DAIMLER

# Modelling of Adhesive Bonding in Crash Simulation

M. Feucht[1], A. Haufe[2], G. Pietsch[2]

[1] *Daimler AG, Sindelfingen*

[2] *Dynamore GmbH, Stuttgart*

DAIMLER

## Overview

Motivation

FEM modelling of adhesives

- Numerical aspects
- Physical behavior
- Material models

Validation & Verification

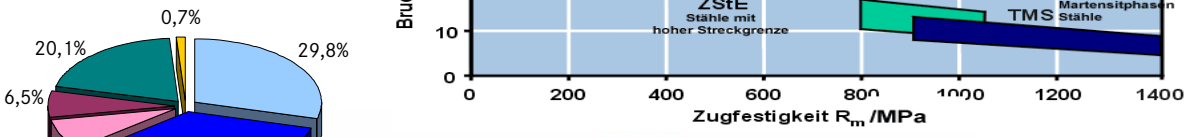
- KS2 specimen tests
- T-component test
- Full car crash test

Summary

DAIMLER

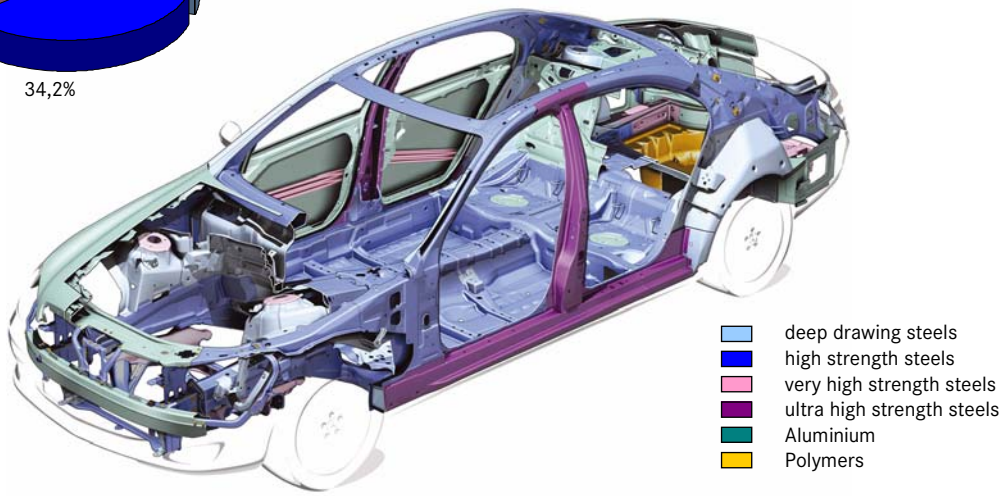
Motivation

# S-Class
## Material mix (body&white)












DAIMLER

Motivation

# S-Class
## Joining technology

| Thermical Joining | | BR220 | BR221 | Mechanical Joining | | BR220 | BR221 |
|---|---|---|---|---|---|---|---|
| Punktschweißen | [Stk.] | 5.486 | 6.343 | Stanznieten | [Stk.] | 93 | 105 |
| Schutzgas-Schweißen | [mm] | 1.820 | 2818 | Durchsetzfügen | [Stk.] | 153 | 658 |
| Laser-Schweißen | [mm] | 2.600 | 13.598 | Falzen | [mm] | 31.600 | 30.000 |
| Bolzenschweißen | [Stk.] | 392 | 460 | Blindnietmuttern | [Stk.] | 6 | 18 |
| Hartlöten | [mm] | 340 | 246 | Blindnieten | [Stk.] | 10 | 8 |

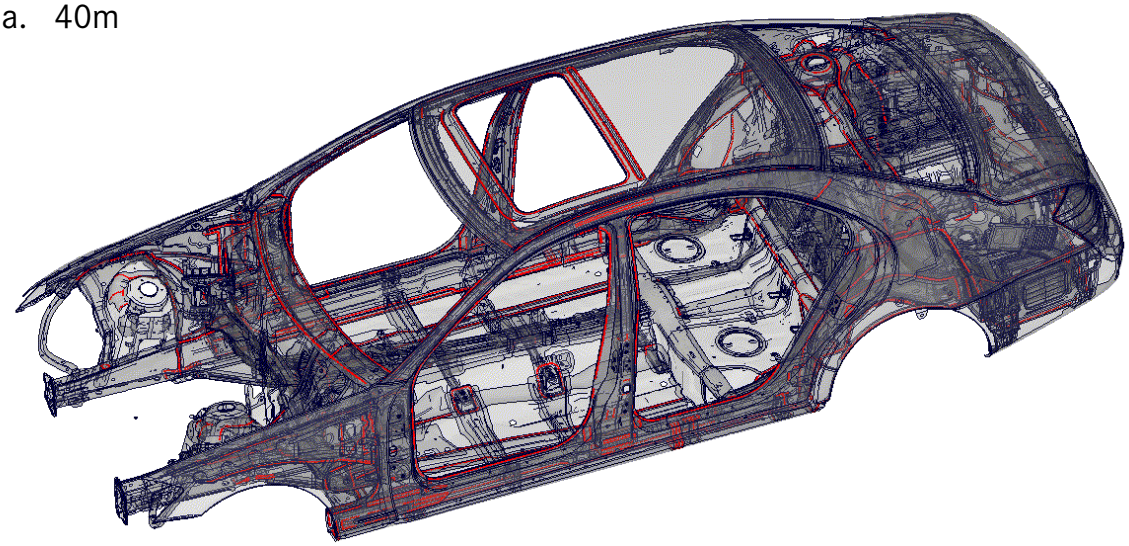
| Other Joining | | BR220 | BR221 |
|---|---|---|---|
| Kleben (Struktur-, Stütz-, und Dichtkleber) | [mm] | 72.500 | 191.704 |
| Nahtabdichtung | [mm] | 5.500 | 6.500 |
| Bauteile | [Stk.] | 405 | 463 |

DAIMLER

Motivation

## S-Class (body&white)
## Structural adhesive

- Structural adhesive
  ca. 150m
- Hood adhesive
  ca. 40m



6th LSDYNA-Forum, Frankenthal / Dr. Feucht (EP-SPB) / 2007-10-11 5

DAIMLER

FEM modelling: numerical aspects

## Joining in full car crash models



6th LSDYNA-Forum, Frankenthal / Dr. Feucht (EP-SPB) / 2007-10-11 6

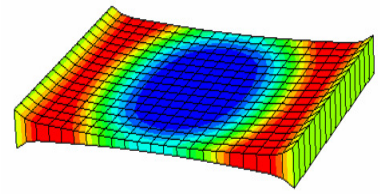
DAIMLER



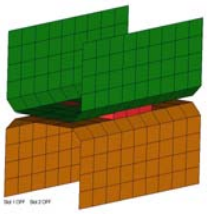
# FEM modelling technique for adhesives

## Spatial discretization

- Detailed model

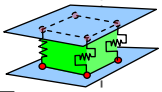


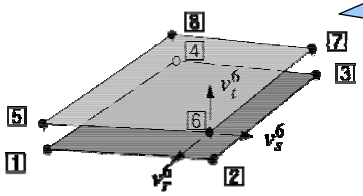
- Substitution model



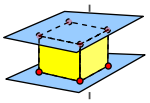
## Choice of finite element model

- Cohesive zone model






- Continuum mechanics model



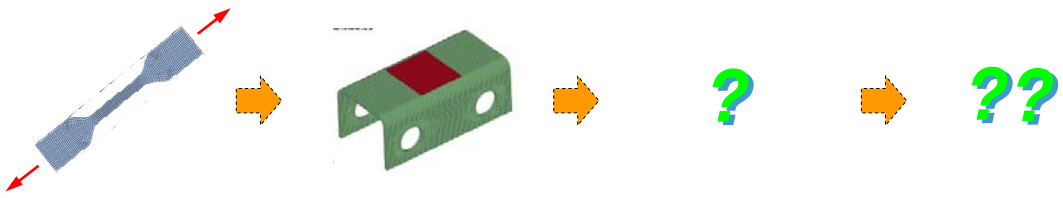


DAIMLER



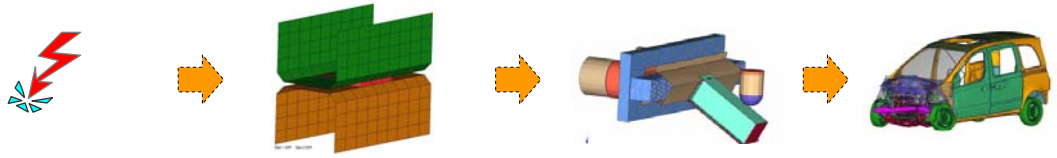
# Verification & validation process
## Consistency

### Detailed model with physical material parameters




Application of measured physical parameters makes sense only in detailed models!

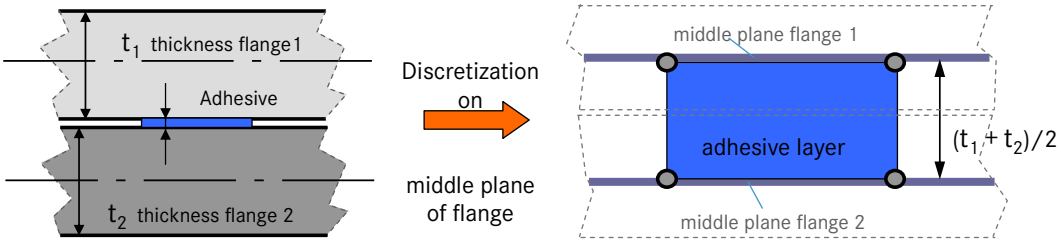
### Substitute model with artificial model parameters



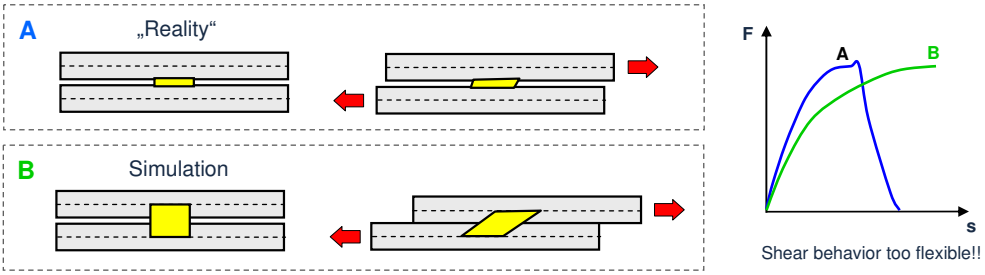
DAIMLER



# Adhesive substitution model for crash application




## A discretization issue

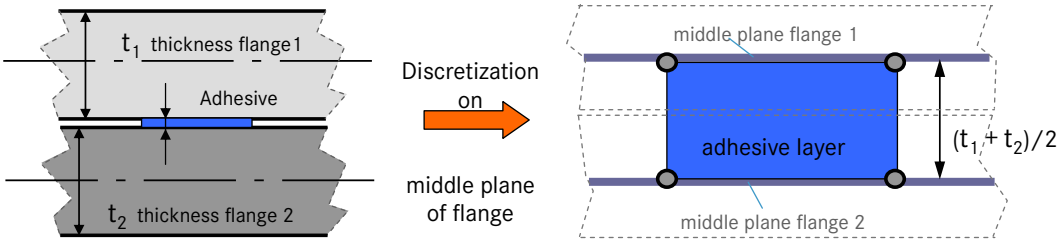




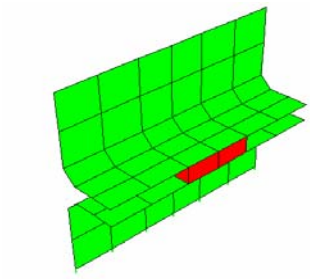

DAIMLER

FEM modelling: numerical aspects

# Adhesive substitution model for crash application




## A discretization issue



Possible discretization of adhesive:

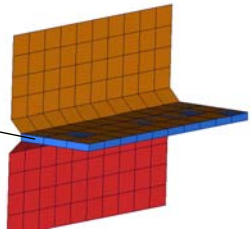
- Volume element
- Cohesive element
- Contact element

DAIMLER

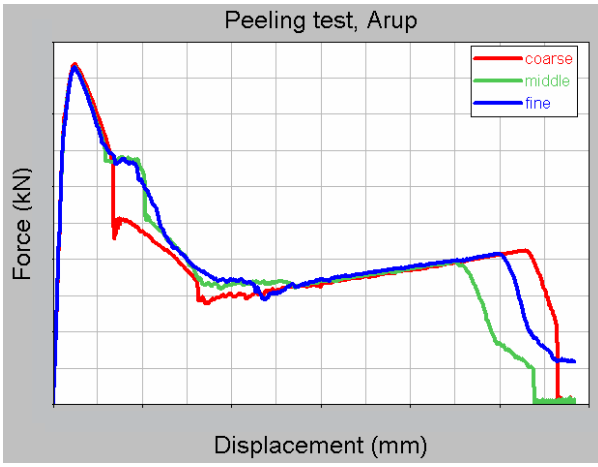


## Influence of mesh size
### Peeling test

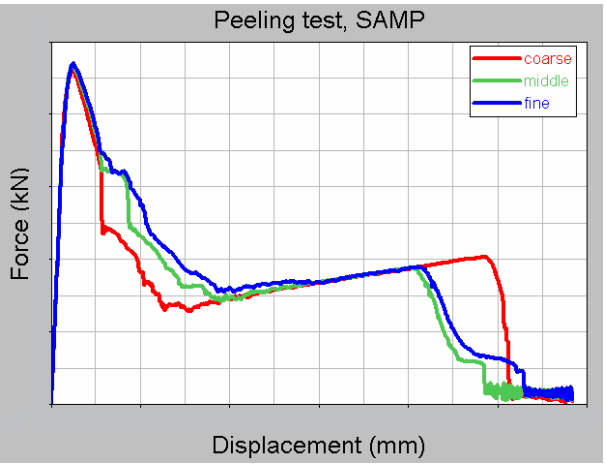
coarse: 3 elements
middle: 6 elements
fine: 12 elements
(only adhesive mesh!)



