institut für windenergiesysteme

Leibniz Universität Hannover

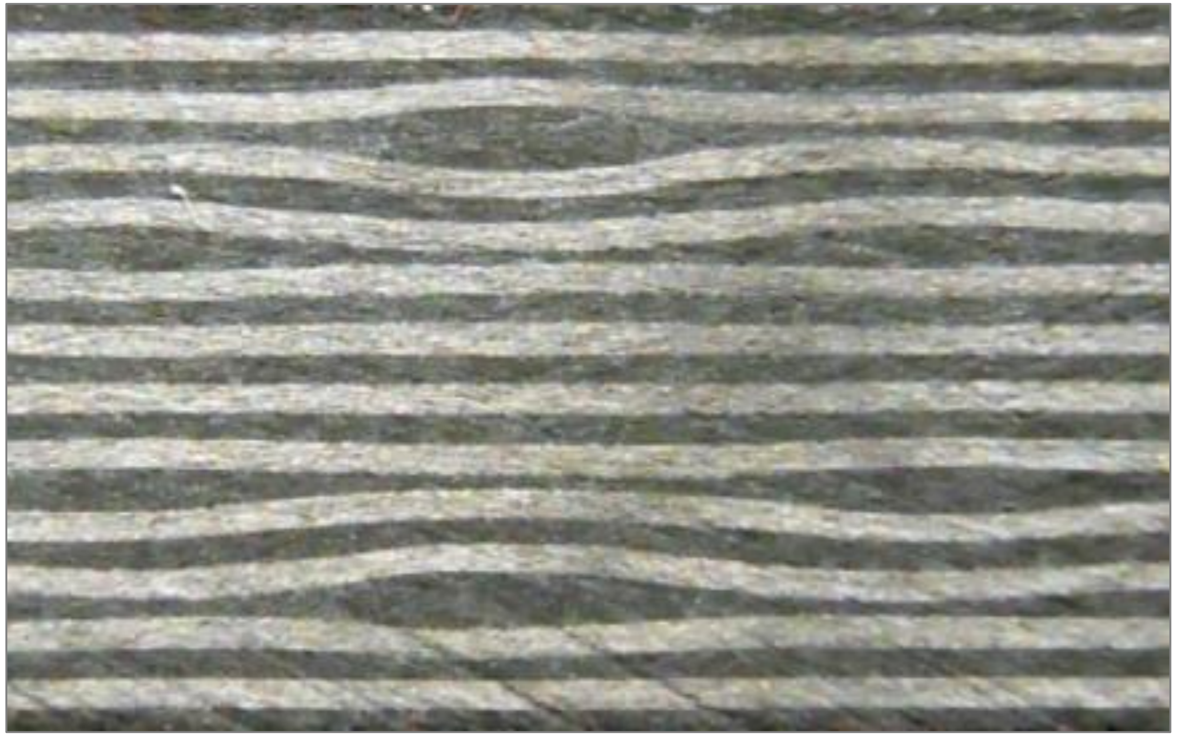
Comparison of viscoelasticity models for the prediction of residual stresses in wind turbine rotor blades

Yixing Wang[a], Claudio Balzani[a]

[a]Leibniz University Hannover, Institute for Wind Energy Systems, Germany

Motivation
Residual stresses

- Manufacturing processes + bi-material
- Influence on static and fatigue strength, buckling resistance, etc.
- Spring-in / spring-back effects
- Trigger ondulations
- Long-term goal: Predict RS-related formation of ondulations in thick laminates



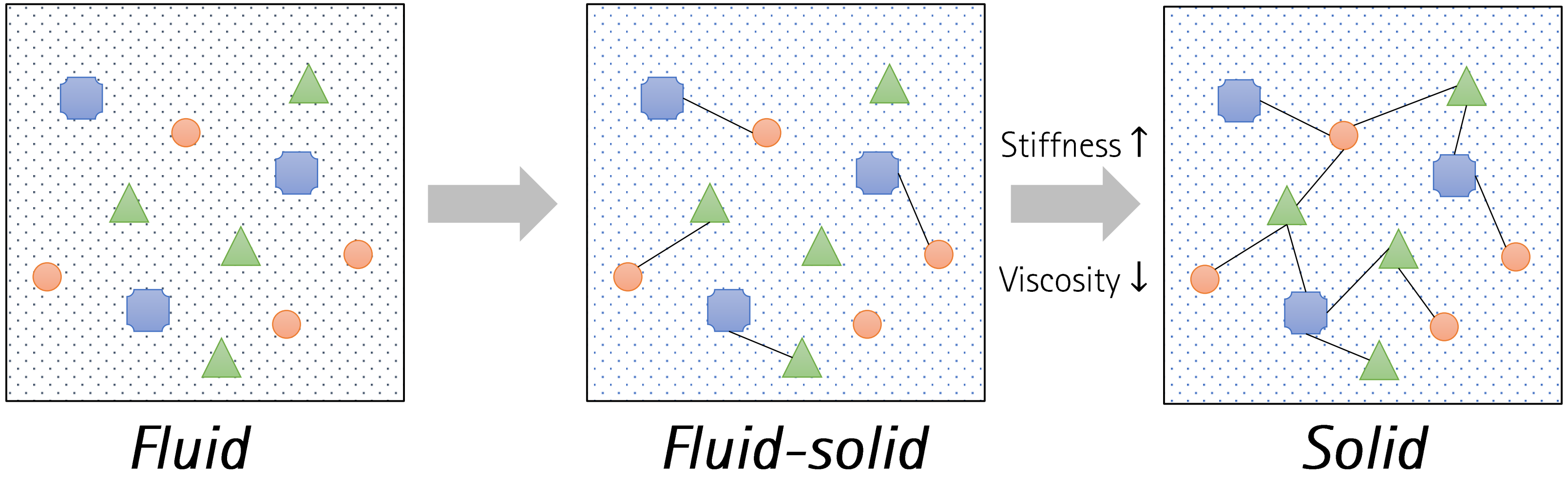
Passakom Duangmuan: Layer waviness effects on compression strength of composite laminates: Progressive failure analysis and experimental validation, PhD Thesis, University of Utah, USA, 2012

