Charakterisierungsversuche und Parameterbestimmung für die Kohäsivzonenmodellierung von Polyurethan-Klebverbindungen

Characterization tests and parameter determination to model polyurethane adhesive bonds with cohesive elements

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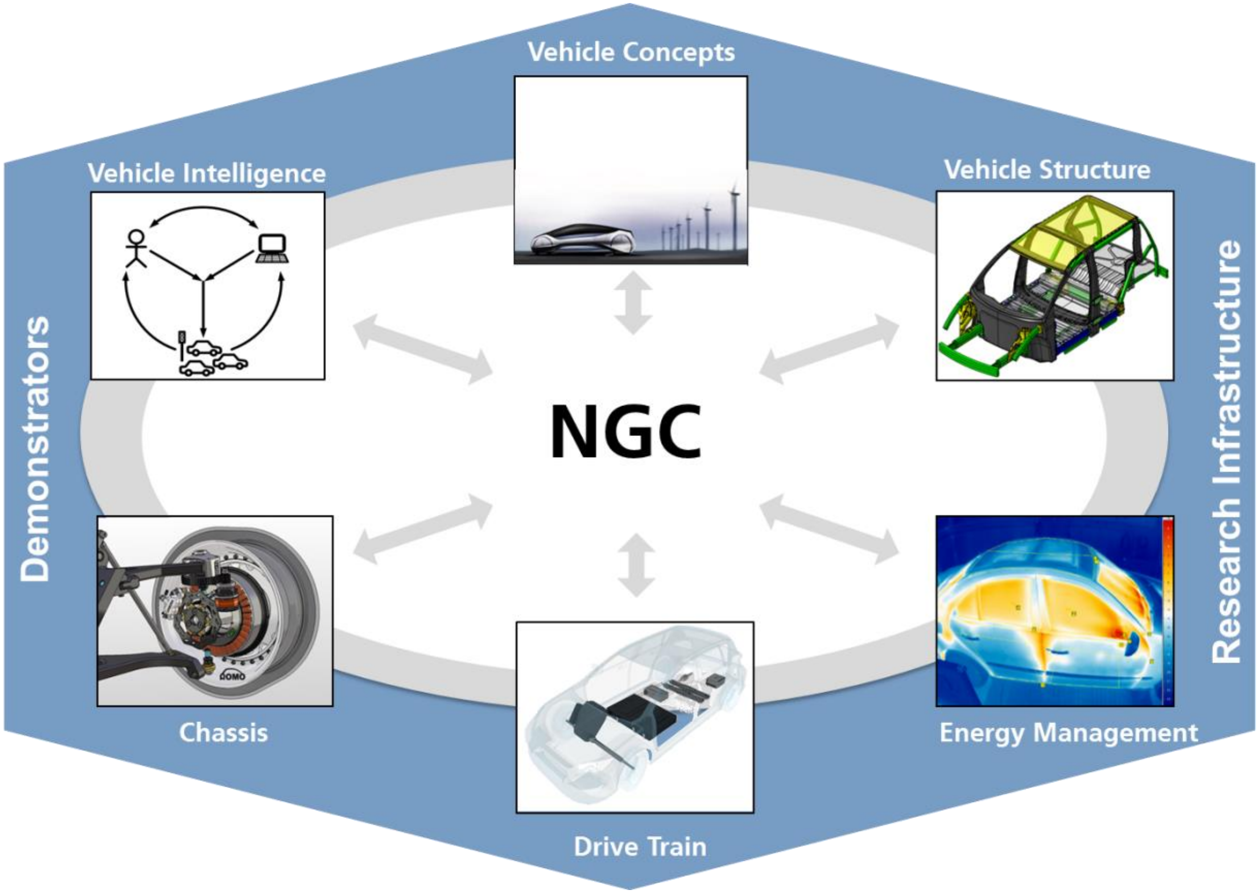
DLR

Agenda

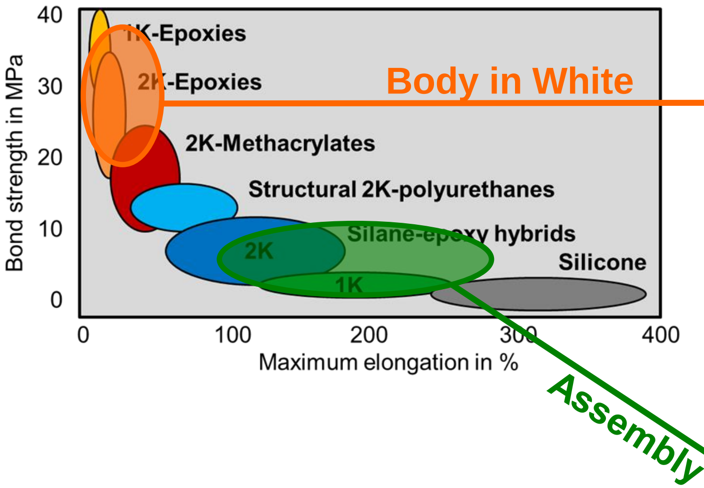
1. DLR-Project „Next Generation Car“
2. Adhesive joining in the automotive manufacturing
3. Simulation methods
4. Tests for material characterization
5. Modelling of PU-bonds
6. Conclusion

1. DLR-Project „Next Generation Car“



Technologies, methods and tools for integrated development of road vehicles of tomorrow

2. Adhesive joining in the automotive manufacturing



Audi AG, Online 2015

- **Epoxy-based (EP)**
- high stiffness
- elastic-plastic
- before painting of car body
- layer thickness 0.1-0.5 mm

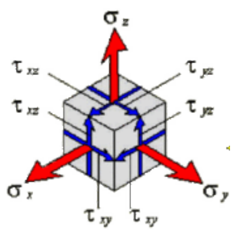
Audi AG, Online 2015

- **Polyurethane-based (PU)**
- flexible
- hyper-elastic
- after painting of car body
- layer thickness 1-5 mm
- reduction of $\Delta\alpha$-caused stress
- semi-structural application

Figure reference: www.adhesivesmag.com

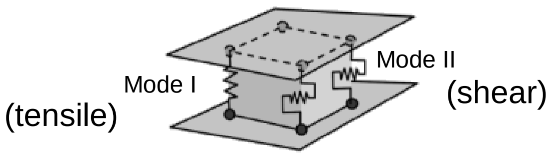
3. Simulation methods:
Modelling approaches (for EP-bonds)