Cohesive model




Volume element

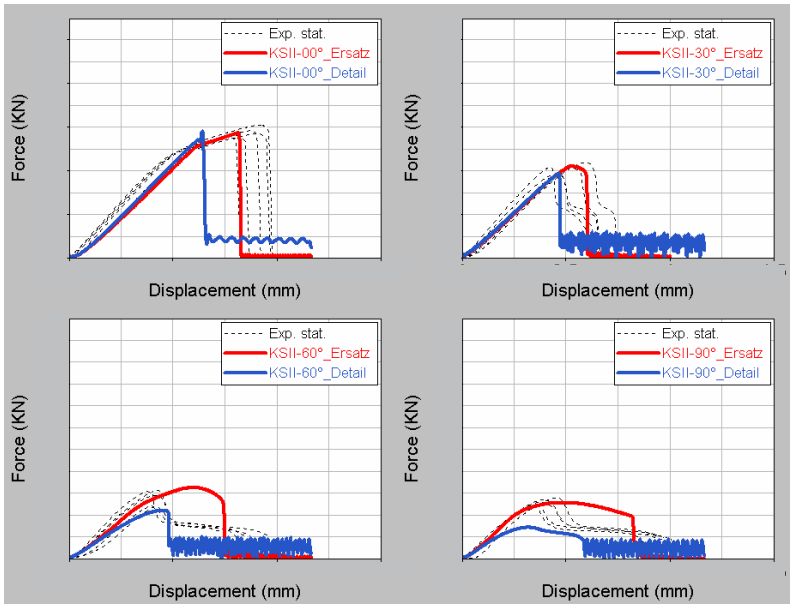


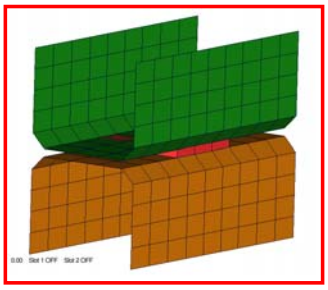


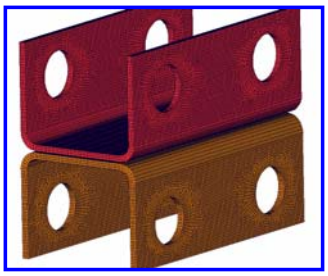

DAIMLER



## Comparison detailed vs. substitute model
### KS2 simulation
### continuum approach (SAMP model)



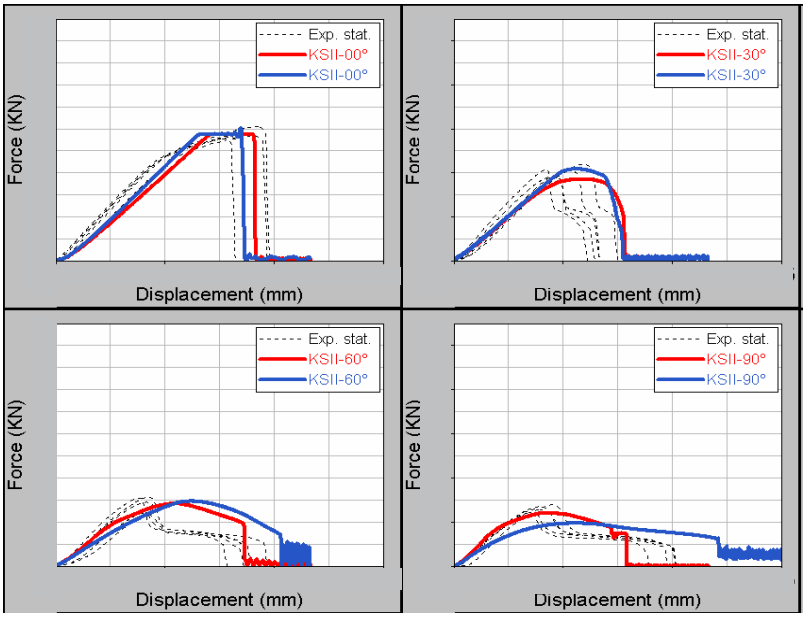


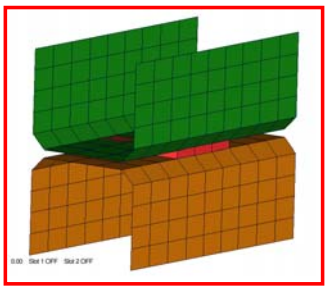
DAIMLER

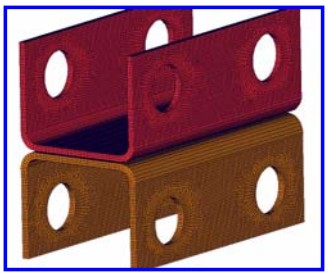


# Comparison detailed vs. substitute model

## KS2 simulation
## cohesive approach (ARUP model)





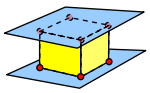


DAIMLER



# Cohesive vs. continuum approach

### Continuum element formulation



$$\boldsymbol{K} = \iiint \boldsymbol{BCB}^T \det \boldsymbol{J}\, d\xi\, d\eta\, d\zeta$$

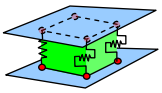
- Integration over volume
- Linear in 3D
- Gaussian integration rule
- Thickness = element length:

$$\boldsymbol{\varepsilon} = \nabla^{sym}\mathbf{u}$$

- Stress vs. strain fully coupled

$$\boldsymbol{C}^{el} = \left[\begin{array}{ccc|c} C_{11} & C_{12} & \dots & C_{16} \\ C_{21} & C_{22} & \dots & C_{26} \\ \dots & \dots & \dots & \dots \\ \hline C_{61} & C_{11} & \dots & C_{66} \end{array}\right]$$

### Cohesive (interface) element formulation



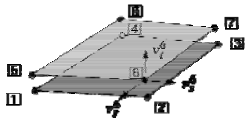
$$\boldsymbol{K} = \iint \boldsymbol{BCB}^T \det \boldsymbol{J}\, d\xi\, d\eta$$

- Integration over area
- No in-plane (stress) components
- Lobatto integration rule
- Thickness =/= element length

$$\varepsilon_z = \frac{\Delta w}{l_c}, \varepsilon_{zx} = \frac{\Delta u}{l_c}, \varepsilon_{zy} = \frac{\Delta v}{l_c}$$

- Traction vs. relative displacement **(=test data)**

$$\boldsymbol{C}^{el} = \begin{bmatrix} d_r & 0 & 0 \\ 0 & d_s & 0 \\ 0 & 0 & d_t \end{bmatrix}$$



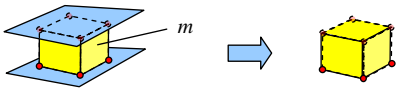
DAIMLER



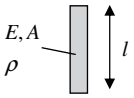
# Critical time step

- Correct time step calculation: consideration of ***structural*** wave propagation
- Practical use in all FEM-codes: consideration of ***elementwise*** wave propagation

**Continuum element formulation**

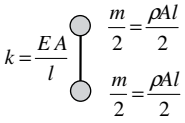



*Consider thickness direction only:*



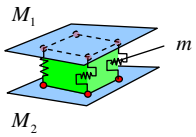

$$\Delta t = \frac{l}{c} = l\sqrt{\frac{\rho}{E}}$$

*Courant-Friedrichs-Levy-criterion (CFL)*

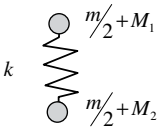



$$\Delta t = \sqrt{\frac{m}{k}} \quad \left( = l\sqrt{\frac{\rho}{E}} \right)$$

**Cohesive (interface) element formulation**




*very similar to spring elements!*

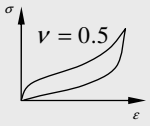
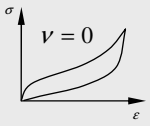
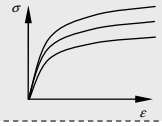



$$\Delta t = \sqrt{\frac{m + M_1 + M_2}{k}}$$



DAIMLER

# Mechanical characterization

| Material behaviour | | Choice of material model |
|---|---|---|
| • PU Windshield => rubber-like, viscous |   | • Hyperelastic<br>• Viscous |
| • Hood => foam-like, viscous |   | • Hyperelastic<br>• Viscous |
| • Structure => visco-plastic |   | • Strain rate dependent<br>• Plastic |

Failure description
- Johnson-Cook
- Energy release rate
- Strain or stress based

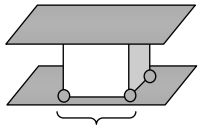
DAIMLER



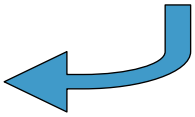
# Commonly used material models in LS-DYNA

**Rubber-like adhesives** (PU windshield)

- MAT_SIMPLIFIED_RUBBER (MAT_181)
  ν=0.01 ... 0.499 (Hill)
  [DuBois/Feng/Kolling 2005]
- MAT_SIMPLIFIED_RUBBER_WITH_DAMAGE (MAT_183)
  ν=0.499 (Ogden)
  [Kolling/DuBois/Benson 2006], work in progress for ν=0.01 ... 0.499
- ...



ν=0
due to constraints



**Foam-like adhesives** (Hood)

- MAT_FU_CHANG_FOAM (MAT_83) ν=0
  modification due to unloading via damage
  [Kolling/Werner/Erhart/DuBois 2007]
- ...

**Visco-plastic adhesives** (Structural adhesive)

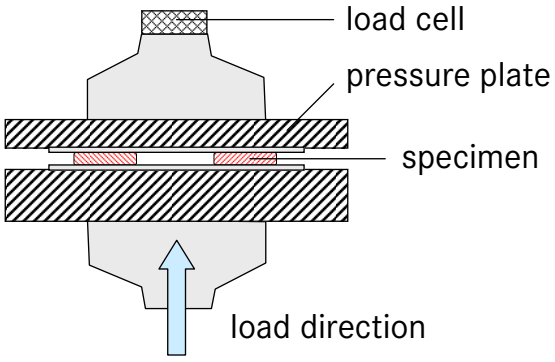
- MAT_ARUP_ADHESIVE
- MAT_SAMP (MAT_187)
  [Kolling/Haufe/Feucht/DuBois 2005]
- ...