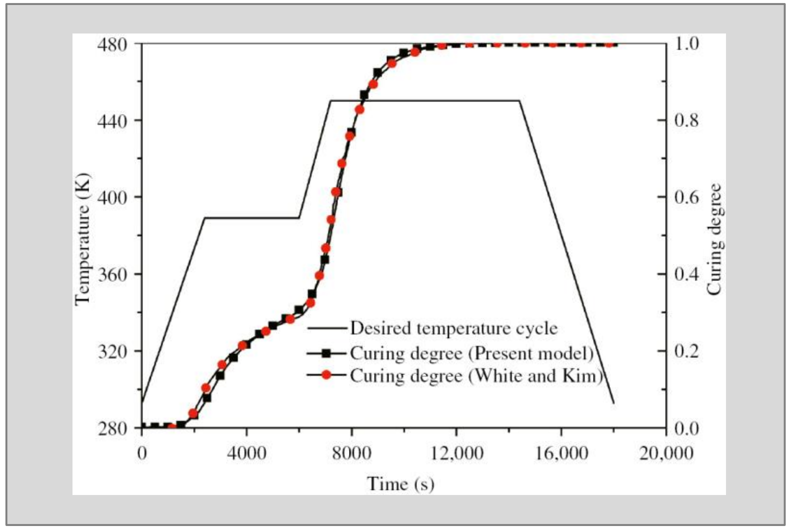
Content

- Models
- Application example
- Conclusions and outlook

Manufacturing process

Thermo-mechanical coupling



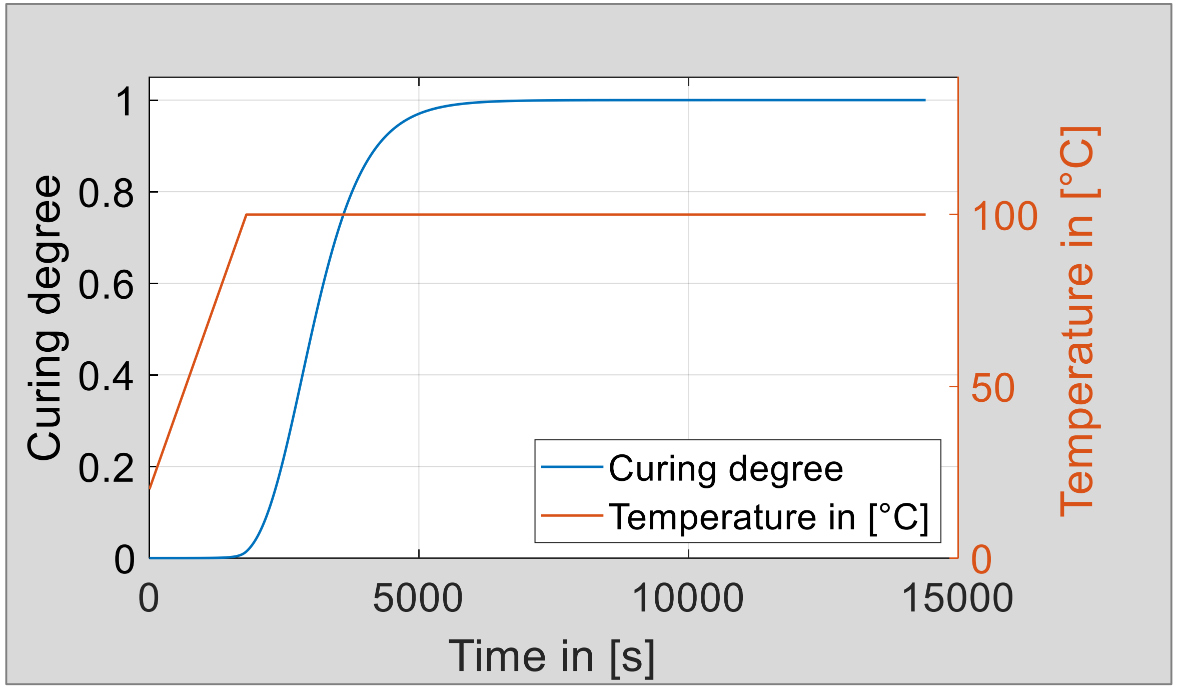


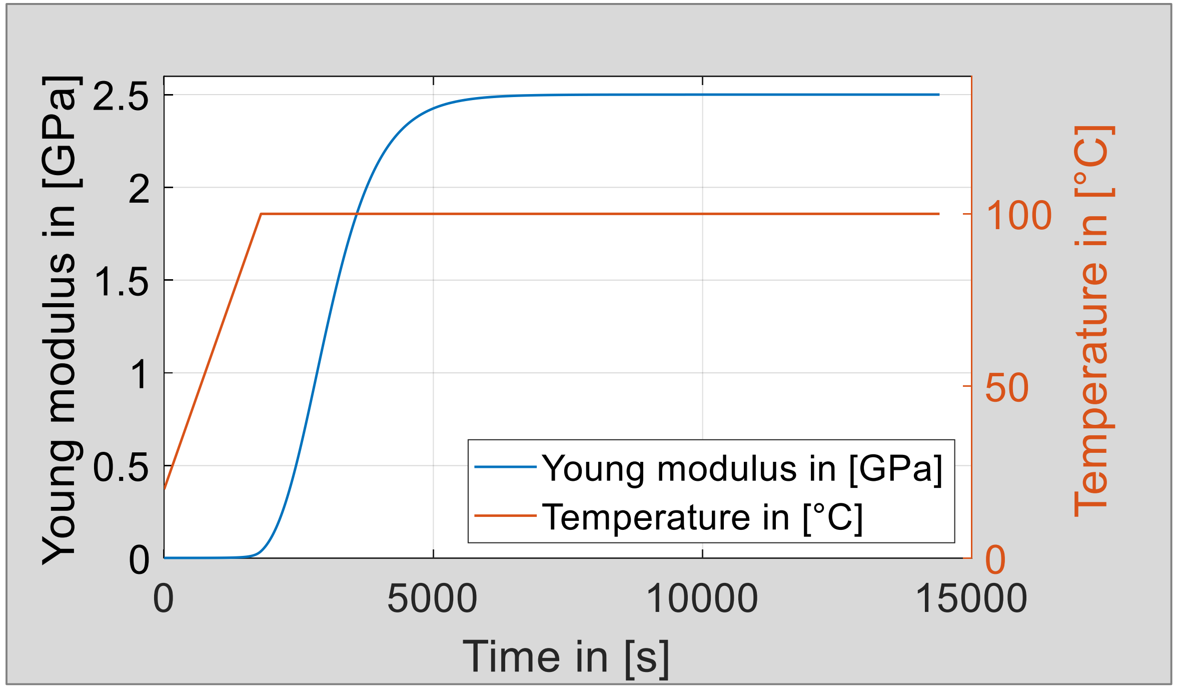
X. Wang etc. : Effects of key thermophysical properties on the curing uniformity of carbon fiber reinforced resin composites , e-Polymers, 2017

- Curing: Chemical reaction → network formation
- Curing degree: Degree of network formation $(0 < \alpha < 1)$
- Thermo-chemical coupling: Acceleration of chemical reaction
- Chemo-mechanical coupling: Formation of stiffness

CHILE model

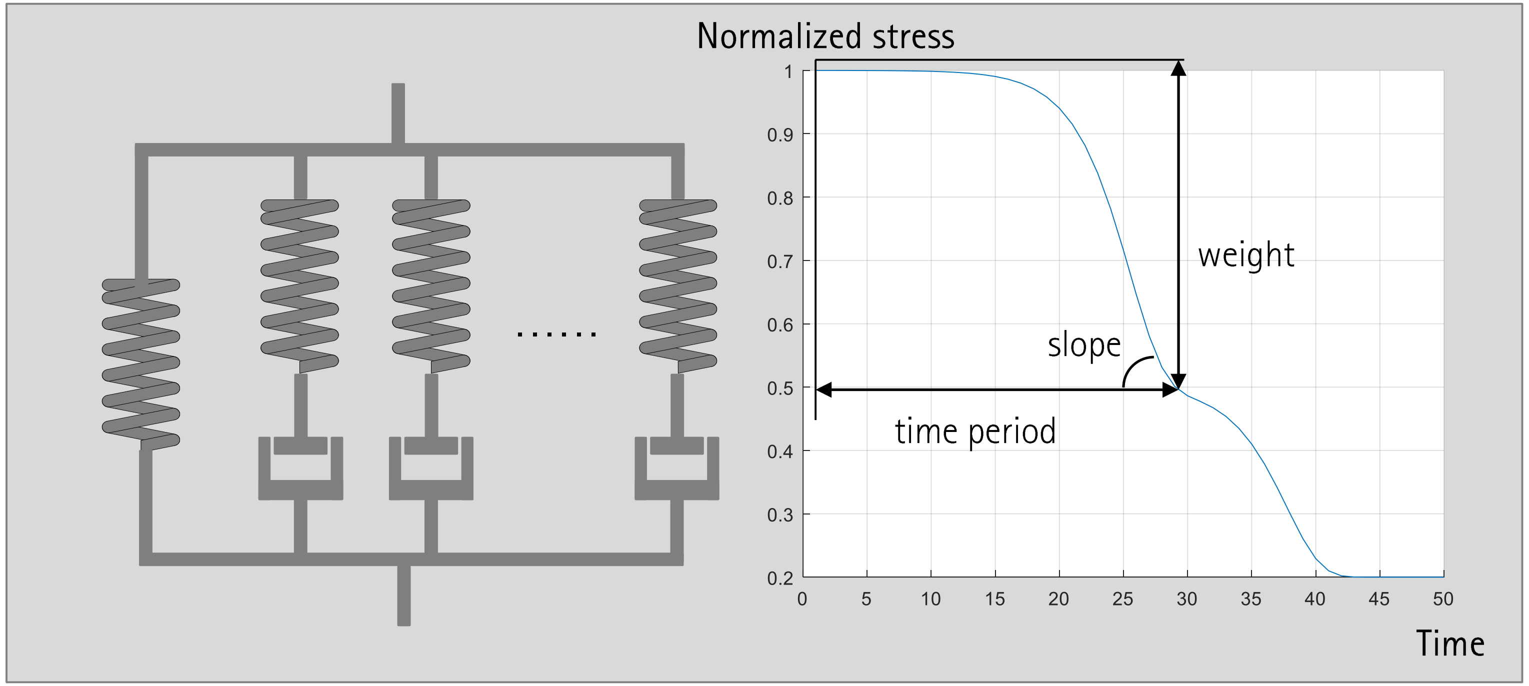
- Assumption #1: **E**lasticity of the material is **L**inear to the **C**uring degree (CHILE)
- Assumption #2: Residual stresses generate on curing and are frozen in the material

