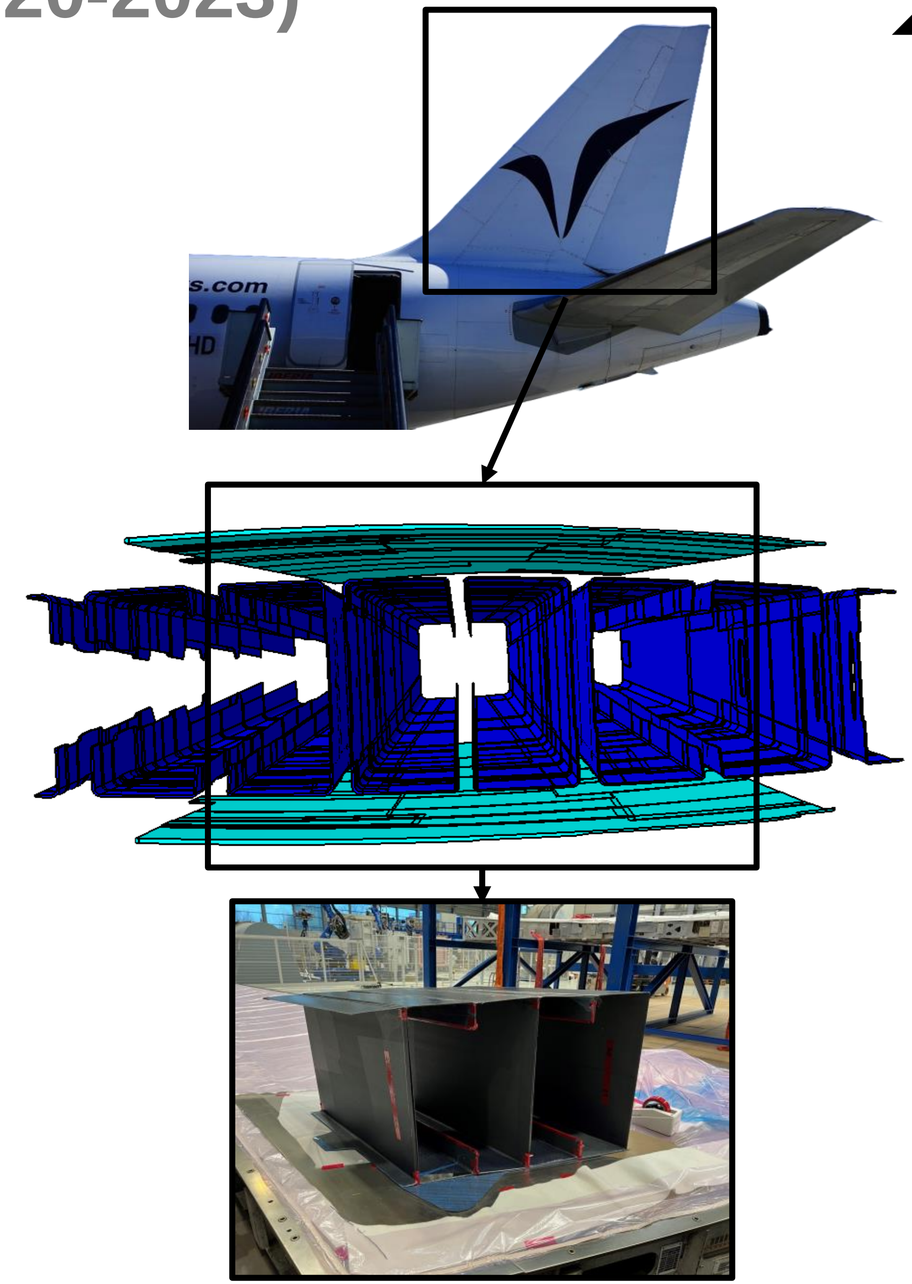
SIMULATION-BASED EVALUATION OF THE MANUFACTURING PROCESS OF AN AIRCRAFT FIN BASED ON THERMOMECHANICAL MEASUREMENTS

Robert Hein, 05.05.-07.05.2025

Regional User Meeting – EuroCentral - Bamberg

Motivation – Project LEITWERK (2020-2023)

- Development of a new process route for multi-spar concept for an aircraft fin
- Typical challenges of full integral manufacturing are the need for complex tooling designs
- Innovative approach: Multi-step cure process



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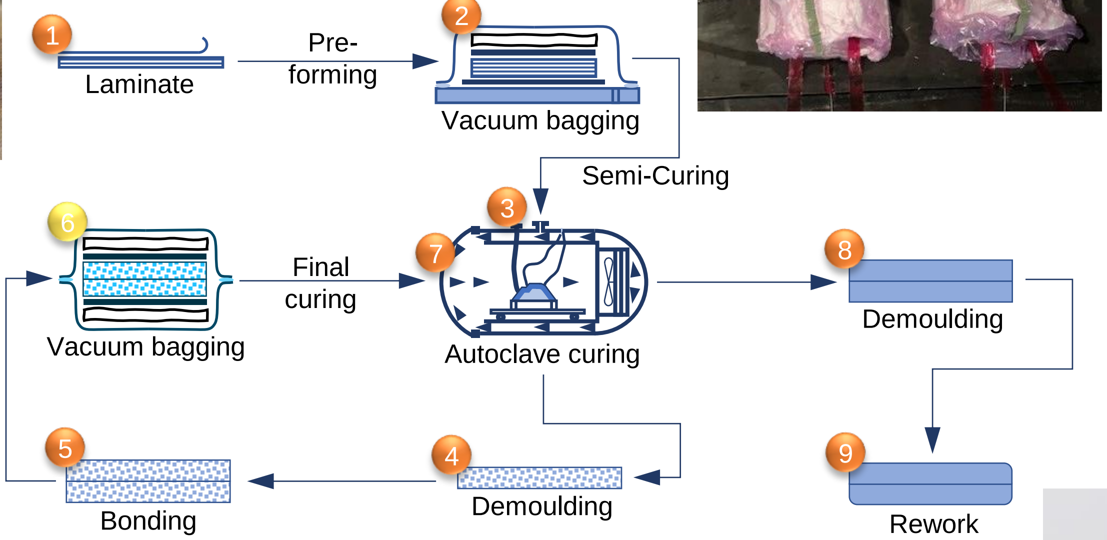
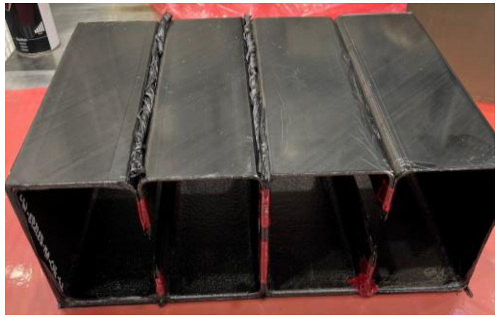