Continuum mechanics



- Volume elements
- Multi-axial stress state
- Many model parameters

Fracture mechanics



- Cohesive elements
- Mode-I & Mode-II; decoupled
- Fewer model parameters

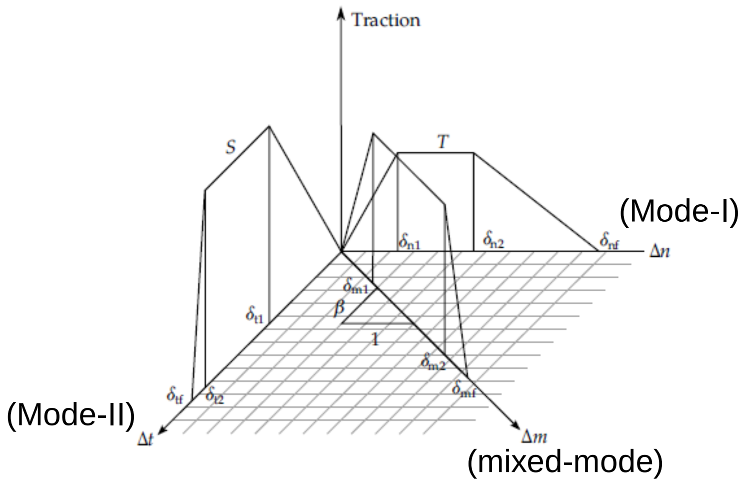
Computation efficiency →

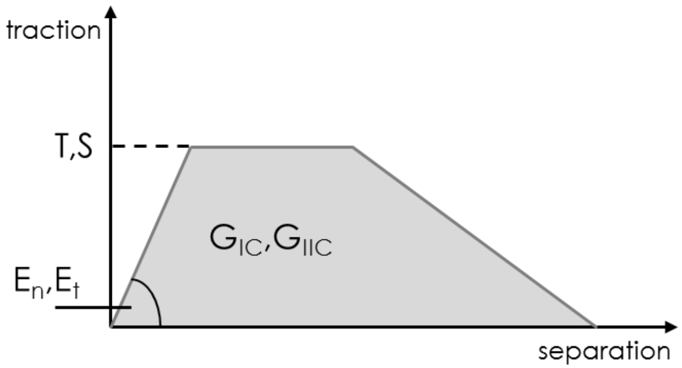
← Detail level

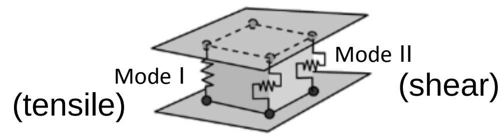
3. Simulation methods:
Cohesive zone modelling

LS-DYNA: `MAT_240`

`*MAT_COHESIVE_MIXED_MODE_ELASTOPLASTIC_RATE`







Required model parameters:

- Young's modulus → stiffness $\mathbf{E_n}$
- shear modulus → stiffness $\mathbf{E_t}$
- failure strength **T** (tensile)
- failure strength **S** (shear)
- energy release rate $\mathbf{G_{IC}}$ (Mode-I)
- energy release rate $\mathbf{G_{IIC}}$ (Mode-II)

These 6 parameters have to be determined for a relevant range of strain rates from suitable material characterization tests.

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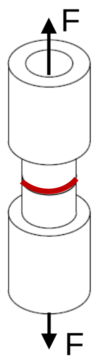
4. Tests for material characterization:
EP-bonds – state of the art

Mode I

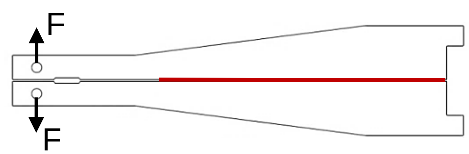
tensile strength **T**
stiffness $\mathbf{E_n}$

Cylinder Butt Joint (CBJ)



energy release rate $\mathbf{G_{IC}}$

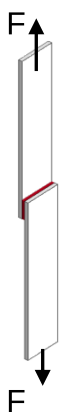
Tapered Double Cantilever Beam (TDCB)



Mode II

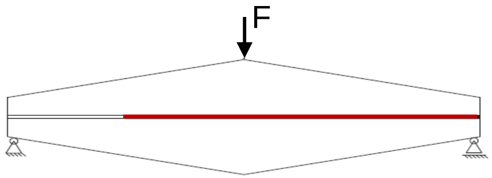
shear strength **S**
stiffness $\mathbf{E_t}$

Thick-Adherend Shear Joint (TAS)



energy release rate $\mathbf{G_{IIC}}$

Tapered End Notched Flexure (TENF)



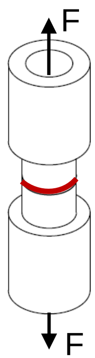
The shown 4 specimen have been identified as a suitable state of the art testing program for the characterization of EP bonds.

4. Tests for material characterization:
PU-bonds – DLR approach

Mode I

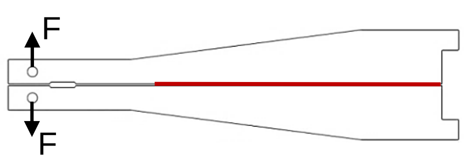
tensile strength **T**
stiffness $\mathbf{E_n}$

Cylinder Butt Joint (CBJ)



energy release rate $\mathbf{G_{IC}}$

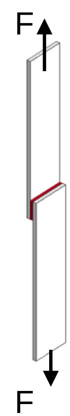
Tapered Double Cantilever Beam (TDCB)



Mode II

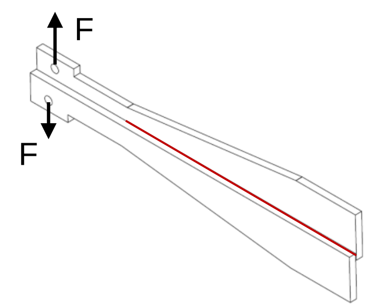
shear strength **S**
stiffness $\mathbf{E_t}$

Thick-Adherend Shear Joint (TAS)



energy release rate $\mathbf{G_{IIC}}$

Tapered Double Cantilever Beam (TDCB-II)



For the determination of G_{IIC}, the TENF specimen is not suitable for PU adhesives because of the high deformations. In our approach a specimen consisting of TDCB adherends is investigated. Thus a mode-III load case is used to characterize the G_{IIC} parameters as in the cohesive zone element definition there is no distinction between mode-II and mode-III load.