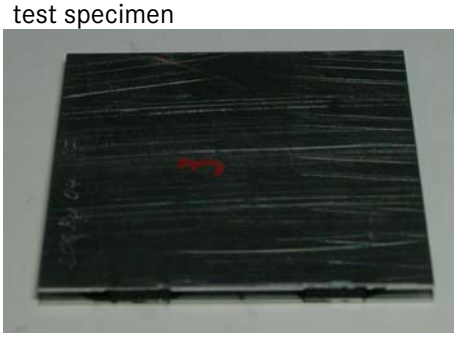
DAIMLER



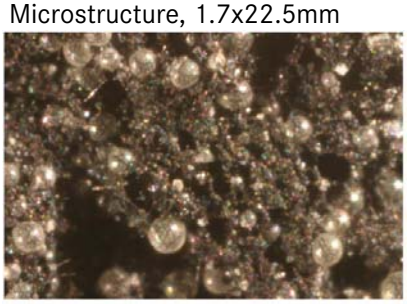
# Foam like adhesive: EFBond




test specimen



Microstructure, 1.7x22.5mm



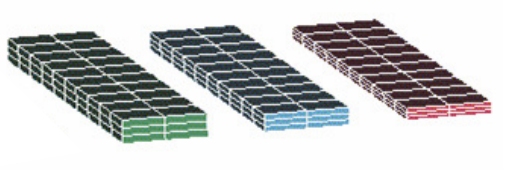
compression

DAIMLER

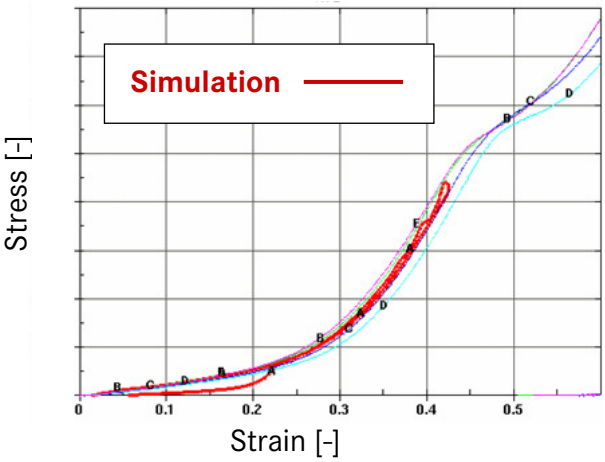


# Foam like adhesive: EFBond

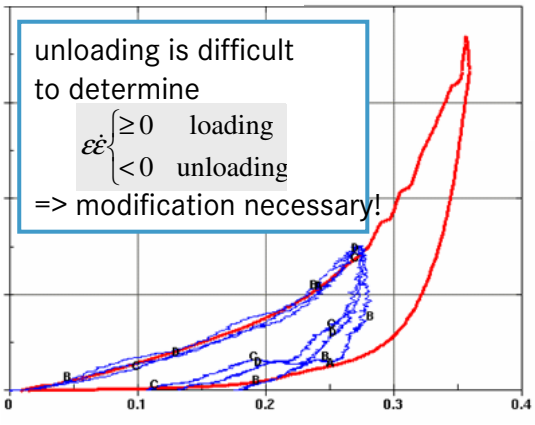
EFBond: MAT_FU_CHANG_FOAM (MAT_83) in LS-DYNA
l=100mm, b=15mm and t=2/3/4 mm
volume elements: min l = 0.67mm
timestep = 6.8 $10^{-6}$ s



quasi static loading




dynamic loading: 800/s



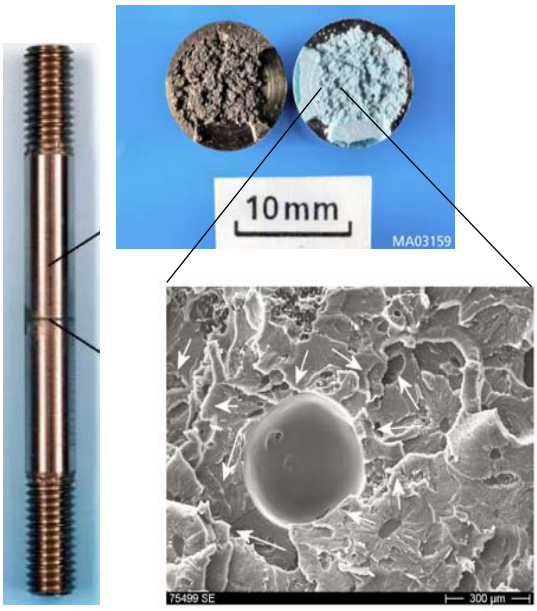



DAIMLER

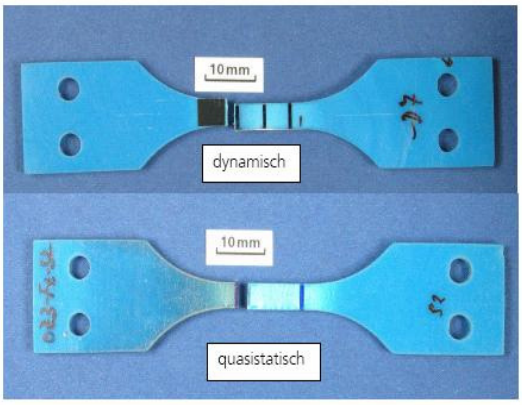


# Structural adhesive: BM1496 (DOW)

Bonded specimen




Substanzprobe



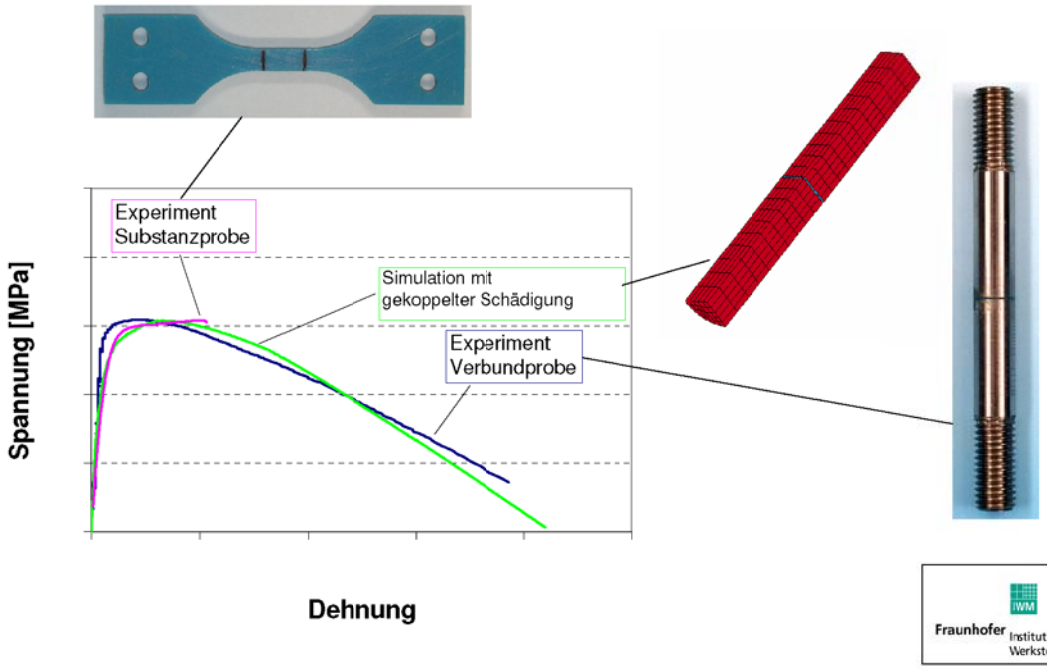

Crazing at static loading

Fraunhofer Institut Werkstoffmechanik IWM

DAIMLER

FEM modelling: physical behavior

## Structural adhesive: BM1496 (DOW)



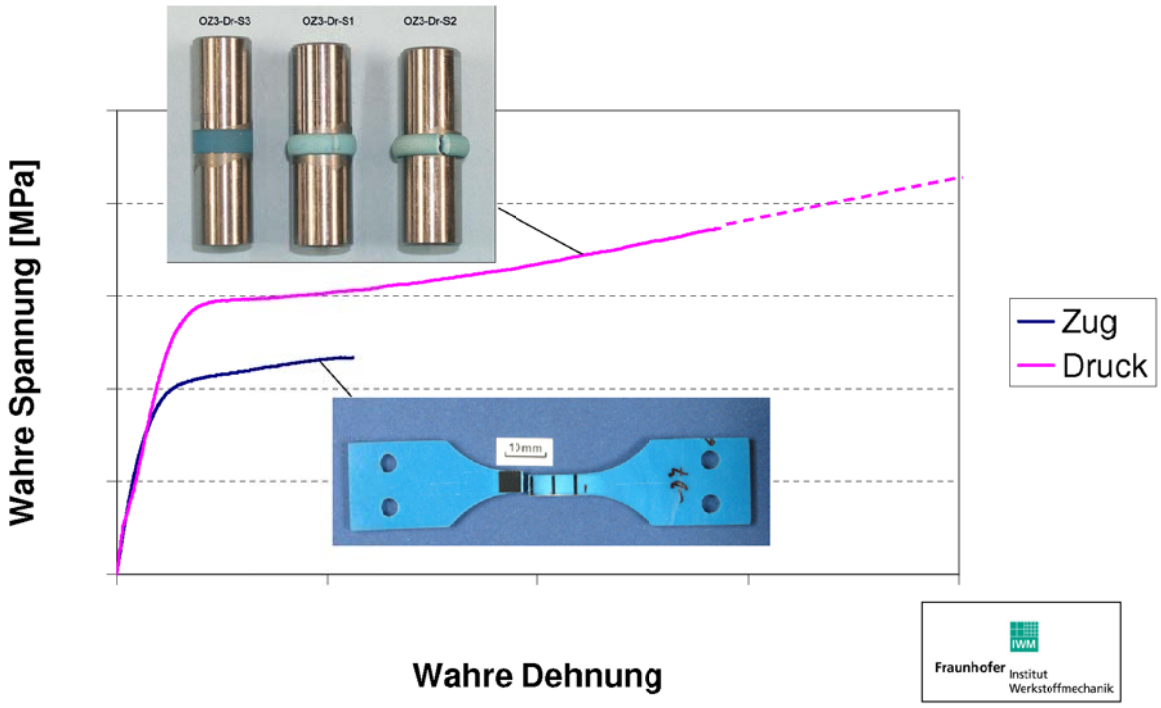

Fraunhofer Institut Werkstoffmechanik



DAIMLER

FEM modelling: physical behavior

## Structural adhesive: BM1496 (DOW)

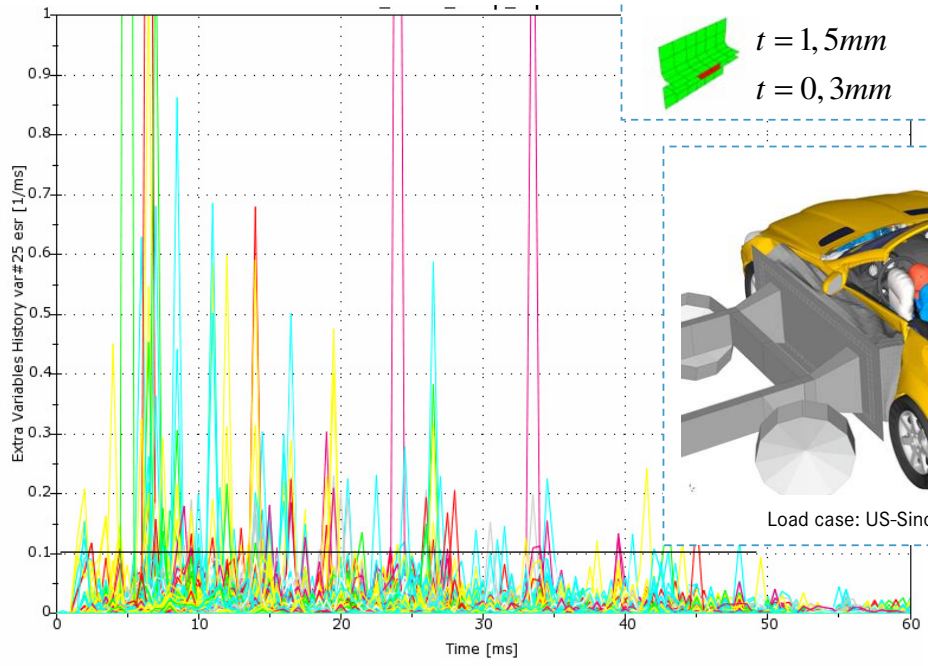



Fraunhofer Institut Werkstoffmechanik

DAIMLER



## Estimate of strain rates from simulation




Modeled thickness of adhesive :



$t = 1,5mm$ $\dot{\varepsilon} \approx 100\ /\ s$

$t = 0,3mm$ $\dot{\varepsilon} \approx 500\ /\ s$

Load case: US-Sincap, v=64 km/h



DAIMLER



## Visco-plastic adhesives
## Investigated models

Continuum model

- **MAT_SAMP-1 (MAT_187)**
- **MAT_GURSON (MAT_120)**
- **Fleck Modell (IWM, User material)**
- Schlimmer (not implemented)
- Spotweld model (MAT_100)

Cohesive model

- **MAT_ARUP_ADHESIVE (MAT_169)**
- **MAT_COHESIVE_GENERAL (MAT_186)**
- **MAT_COHESIVE_MIXED_MODE (Matzenmiller, MAT_138)**

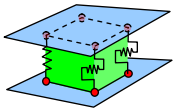
Contact formulation

- Contact_One_Way_Surface_ To_Surface_Tiebreak (opt=9)

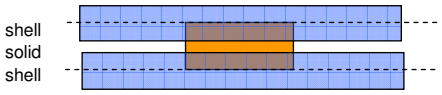
DAIMLER



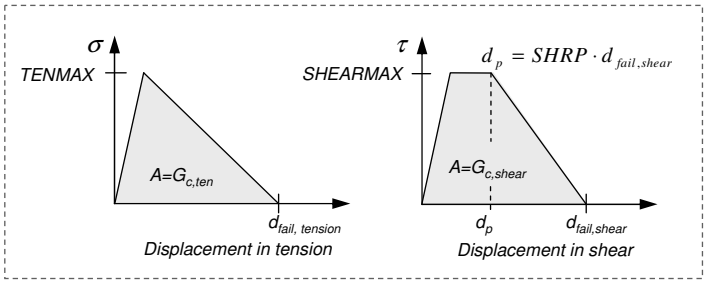
# Cohesive approach
## MAT_ARUP_ADHESIVE