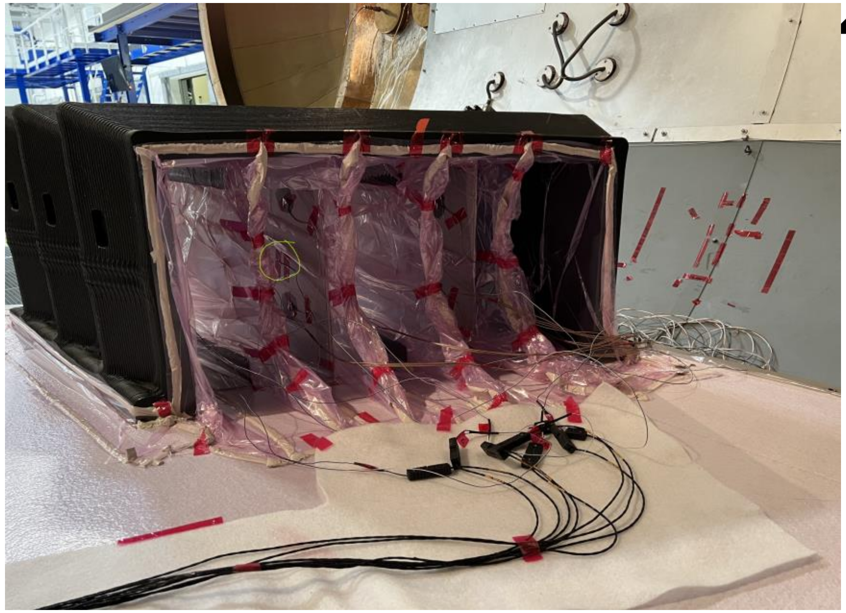


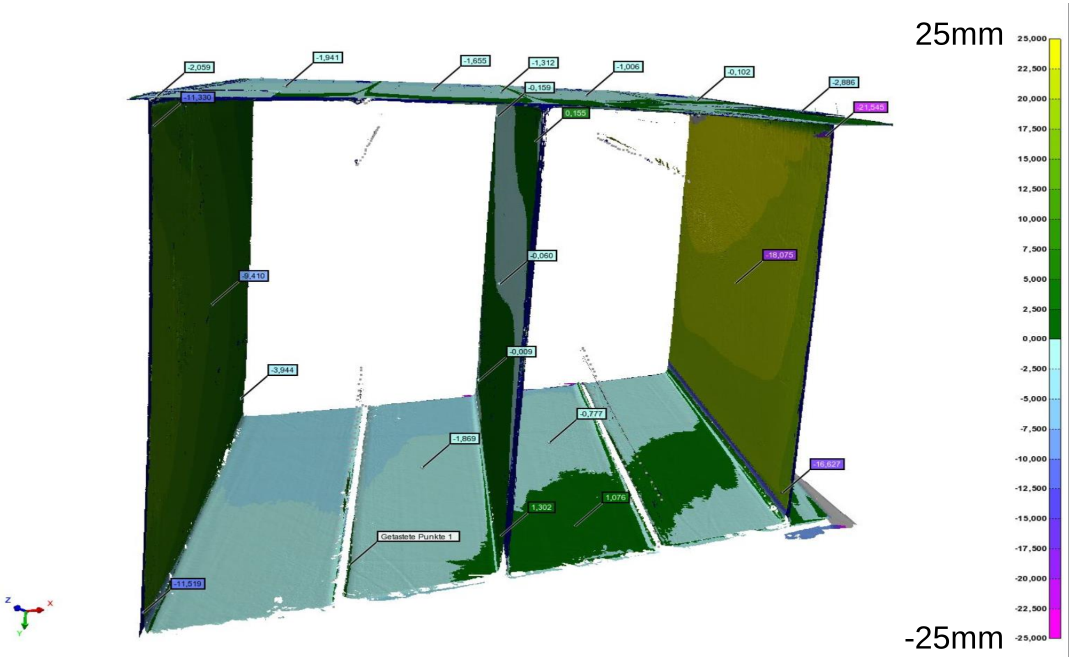
Motivation – Challenge

- Demonstrator with unexpected high part deformations observed

- Research Question: What are the causes for the high part deformations observed?

- Manufacturing process simulation can be benifical to provide answers



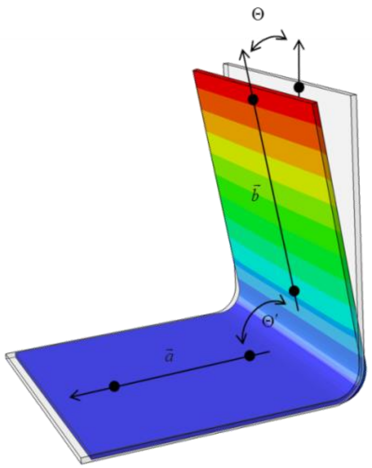


Outline

- Simulation challenge
- Material characterization and model calibration
- Simulation approach
- Comparison with measurements
- Summary