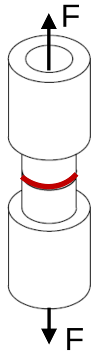
Adhesive: Sikaflex UHM (1-K-PU)

4. Tests for material characterization:
PU-bonds – DLR approach

Mode I

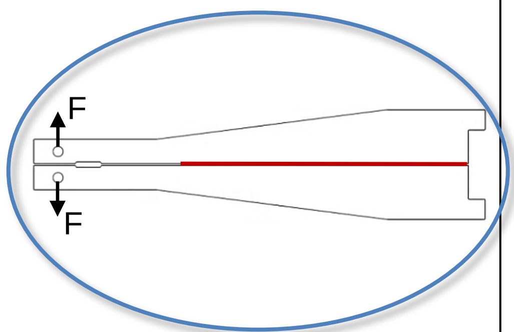
tensile strength **T**
stiffness **E_n**

Cylinder Butt Joint (CBJ)



energy release rate **G_{IC}**

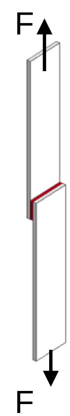
Tapered Double Cantilever Beam (TDCB)



Mode II

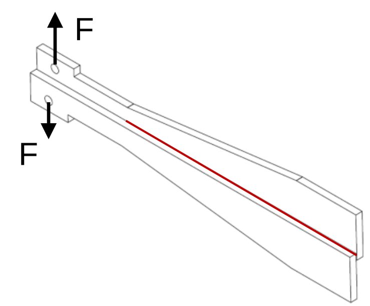
shear strength **S**
stiffness **E_t**

Thick-Adherend Shear Joint (TAS)



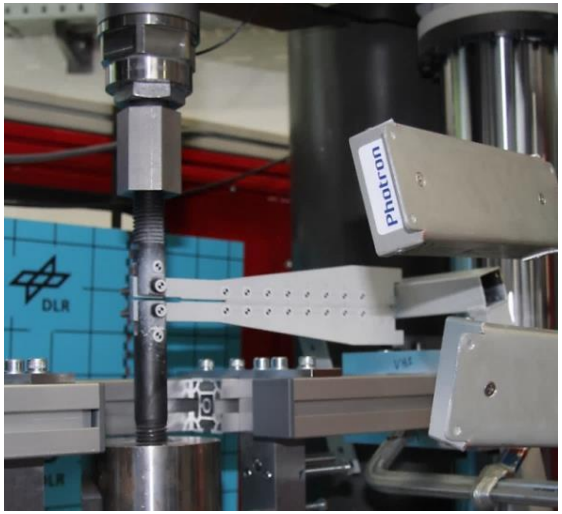
energy release rate **G_{IIC}**

Tapered Double Cantilever Beam (TDCB-II)

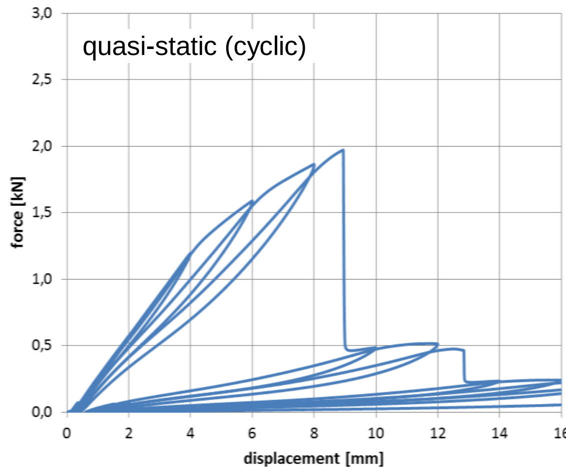


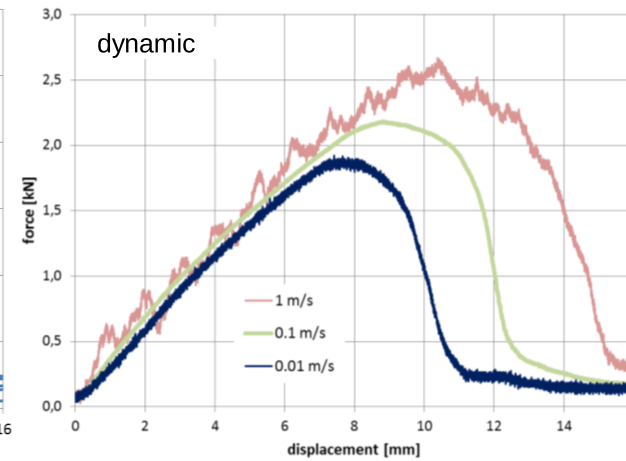
Adhesive: Sikaflex UHM (1-K-PU)

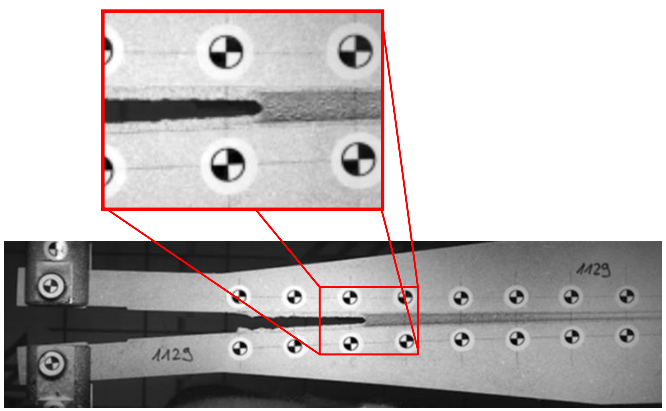
4. Tests for material characterization: TDCB



