A new material model to simulate the thermo-viscoelastic behavior of adhesives within the curing process with LS-DYNA

Dr.-Ing. Thomas Klöppel
DYNAmore GmbH

automotive CAE Grand Challenge 2017

April 5–6, 2017

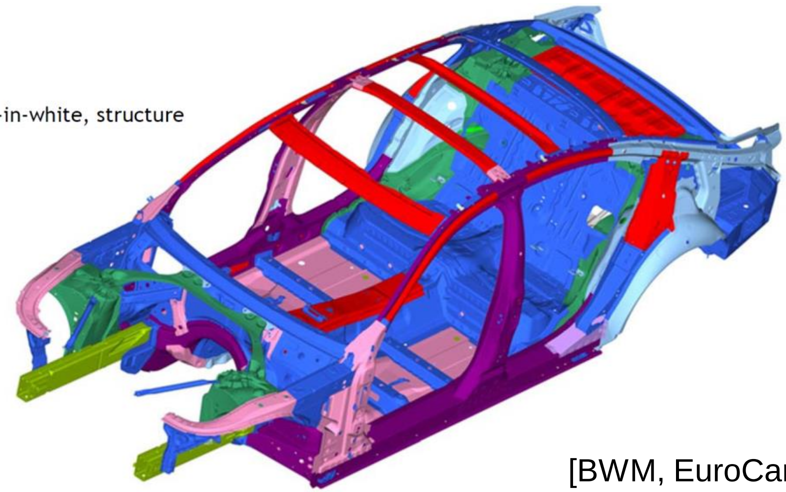
Overview and Acknoledgments

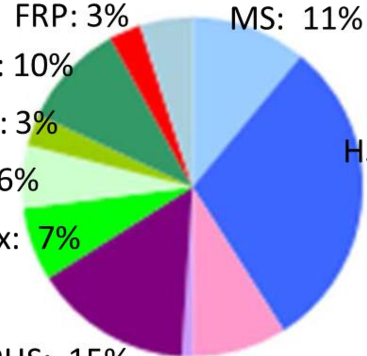
- Overview
  - Motivation
  - Material characterization & Numerical implementation in *MAT_277
  - Examples
  - Summary and Outlook

- The presented work is the result of a joint development of LSTC, DOW Automotive Systems, and DYNAmore. Many thanks to
  - Dr. Alexander Droste
  - Dr. Deep Wang
  - Dr. Qiangsheng Zhao

Motivation: Light-Weight Design

- Current and future legal requirements necessitate a reasonable Multi Material Mix
  - Example: BMW 7 car body-in-white

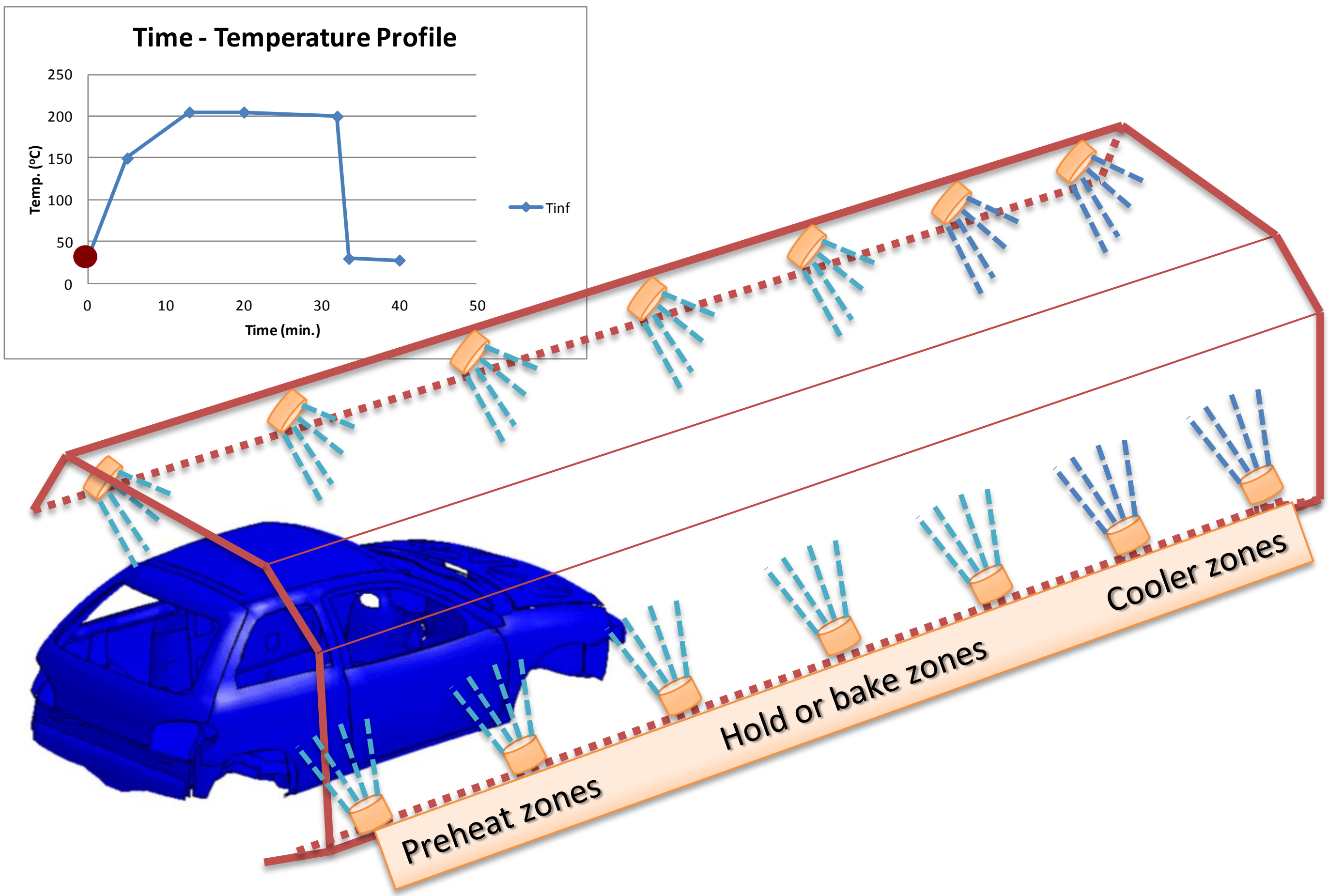


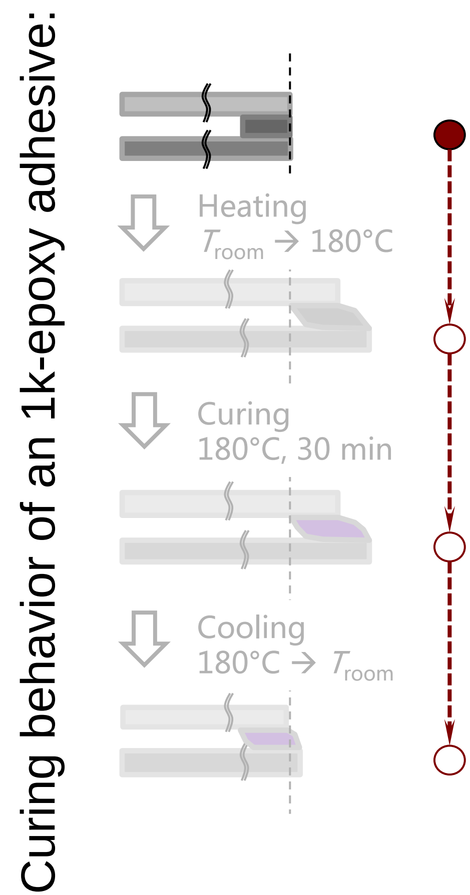


[BWM, EuroCarBody 2015]

- The joint performance of state-of-the art 1k-epoxy adhesives depends on
  - temperature distribution in oven of the paint shop (bonding happens)
  - material mix (delta alpha problem)

Motivation: Adhesive curing process – “oven”





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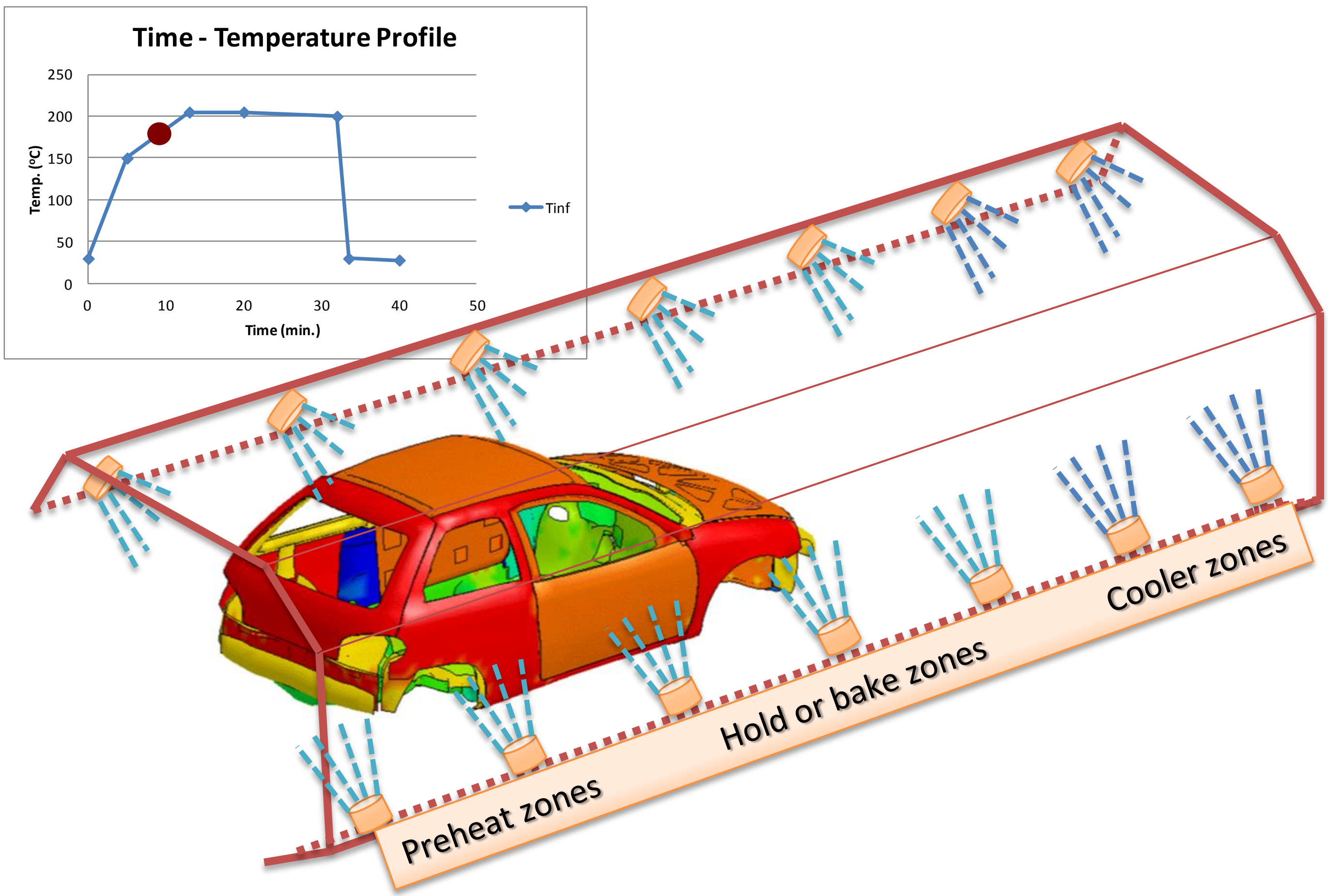