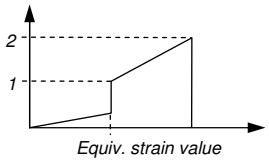
- Modeling with array of solid elements
- Identical solid formulation as in spot weld modeling
- Tied contact in combination with automatic contact
- Failure criterion:




$$\left(\frac{\sigma}{\sigma_{\max}}\right)^{PWRT}+\left(\frac{\tau}{\tau_{\max}}\right)^{PWRS}-1.0=0$$




- Fracture energies for tension and shear as input parameters
- Plastic flow is not volume conserving (not isochoric, ν ≠ 0.5)
- Special output of equiv. plastic strain if element is fading:
  equiv. pl. strain > 1.0 => Element started fading
  equiv. pl. strain = 2.0 => Element failed

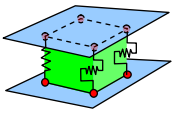





DAIMLER



# Cohesive approach
## MAT_COHESIVE_MIXED_MODE



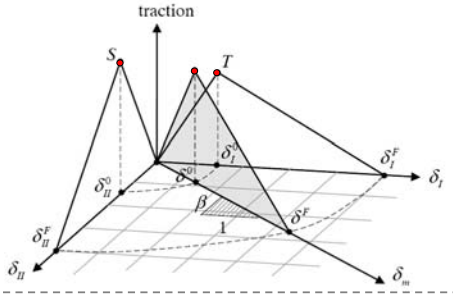
- To be used with cohesive element formulation
- Based on works of Matzenmiller et al.
- Failure occurs when 1 or up to 4 integration points fail (selectable)
- Loading and unloading **do not** follow same path
- Elastic behaviour under compression
- The mixed mode model allows definition of bilinear traction – relative displacement behaviour in mode I (tension) and mode II (shear) loading
- Mode I relative displacement: $\delta_I = \delta_3$ ; mode II relative displacement: $\delta_{II} = \sqrt{\delta_1^2 + \delta_2^2}$
- Computed mixed mode displacement: $\delta_m = \sqrt{\delta_I^2 + \delta_{II}^2}$

[see Gerlach & Matzenmiller 2006]

- Onset of softening is given $\delta^0 = \delta_I^0 \delta_{II}^0 \sqrt{\frac{1+\beta^2}{\left(\delta_{II}^0\right)^2 + \left(\beta\delta_I^0\right)^2}}$

where $\beta = \delta_{II} / \delta_I$ *"mode mixity"*

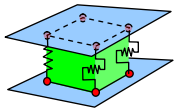
$\delta_I^0 = T / EN$, $\delta_{II}^0 = S / ET$ *"peak tractions"*



DAIMLER



# Cohesive approach
## MAT_COHESIVE GENERAL

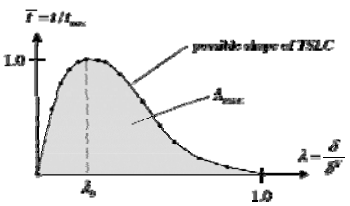


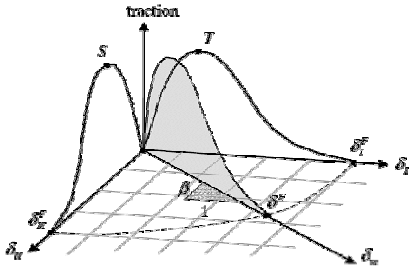
- To be used with cohesive element
- A normalized traction separation curve must be defined.
  From this, the maximum (failure) separations for mode I and mode II are computed according to:

Mode I : $\delta_I^F = \frac{G_I^C}{A_{TSLC} \cdot T}$ Mode II : $\delta_{II}^F = \frac{G_{II}^C}{A_{TSLC} \cdot S}$

where A represents the are under the tabulated curve and G the fracture energy release rate of the corresponding mode. T and S are maximum tractions in tension and shear.

- Failure occurs when 1 or up to 4 integration points fail (selectable)
- Loading and unloading **do not** follow same path




$\delta_1 = \delta_3$

$\delta_{II} = \sqrt{\delta_1^2 + \delta_2^2}$

$\delta_m = \sqrt{\delta_I^2 + \delta_{II}^2}$

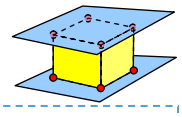
Local coordinate system

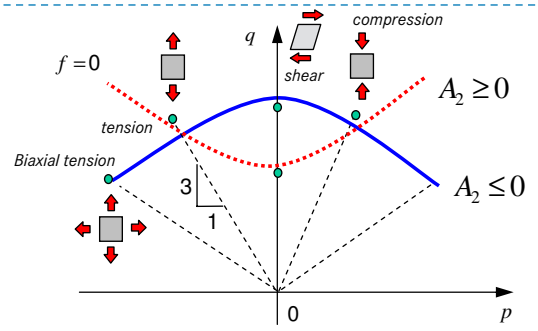


DAIMLER



# Continuum model
## MAT_SAMP (R4)



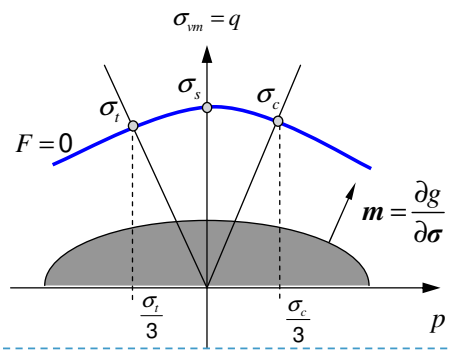



Yield surface (modified Schlimmer):

$$f(p, \sigma_{vm}, \bar{\varepsilon}^{pl}) = \sigma_{vm}^2 - A_0 - A_1 p - A_2 p^2 \le 0$$

Condition for convexity :

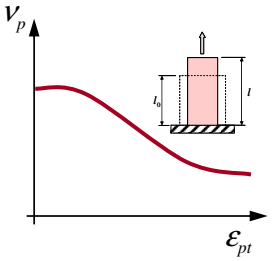
$$A_2 \le 0 \Leftrightarrow \sigma_s \ge \frac{\sqrt{\sigma_t \sigma_c}}{\sqrt{3}}$$




$$g = \sqrt{\sigma_{vm}^2 + \alpha p^2}$$

Flow parameter correlates to plastic Poisson's ratio:

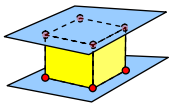
$$\alpha \propto \upsilon_p = \frac{9 - 2\alpha}{18 + 2\alpha} \le 0.5$$



DAIMLER



# Continuum model
## Fleck model (User routine)



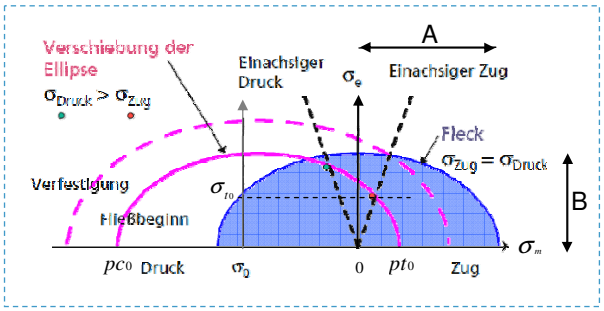
- Yield function

$$\Phi = \hat{\sigma} - \sigma_{t,y}(\bar{\varepsilon}_p) \le 0$$

$$\hat{\sigma}^2 = \sigma_e^2 + \alpha^2(\sigma_m - \sigma_0)^2$$

$$\alpha = \frac{B}{A} \qquad \sigma_0 = \frac{|p_t^0| - |p_c^0|}{2}$$

$$\alpha_0 = \frac{3k_0}{\sqrt{(3k_t^0 + k_0)(3 - k_0)}} \quad \text{and} \quad k_0 = \left|\frac{\sigma_c^0}{p_c^0}\right| \qquad k_t^0 = \left|\frac{p_t^0}{p_c^0}\right|$$




[Source: IWM]

Strain rate dependence via Johnson & Cook: $\sigma_t = \sigma_{t0} \cdot [1 + C \cdot \ln(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})]$

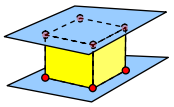
Fraunhofer Institut Werkstoffmechanik



DAIMLER



# Continuum model
## Fleck model (User routine)

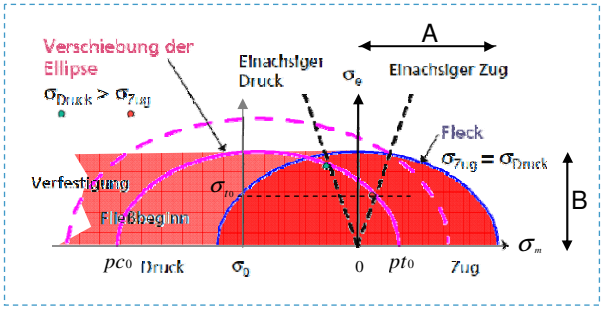


- Plastic Potential

$$G = \sqrt{\sigma_e^2 + \beta^2 \sigma_m^2}$$

$$\beta = \frac{3}{\sqrt{2}} \sqrt{\frac{1 - 2\nu_p}{1 + \nu_p}}$$

$$\Leftrightarrow \quad \nu_p = -\frac{\Delta\varepsilon_{11}^p}{\Delta\varepsilon_{33}^p} = \frac{\frac{1}{2} - \left(\frac{\beta}{3}\right)^2}{1 + \left(\frac{\beta}{3}\right)^2}$$




[Source: IWM]

i.e. β determines plastic Poisson's ratio (dilatancy!).

If β < 0, potential switches to vonMises type.

- Failure criterion

Johnson & Cook (with strain rate dependency): $\bar{\sigma}_y^{pl} = \left[d_1 + d_2 \exp\left(d_3 \frac{p}{q}\right)\right]\left[1 + d_4 \ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\bar{\varepsilon}}_0}\right)\right]$

DAIMLER



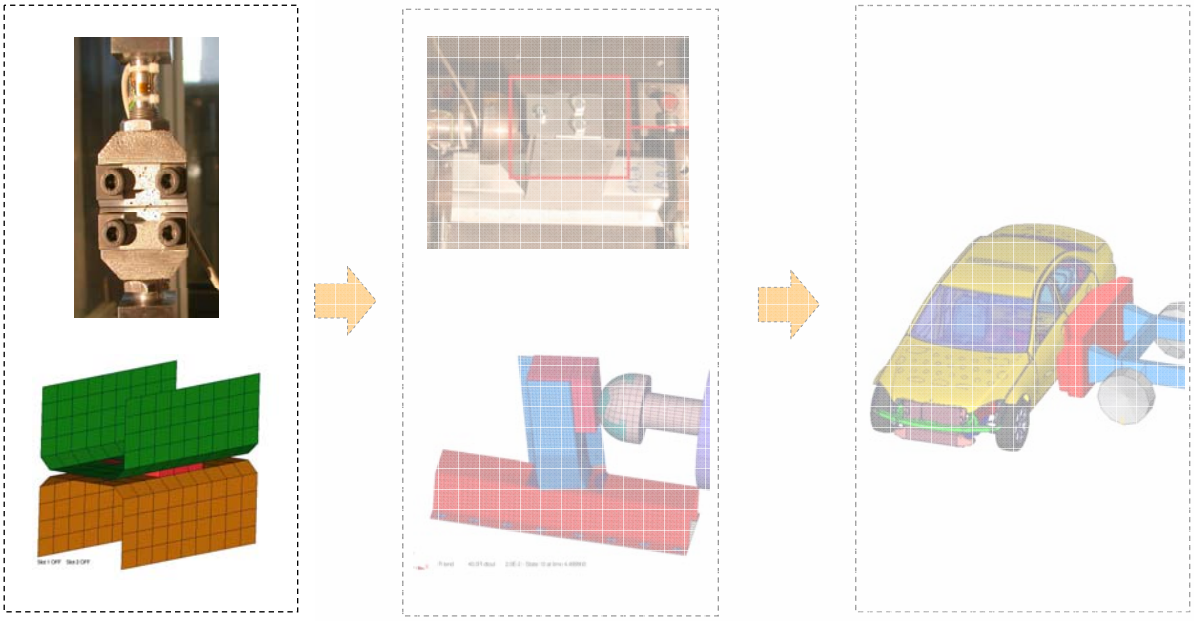
# Continuum theory based models
## Comparison

| | Schlimmer | IWM-Fleck | SAMP-1 |
|---|---|---|---|
| Yield function | $f=\sigma_{vm}^2+9a_2(p-\sigma_0)^2-Y^2$ | $f=\sqrt{\sigma_{vm}^2+\alpha^2(p-\sigma_0)^2}-Y$ | $f=\sigma_{vm}^2-A_0-A_1p-A_2p^2$ |
| Plastic potential | $g=\sigma_{vm}^2+\beta^2p^2$ | $g=\sqrt{\sigma_{vm}^2+\langle\beta\rangle^2p^2}$ | $g=\sigma_{vm}^2+\alpha p^2$ |
| Yield stress<br>- Reference | Shear / Torsion | Shear/Compression/ Tension | Shear/Compression/ Tension/Biaxial |
| - Defined by | Parameter | Parameter | Tabulated |
| - Strain rate | × | ✓ | ✓ |
| Failure model | × | Johnson-Cook | tabulated regularized |