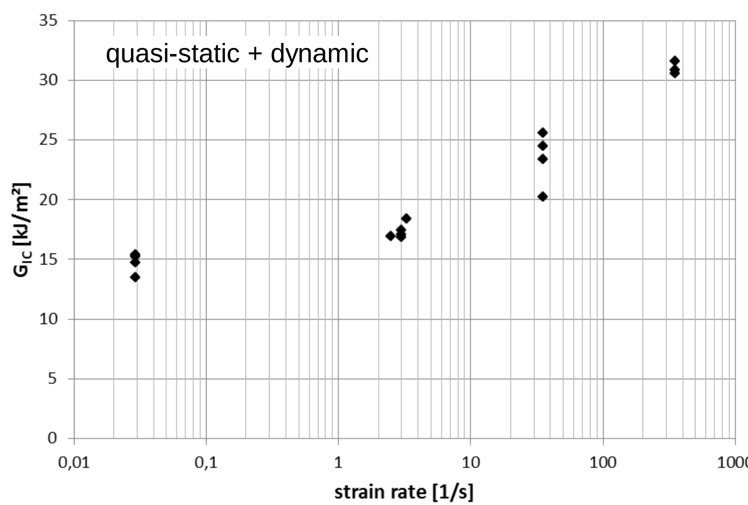
testing setup – high-speed testing machine







High-speed camera picture



The PU adhesive shows “slip-stick” crack growth behavior in the quasi-static test. The cyclic quasi-static test is necessary to determine the elastic energy of the adherends.

The PU adhesive shows highly strain rate dependent material behavior.

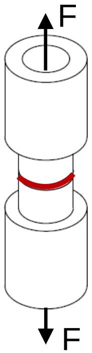
G_{IC} is determined by correlating the fracture energy (integration of the force-displacement curve) with the optically measured crack propagation.

4. Tests for material characterization:
PU-bonds – DLR approach

Mode I

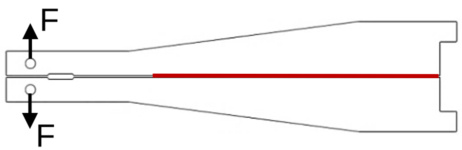
tensile strength **T**
stiffness $\mathbf{E_n}$

Cylinder Butt Joint (CBJ)



energy release rate $\mathbf{G_{IC}}$

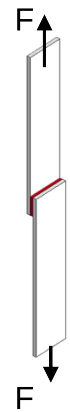
Tapered Double Cantilever Beam (TDCB)



Mode II

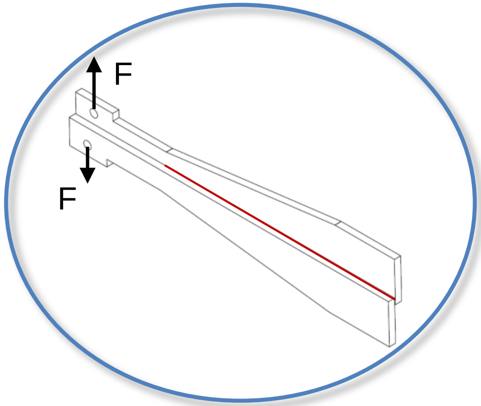
shear strength **S**
stiffness $\mathbf{E_t}$

Thick-Adherend Shear Joint (TAS)



energy release rate $\mathbf{G_{IIC}}$

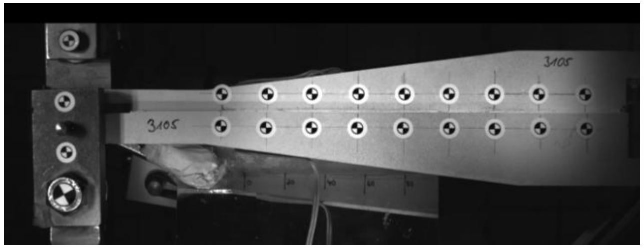
Tapered Double Cantilever Beam (TDCB-II)



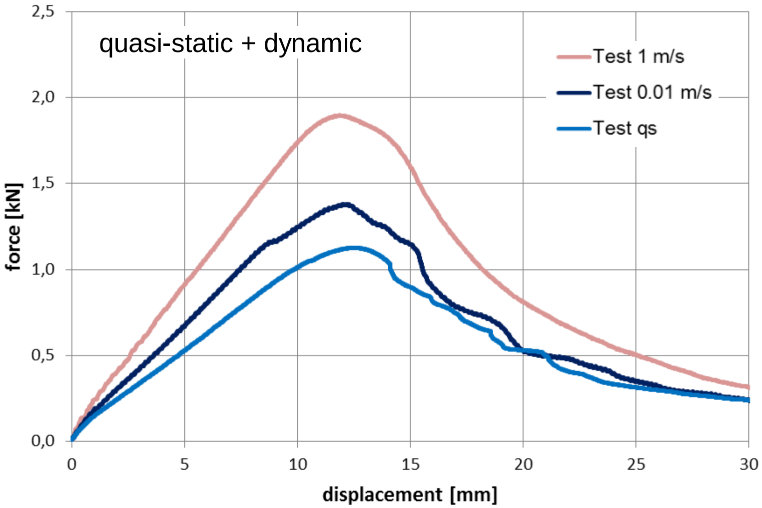
Adhesive: Sikaflex UHM (1-K-PU)

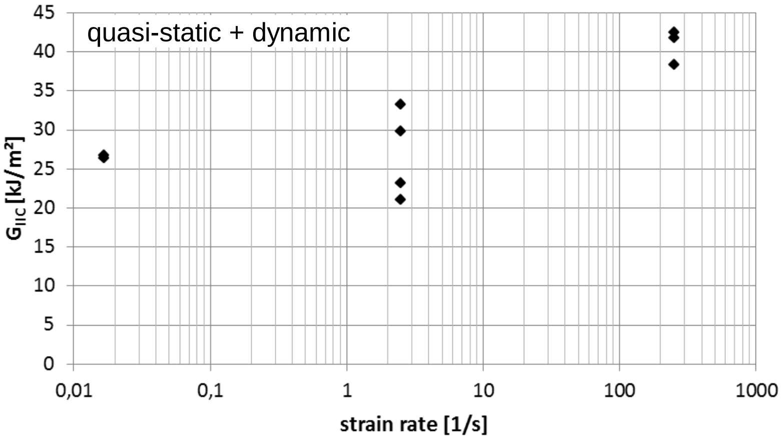
4. Tests for material characterization: TDCB-II

Testing setup – high-speed testing machine



High-speed camera picture





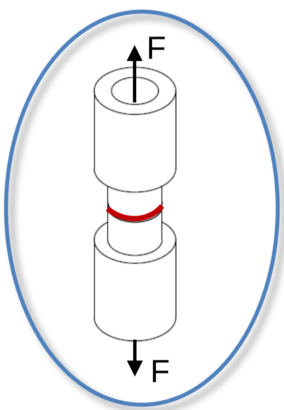
Also for the mode-III loaded specimen the PU adhesive shows strain rate dependent material behavior.