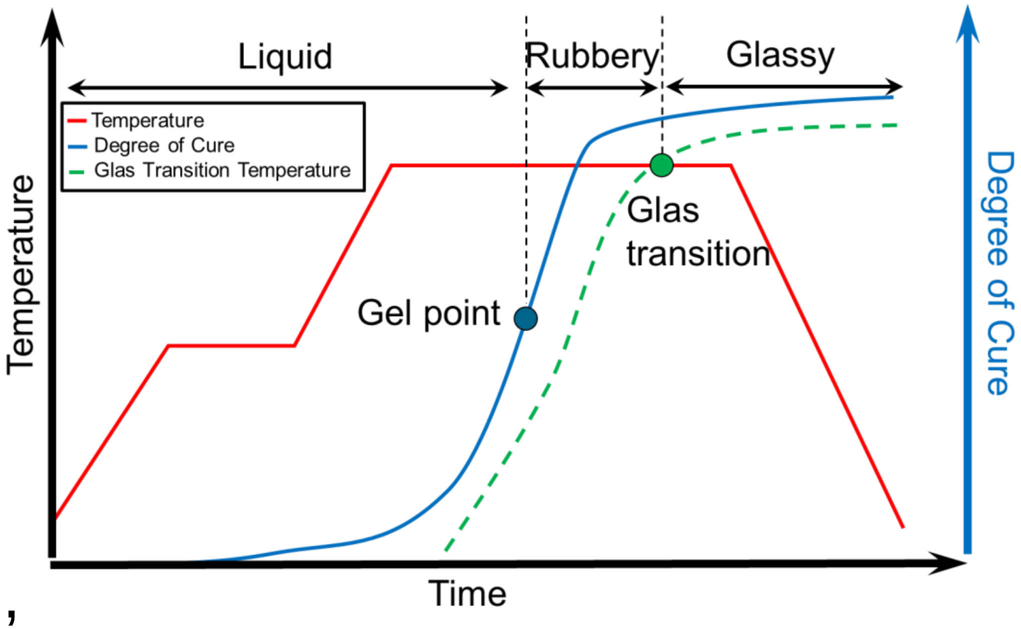
Simulation Challenge

- Objective: Prediction of process-induced part deformation (PID) in order to derive distortion-compensating tool design



PID (Spring-in) of L-shaped specimen

- Multi-physics problem
  - Chemical shrinkage
  - Anisotropic thermal shrinkage
  - Different material states (liquid, rubbery, glassy)
  - Stress relaxation
  - Tool-part interactions

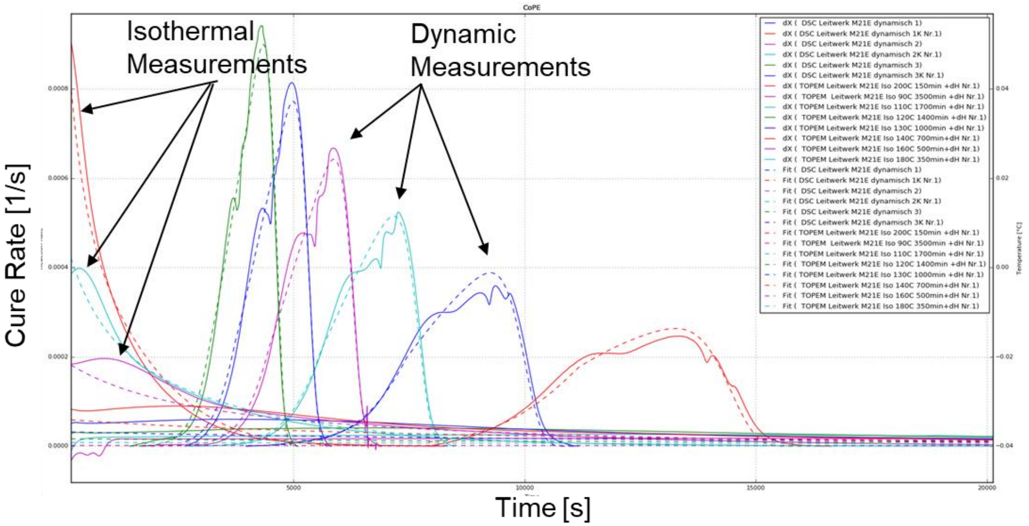


- Stiffness =f (Degree of Cure X, Temperature, Time)

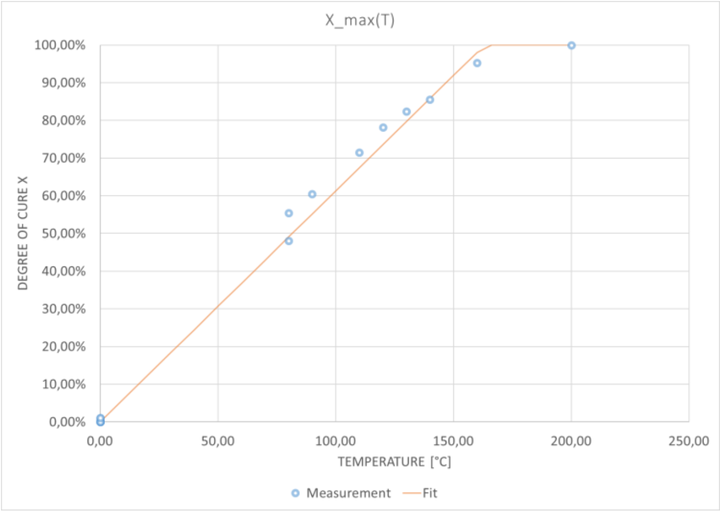
Material characterization: Reaction Model

- Fit of a reaction model to DSC measurements
- Cure model: $A \xrightarrow{k_1} B$, $A \xrightarrow{k_2} C$, $\frac{dX}{dt} = \mathrm{k(T)} \cdot f(X)$, $k_i = A_i exp\left(\frac{-E_{Ai}}{RT}\right)$
- $\frac{dX}{dt} = k_1(X_{max} - X)^l + k_2 X^m (X_{max} - X)^n$

CoPE – Inhouse Fitting Tool for Cure Kinetics



X_{Max}-Function covers diffusion-controlled reactions



Material characterization: Temperature and Time Dependency (UMAT)

- Development of a viscoelastic material model from DMA measurements
  - Construction of master curve (0° and 90°)
  - Fit with prony-series
  - Calculation of master curves
  - Generation of material card

