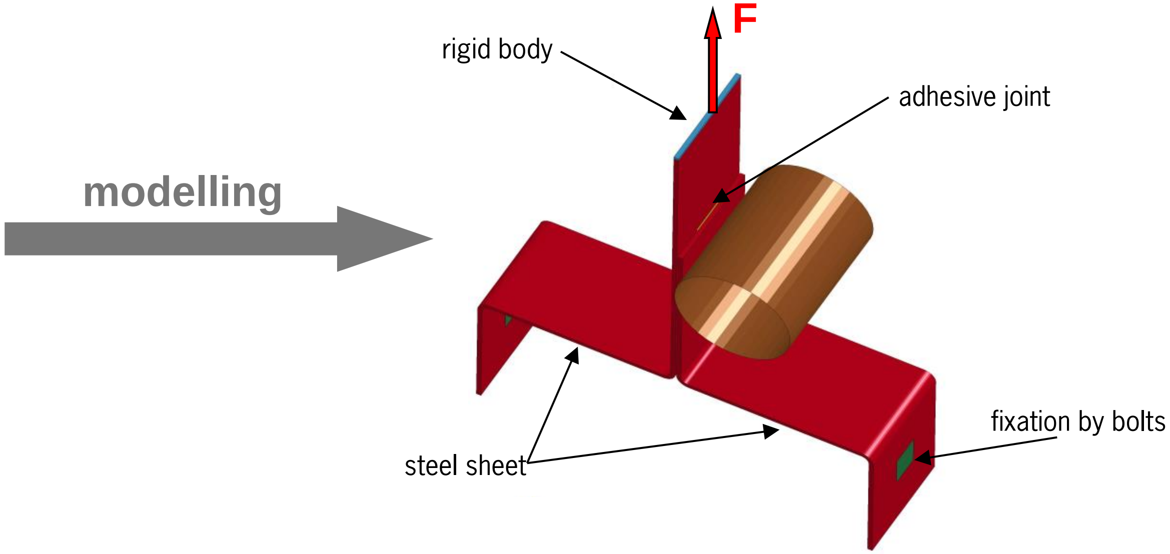
cross section of the KS2-specimen

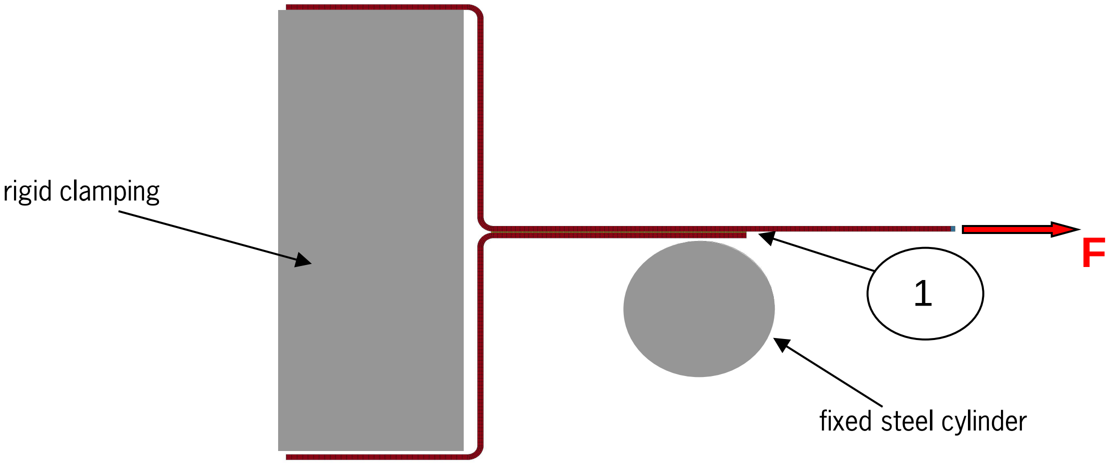


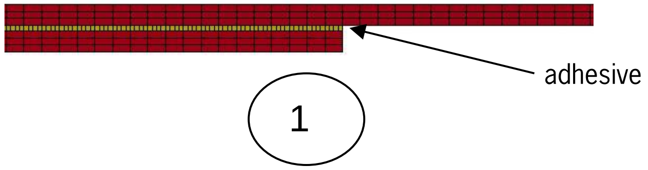


Validation by means of Peel-Shear-Test*



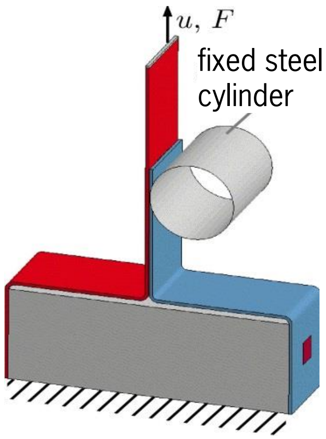


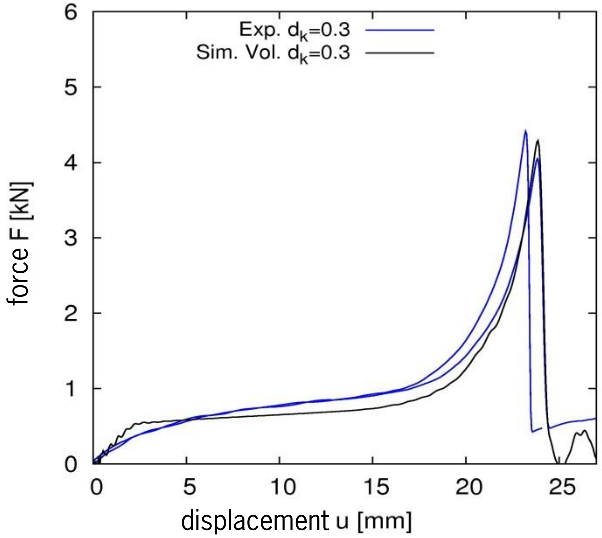


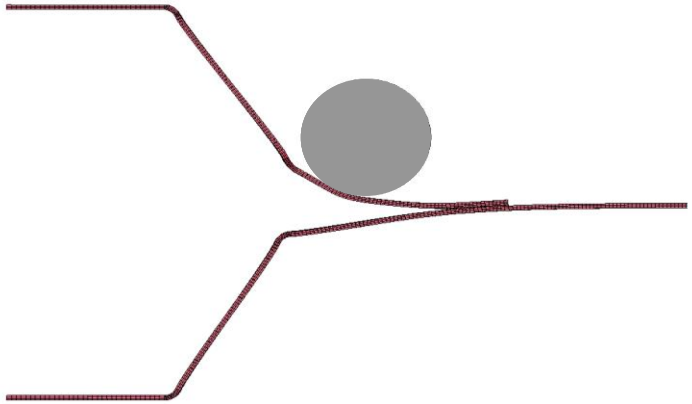


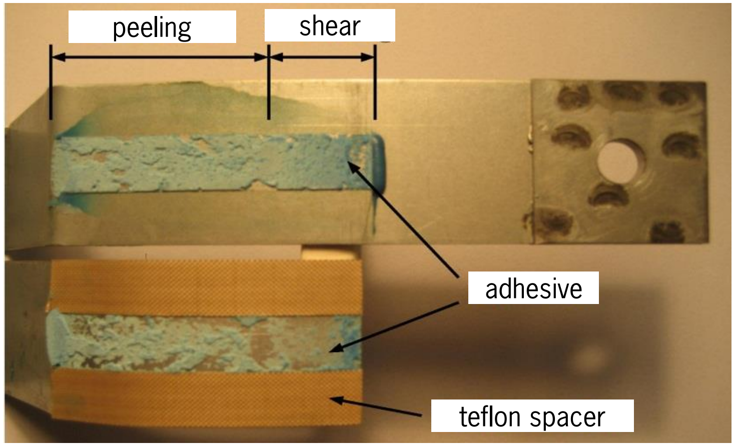
*) F. Burbulla, L. Schreiber, IfM, University of Kassel, 2010