4. Tests for material characterization:
PU-bonds – DLR approach

Mode I

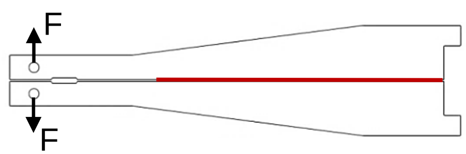
tensile strength **T**
stiffness $\mathbf{E_n}$

Cylinder Butt Joint (CBJ)



energy release rate $\mathbf{G_{IC}}$

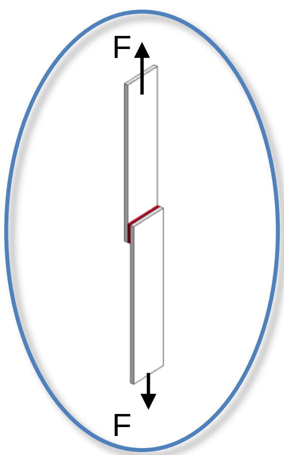
Tapered Double Cantilever Beam (TDCB)



Mode II

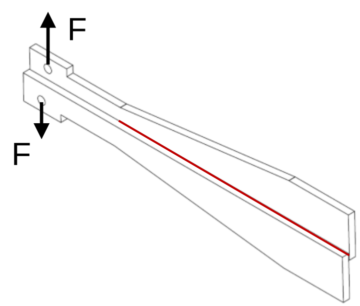
shear strength **S**
stiffness $\mathbf{E_t}$

Thick-Adherend Shear Joint (TAS)



energy release rate $\mathbf{G_{IIC}}$

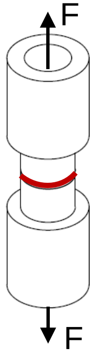
Tapered Double Cantilever Beam (TDCB-II)

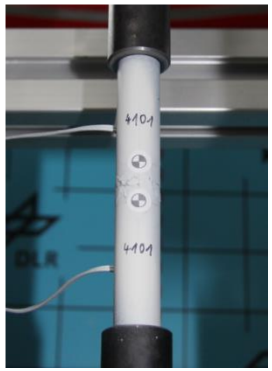


Adhesive: Sikaflex UHM (1-K-PU)

4. Tests for material characterization:

Cylinder Butt Joint

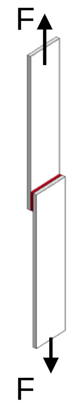


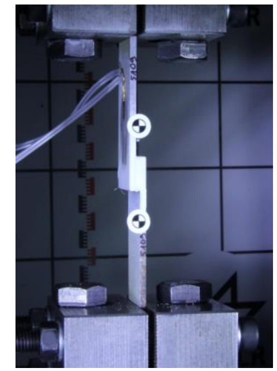


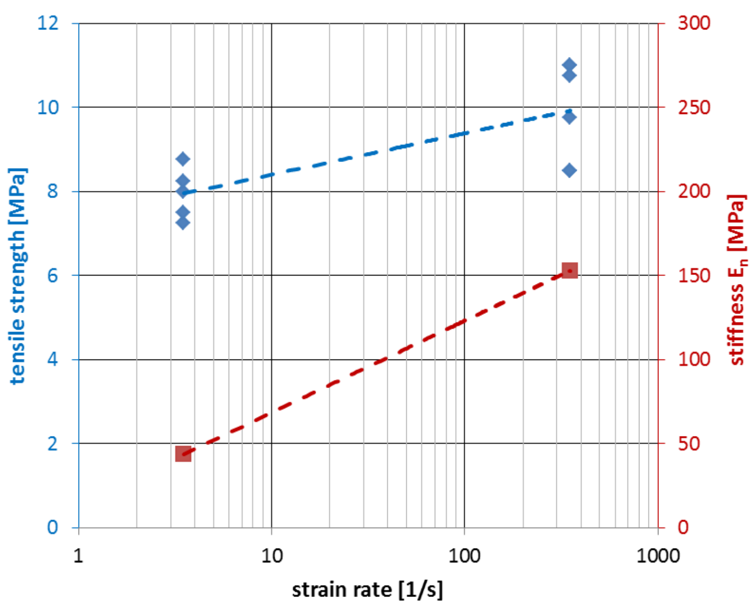
Normal and shear stiffness of the PU adhesive are strain rate dependent.

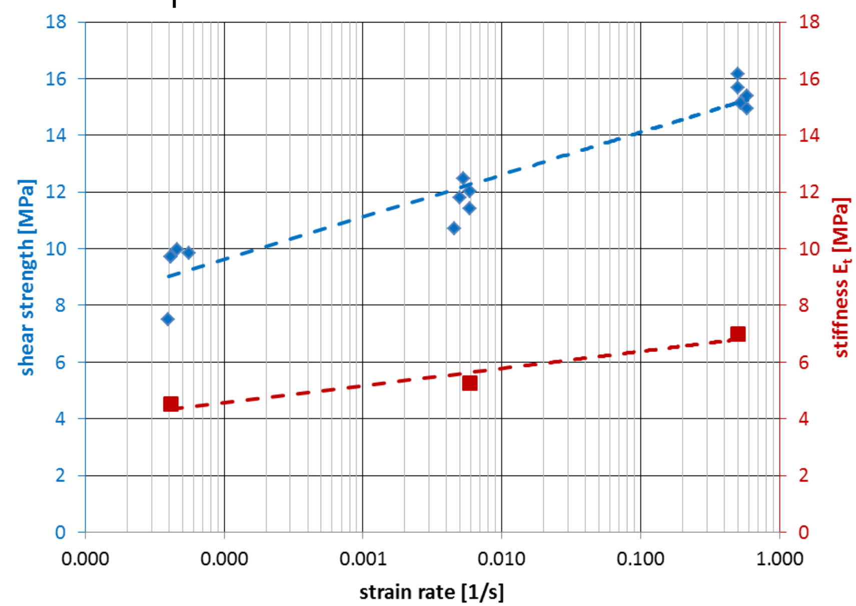
Normal and shear strength of the PU adhesive are strain rate dependent.