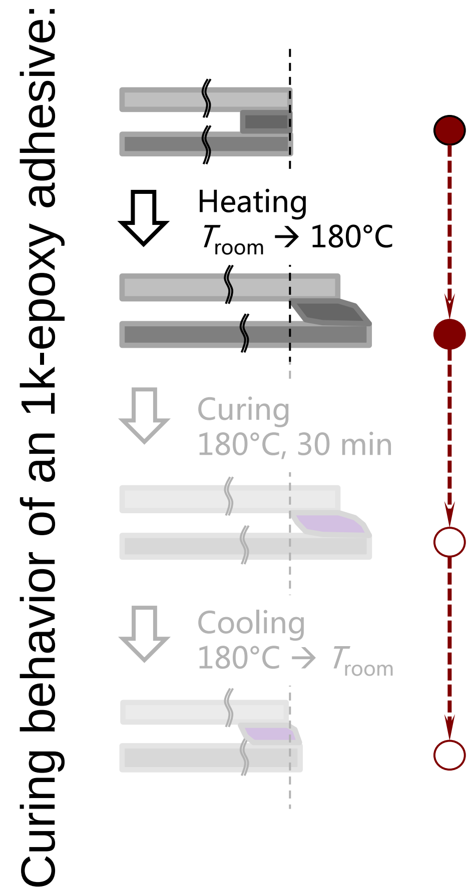

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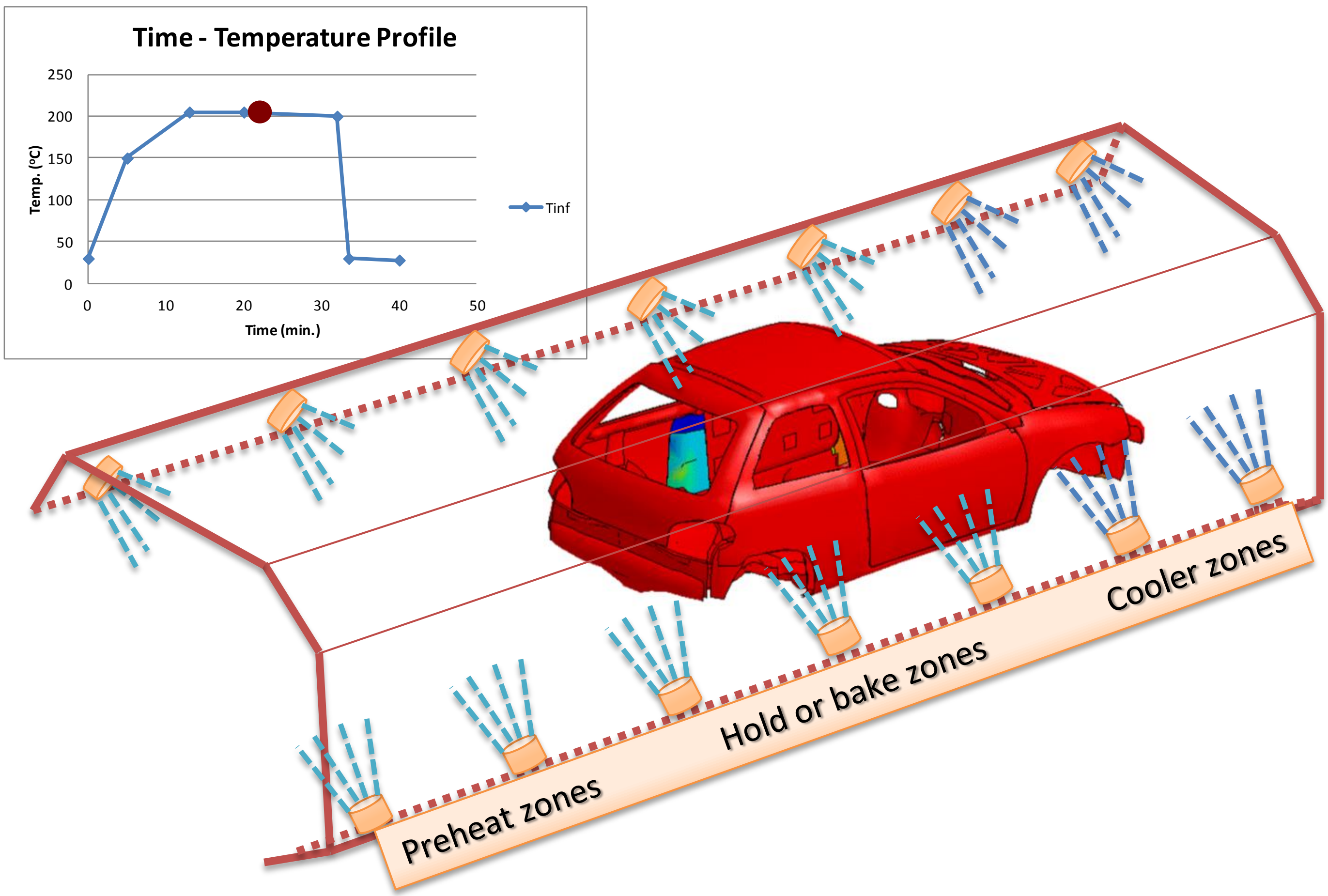
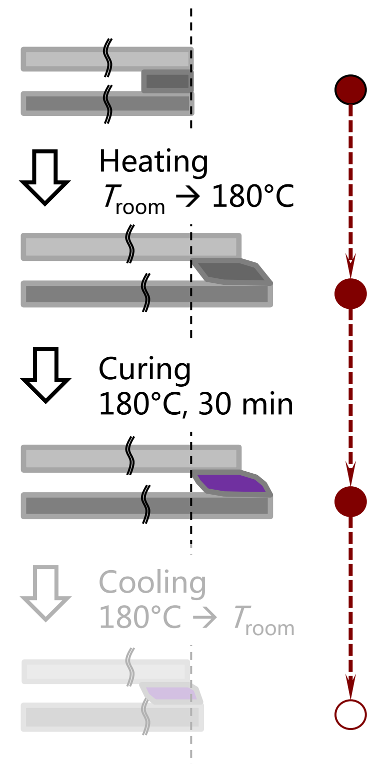
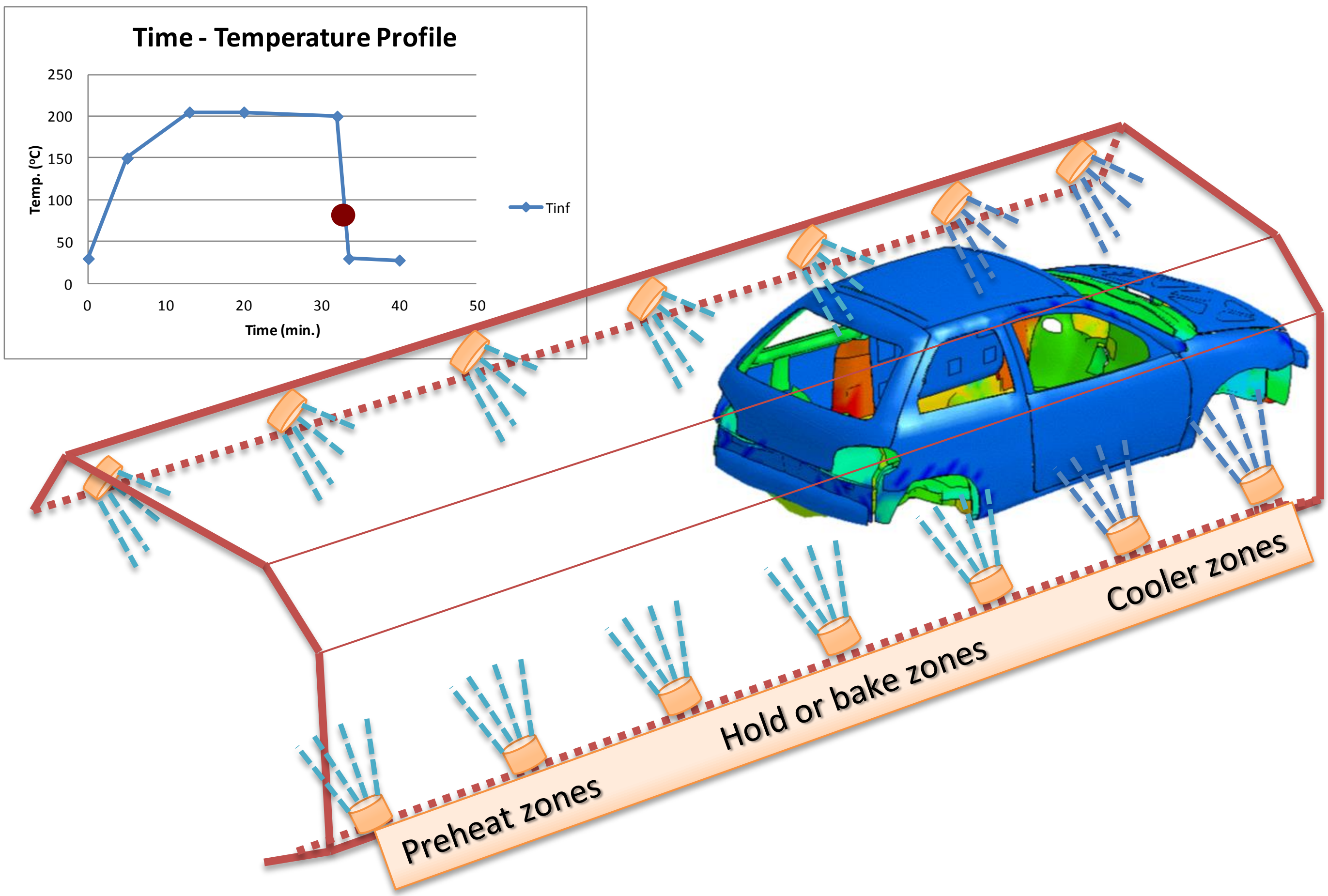
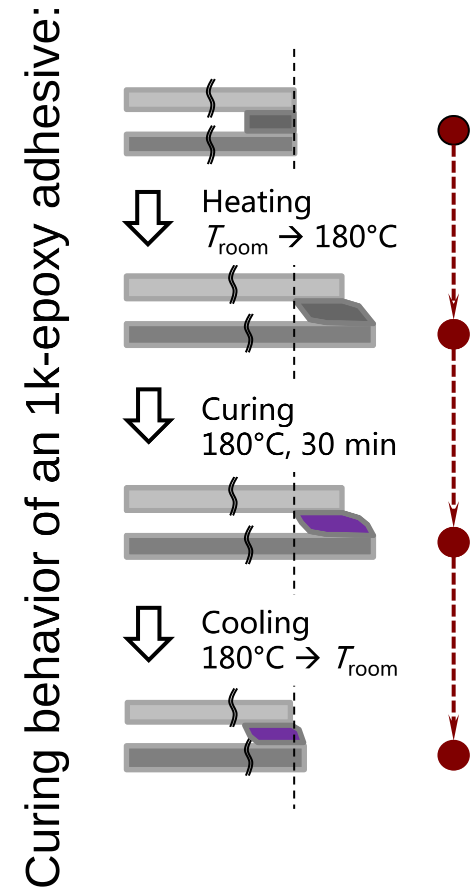