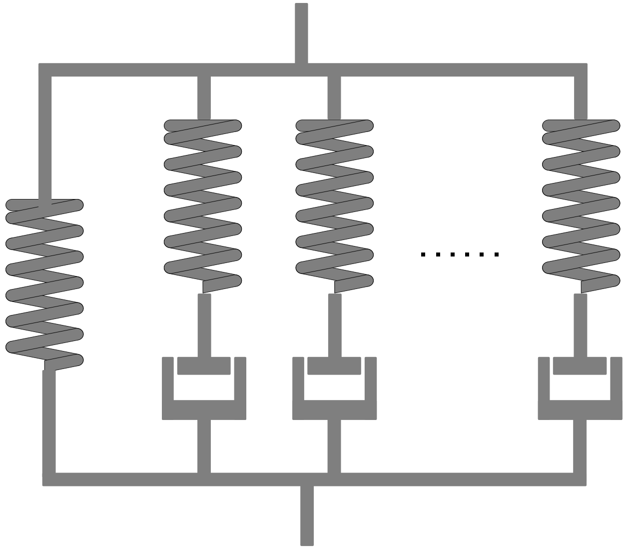


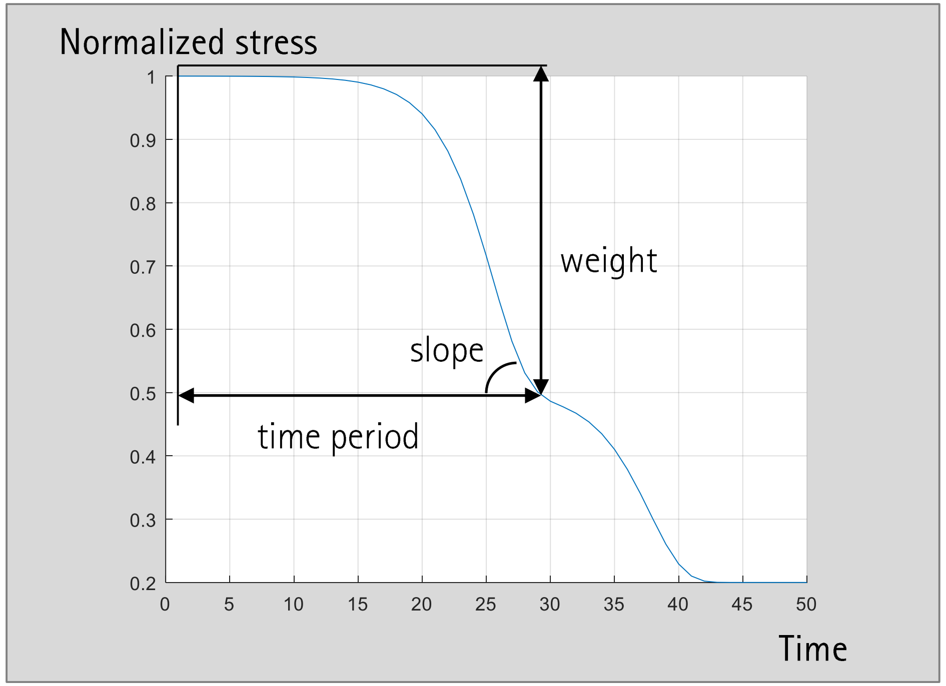


Maxwell model

- Rheological model
- Parameters need to be defined:
  - Number of elements (stages)
  - Time period
  - Weight factor
  - Stretch factor (slope)

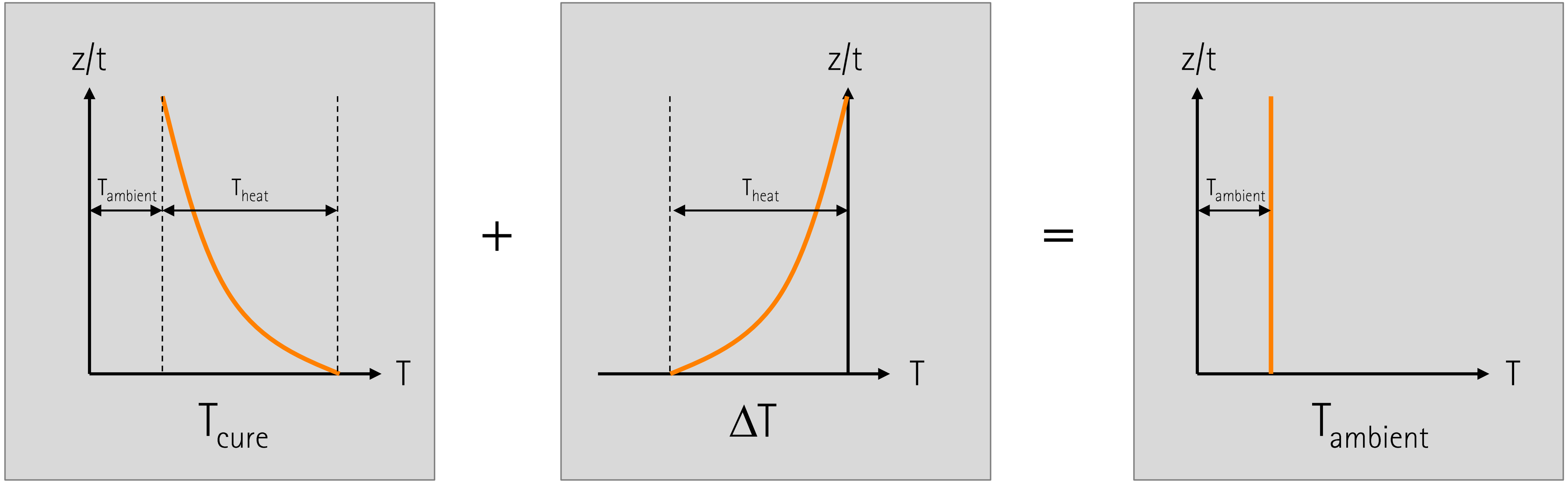





Normalized stress
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
5
10
15
20
25
30
35
40
45
50
weight
slope
time period
Time