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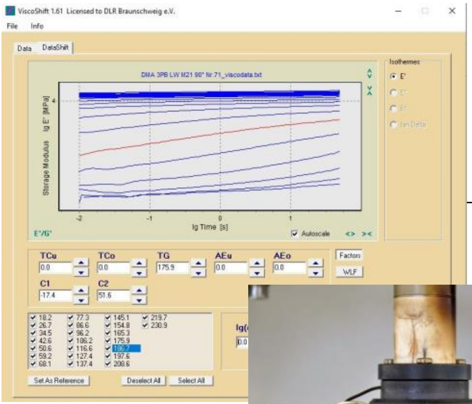

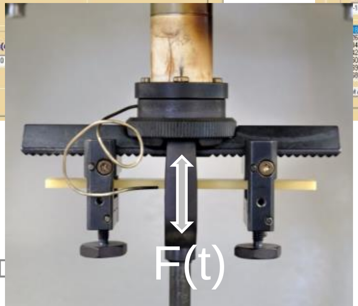

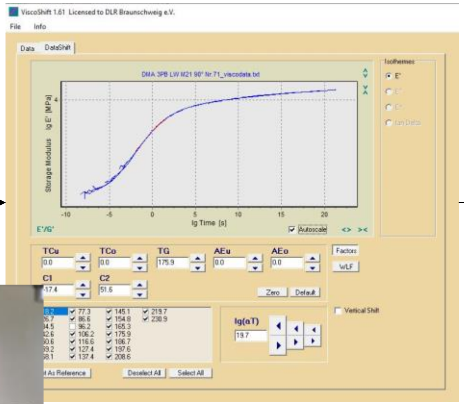

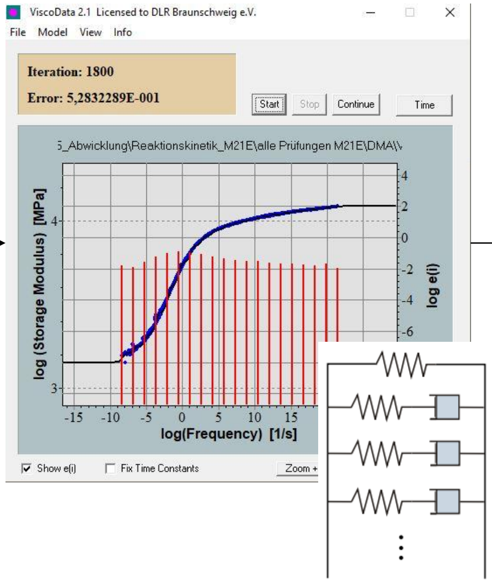

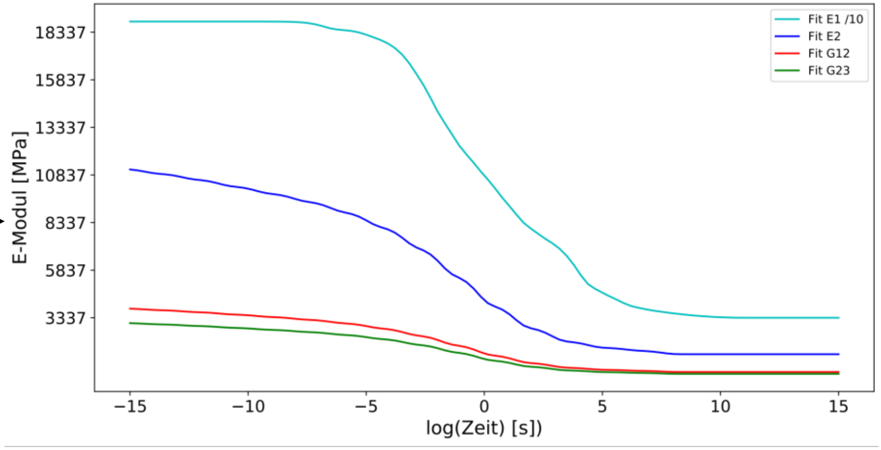