Thick Adherend Shear Joint









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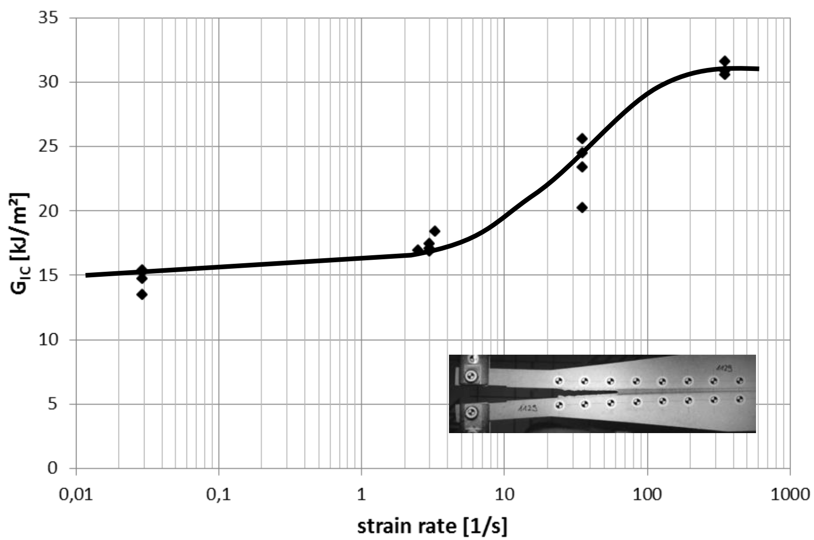
5. Modelling of PU-bonds:
Parameter determination Mode-I

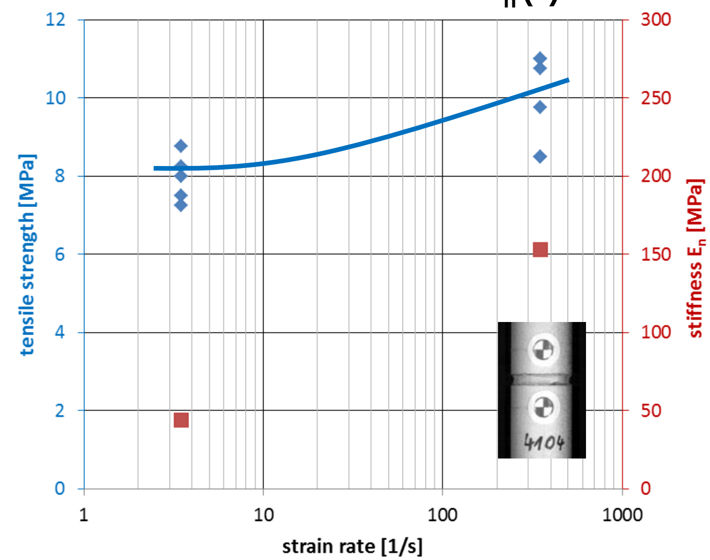
TDCB - energy release rate $\mathbf{G_{IC}(\dot{\varepsilon})}$



$$G_{IC}(\dot{\varepsilon}_{eq}) = G_{IC\_0} + (G_{IC\_inf} - G_{IC\_0})^{\frac{-\dot{\varepsilon}_{GC}}{\dot{\varepsilon}_{eq}}}$$

Cylinder Butt Joint - tensile strength $\mathbf{T(\dot{\varepsilon})}$

- stiffness $\mathbf{E_n(\dot{\varepsilon})}$



$$T(\dot{\varepsilon}_{eq}) = T_0 + T_1 \langle \ln \frac{\dot{\varepsilon}_{eq}}{\dot{\varepsilon}_T} \rangle^2 \qquad E_n\ ?$$

Parameter set for Mode-I has been optimized!

For the strain rate dependent normal stiffness E_n there is no function available in the material card MAT_240.

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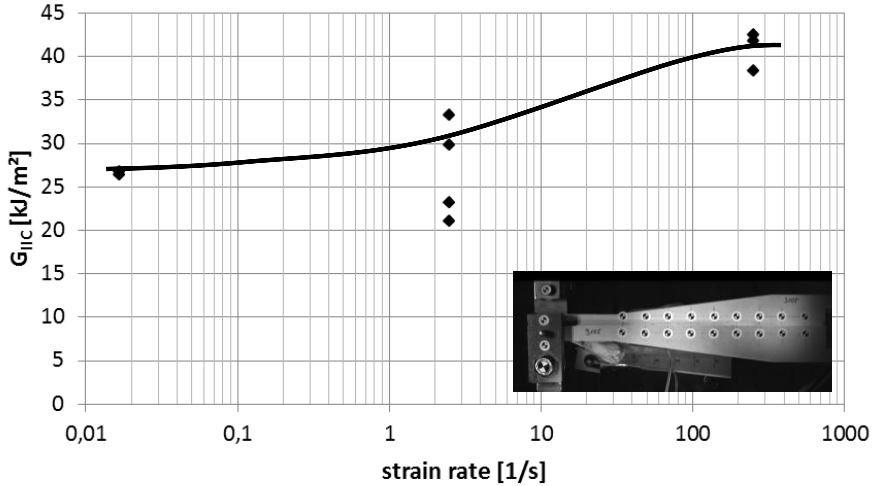
5. Modelling of PU-bonds:
Parameter determination Mode-II