Curing behavior of an 1k-epoxy adhesive:



Motivation: Adhesive curing process – “oven”

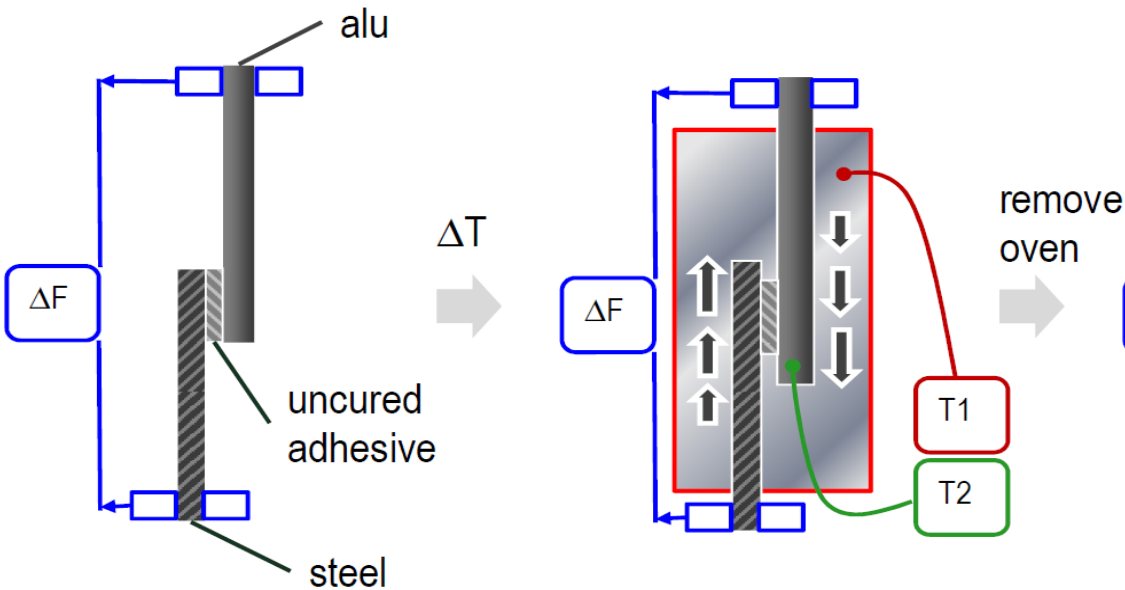




Material Characterization and Numerical Implementation in *MAT_277

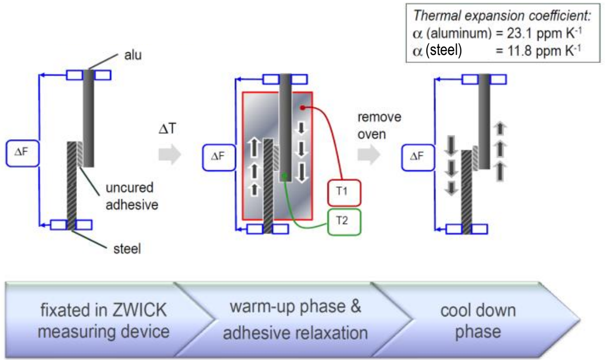
Experiment: Internal Strain Measurement

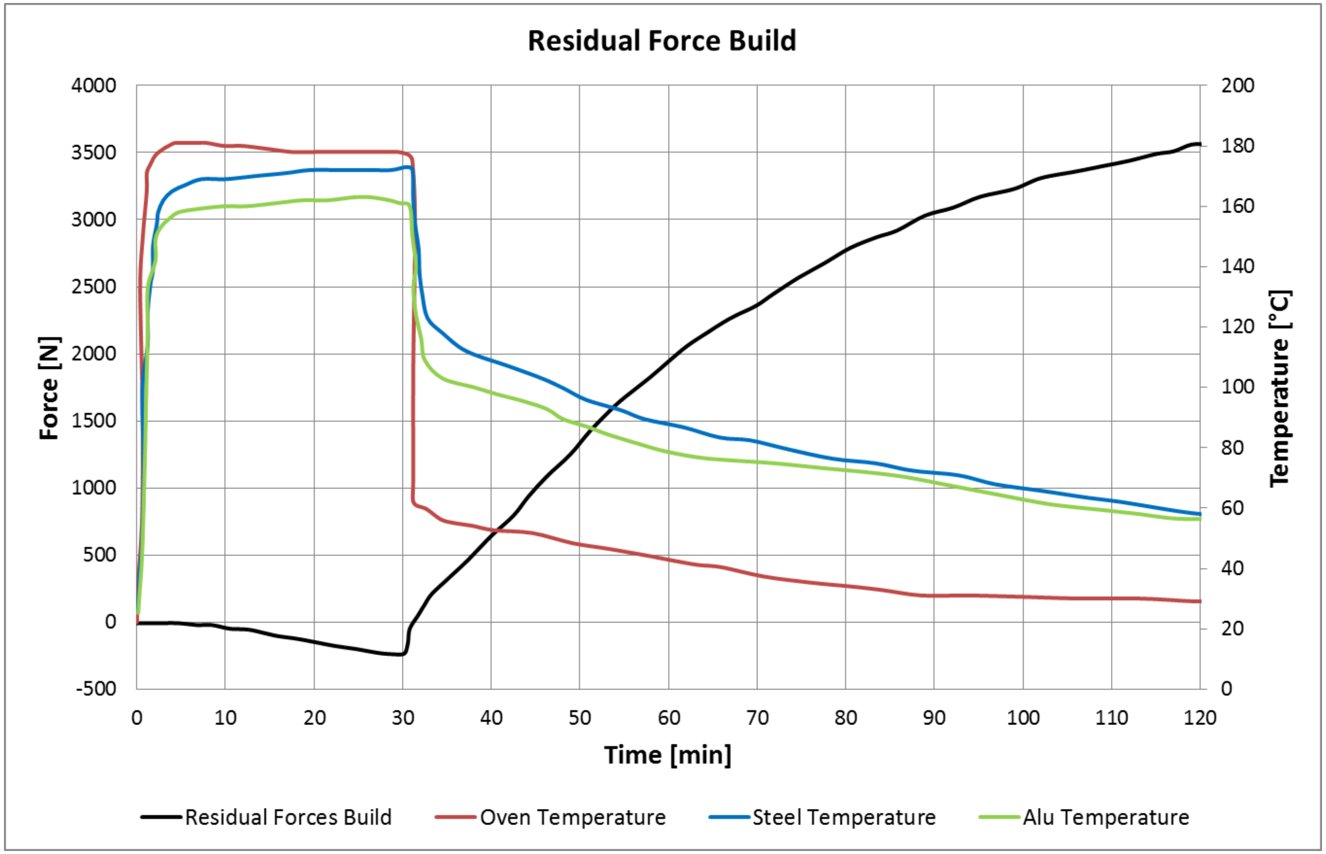
Thermal expansion coefficient:
α (aluminum) = 23.1 ppm K^{-1}
α (steel) = 11.8 ppm K^{-1}



fixated in ZWICK measuring device → warm-up phase & adhesive relaxation → cool down phase

Experiment: Internal Strain Measurement





Embedding "state of cure" in viscoelasticity

Mechanical viscoelasticity

$$\sigma_{ij} = \int_0^t G_{ijkl}(t-\tau)\frac{\partial \varepsilon_{kl}^{me}}{\partial \tau}\,\mathrm{d}\tau$$

Cure dependant Prony series

$$G(t,p) = G_\infty(p) + \sum_{i=1}^{n} G_i(p)\exp\left(\frac{-t}{\tau_i(p)}\right)$$

p

Curing kinetics (Kamal model)

$$\frac{dp}{dt} = (K_1 + K_2 p^m)(1-p)^n$$

$$K_1 = k_1 \exp\left(\frac{-c_1}{RT}\right) \quad K_2 = k_2 \exp\left(\frac{-c_2}{RT}\right)$$

p: curing degree
k_1, k_2, c_1, c_2, m, n: material constants
R: universal gas constant
T: absolute temperature

p

Thermal strain equation:

$$\varepsilon_{ij}^{th} = \int_{T_0}^{T} \alpha(p,T)\delta_{ij}\,dT$$

Cure state dependence:

$$\alpha(p,T) = (1-p)\alpha^0(T) + p\alpha^1(T)$$

α : coefficient of thermal expansion
superscript 0: uncured resin
superscript 1: fully cured resin

p

Chemical shrinkage:

$$\varepsilon_{ij}^{ch} = \int_0^1 \gamma(p)\delta_{ij}\,dp$$

Evolution law of CCS:

$$\gamma(p) = Ap^2 + Bp + C$$

γ: coefficient of chemical shrinkage
A, B, C: material constants

ε_{ij}^{th} ε_{ij}^{ch}

Strain composition:

The total strain is composed by mechanical, chemical and thermal strains

$$\varepsilon_{ij} = \varepsilon_{ij}^{me} + \varepsilon_{ij}^{ch} + \varepsilon_{ij}^{th}$$

ε_{ij}^{me}

Keyword input for *MAT_277

*MAT_ADHESIVE_CURING_VISCOELASTIC

	1	2	3	4	5	6	7	8
Card 1	MID	RO	K1	K2	C1	C2	M	N
Card 2	CHEX1	CHEX2	CHEXP3	LCCHEX	LCTHEX	R	TREFEX	DOCREF
Card 3	WLFTREF	WLFA	WLFB	LCG0	LCK0	IDOC	INCR	
Opt. I	GI	BETAGI	KI	BETAKI				

- thermo-viscoelastic material model with curing dependency
- generalized Maxwell model with Prony series expansion
- each optional card represents one term of up to 16 terms in Prony series

Description of "State of Cure"