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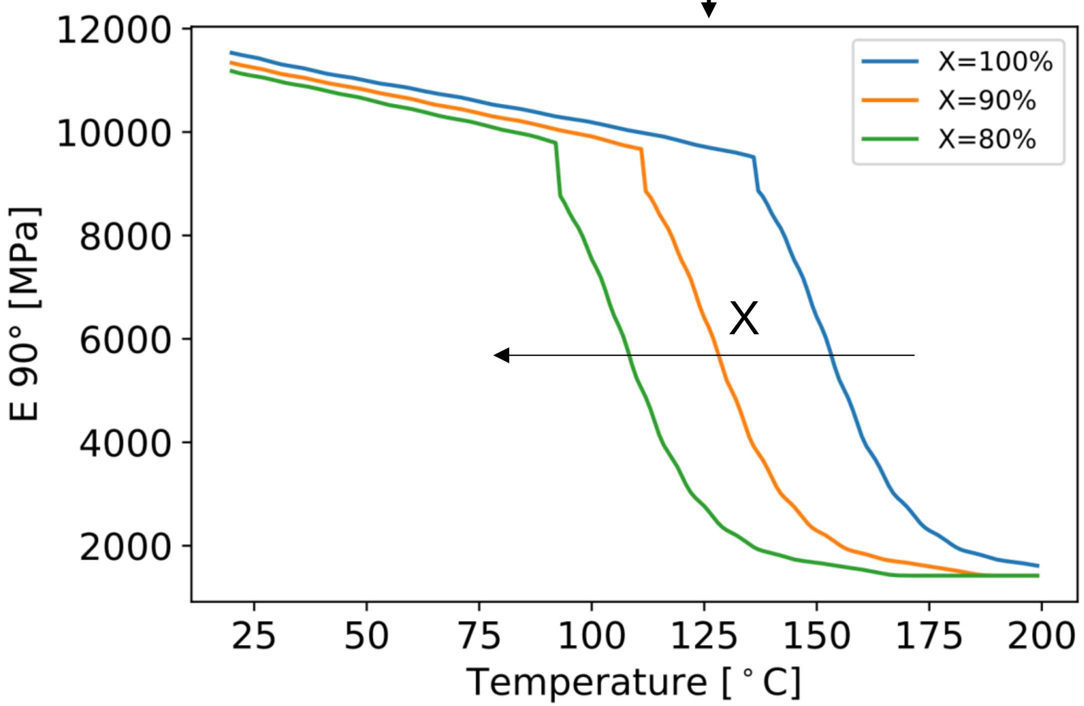
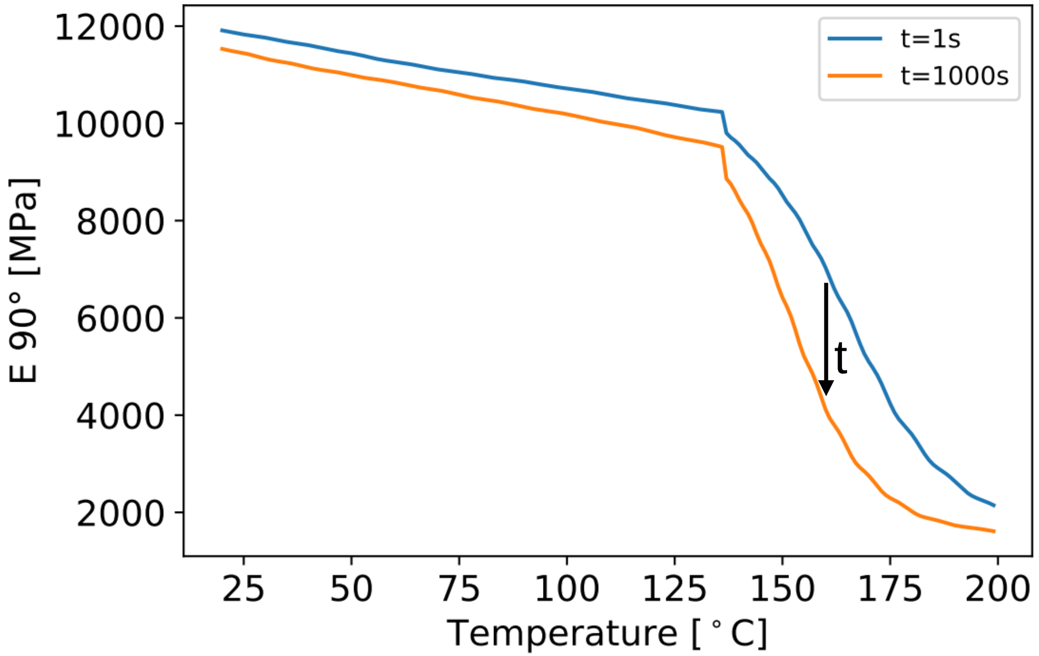
Material characterization: Cure and Time Dependency

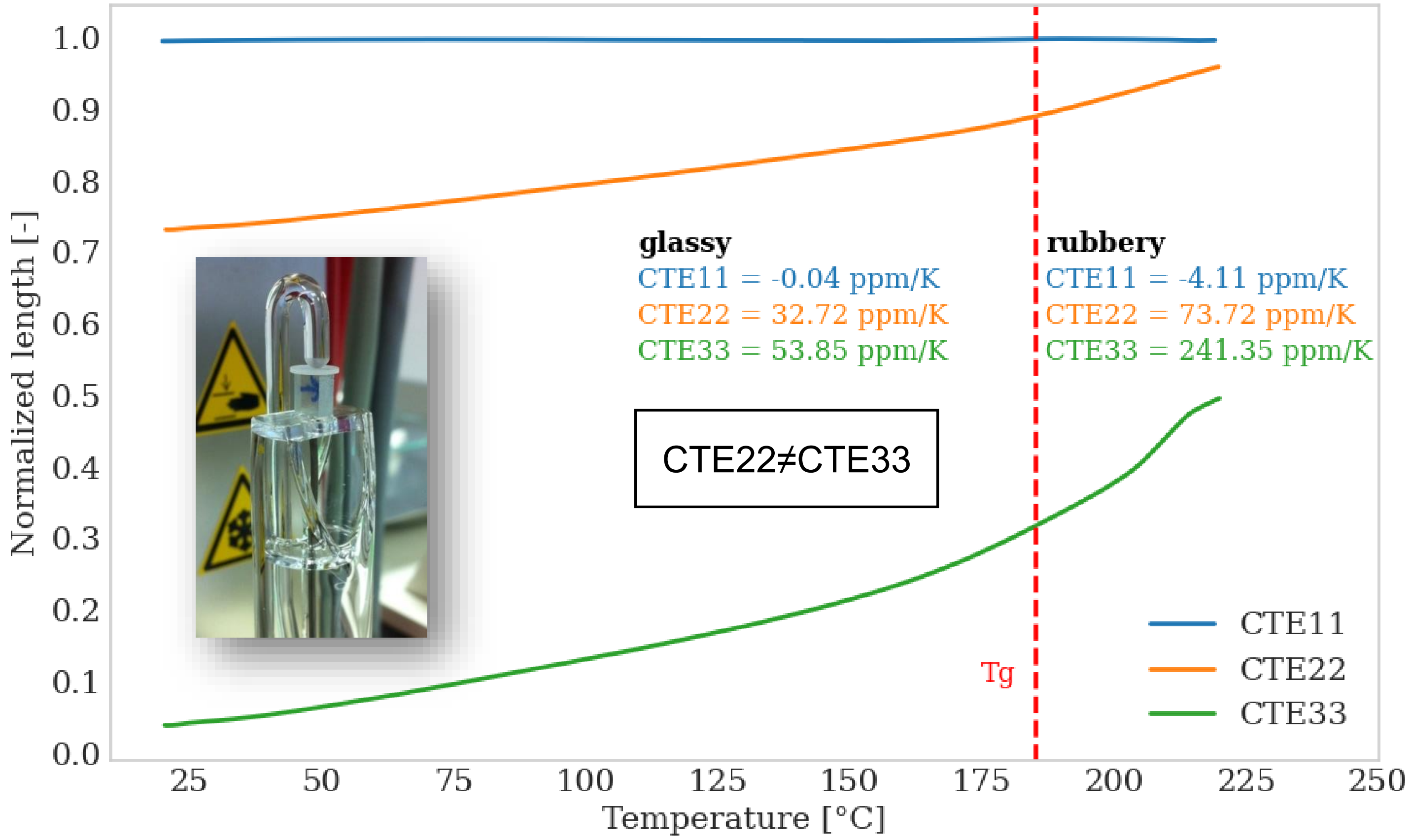
- Stiffness =f (Degree of Cure X, Temperature, time)