DAIMLER

# Verification & validation process
## KS2 test verification

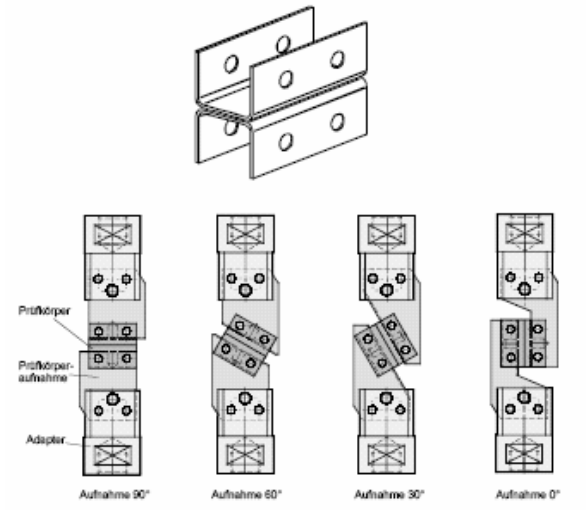


DAIMLER

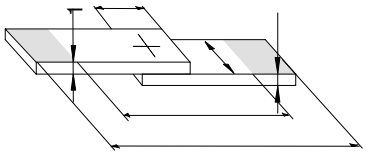


# Verification experiments
## KS2 tests

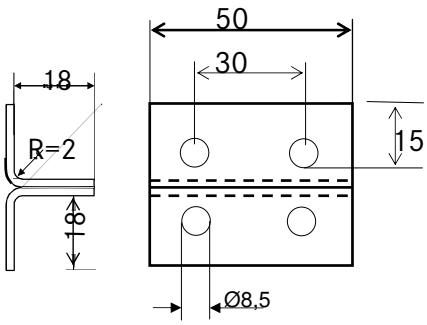
KS2 Specimen
90°, 60°, 30°, 0°




Shear



Peel-test



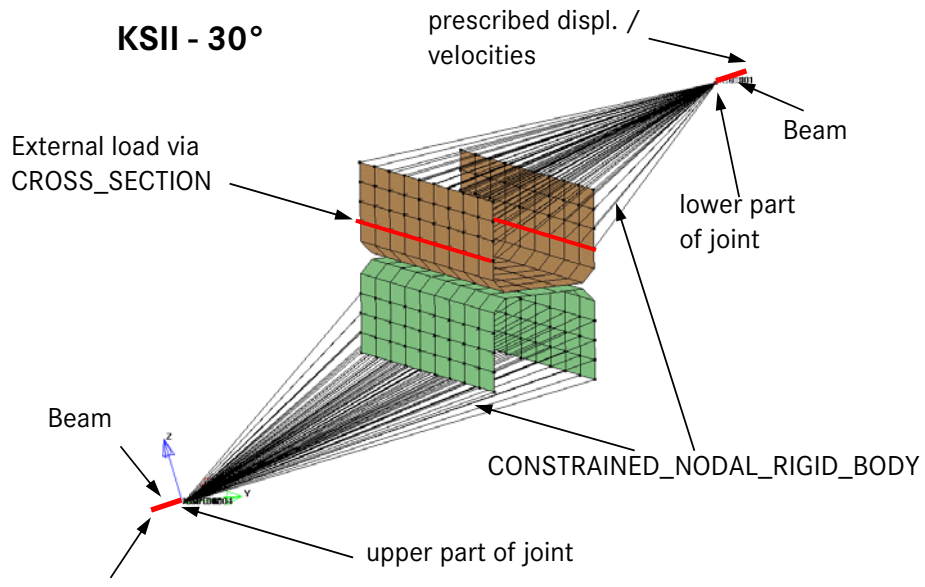



DAIMLER



# KSII test configuration
## Crash consistent simulation model

**KSII - 30°**



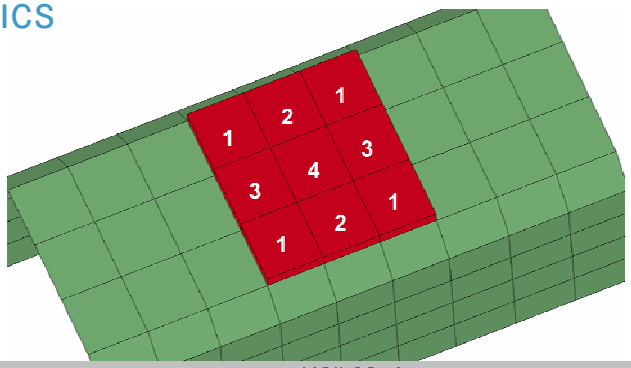

**KSII – 0°**

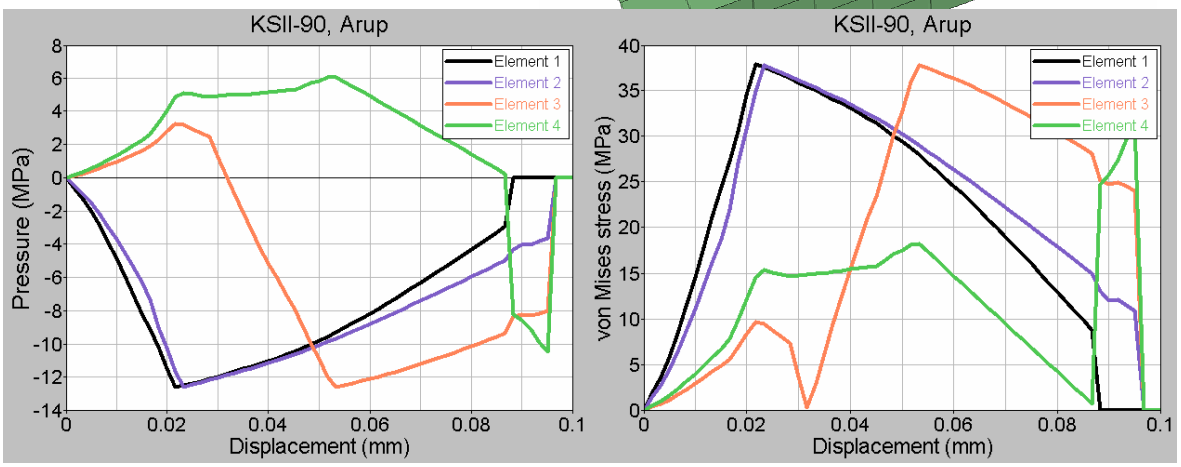
LWF
Uni Paderborn

DAIMLER

Validation & Verification: KS2 tests

# Cross tension characteristics
## KS2 - 90°



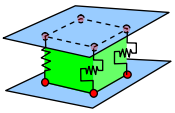






DAIMLER

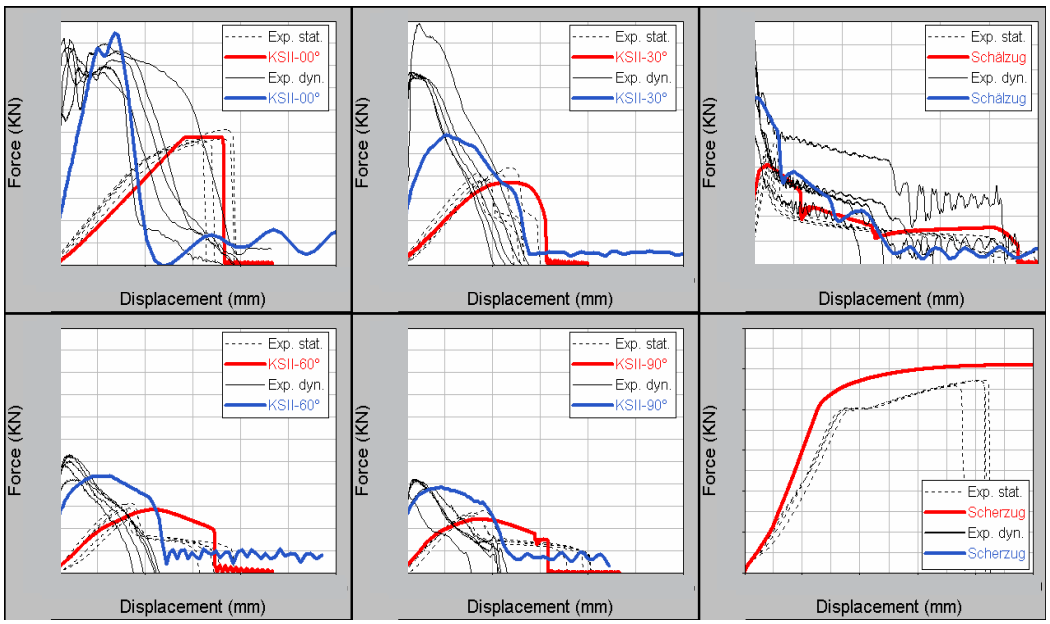
Validation & Verification: KS2 tests

# KS2 simulation results
## ARUP model



1 strain rate dependent material card!

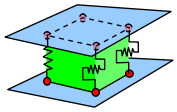
dynamic loading (2.5 m/s)
quasi-static loading



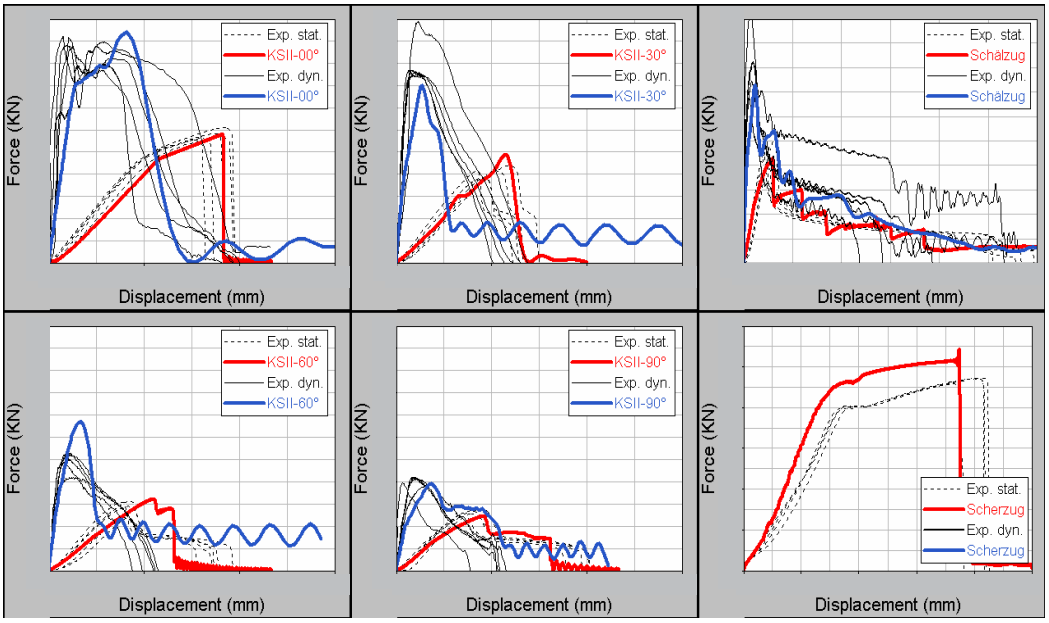

DAIMLER



# KS2 simulation results
## Cohesive general model



2 Materialcards, because model is not strain rate dependent!

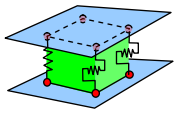




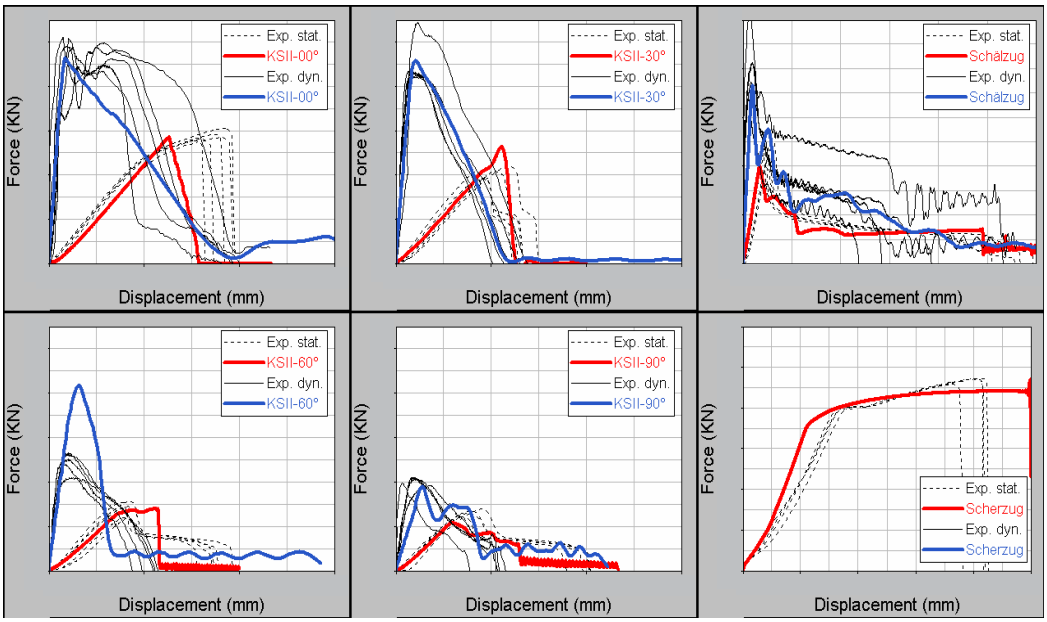

DAIMLER

Validation & Verification: KS2 tests

# KS2 simulation results
## Cohesive mixed mode model



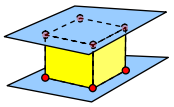
2 Materialcards, because model is not strain rate dependent!