Curing kinetics (Kamal model)

$$\frac{dp}{dt} = (K_1 + K_2 p^m)(1-p)^n$$

$$K_1 = k_1 \exp\left(\frac{-c_1}{RT}\right) \quad K_2 = k_2 \exp\left(\frac{-c_2}{RT}\right)$$

p: curing degree
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1	2	3	4	5	6	7	8
MID	RO	K1	K2	C1	C2	M	N
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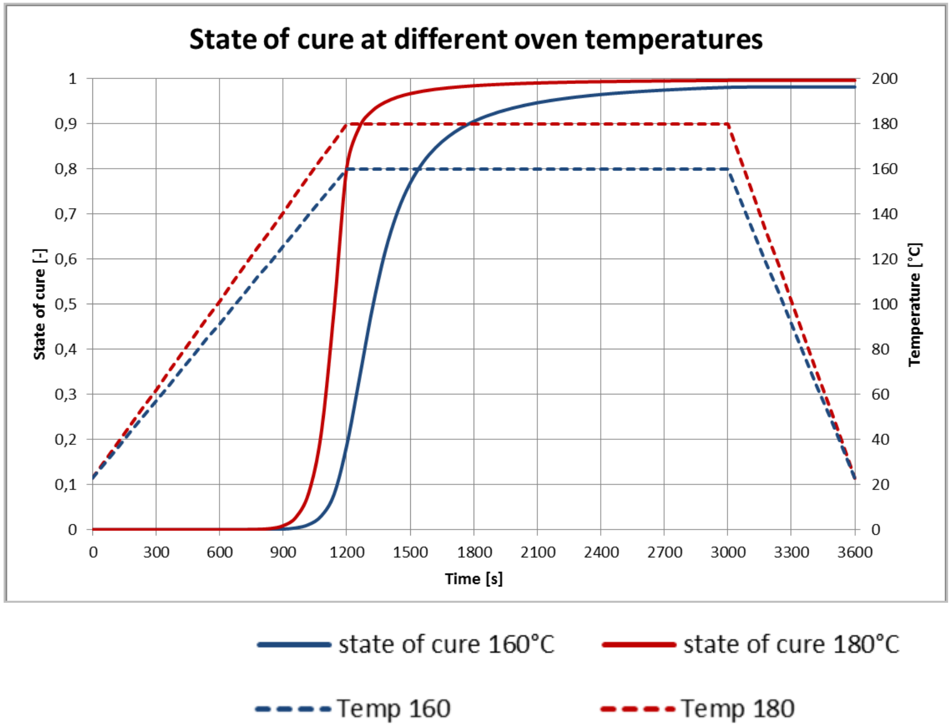
GI	BETAGI	KI	BETAKI				

- Kamal model allows a more flexible handling than direct curve input
- requires a more or less complex identification process
- Initial degree of cure p_I is accounted for



Cure dependent thermal strains

Thermal strain equation:

$$\varepsilon_{ij}^{th} = \int_{T_0}^{T} \alpha(p,T)\delta_{ij}\, dT$$

Cure state dependence:

$$\alpha(p,T) = (1-p)\alpha^0(T) + p\alpha^1(T)$$

α : coefficient of thermal expansion
superscript 0: uncured resin
superscript 1: fully cured resin

1	2	3	4	5	6	7	8
MID	RO	K1	K2	C1	C2	M	N
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WLFTREF	WLFA	WLFB	LCG0	LCK0	IDOC	INCR	
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- coefficient of thermal expansion $\alpha(p,T)$ given as tabular data
- for negative value of LCTHEX secant formulation is used for strain data

$$\varepsilon^{th} = \alpha(p,T)\left(T - T_{ref}\right) - \alpha(p,T_I)(T_I - T_{ref})$$

- for positive LCCHEX differential form is employed

$$d\varepsilon^{th} = \alpha(p,T)dT$$

Chemical strains

Chemical shrinkage:

$$\varepsilon_{ij}^{ch} = \int_0^1 \gamma(p)\delta_{ij}dp$$

Evolution law of CCS:

$$\gamma(p) = Ap^2 + Bp + C$$

γ: coefficient of chemical shrinkage
A,B,C: material constants

1	2	3	4	5	6	7	8
MID	RO	K1	K2	C1	C2	M	N
CHEX1	CHEX2	CHEXP3	LCCHEX	LCTHEX	R	TREFEX	DOCREF
WLFTREF	WLFA	WLFB	LCG0	LCK0	IDOC	INCR	
GI	BETAGI	KI	BETAKI				

- coefficient of chemical shrinkage γ can either be given by quadratic expression or by a load curve with ID=|LCCHEX|
- for quadratic exp. or negative LCCHEX secant form is used for strain data

$$\varepsilon^{ch} = \gamma(p)(p - p_0) - \gamma(p_I)(p_I - p_{ref})$$

- for positive LCCHEX differential form is employed

$$d\varepsilon^{ch} = \gamma(p)dp$$

Mechanical viscoelasticity (Prony series input)

Mechanical viscoelasticity

$$\sigma_{ij} = \int_0^t G_{ijkl}(t-\tau)\frac{\partial \varepsilon_{kl}^{me}}{\partial \tau}\mathrm{d}\tau$$

Cure dependant Prony series

$$G(t,p) = G_\infty(p) + \sum_{i=1}^{n} G_i(p)\exp\left(\frac{-t}{\tau_i(p)}\right)$$

1	2	3	4	5	6	7	8
MID	RO	K1	K2	C1	C2	M	N
CHEX1	CHEX2	CHEXP3	LCCHEX	LCTHEX	R	TREFEX	DOCREF
WLFTREF	WLFA	WLFB	LCG0	LCK0	IDOC	INCR	
GI	BETAGI	KI	BETAKI				

- Assumption I: ratio $G_i(p)/G_0(p)$ is constant and independent of temperature
- Assumption II: relaxation parameter $\beta_i(T)$ independent of state of cure
- Assumption III: Wiliams –Landel-Ferry equation describes temperature dependency

$$\mathrm{G}(t,p,T) = G_0(p)\left(1 - \sum_i \frac{G_{i,p=1.0}}{G_{0,p=1.0}}\left(1 - e^{-\beta_i \cdot a_H(T)\cdot t}\right)\right)$$

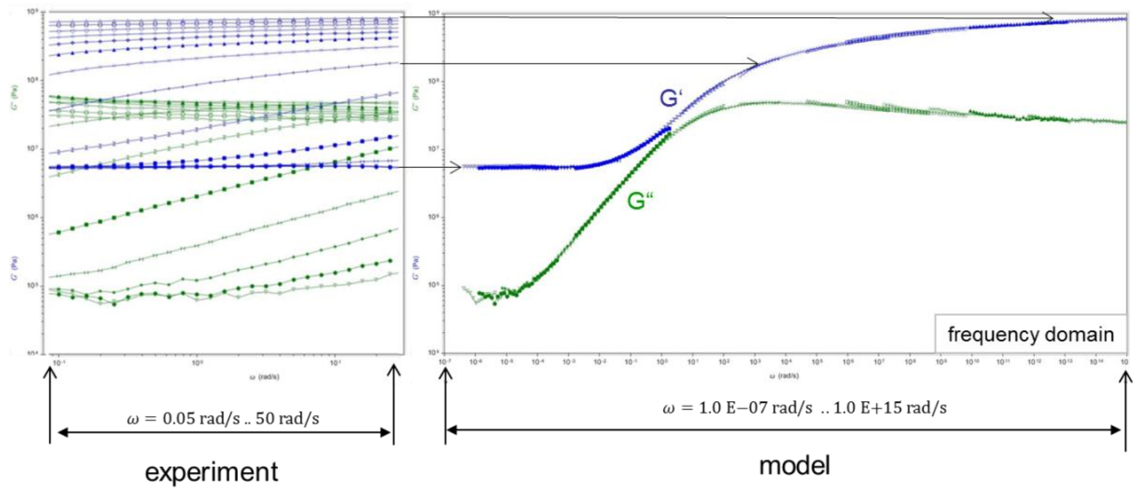
Mechanical viscoelasticity (temperature dependency)

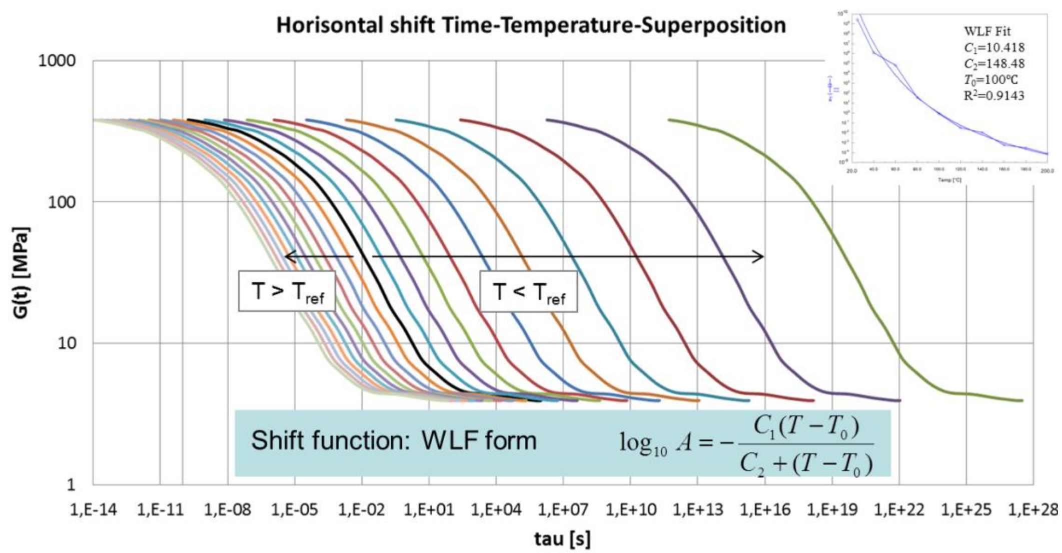
- properties can be identified with Time-Step-Frequency-Sweep DTMA analysis