Material characterization: Further thermal Mechanical Properties (UEXPAN)

- Coefficient of Thermal Expansion (CTE) by TMA



Not shown:

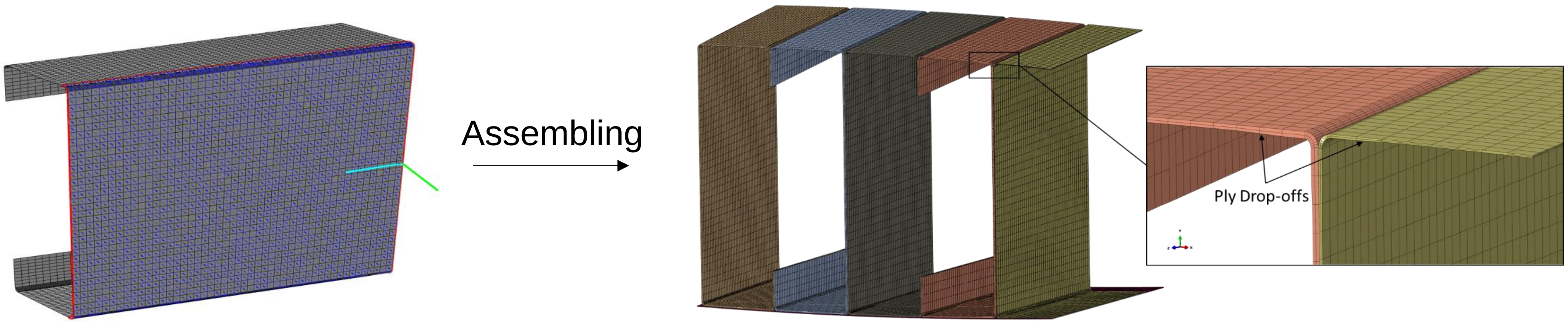
- Heat Capacity by DSC
- Thermal Conductivity
- Density
- Fiber Volume Fraction

Simulation Approach

- Sequentially coupled temperature-displacement analysis
- Ply-based model according manufacturing process (Abaqus CMA for CAE)
  - Draping effects
  - Thickness variations through ply-drops
- Extrusion to solid model and assembling by tie constraints