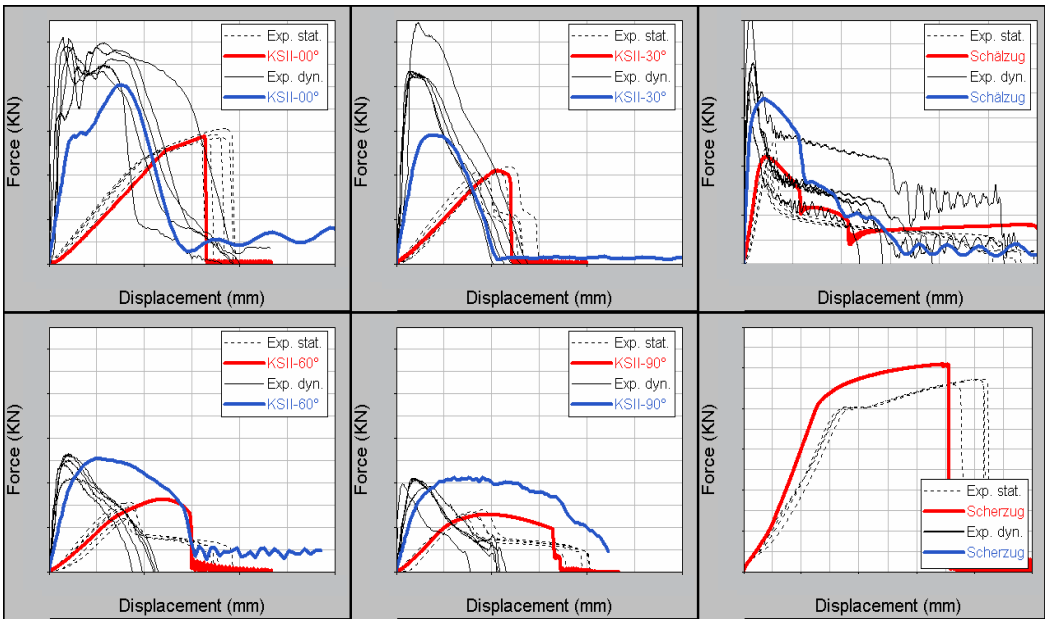

DAIMLER

Validation & Verification: KS2 tests

# KS2 simulation results
## SAMP model (R4)



1 strain rate dependent material card!

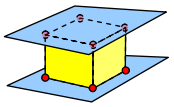




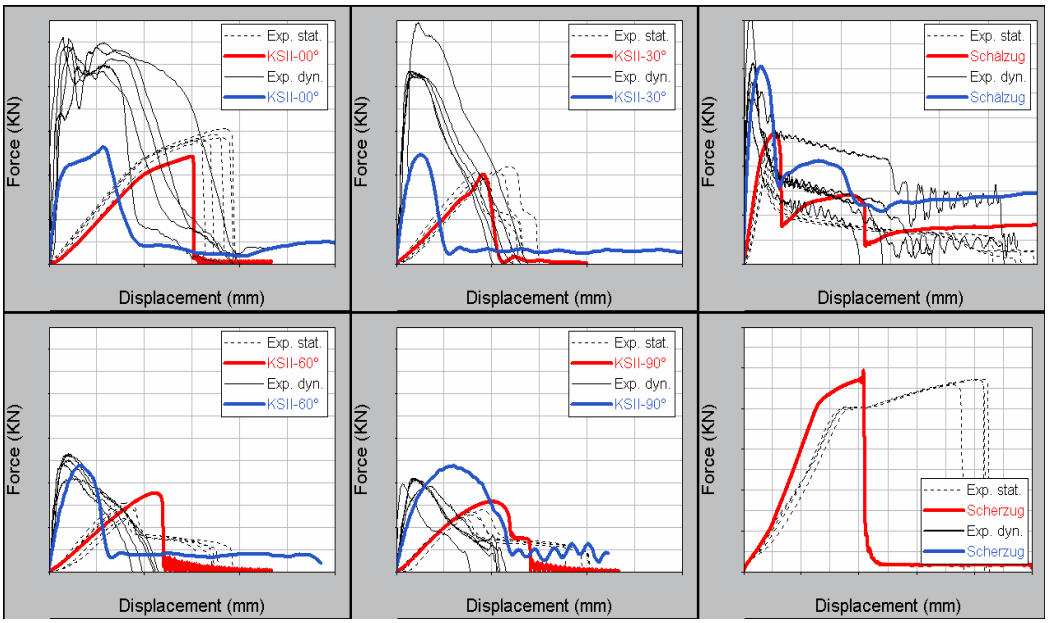

DAIMLER

Validation & Verification: KS2 tests

# KS2 simulation results
## Fleck model



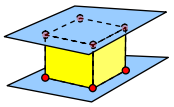
1 strain rate dependent material card!



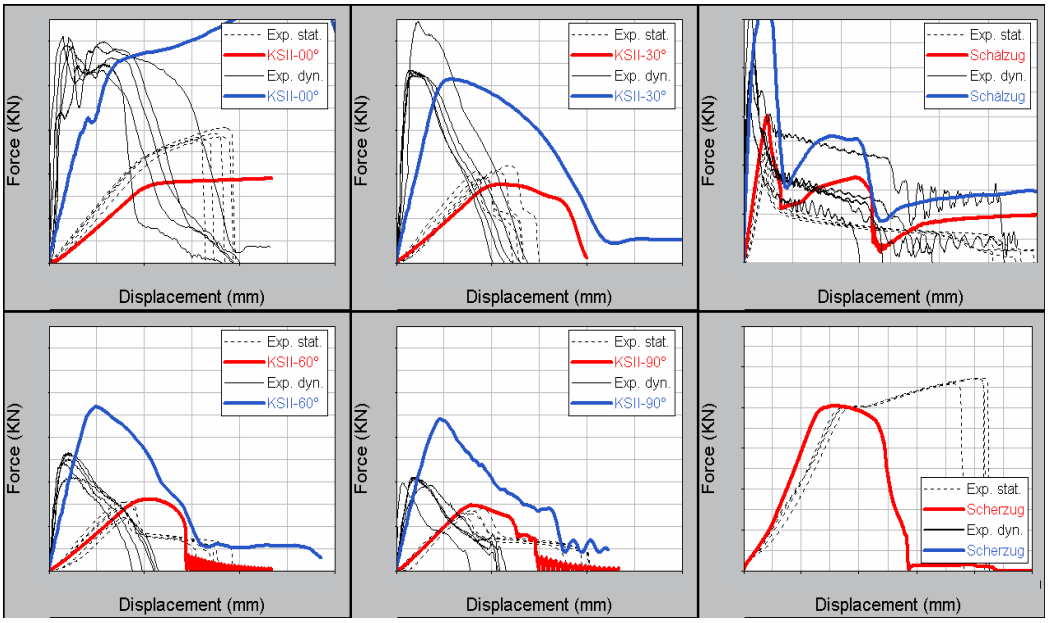

DAIMLER

Validation & Verification: KS2 tests

# KS2 simulation results
## Gurson model



1 strain rate dependent material card!

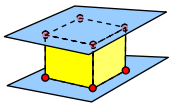




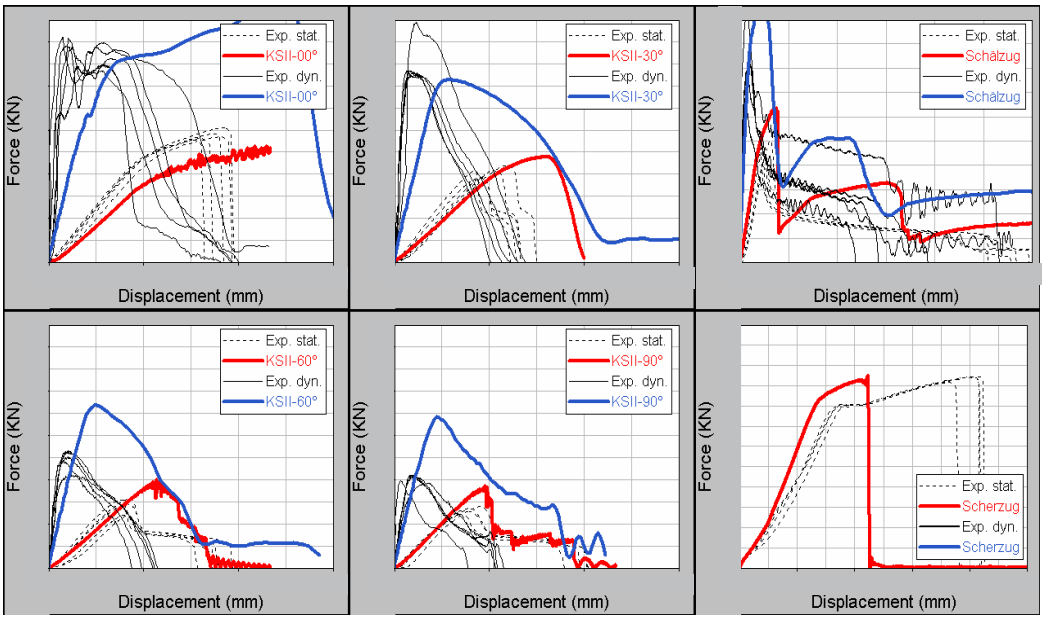

DAIMLER

Validation & Verification: KS2 tests

# KS2 simulation results
## Gurson-Johnson-Cook model

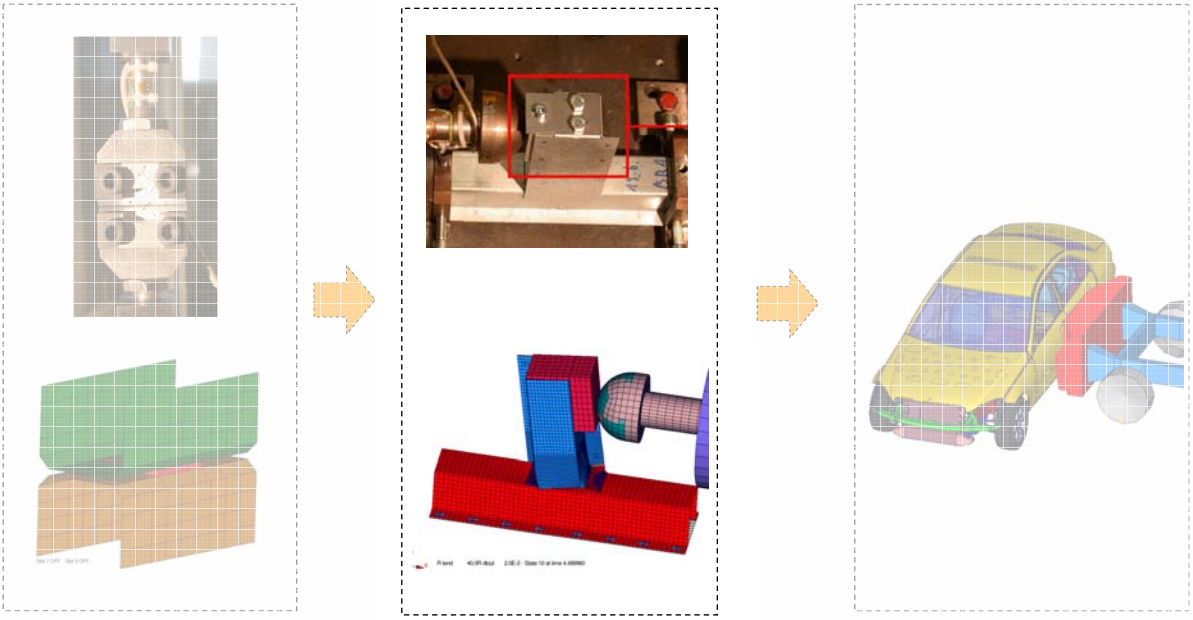


1 strain rate dependent material card!