- Time-Temperature-Superposition with WLF-shift

$$\ln a_H(T) = -\frac{A(T - T_{ref})}{B + (T - T_{ref})}$$

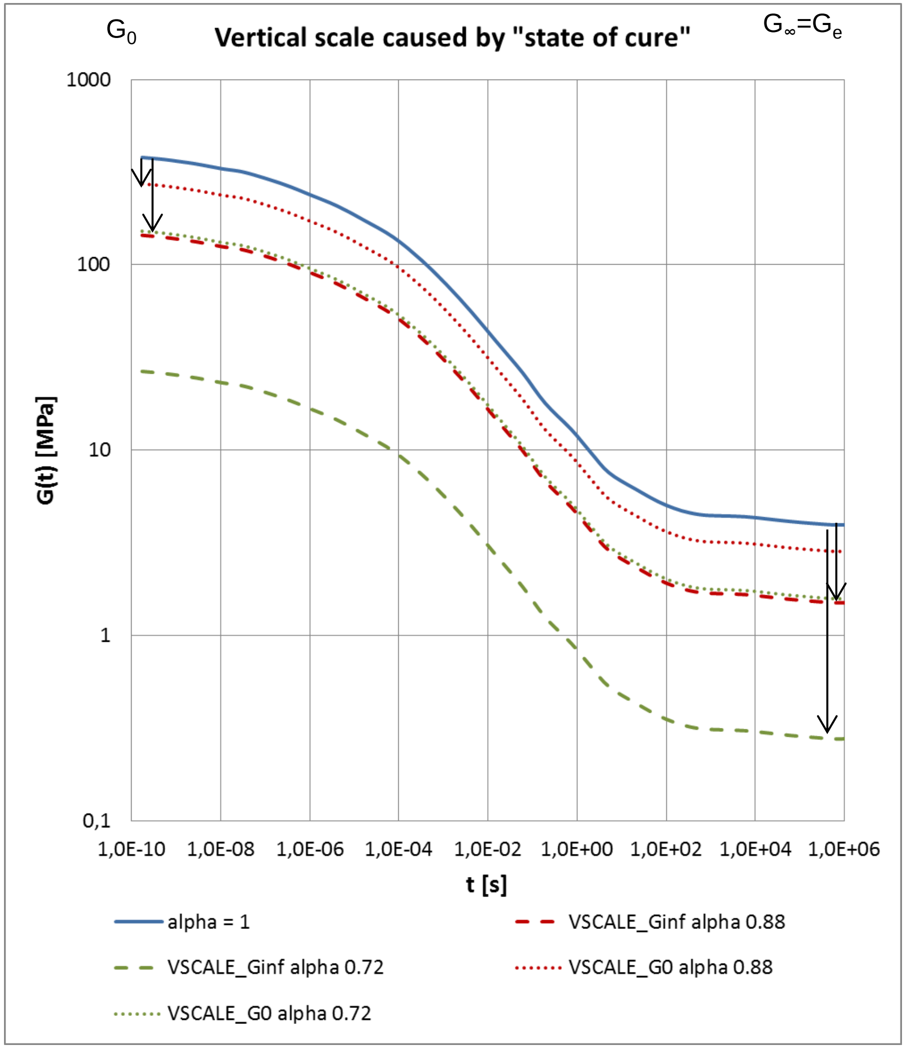
[Williams-Landel-Ferry, 1955]





Mechanical viscoelasticity (cure dependency)

- curing causes a vertical shift in the relaxation curve
- instantaneous moduli $G_0(p)$ and $K_0(p)$ are input as load curves



Further remarks on material formulation

- parameter INCR switches between a total and an incremental (recommended) stress update routine

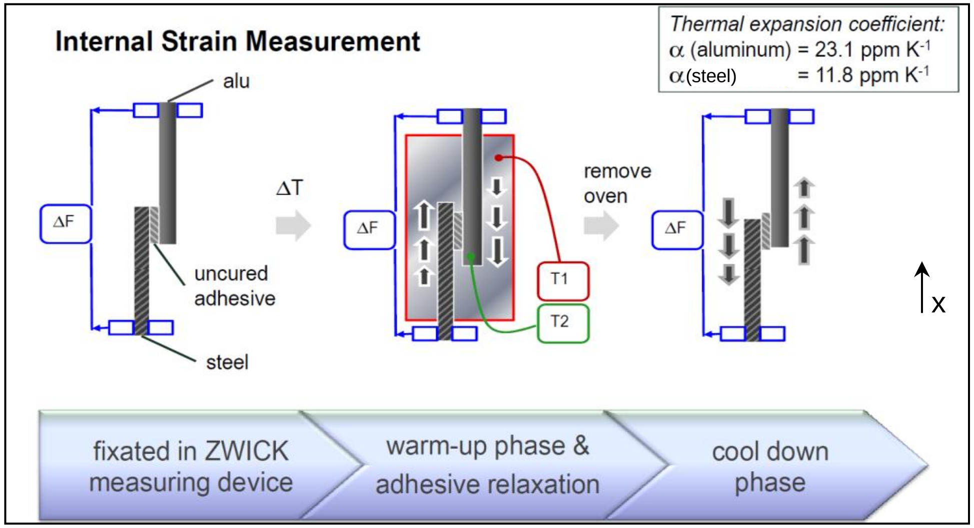
- material is available for
  - solid, shell and cohesive‡ elements
  - explicit and implicit simulations

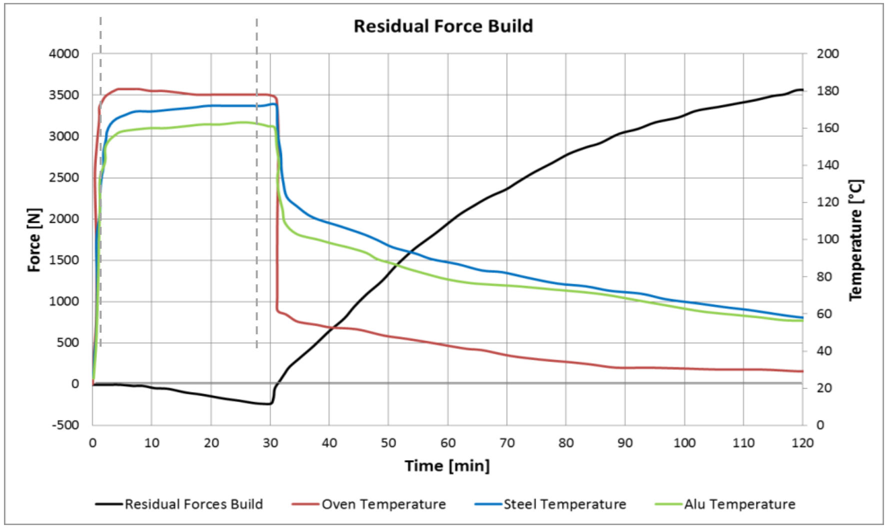
- most important quantities are output into history variables
  - state of cure
  - thermal strain
  - chemical strain