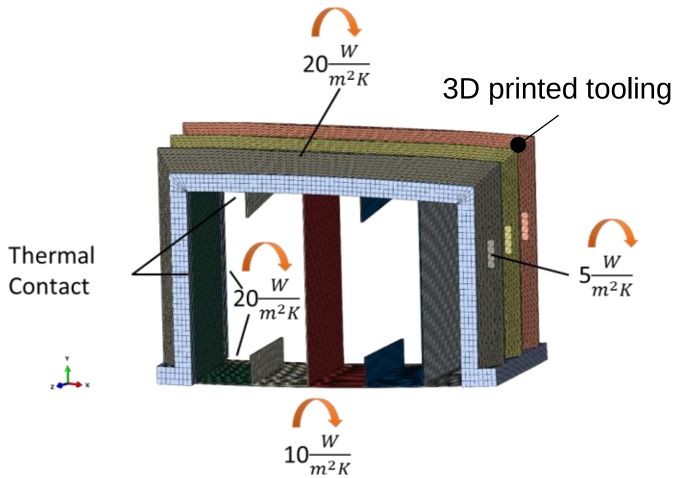
Simple Geometries

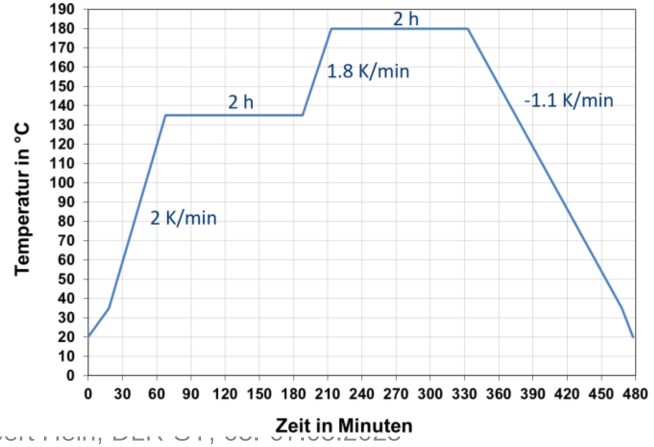
Final Demonstrator



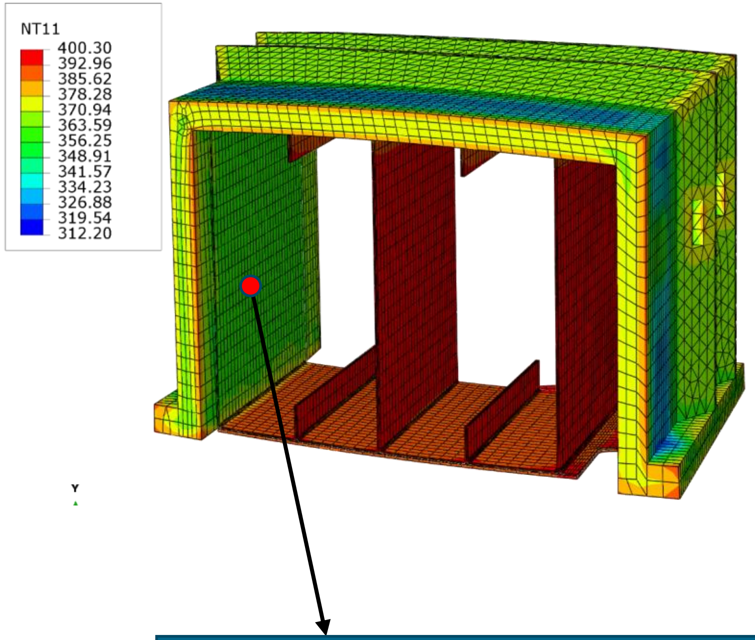
Simulation Approach – Thermal Analysis

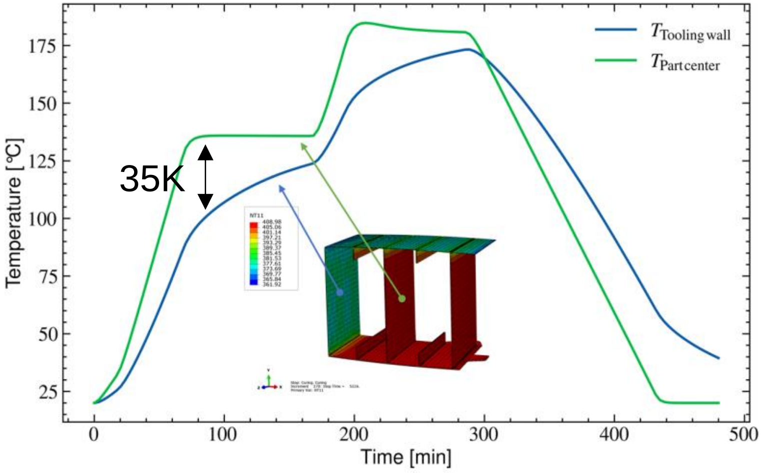
Thermal BC





Temperature distribution for isothermel curing at 135°C

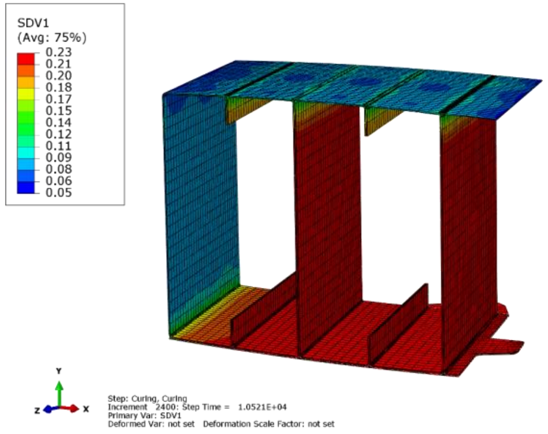


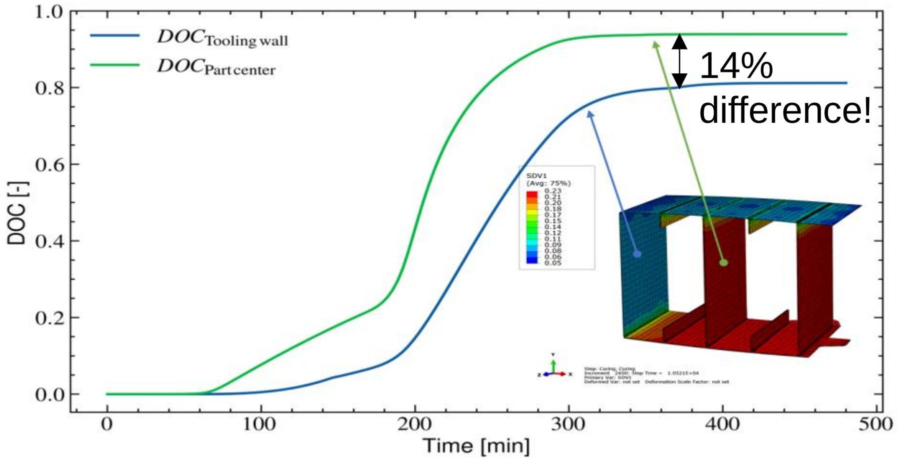


Tool contact result in inhomogenous heating (ΔT=35K)