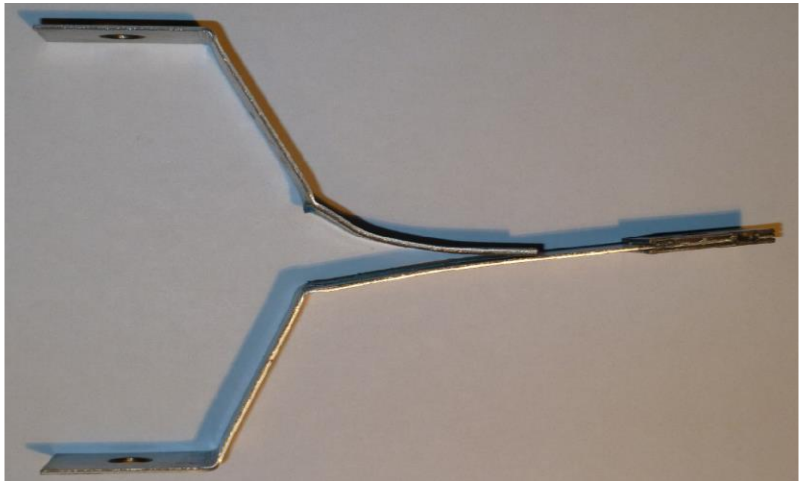
Validation by means of Peel-Shear-Test*





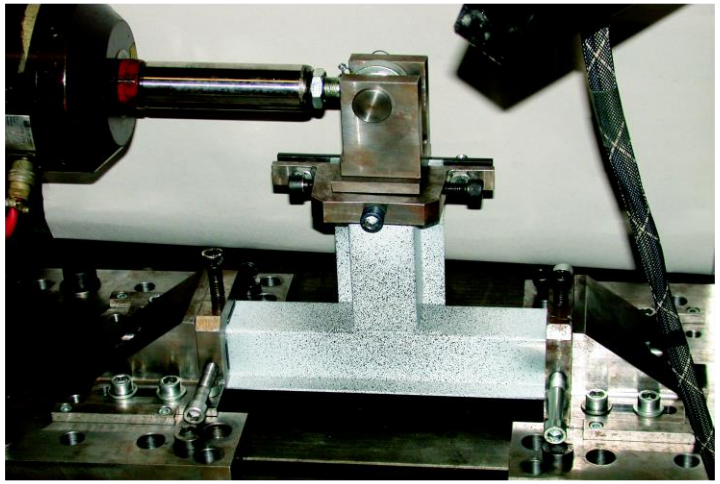




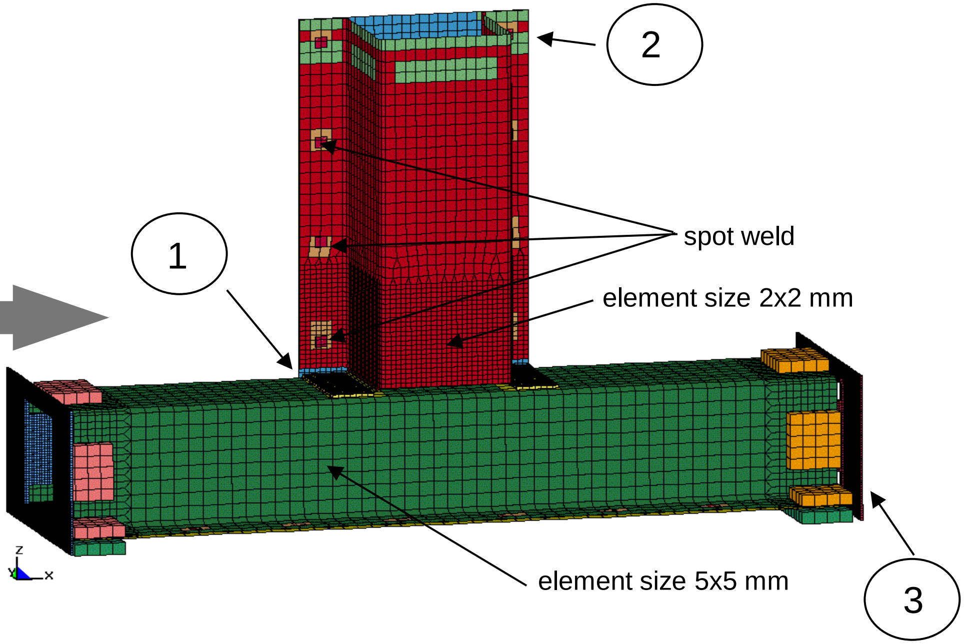


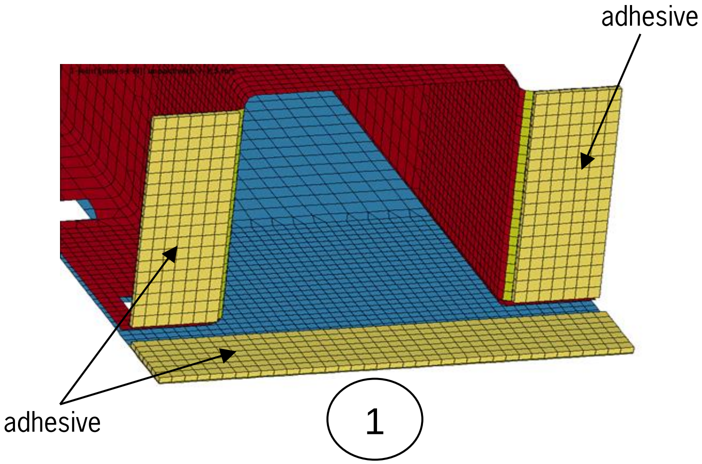
*) F. Burbulla, L. Schreiber, IfM, University of Kassel, 2010

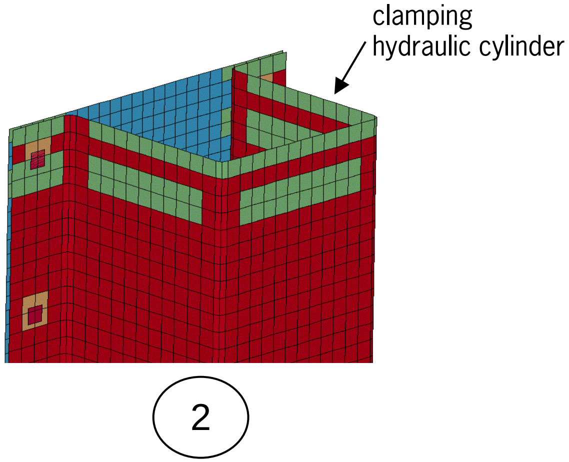
Validation by means of T-intersection* (quasistatic)