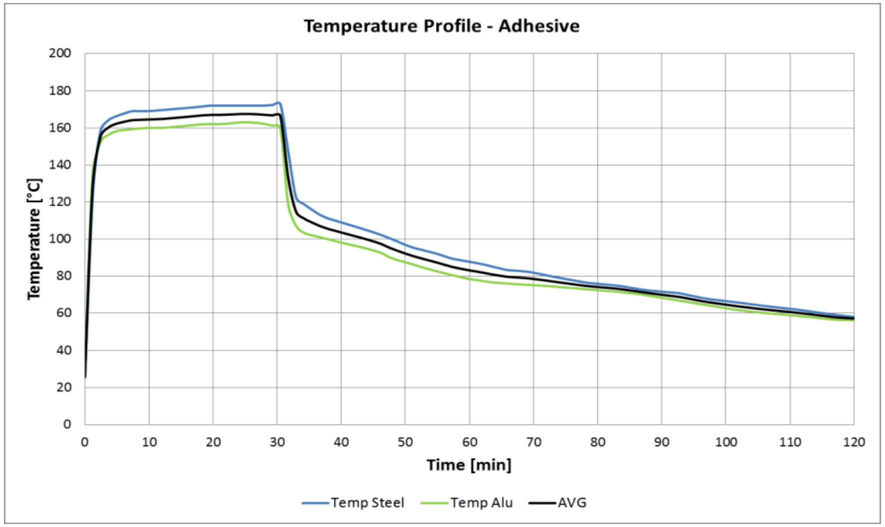
‡ requires interface *MAT_ADD_COHESIVE

Examples

Example 1: Internal Strain Measurement



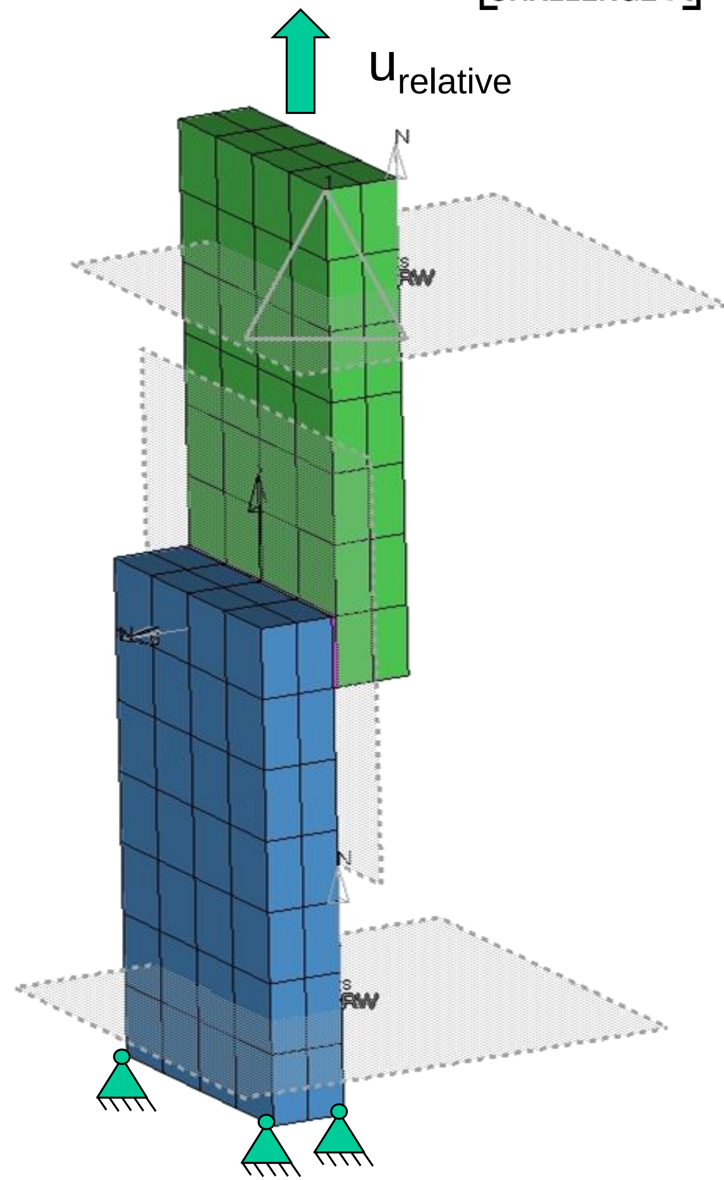




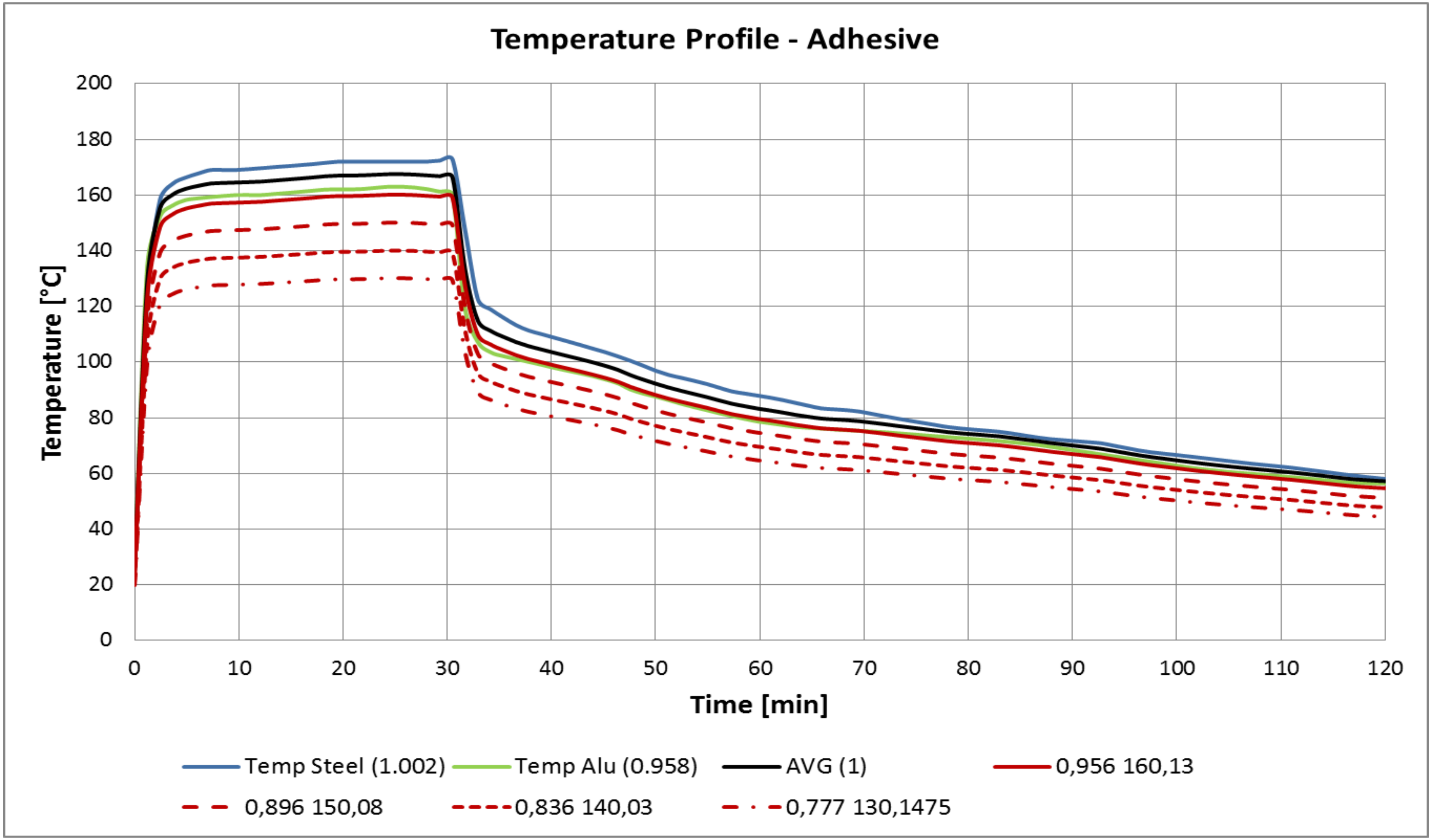
- Only concept can be shown
- Boundary conditions extracted from real experiment
- Variation of temperature condition for adhesive studied

Example 1 - Simulation approach

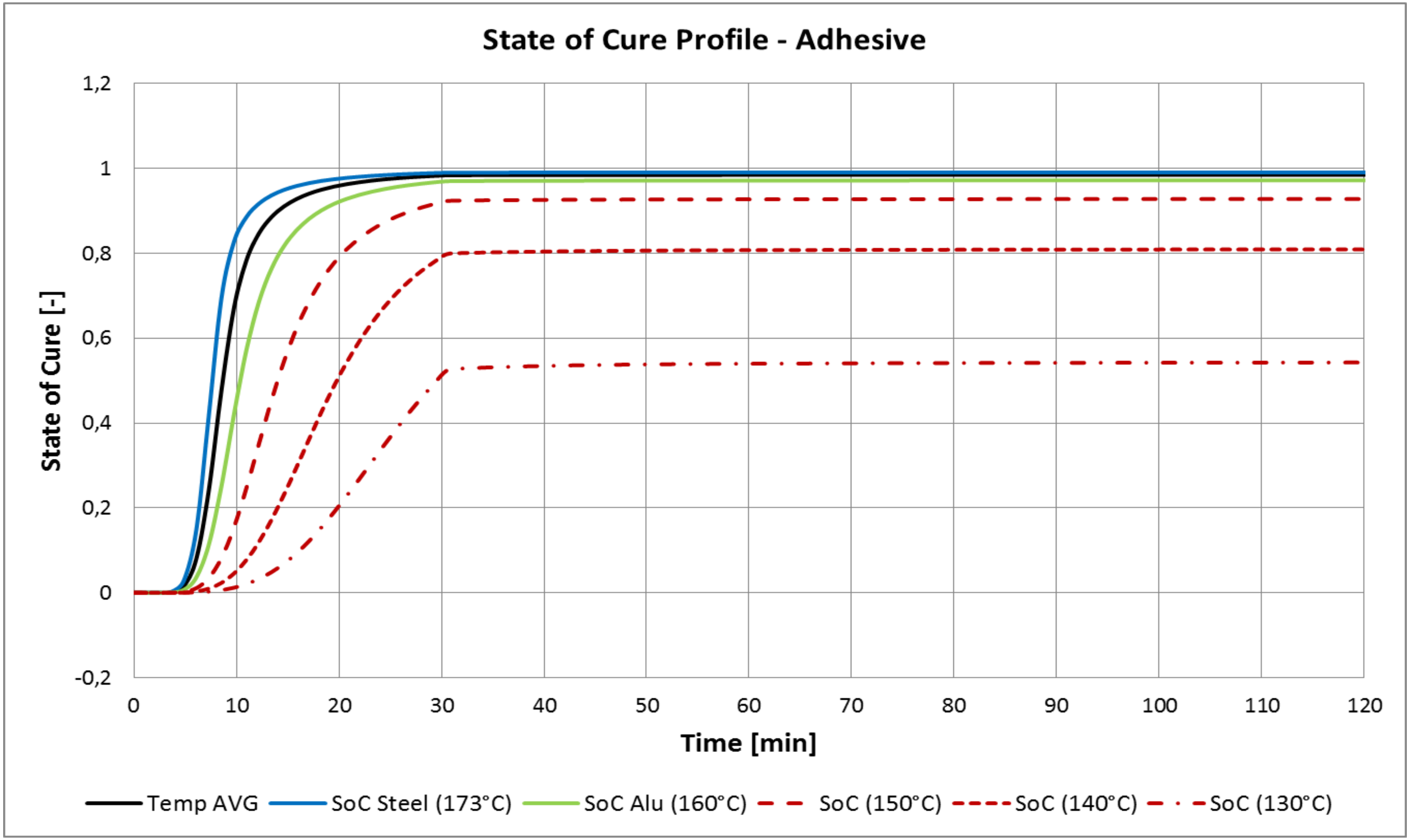
- Relative movement of the bond area assuming stiff substrate behavior
- Steel part is fixed at the bottom, Alu-part is moving with the relative displacement profile
- Simulation bond area is 5 x 19.2 mm with bondline thickness of 0.3 mm
- Coarse meshing is studied
- Thermal strain would represent substrate length of 100 mm (Steel and Alu) vs. meshed 35 mm.
- Different adhesives, different geometry – only tendency is of interest (for the time being)



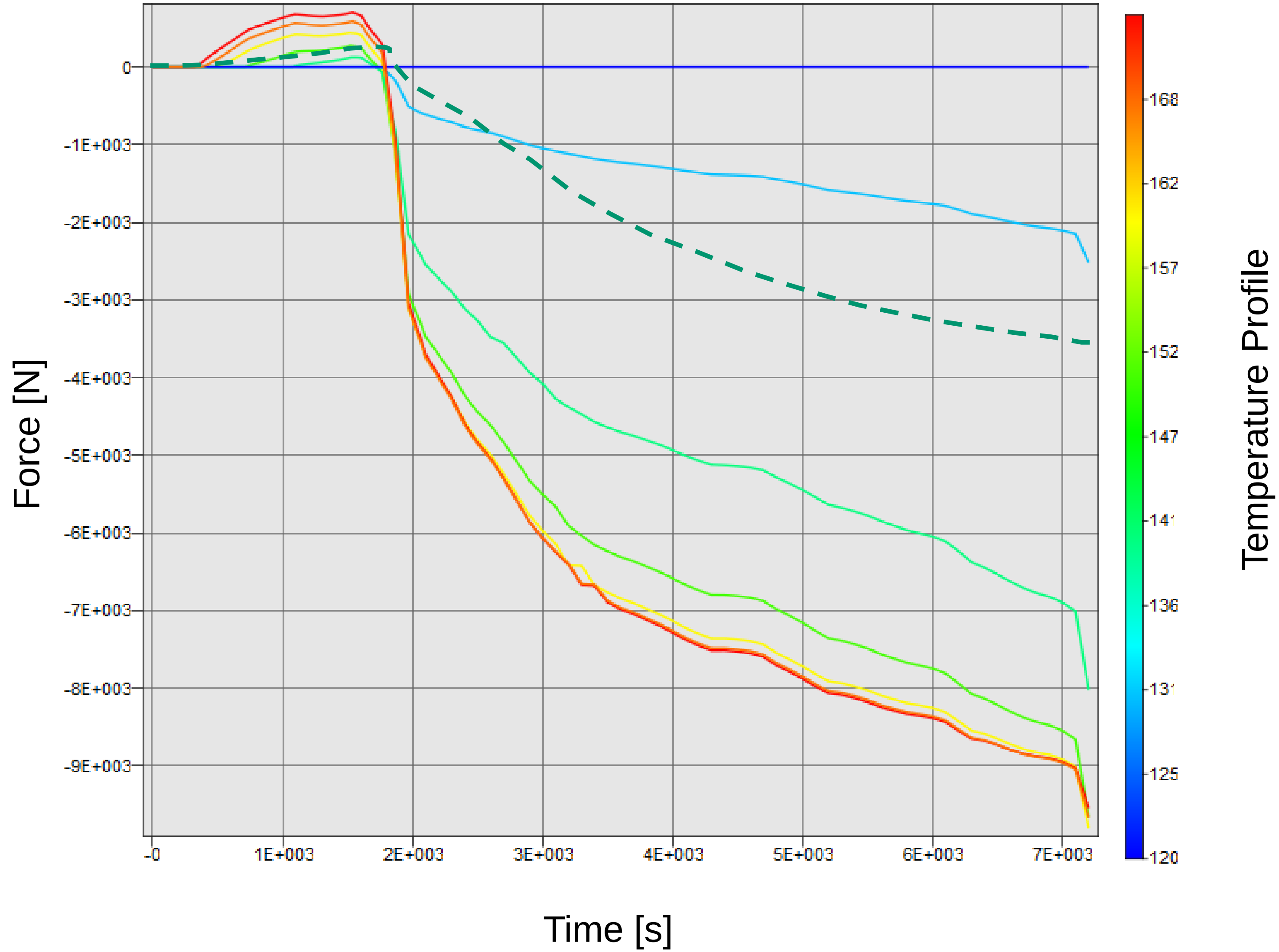
Example 1 - Study of temperature influence