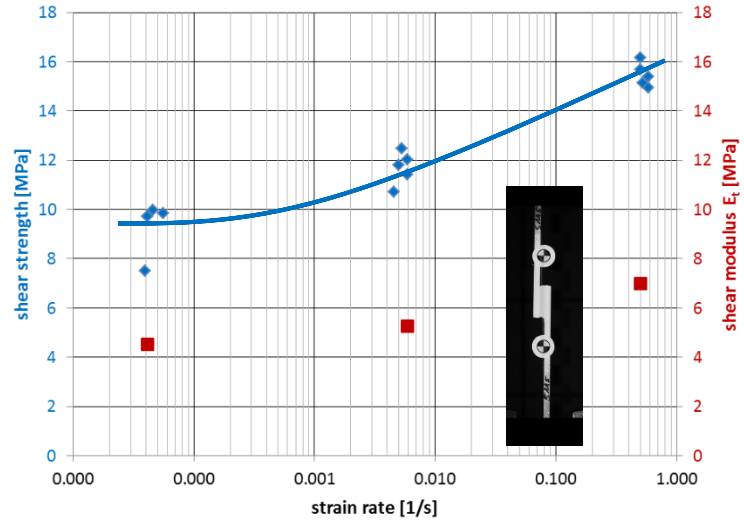
TDCB-II - energy release rate $\mathbf{G_{IIC}(\dot{\varepsilon})}$



$$G_{IIC}(\dot{\varepsilon}_{eq}) = G_{IIC\_0} + (G_{IIC\_inf} - G_{IIC\_0})^{\frac{-\dot{\varepsilon}_{GC}}{\dot{\varepsilon}_{eq}}}$$

Thick Adherend Shear Joint - shear strength $\mathbf{S(\dot{\varepsilon})}$

- stiffness $\mathbf{E_t\,(\dot{\varepsilon})}$



$$S(\dot{\varepsilon}_{eq}) = S_0 + S_1 \langle \ln \frac{\dot{\varepsilon}_{eq}}{\dot{\varepsilon}_T} \rangle^2$$

E_t ?

Parameter set for Mode-II has been optimized!

For the strain rate dependent shear stiffness E_t there is no function available in the material card MAT_240.

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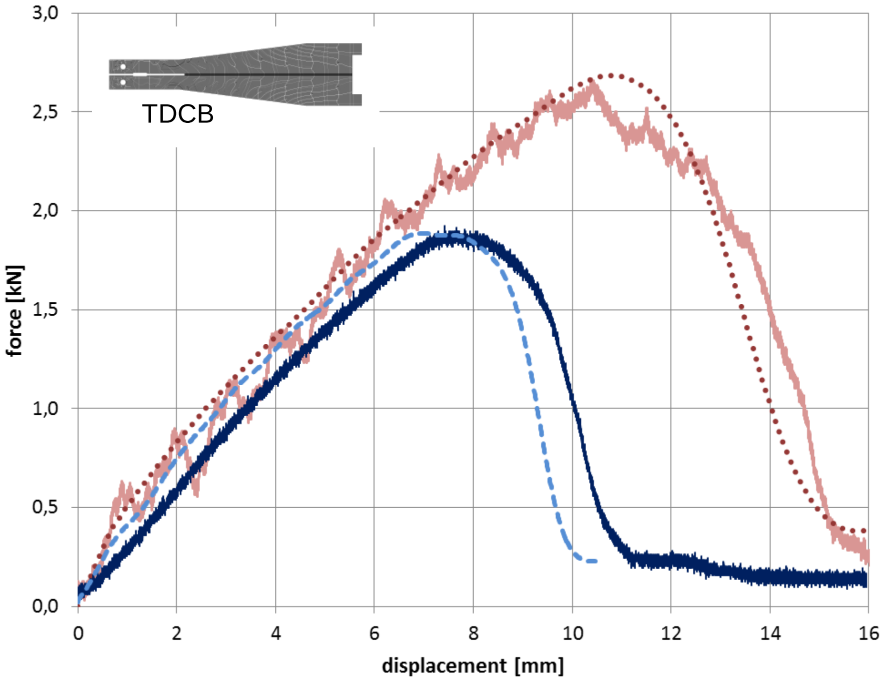
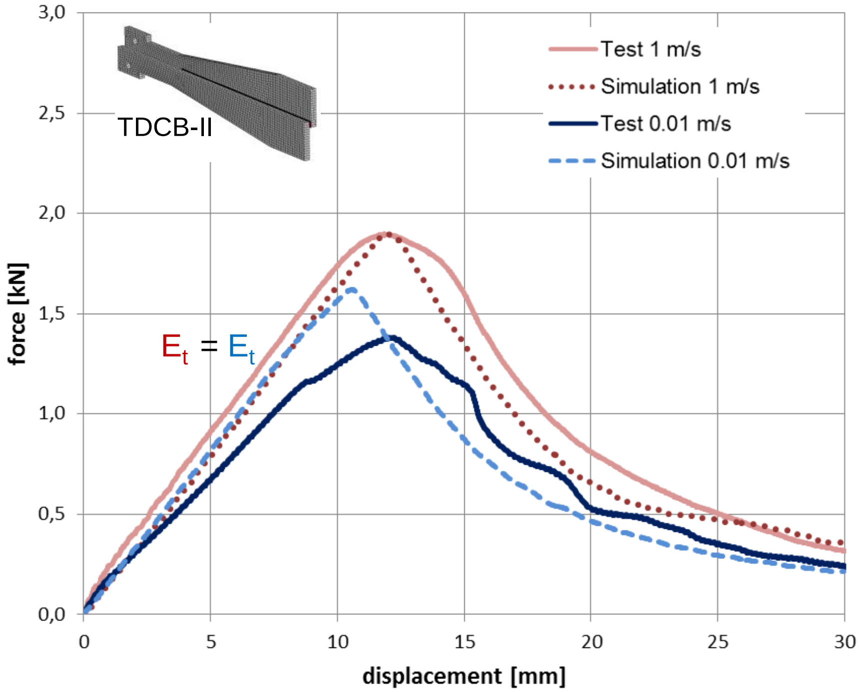
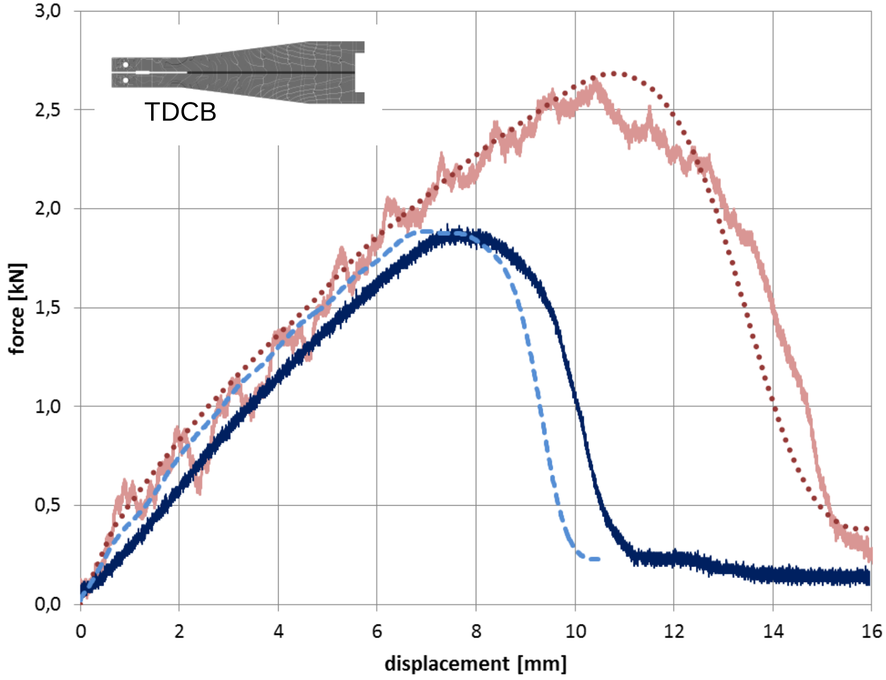
5. Modelling of PU-bonds:
TDCB and TDCB-II verification