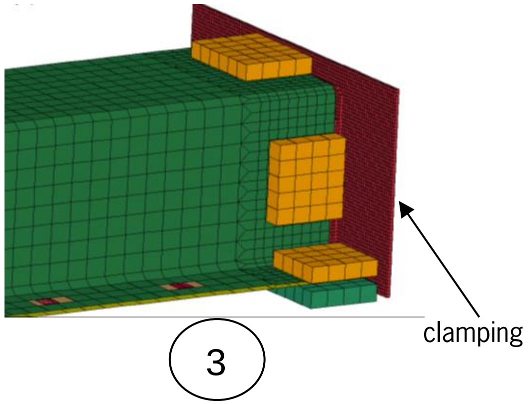


modelling



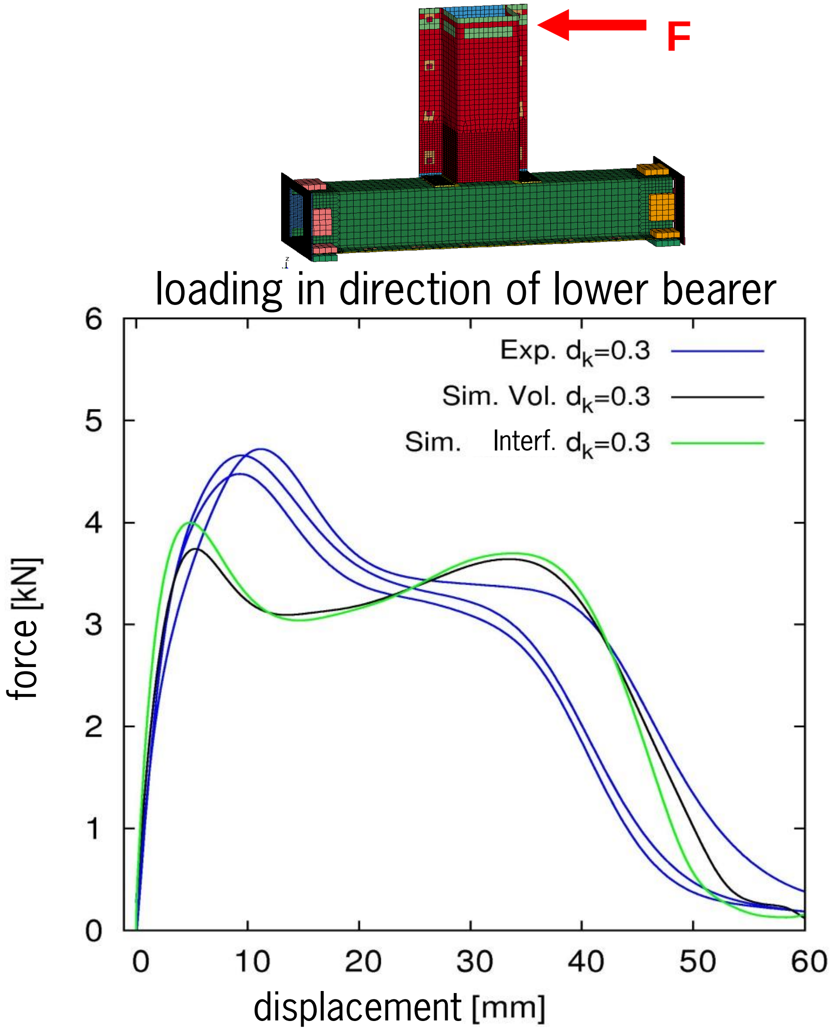


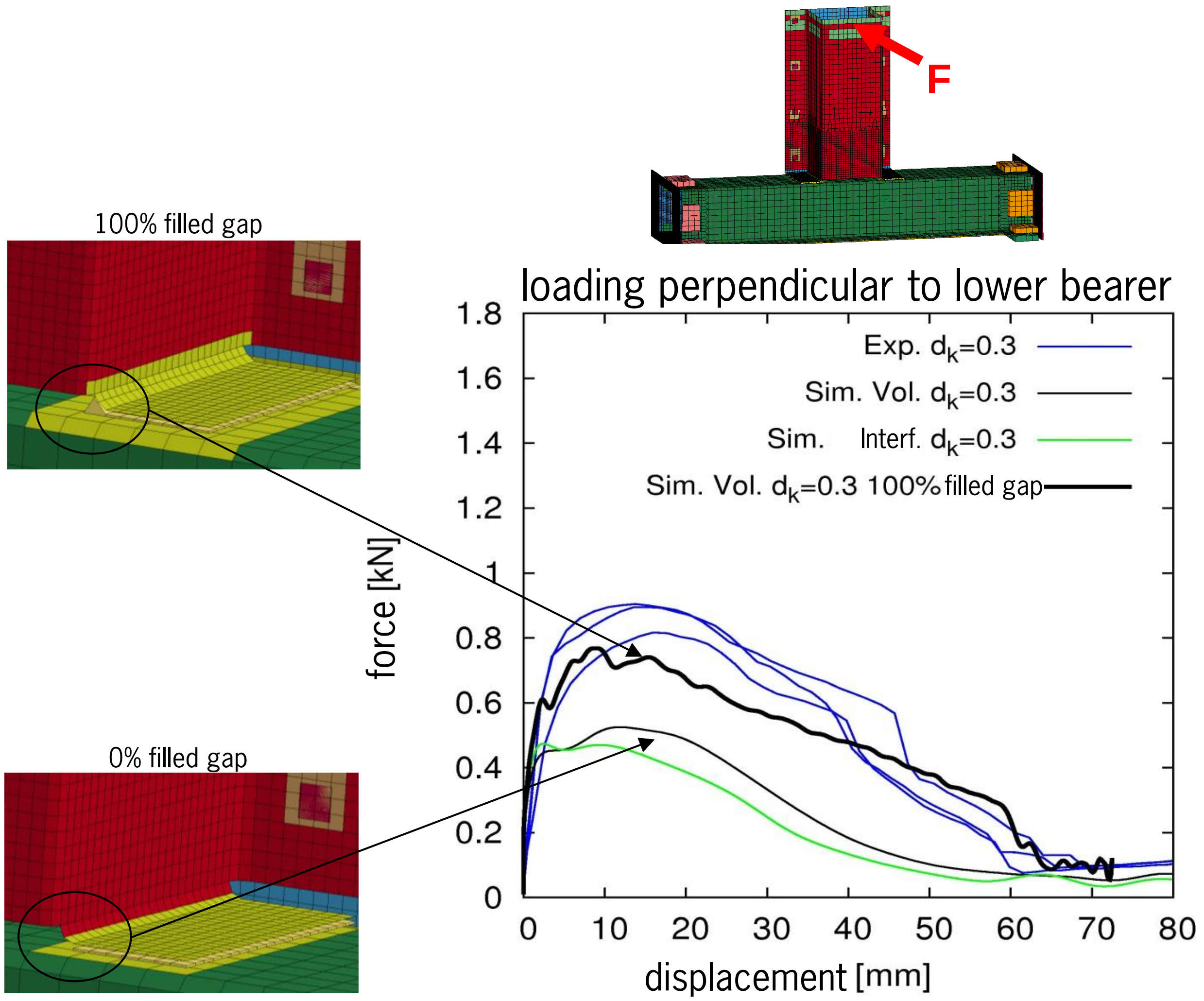




*) O. Hahn, M. Wißling, LWF, University of Paderborn, Report of project P676, FOSTA, 2007

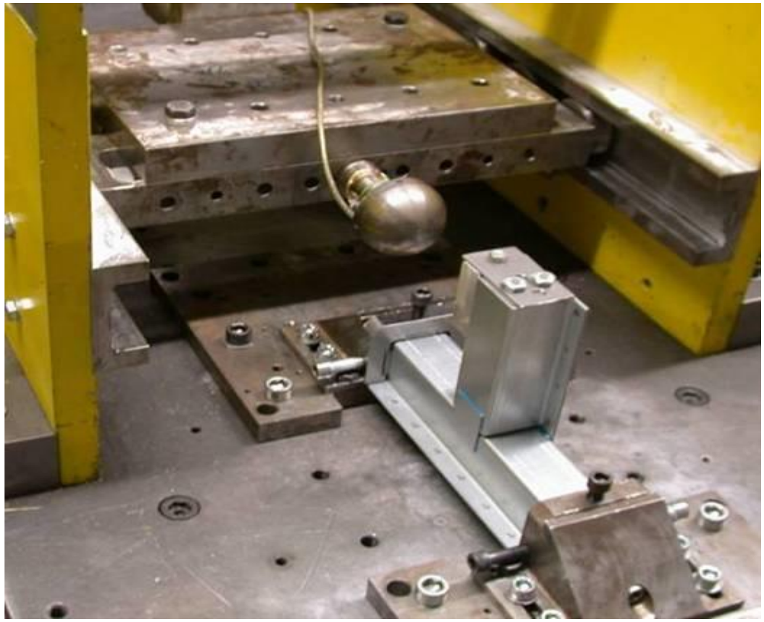