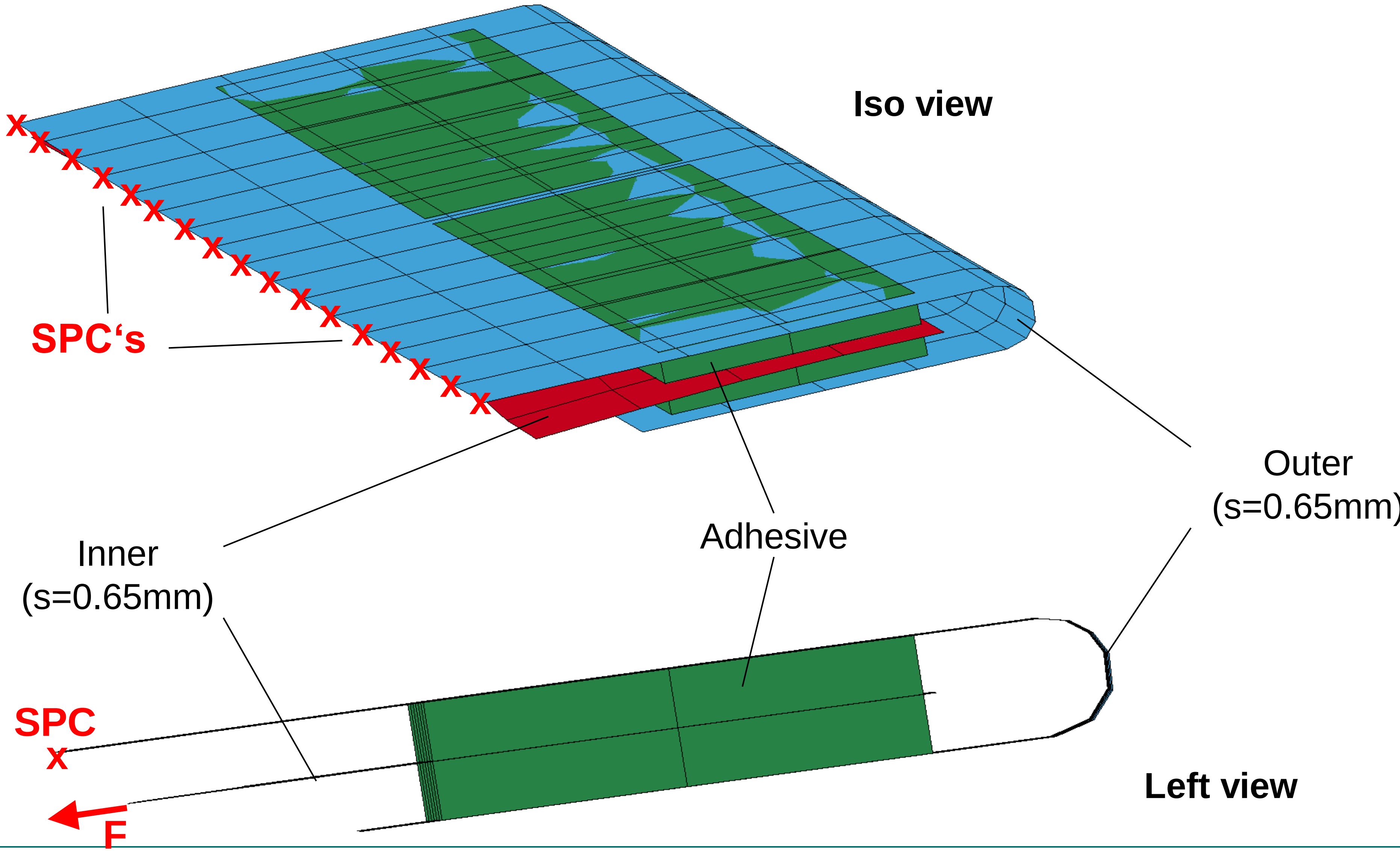
Example 1 - State of Cure relation of temperature study



Example1 - Force response

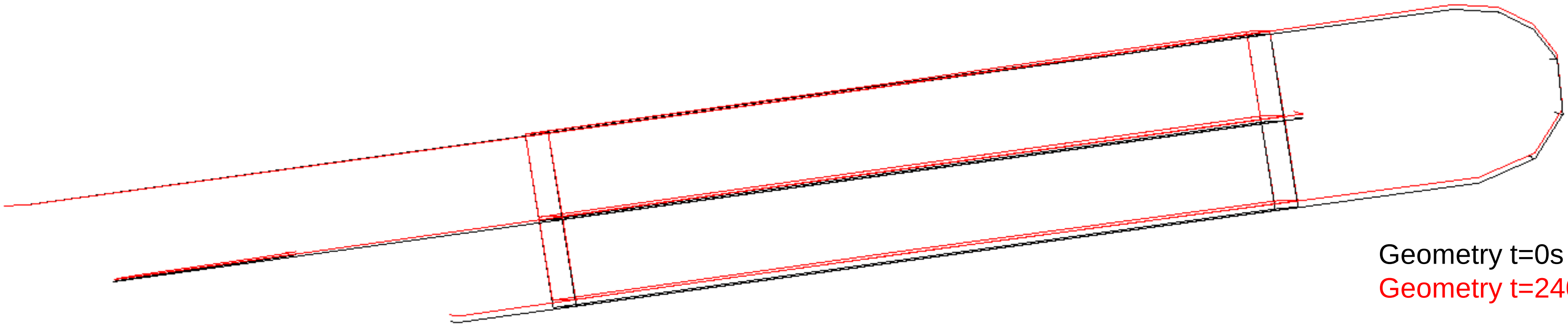


Example 2: Roller hemming



Example 2 - Variant 1

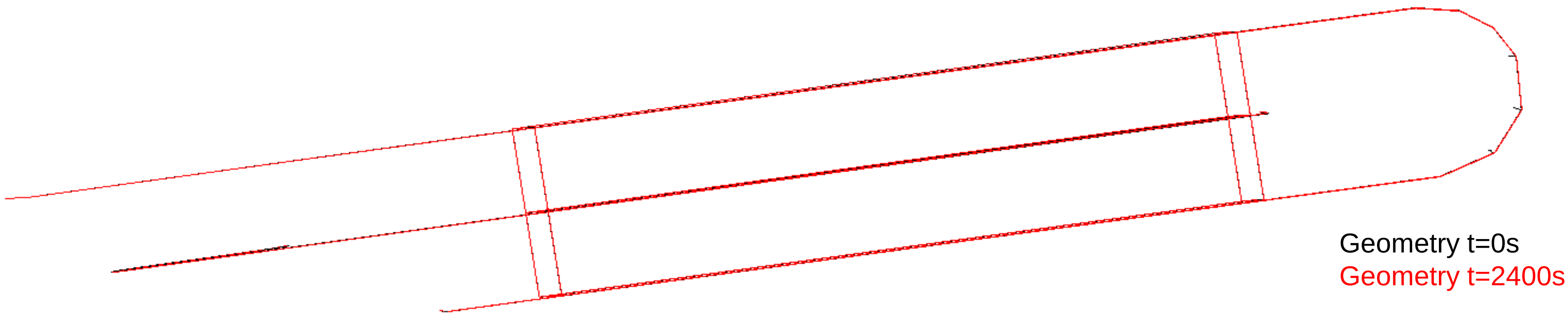
- Adhesive modelling
  - Solid element type -1 => thickness of adhesive layer s = 0.65 mm
  - Material model: *MAT_277



- Results
  - Residual deformation after curing process too large due to chemical shrinkage
  - Model does not account for real thickness of the adhesive layer and thus overestimates the deformation

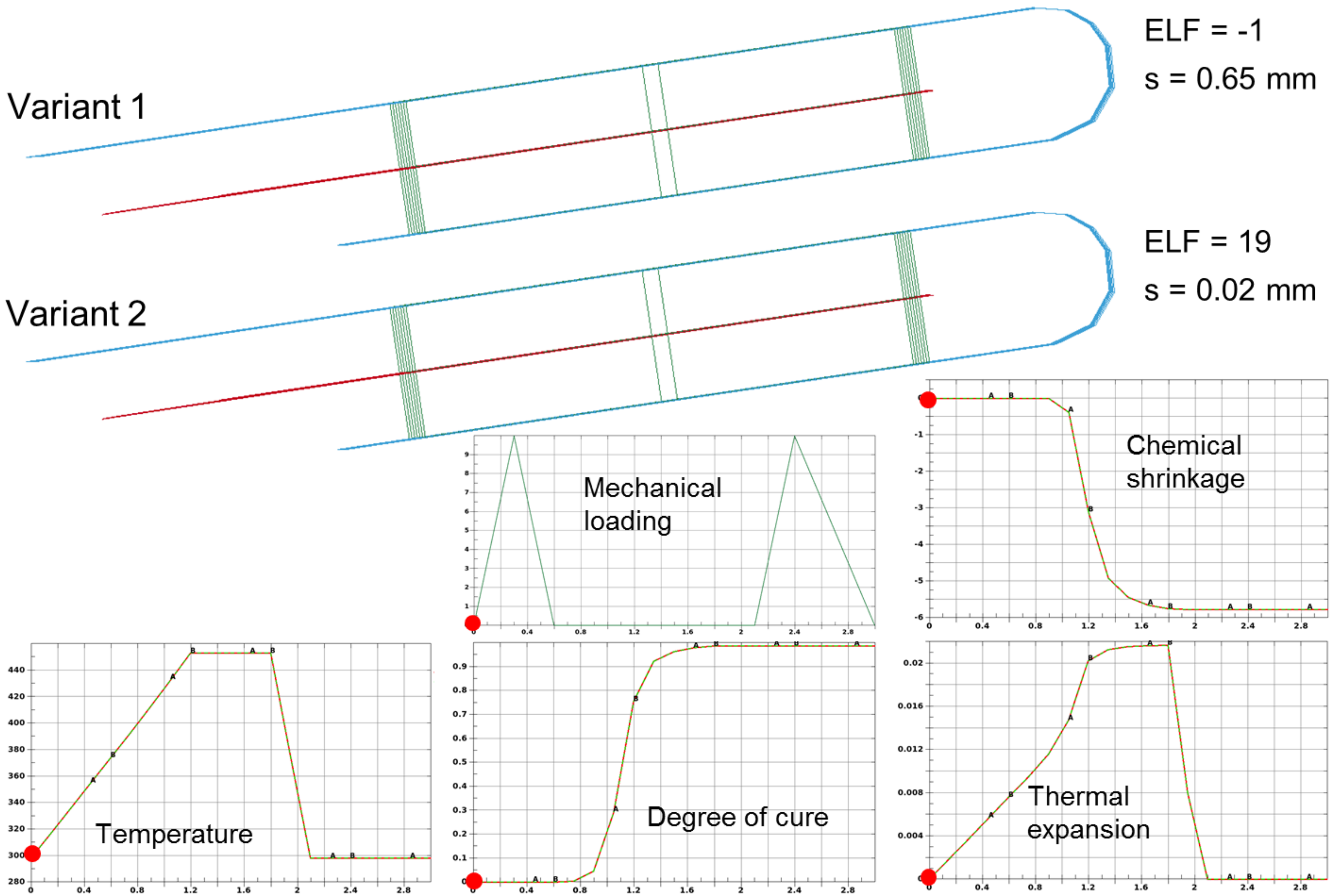
Example 2 - Variant 2

- Adhesive modelling
  - Solid element type 19
  - *MAT_277 + *MAT_ADD_COHESIVE with parameter THICK=0.02