DAIMLER

## Verification & validation process
### T-component validation

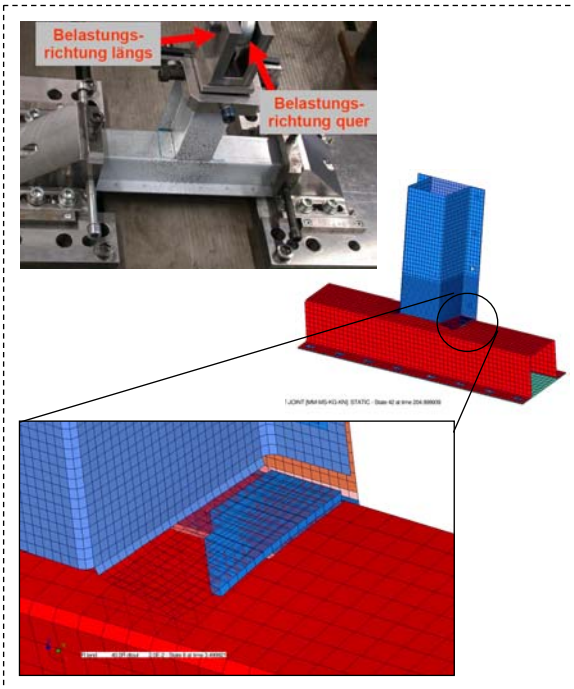




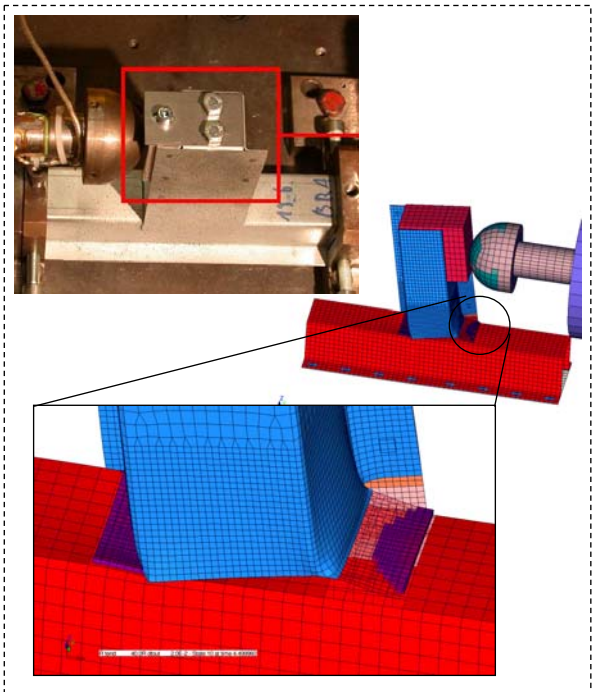
DAIMLER



## T-component tests
### Lateral loading



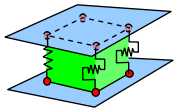

### longitudinal loading



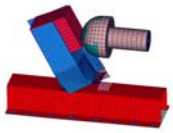
DAIMLER

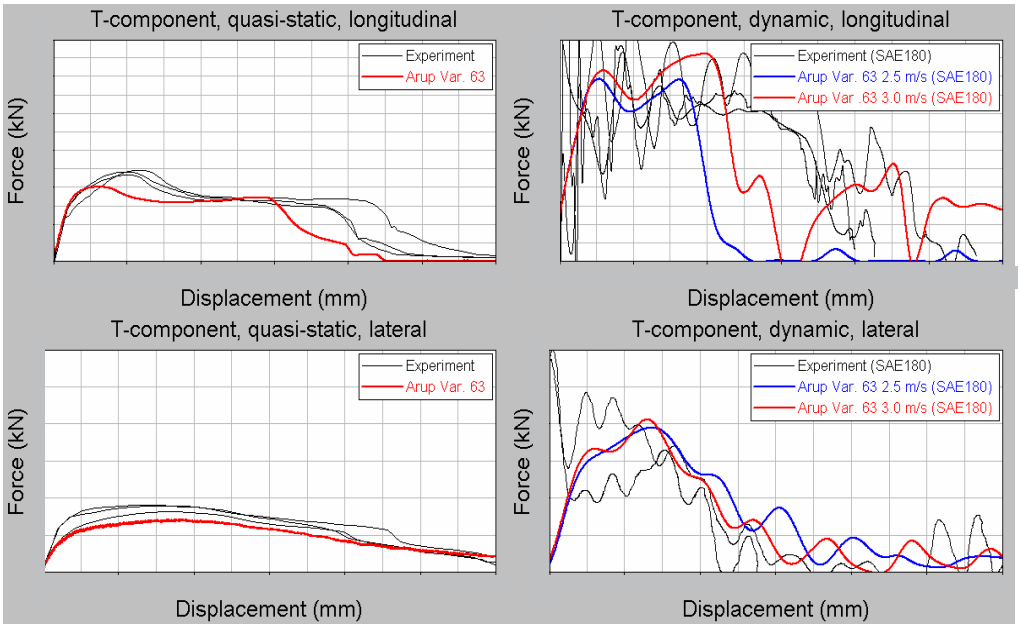
Validation & Verification: T-component

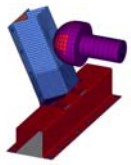
# T-component simulation results
## ARUP model



quasistatic dynamic loading





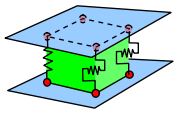





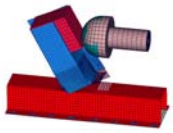
DAIMLER

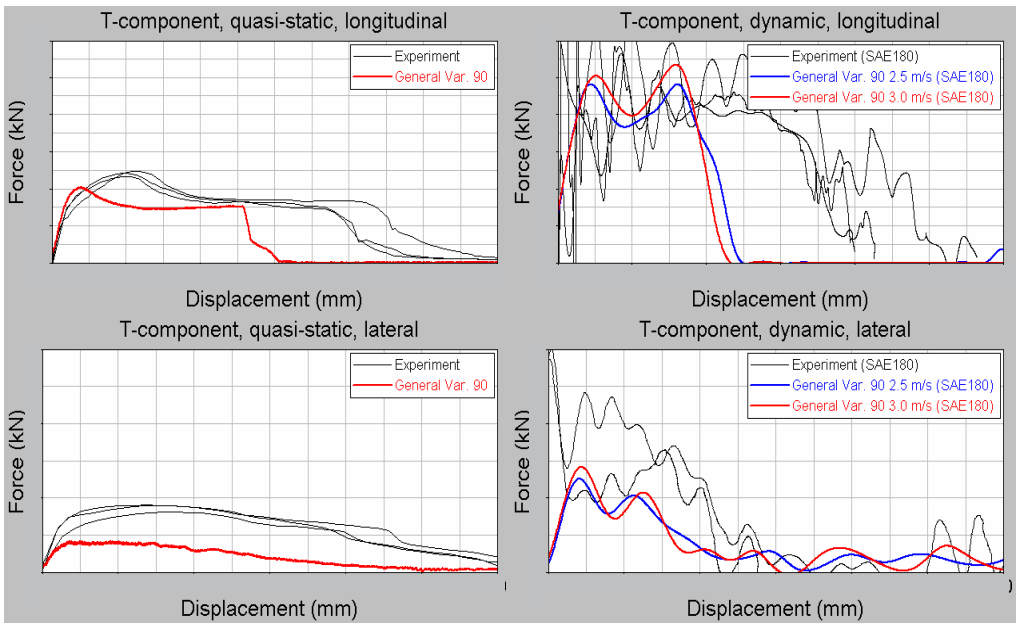
Validation & Verification: T-component

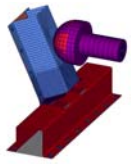
# T-component simulation results
## Cohesive general model



quasistatic dynamic loading



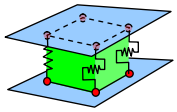


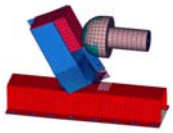
DAIMLER

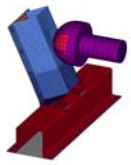
Validation & Verification: T-component

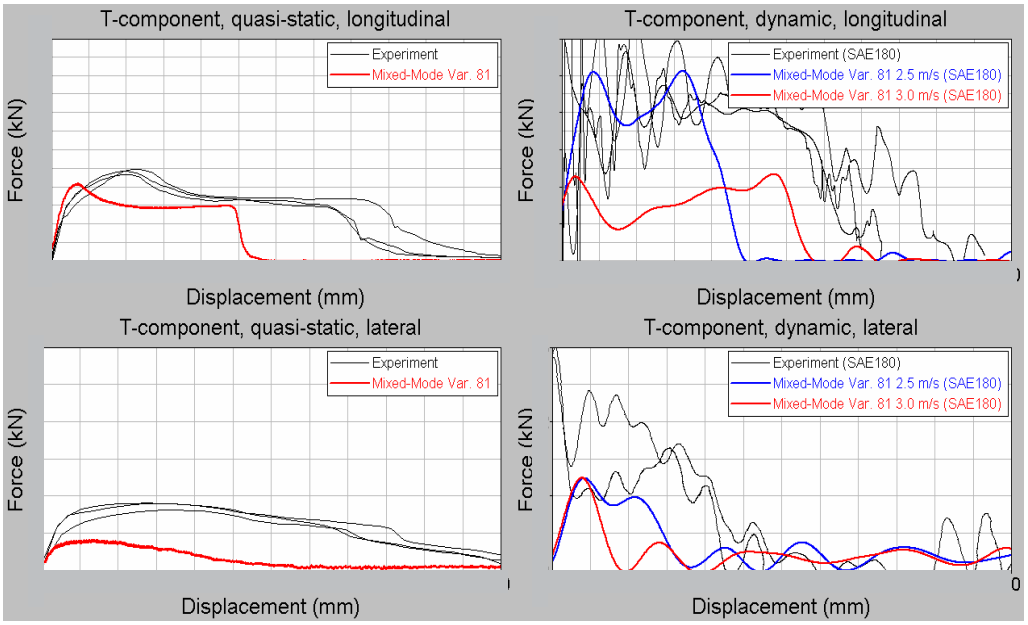
# T-component simulation results
## Cohesive mixed mode model



quasistatic dynamic loading





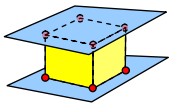




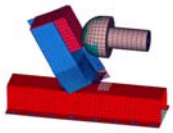

DAIMLER

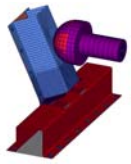
Validation & Verification: T-component

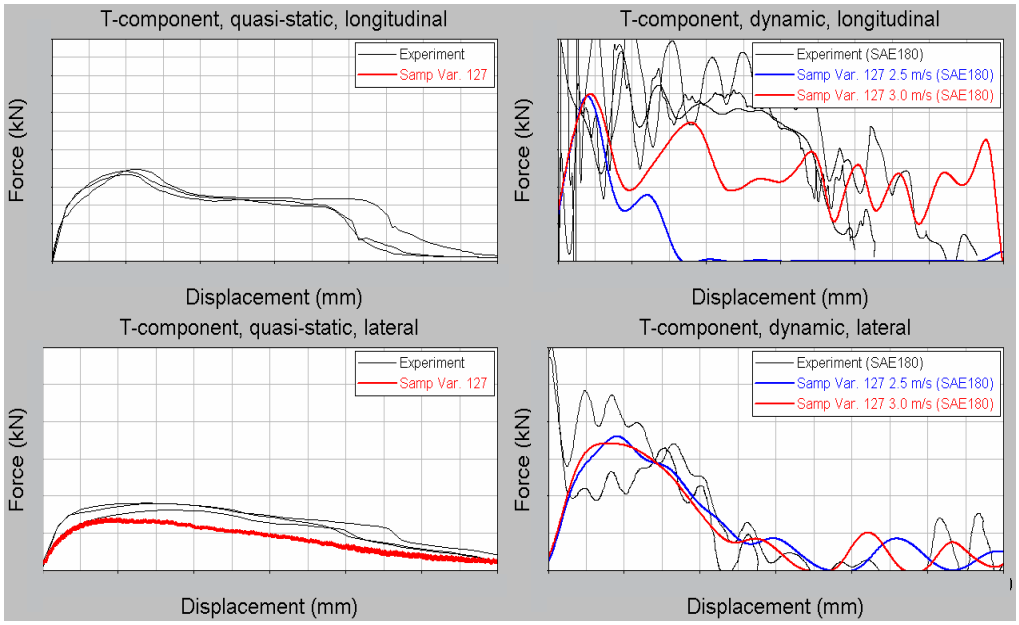
# T-component simulation results
## SAMP model