Validation by means of T-intersection* (quasistatic loading)



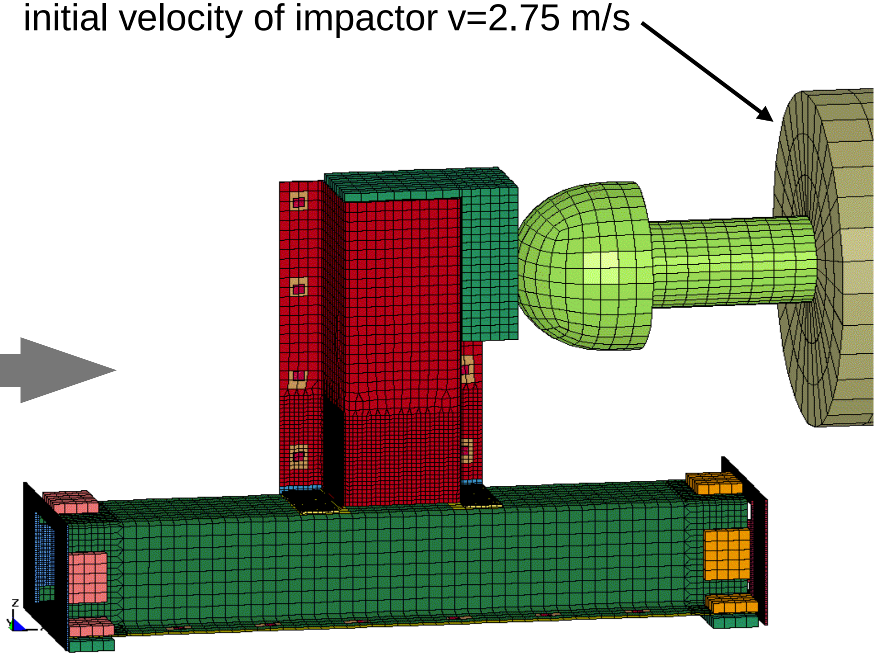


*) A. Matzenmiller, F. Burbulla,: Kontinuumsmechanische Modellierung von Stahlblechklebverbindungen für die FE-Crashanalyse, 7th German LS-DYNA Forum, Bamberg, 2008