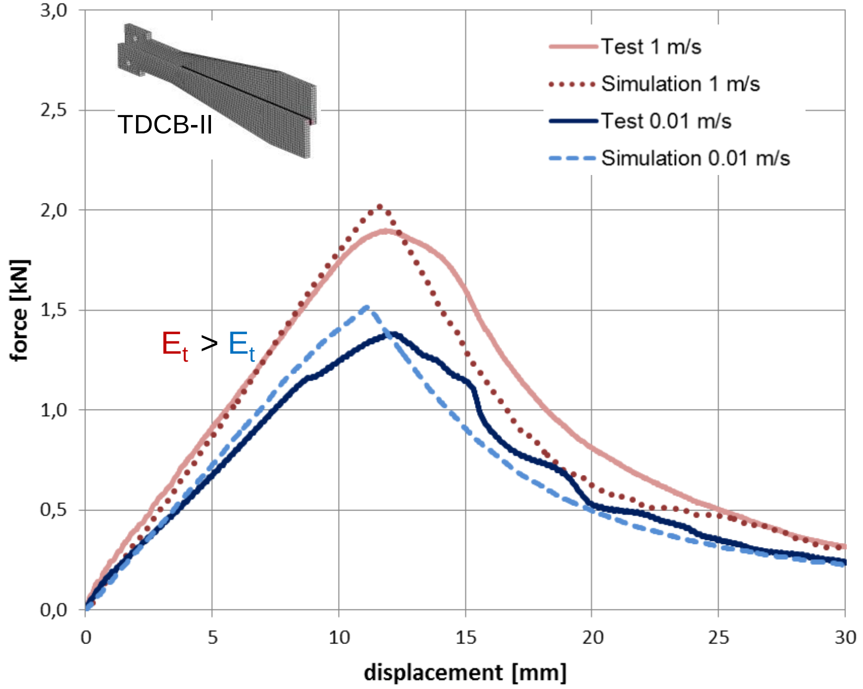




TDCB and TDCB-II tests at various strain rates <u>cannot</u> be modelled with <u>one parameter setup</u> for MAT_240!

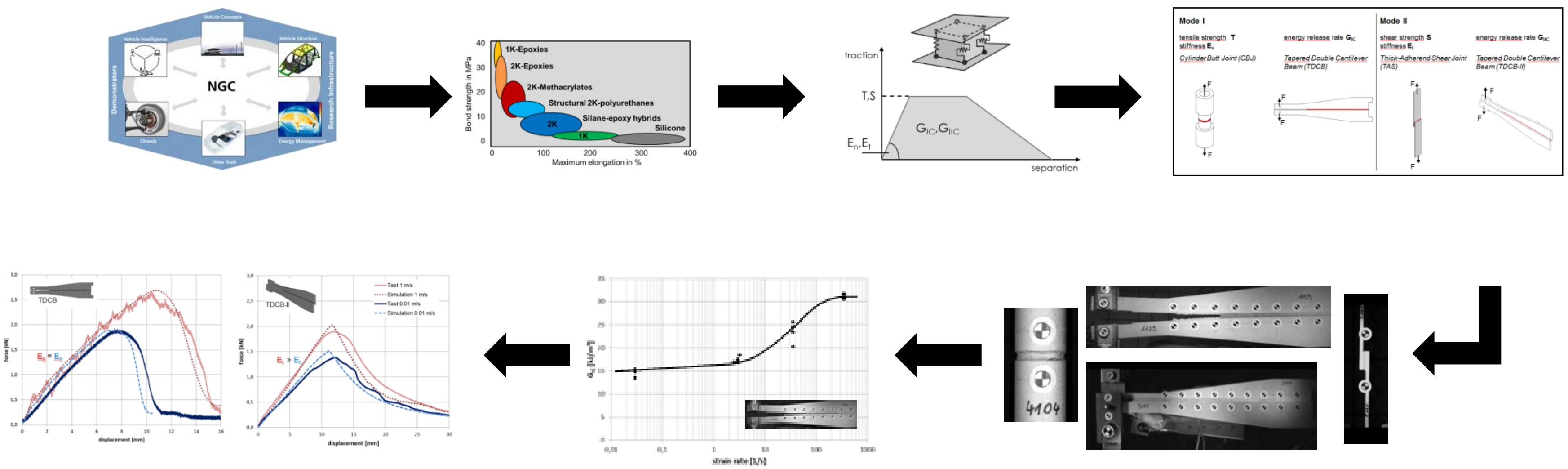
5. Modelling of PU-bonds:
TDCB and TDCB-II verification





TDCB and TDCB-II tests at various strain rates could be modelled with one parameter setup for MAT_240, if the shear stiffness E_t could be adjusted with strain rate!

6. Conclusion



The chosen 1-K-PU adhesive can be modeled succesfully with cohesive elements

- **for the investigated load cases**
- **for the investigated range of strain rates**
- **<u>for the option that strain rate dependant shear stiffness can be considered</u>**

Thanks for your attention!

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