quasistatic dynamic loading



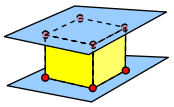




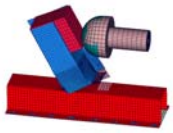
DAIMLER

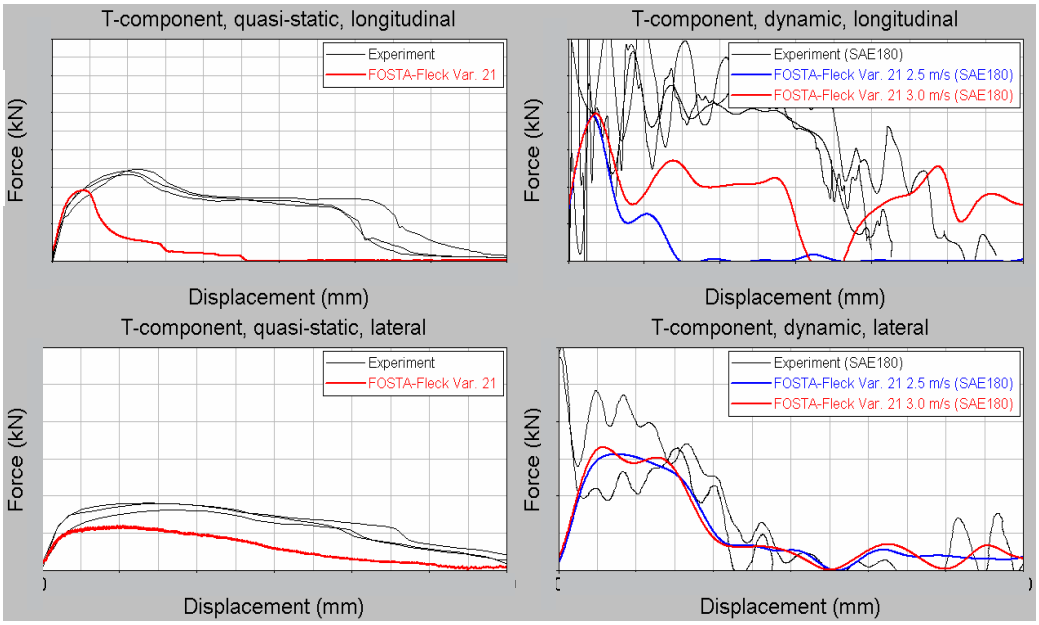


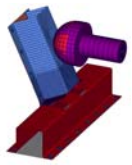
# T-component simulation results
## Fleck model



quasistatic dynamic loading





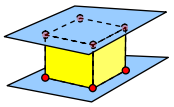





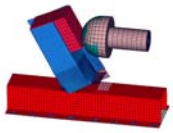
DAIMLER

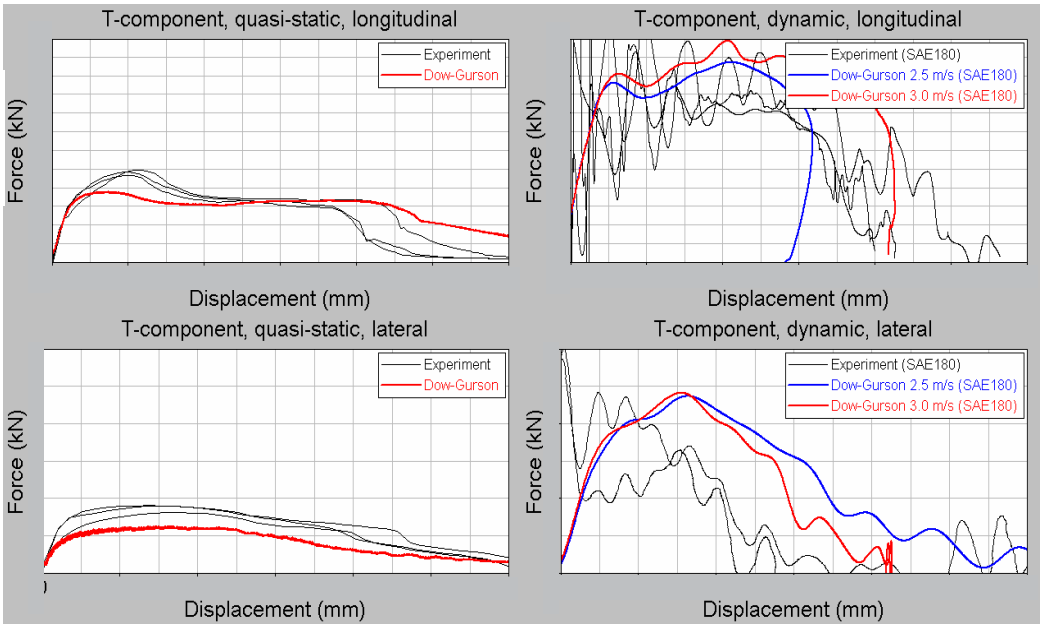


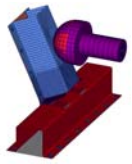
# T-component simulation results
## Gurson model



quasistatic dynamic loading



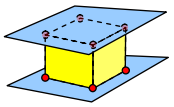


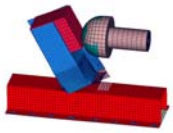
DAIMLER

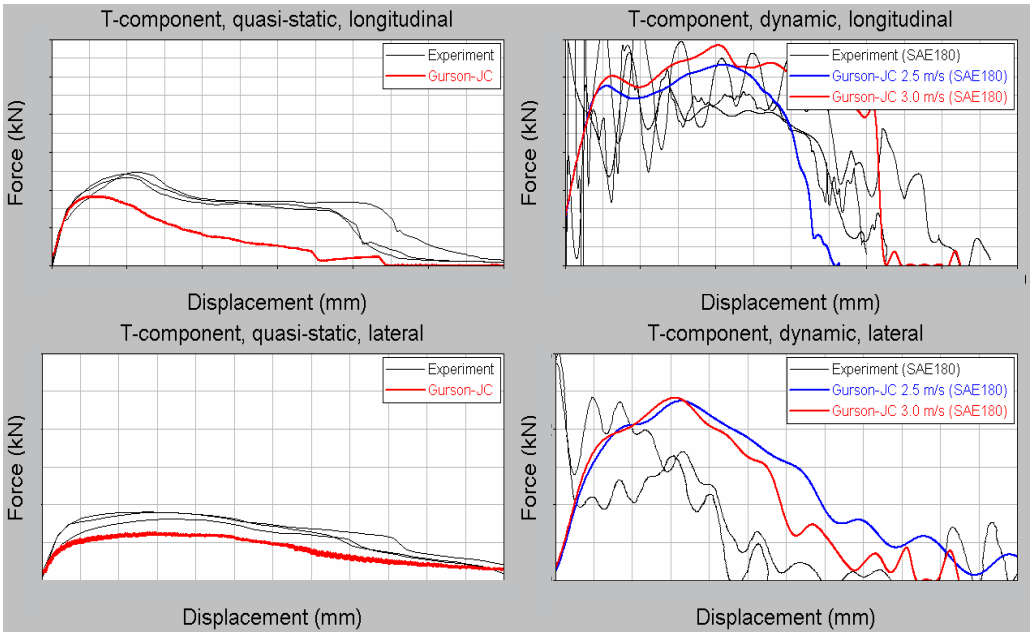


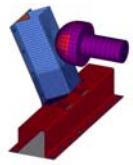
# T-component simulation results
## Gurson-Johnson-Cook model



quasistatic dynamic loading



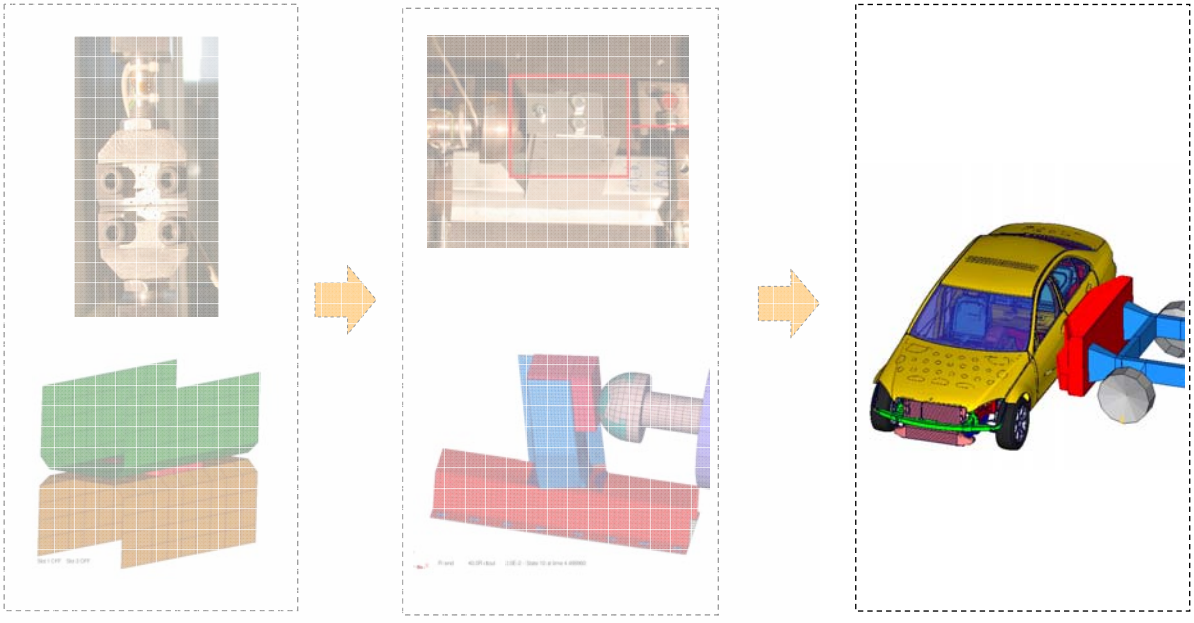




DAIMLER

# Verification & validation process
## Full car crash simulation validation

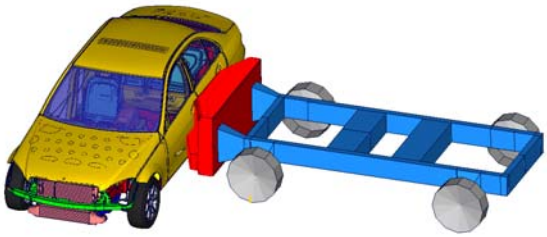


DAIMLER

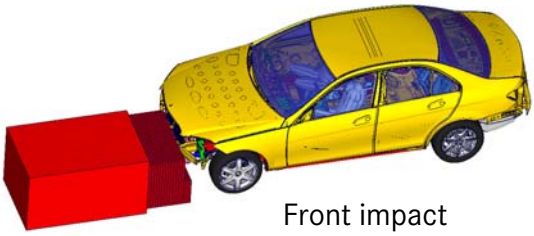


# Full car crash simulation

Front impact
(US NCAP)



Side impact
(IIHS)



Front impact
(Euro NCAP)



DAIMLER

# Summary

- Comprehensive investigations to find a suitable model for different adhesives in crashworthiness simulations has been performed
- Adhesives must be categorized (rubber, foam, structural adhesive bonding) with respect to the application first
- For structural adhesive bonding, most of the shown visco-plastic models are able to describe the material behaviour.
- Verification process must contain peeling tests for correct representation of energy dissipation
- Continuum formulations are prefered for detailed modelling (correct mechanical behavior)
- Cohesive models have advantages for substitute modelling (direct parameter fitting, independent constant thickness definition)
- Time step is not critical for substitution models, cohesive formulations have the advantage of independent thickness definition
- Full car crash simulations are still problematic in front impact load cases
- A rigorous verification and validation procedure is needed to gain robust, reliable and predictable results

DAIMLER

## FOSTA P676

**FOSTA-Projekt P676:**

**Methodenentwicklung zur Berechnung von höherfesten Stahlklebverbindungen des Fahrzeugbaus unter Crashbelastung**

- BMW AG
- Brose Fahrzeugteile GmbH
- cadfem
- DaimlerChrysler AG
- DOW Automotive AG
- ESI GmbH
- Ford Werke AG
- Henkel KGaA
- 3M
- Adam Opel AG
- Dr.-Ing. h.c. Porsche AG
- Salzgitter Mannesmann
- Sika Technology AG
- ThyssenKrupp Stahl
- Volkswagen AG
- Dynamore

LTM

Fraunhofer Institut Kurzzeitdynamik Ernst-Mach-Institut

ifs

Fraunhofer Institut Werkstoffmechanik

FOSTA

Universität Paderborn Laboratorium für Werkstoff- und Fügetechnik

LWF

Fraunhofer Institut Fertigungstechnik Materialforschung

Werkstofftechnik Werkstoffverbunde Verbundwerkstoffe UNIKASSEL VERSITÄT

DYNA MORE home



DAIMLER

## Thank you for your attention!