Validation by means of T-intersection* (dynamic loading)



modelling



initial velocity of impactor v=2.75 m/s

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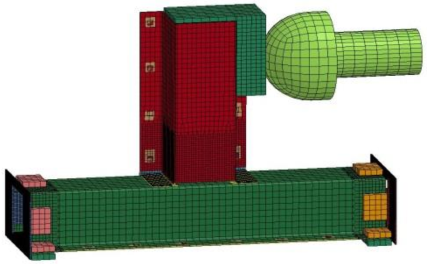
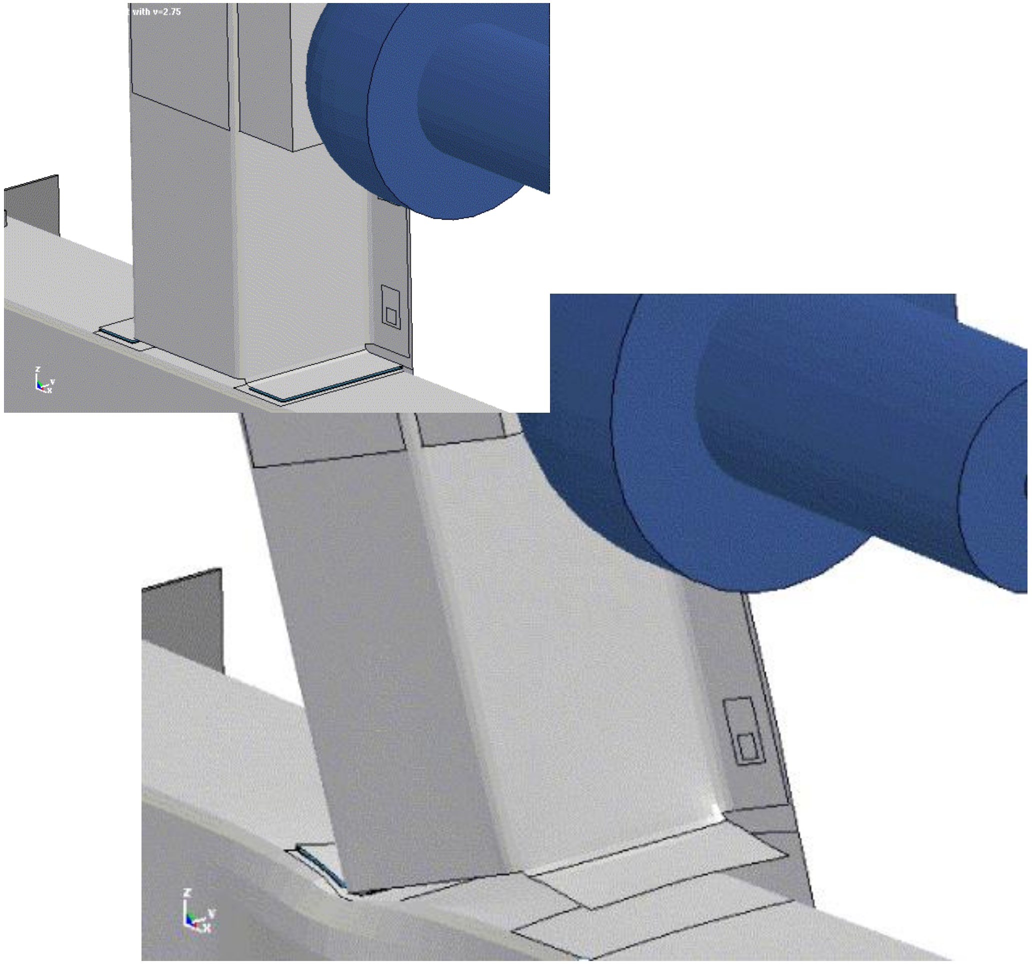
*) O. Hahn, M. Wißling, LWF, University of Paderborn, Report of project P676, FOSTA, 2007