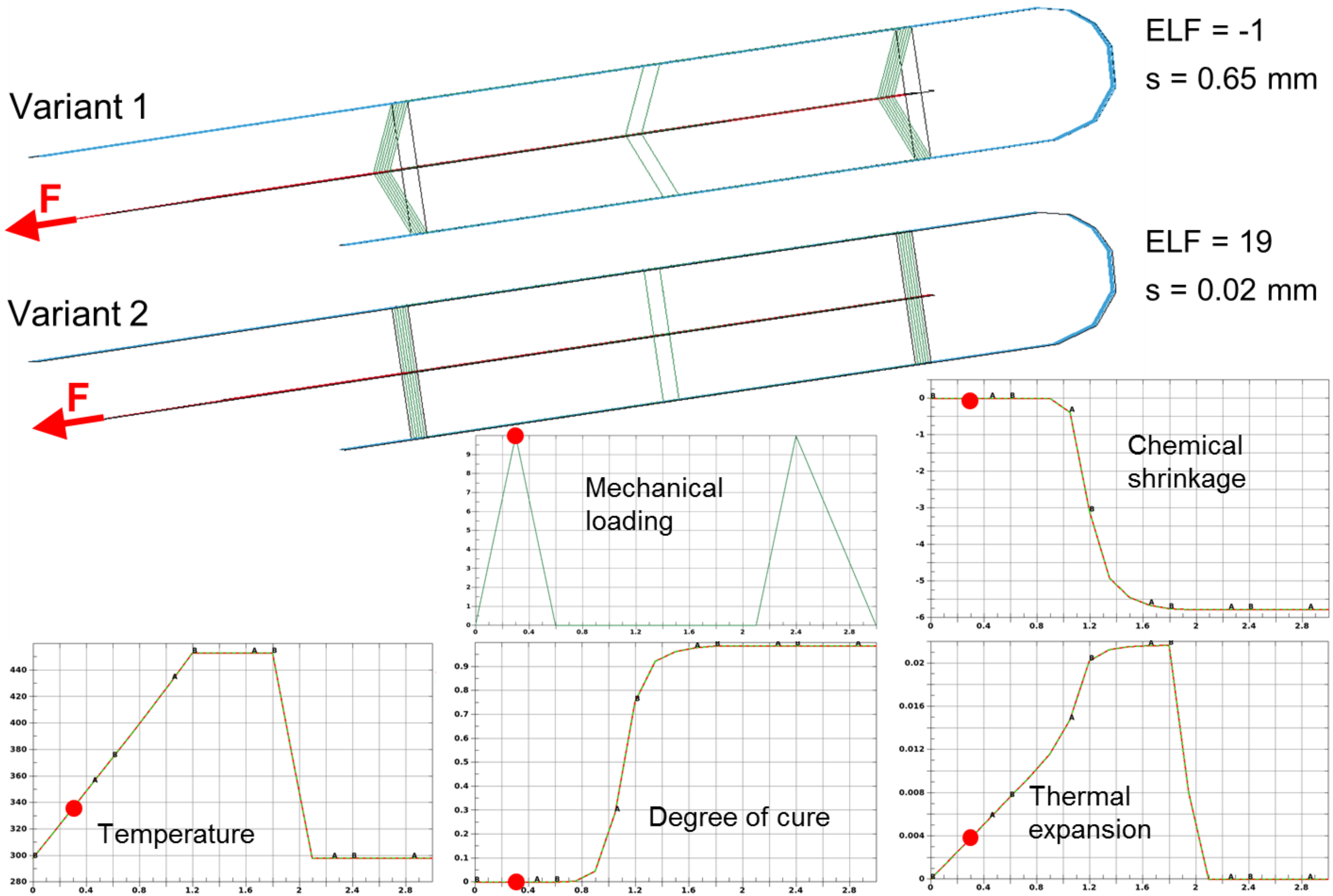


- Results
  - The correct thickness is of the adhesive is now accounted for
  - Remaining deformation is reasonable

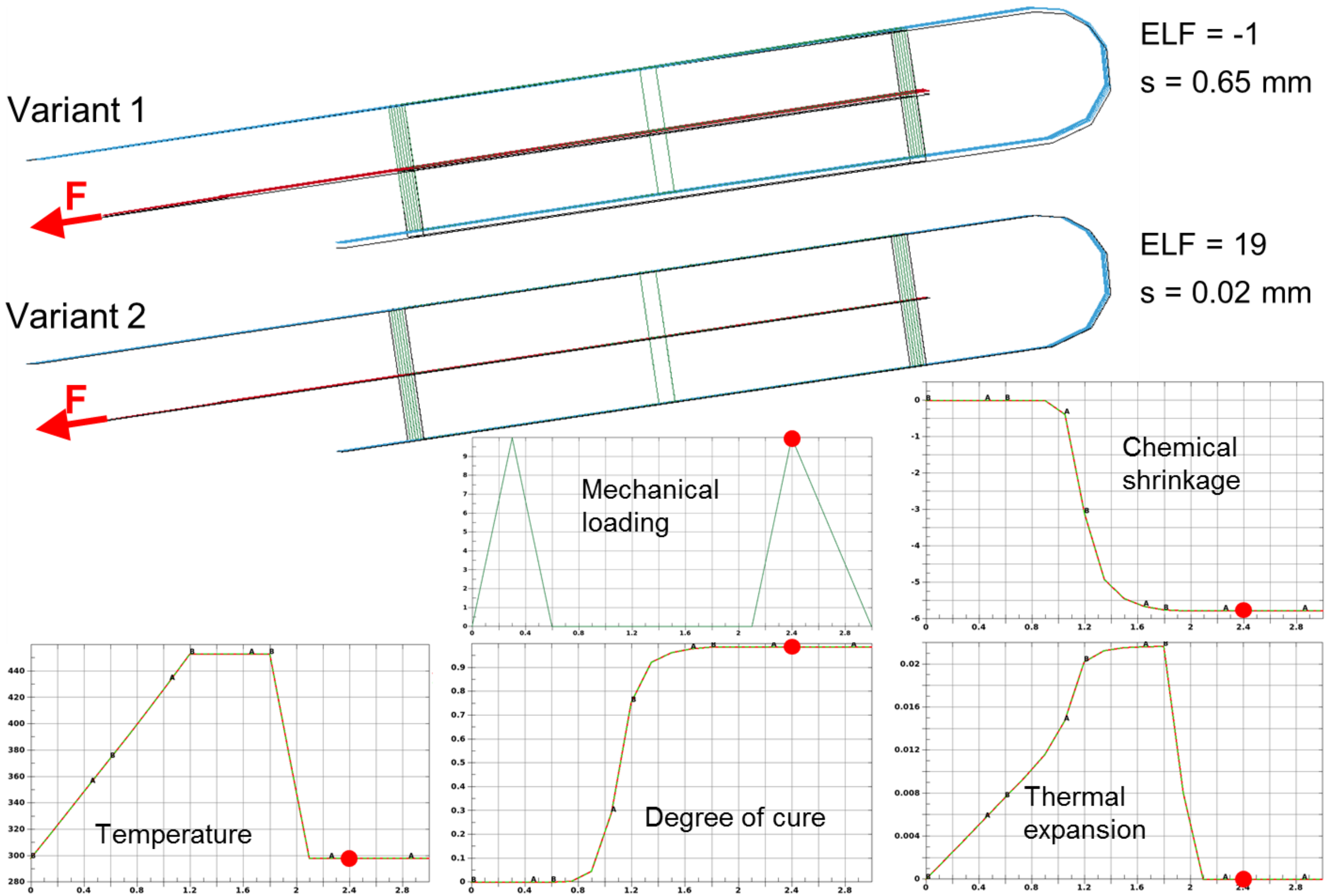
Example 2 – Result for t = 0s



Example 2 – Result for t = 240s



Example 2 – Result for t = 3600 s



Summary and Outlook

Summary and Conclusion

- The oven process (drying e-coat, curing adhesives) was used to motivate the consideration of the phase change in material modeling for the adhesive
- The delta-alpha problem (thermal expansion problem) based on changing temperature fields and multi-material-mix during cure was introduced

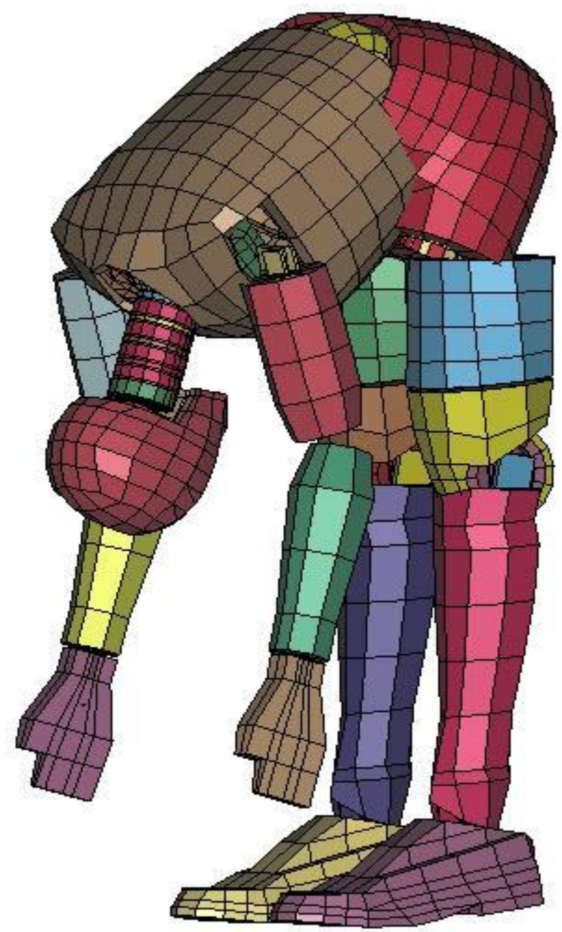
- The material model development for structural adhesives was discussed
  - curing model implemented based on Kamal
  - mechanical strain, thermal strain and chemical strain are considered
  - dependence on the state of cure and temperature on mechanical properties

- Application of the material model into two simple boundary value problems was presented to discuss the predictive potential of the material model

Outlook

- Further model verification and validation
- More general formulation of the Prony series parameters in terms of state of cure might become necessary
- Extension of the material model towards plasticity
- Implementation of a damage and failure model
- Parameterization of the models might be useful to reverse engineer material property demands to improve or design new products

Thank you
for your attention!



thomas.kloeppel@dynamore.de