Elastic cool-down model

- Based on cool-down process
- Temperature gradient in the material due to heat exchange with environment



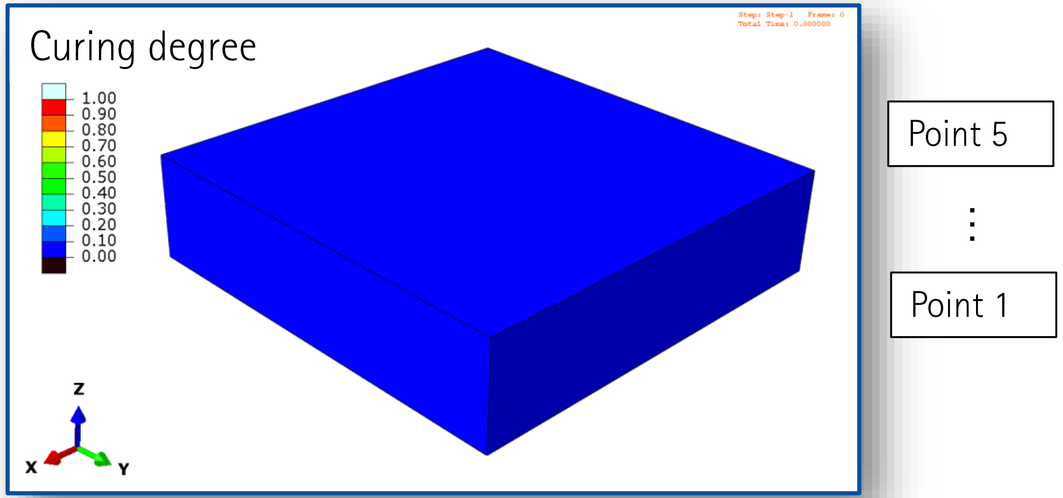
Content

- Models
- <u>Application example</u>
- Conclusions and outlook

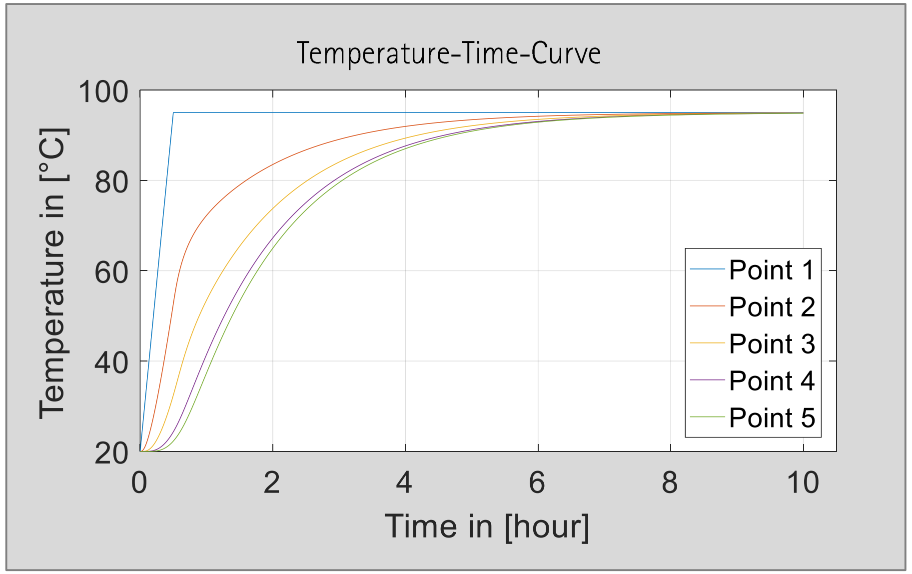
Application Example

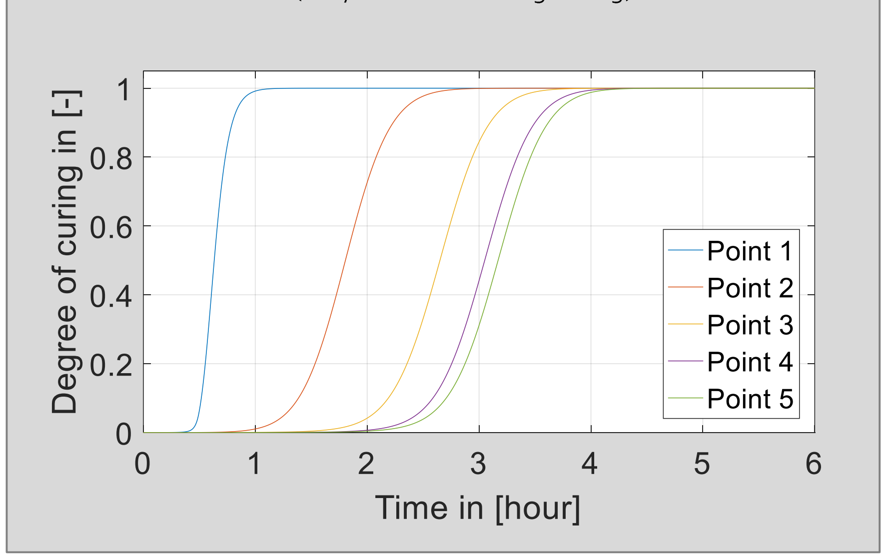
Piece of a spar cap, GFRP

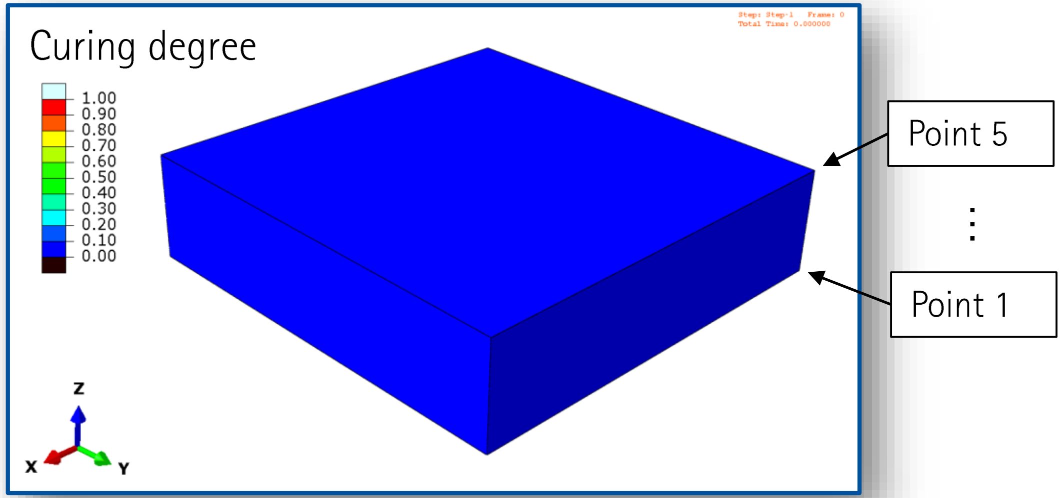
- Size: 20 x 20 x 5 cm^3 uni-directional
- Constant temperature of the bottom surface: 95 °C, dt=30s
- 5 sampling points in thickness direction
- No heat dissipation, no curing exotherm