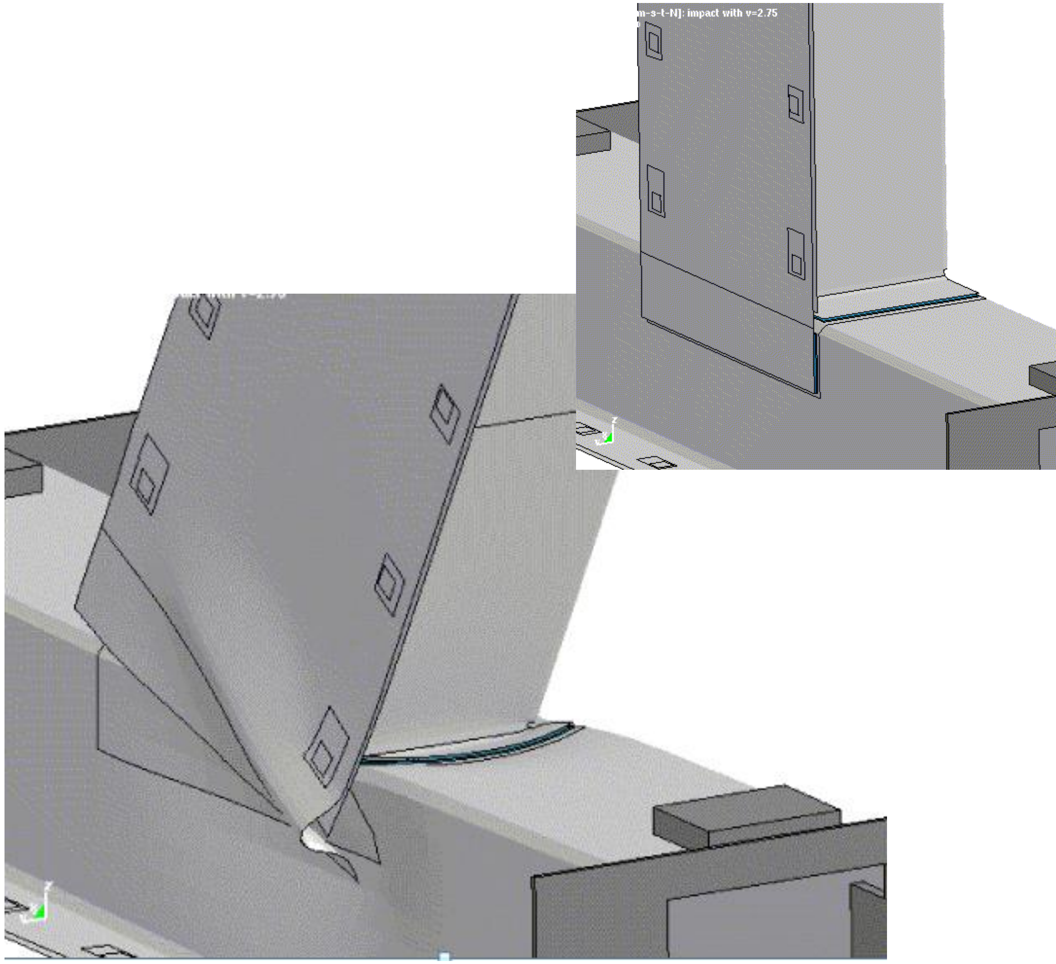
Validation by means of T-intersection (dynamic loading)



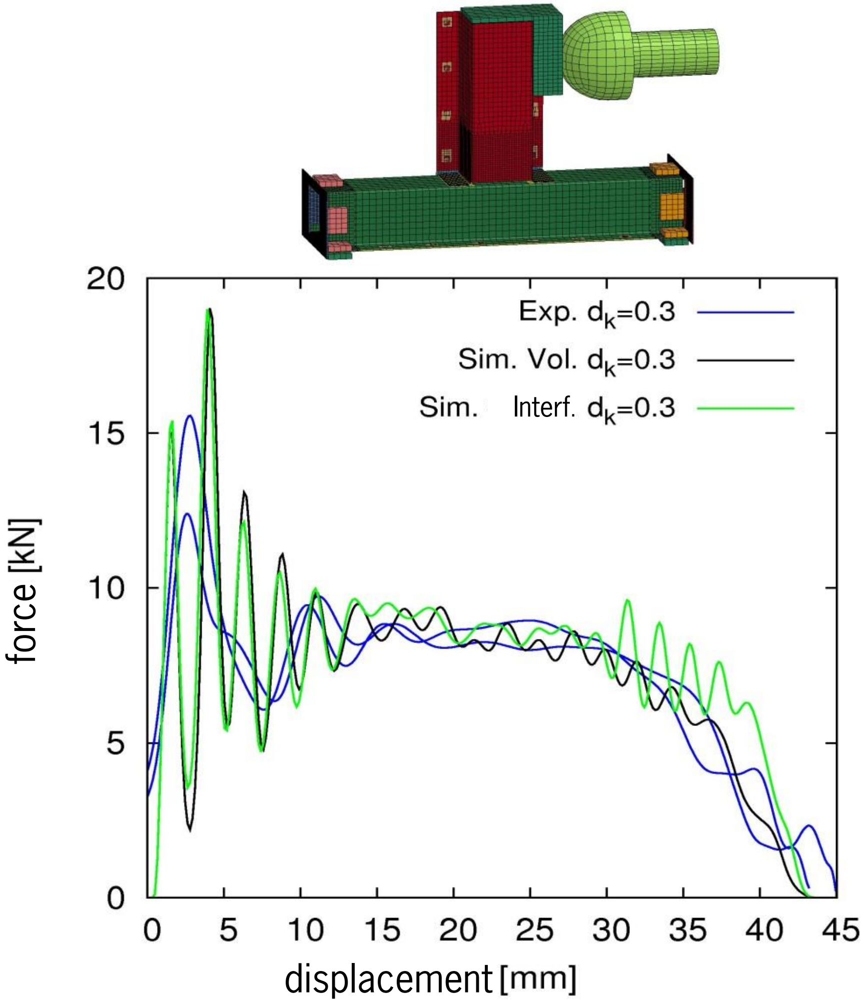
front:

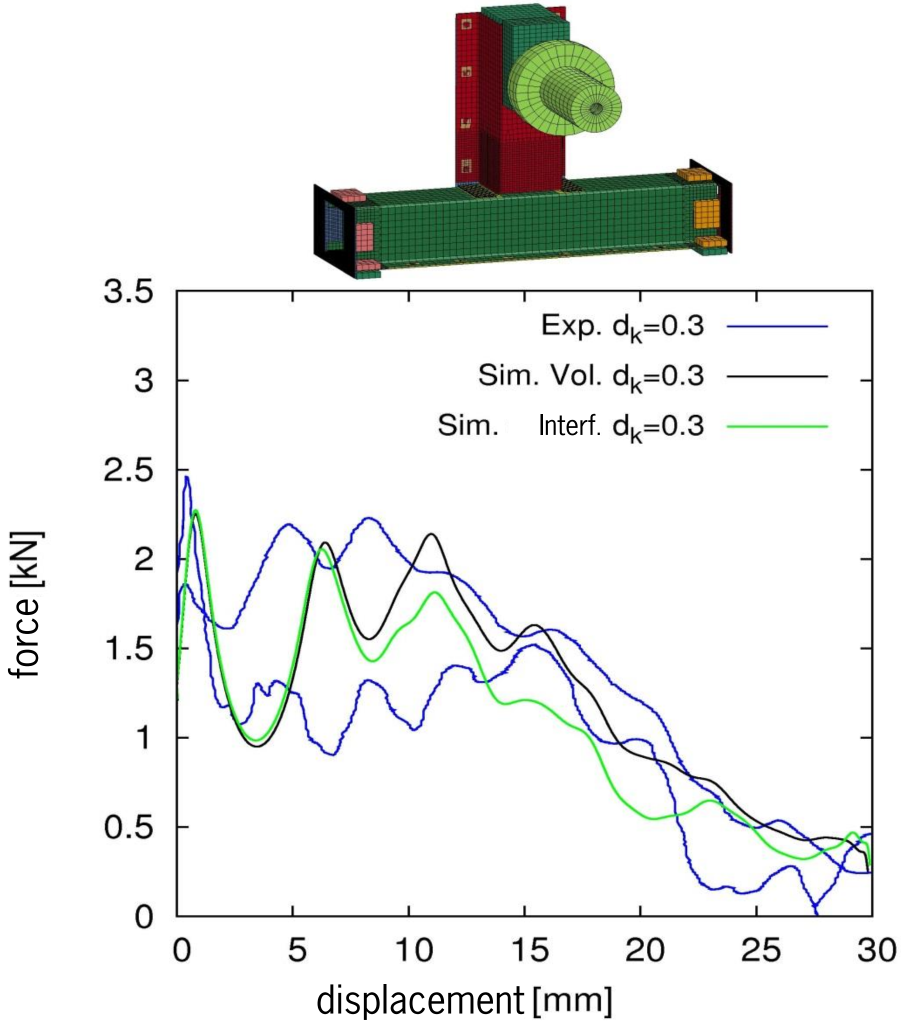


back:



Validation by means of T-intersection* (dynamic loading)





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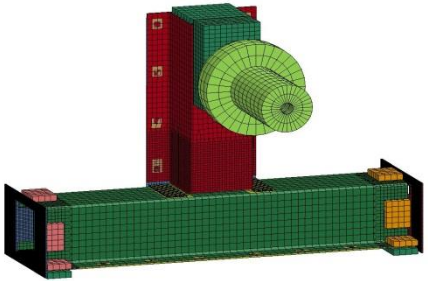
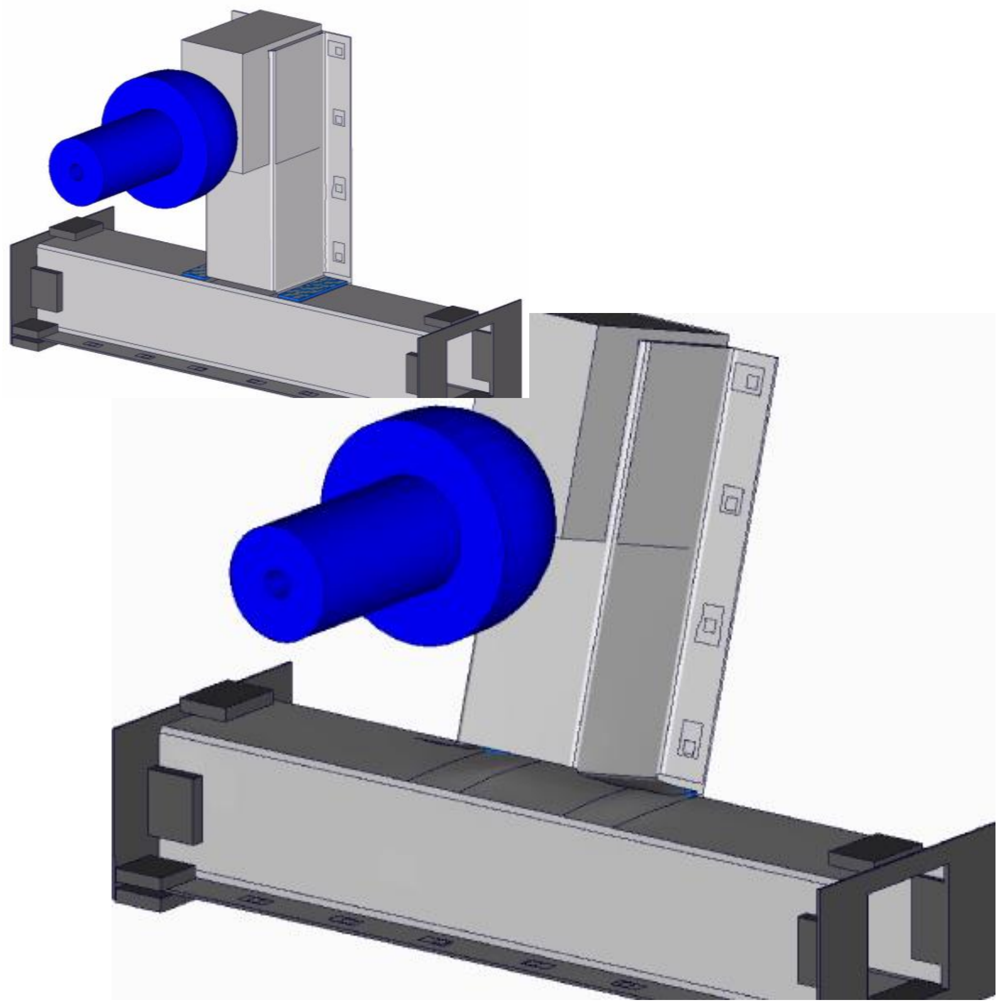
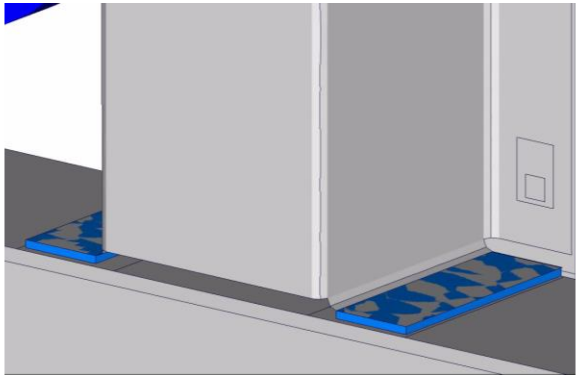
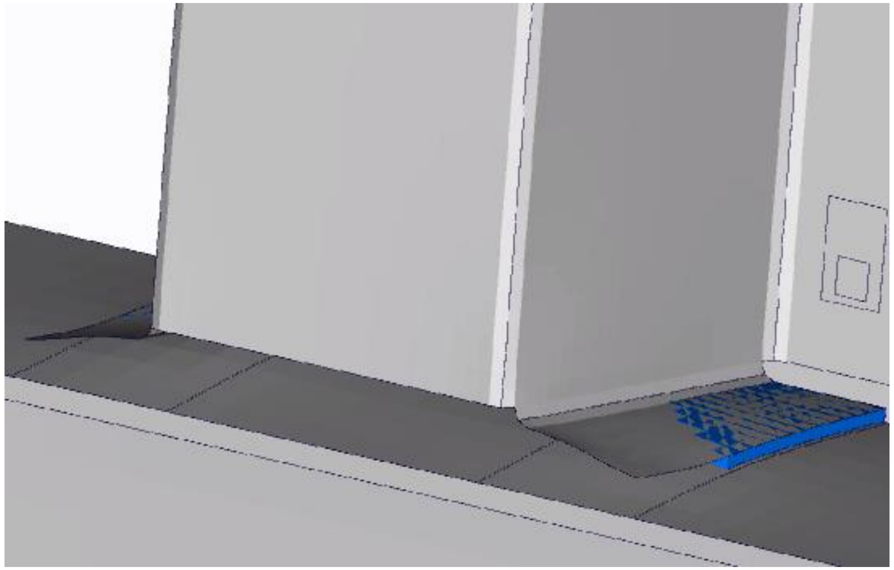
*) A. Matzenmiller, F. Burbulla,: Kontinuumsmechanische Modellierung von Stahlblechklebverbindungen für die FE-Crashanalyse, 7th German LS-DYNA Forum, Bamberg, 2008