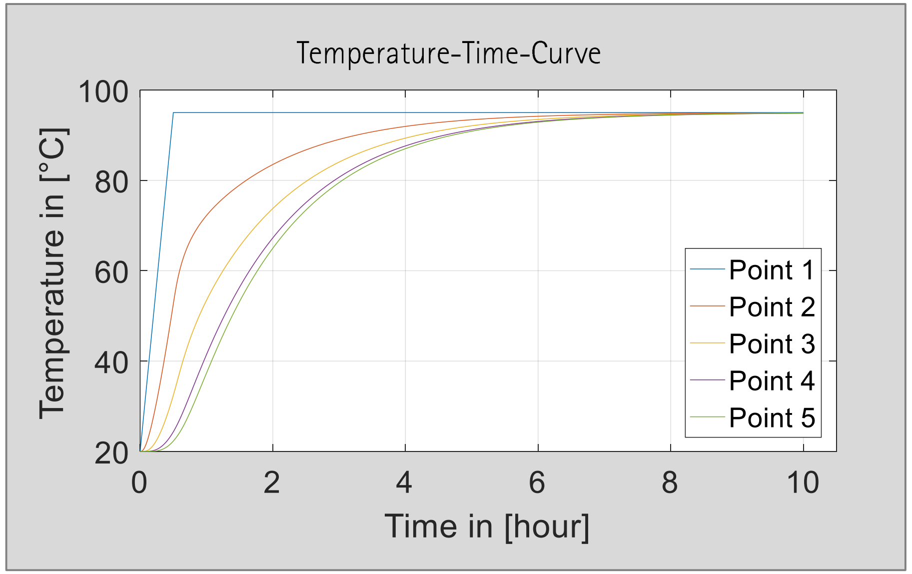


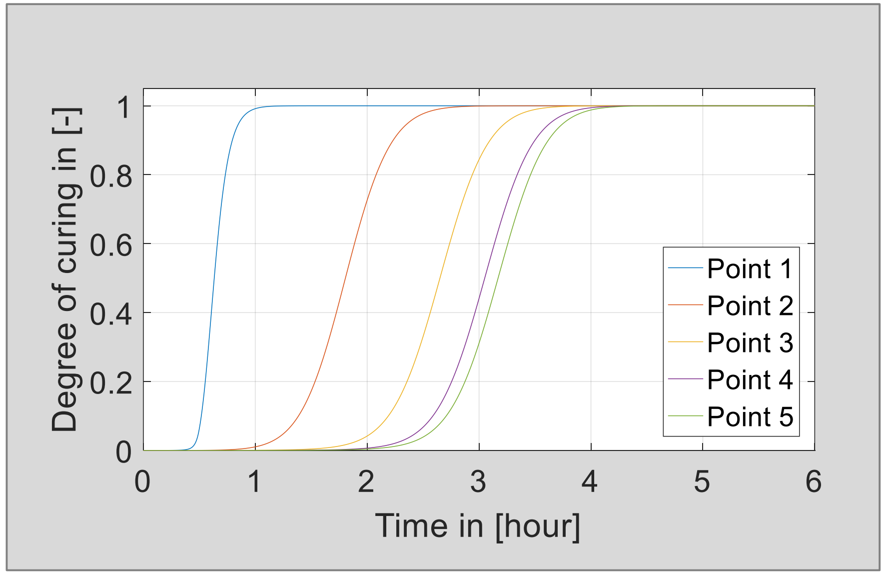
Animation of the curing degree development (very slow at the beginning)



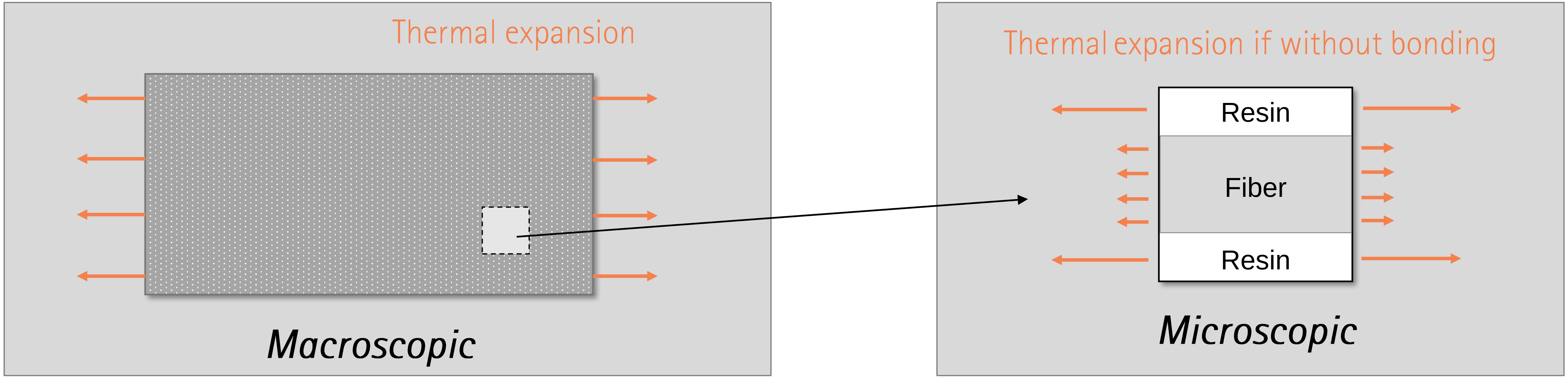



Curing degree
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Z
X
Y
Point 5
⋮
Point 1


Temperature-Time-Curve
Temperature in [°C]
Time in [hour]
100
80
60
40
20
0
2
4
6
8
10
Point 1
Point 2
Point 3
Point 4
Point 5


Degree of curing in [-]
Time in [hour]
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
Point 1
Point 2
Point 3
Point 4
Point 5

Bridging the scales

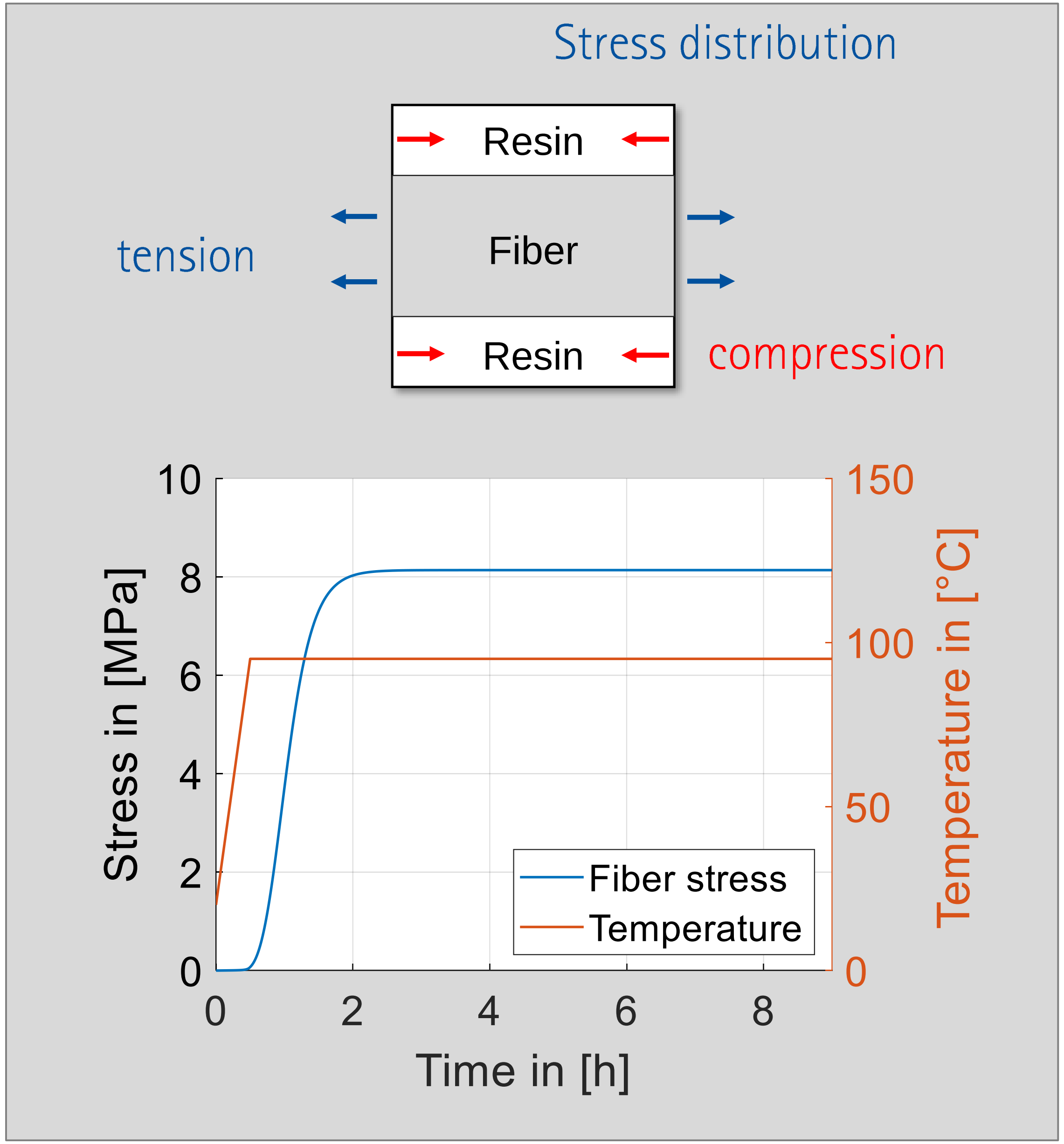


- Assumption: Classical Laminate Theory, perfect bonding
- Approach: RVE model on micro scale
- Things not considered:
  No exotherm, no chemical shrinkage, no mold-part interaction, no phase transition

Thermal expansion coefficient
Epoxy resin: 50 x 1e-6/K
Glass fiber: 5.1 x 1e-6/K

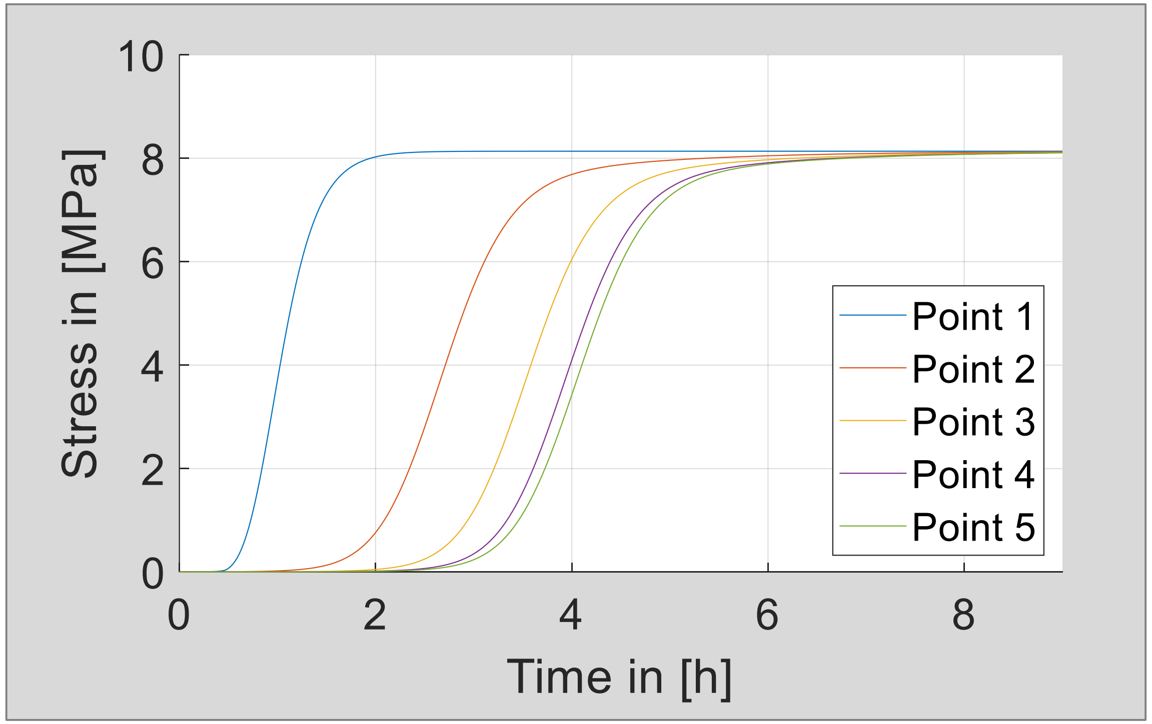
CHILE model
Microscopic residual stress

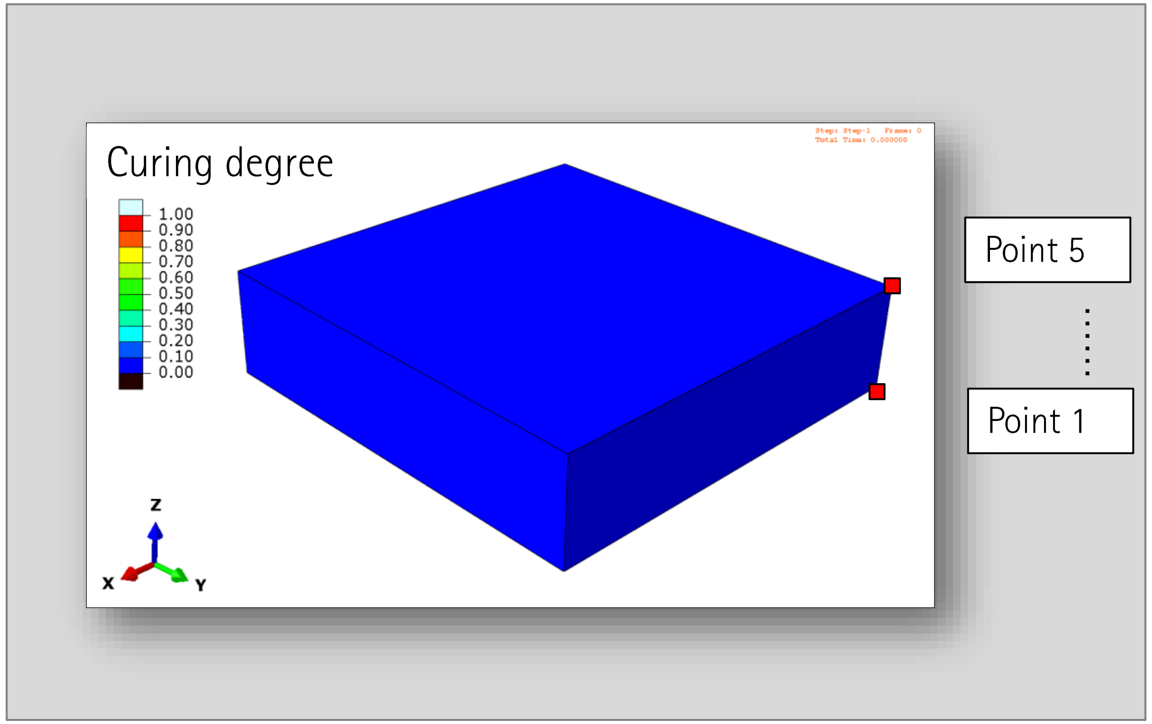
- Representative Volume Element (RVE)
- Fiber: tension
  matrix: compression
- Their stresses are same in value, opposite in sign due to the fiber volume content of 50%
- Fiber tensile stress as the residual stress