Validation by means of T-intersection (dynamic loading)

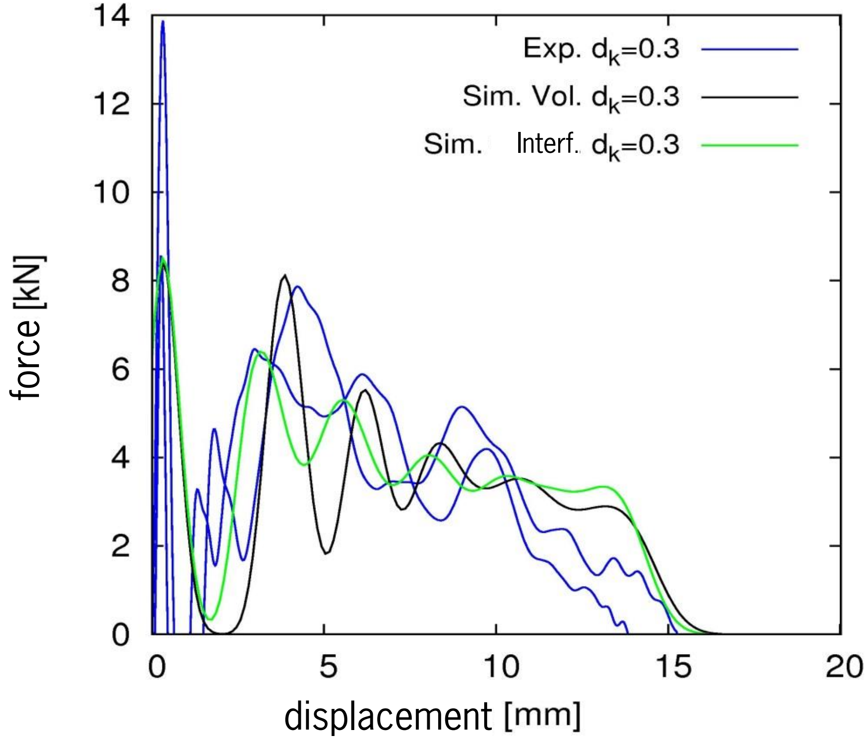




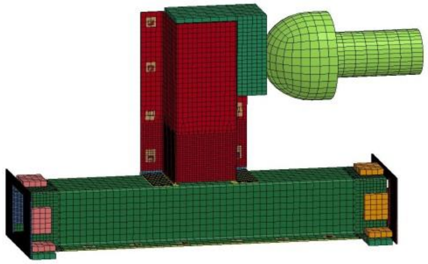


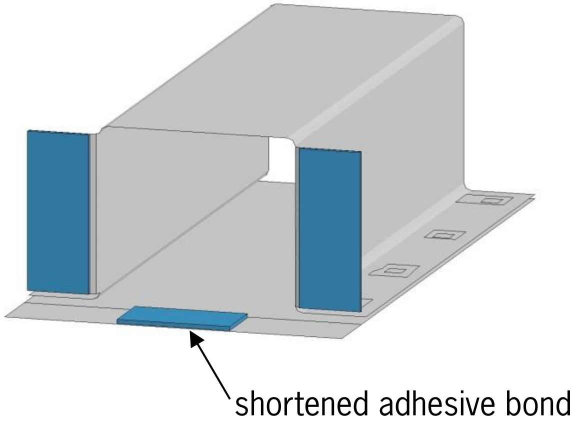


Validation by means of T-intersection* (dynamic loading)



loading in direction of the lower bearer
with shortened adhesive bond





*) A. Matzenmiller, F. Burbulla,: Kontinuumsmechanische Modellierung von Stahlblechklebverbindungen für die FE-Crashanalyse, 7th German LS-DYNA Forum, Bamberg, 2008

Future work

- The TAPO-model captures the basic phenomenological material properties of the rubber-toughened adhesive polymere → Transfer to different classes of adhesives possible
- Validation of TAPO-model and *MAT_ADD_COHESIVE by full vehicle simulations for different load cases will be finished in sommer 2015
- Damage initiation and fracture through *CURVES (function of triaxiality) resp. *TABLES (function of triaxiality and strain rate) will be possible
- Fracture shear strain will additionally be equipped with element size regularization
- Extension of the HISTORY variables
- Report in message file at beginning of damage - equivalent to spot weld formulation
- Effective default values for all material parameters
- …

Thank you for your attention!

Special thanks to Dr. Tobias Erhart (DYNAmore)

Acknowledgement:

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for the program
„Zukunftstechnologien für kleine und mittlere Unternehmen“ (ZUTECH)
on behalf of the
„Forschungsvereinigung Stahlanwendung e. V.“ (FOSTA).