CHILE model

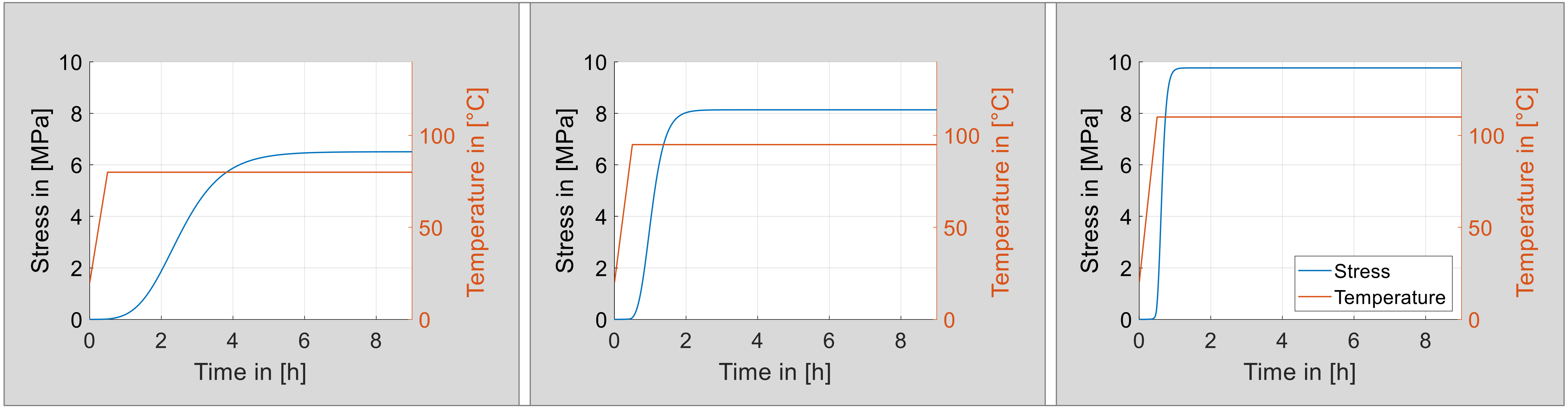
Through-thickness stress distribution





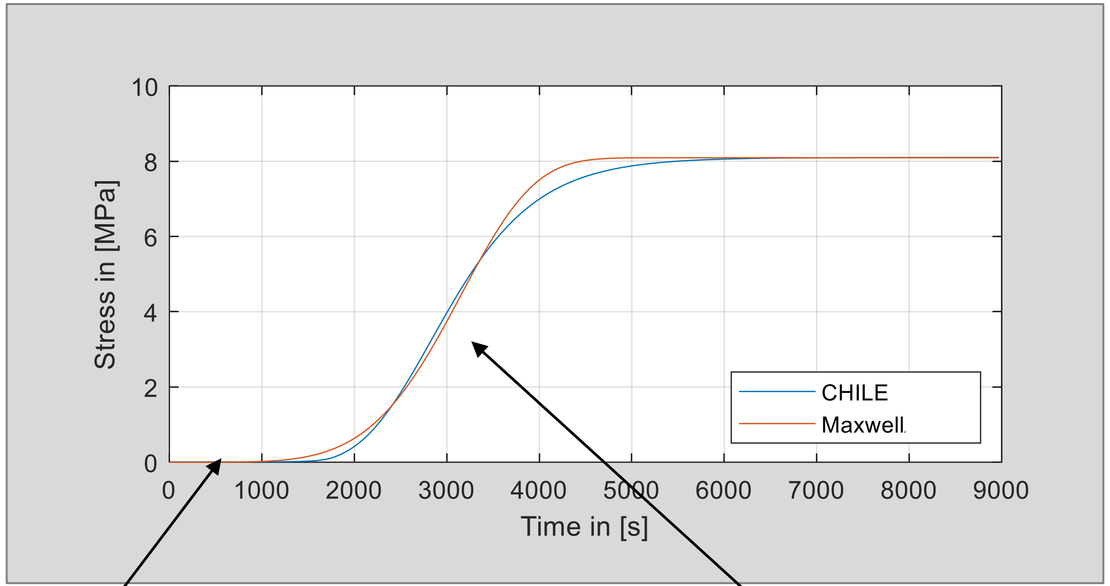
- The temperature increase is not linear to the molecular growth , there is a time delay
- The time delay of the growth results in a certain delay in stress changes
- This is the reason for the visco-elasticity in the curing process.

CHILE model
Different curing temperatures



- Comparison between different curing temperature 80 °C, 95 °C and 110 °C

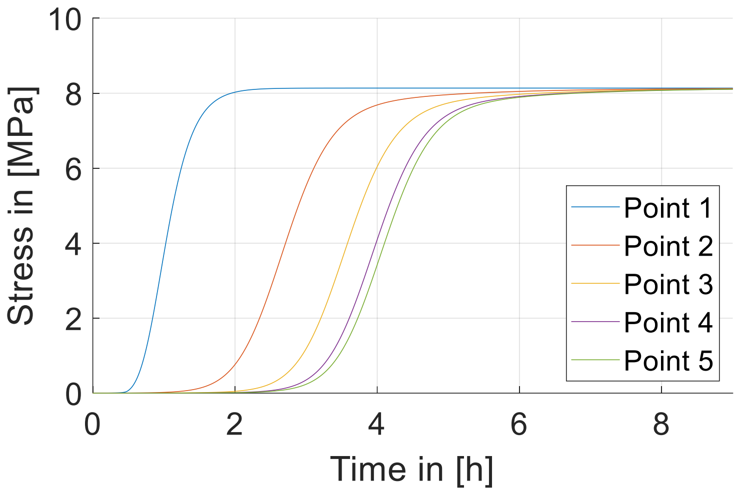
Visco-elasticity, Maxwell model

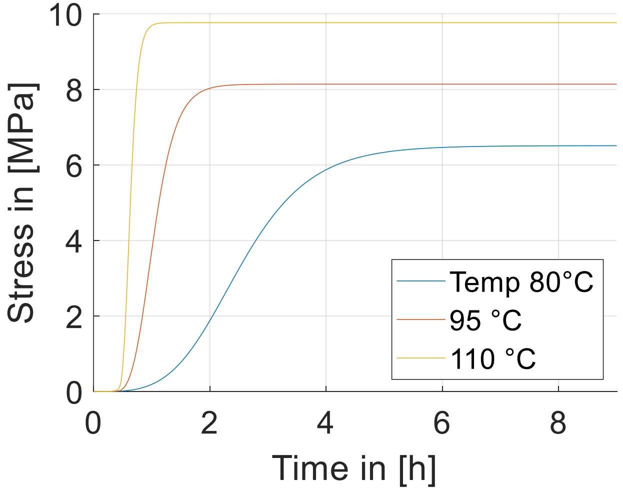


p1= 0.001

p2= 0.999*exp(-(t/3300)^5)

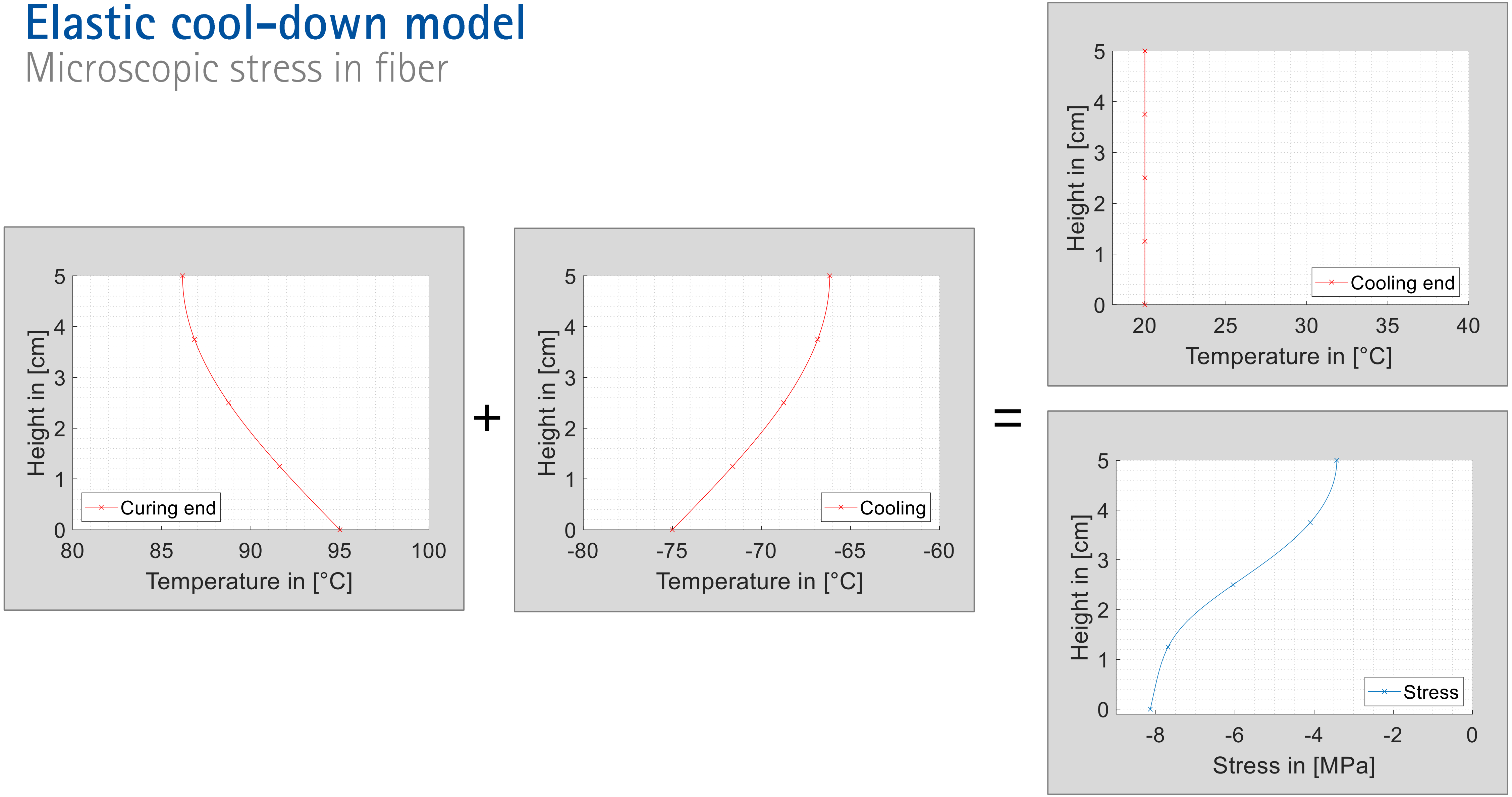
Prony function: $\sigma(t) = (1-(p_1+p_2))*f$



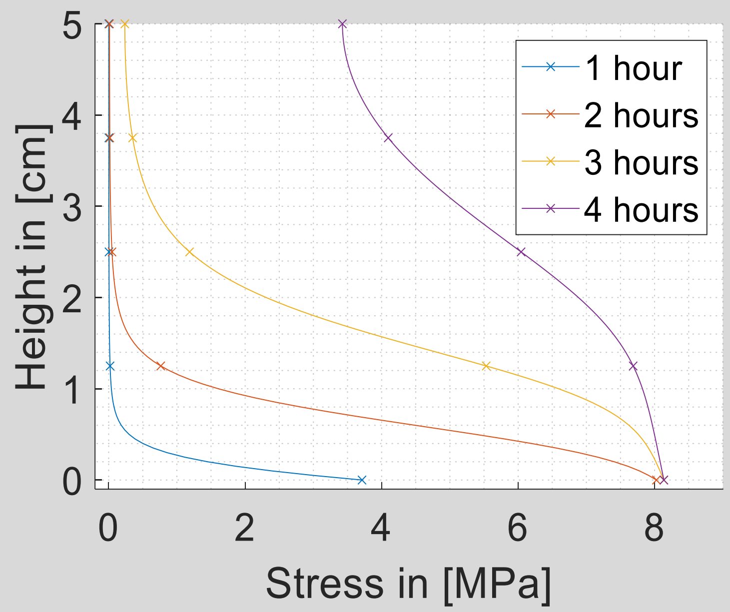


Elastic cool–down model

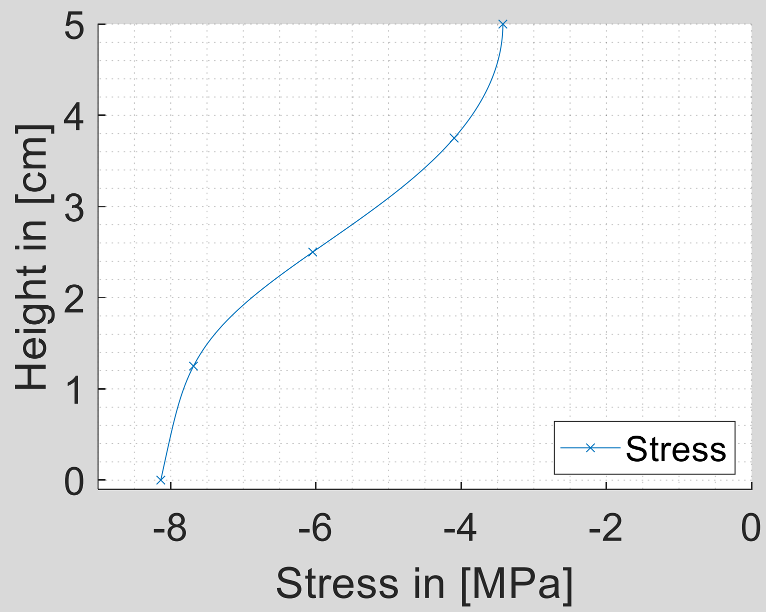
Microscopic stress in fiber



Comparison of results



CHILE model: bottom heating temperature of 95 °C



Cool down model: heating for 4 hours then cool-down

- No discussion about sign
- Show curing development
- Cool-down process not discussed

- No discussion about curing process
- Low calculation cost

Conclusions and outlook

- Lowering the curing temperature can reduce the residual stress, but it will increase the time required to complete the curing.
- CHILE model and Cool-down model can result in identical residual stresses, but with opposite sign.
- Cool-down model has better physical background and CHILE model reproduce this process with another sign.
- Discuss exotherm, chemical shrinkage, tool/part-interaction and more details in the future

Contact Details

Yixing Wang
Institute for Wind Energy Systems
Leibniz University Hannover
Appelstr. 9A, D – 30167 Hannover
E-Mail: yixing.wang@iwes.uni-hannover.de