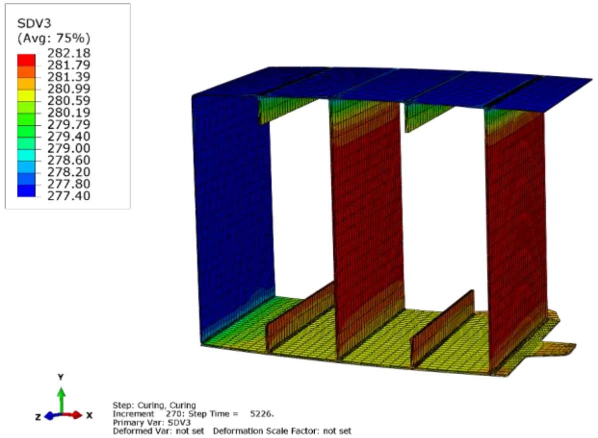
Simulation Approach – Curing state

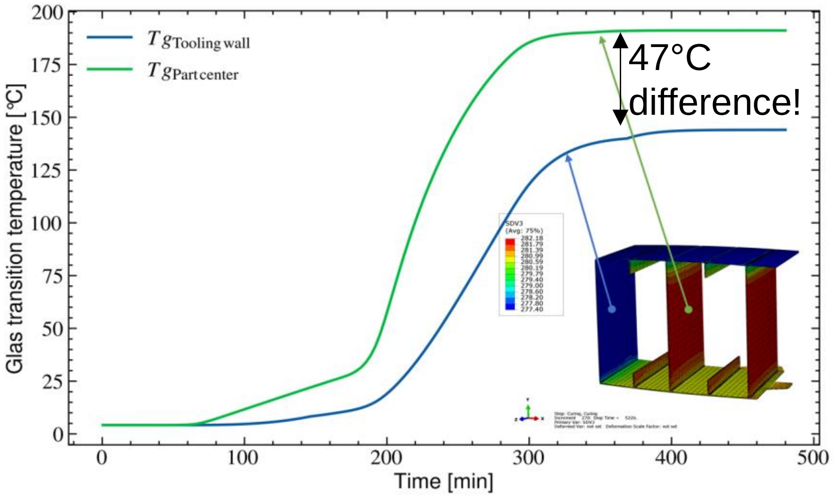
Inhomogenous and insufficent curing





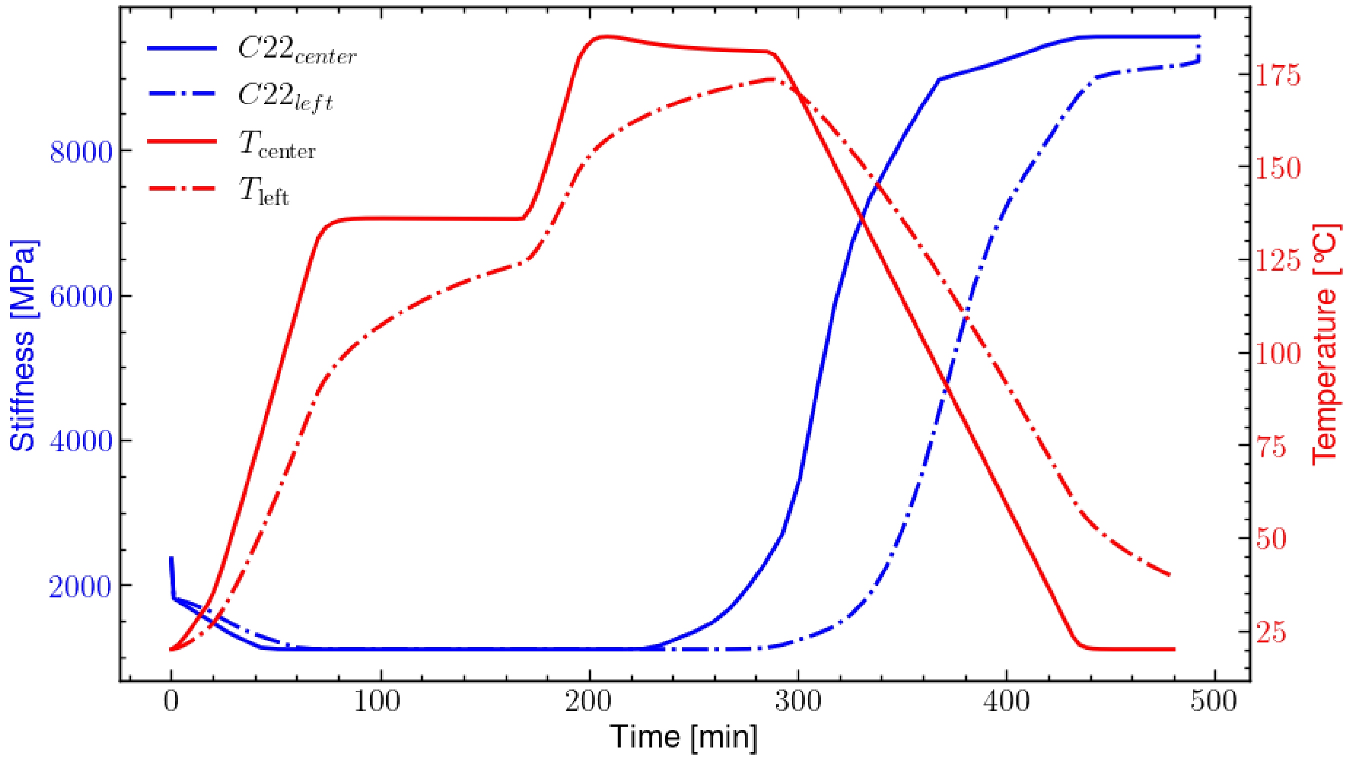
Inhomogenous glass transition temperature





Simulation Approach – Stiffness Development

Stiffness in fiber cross direction

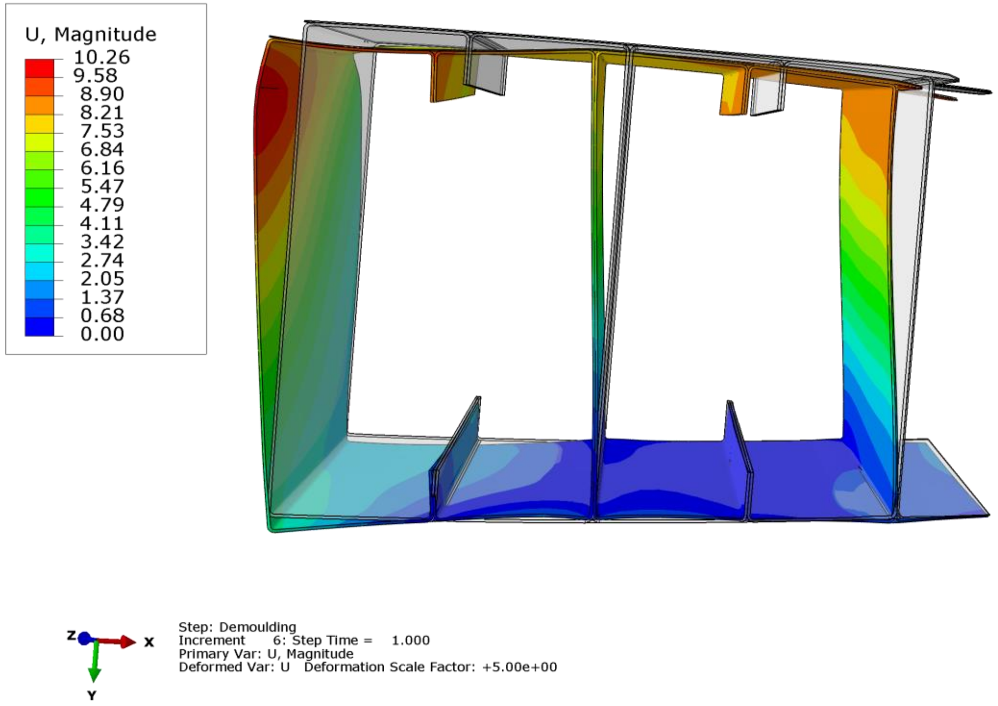


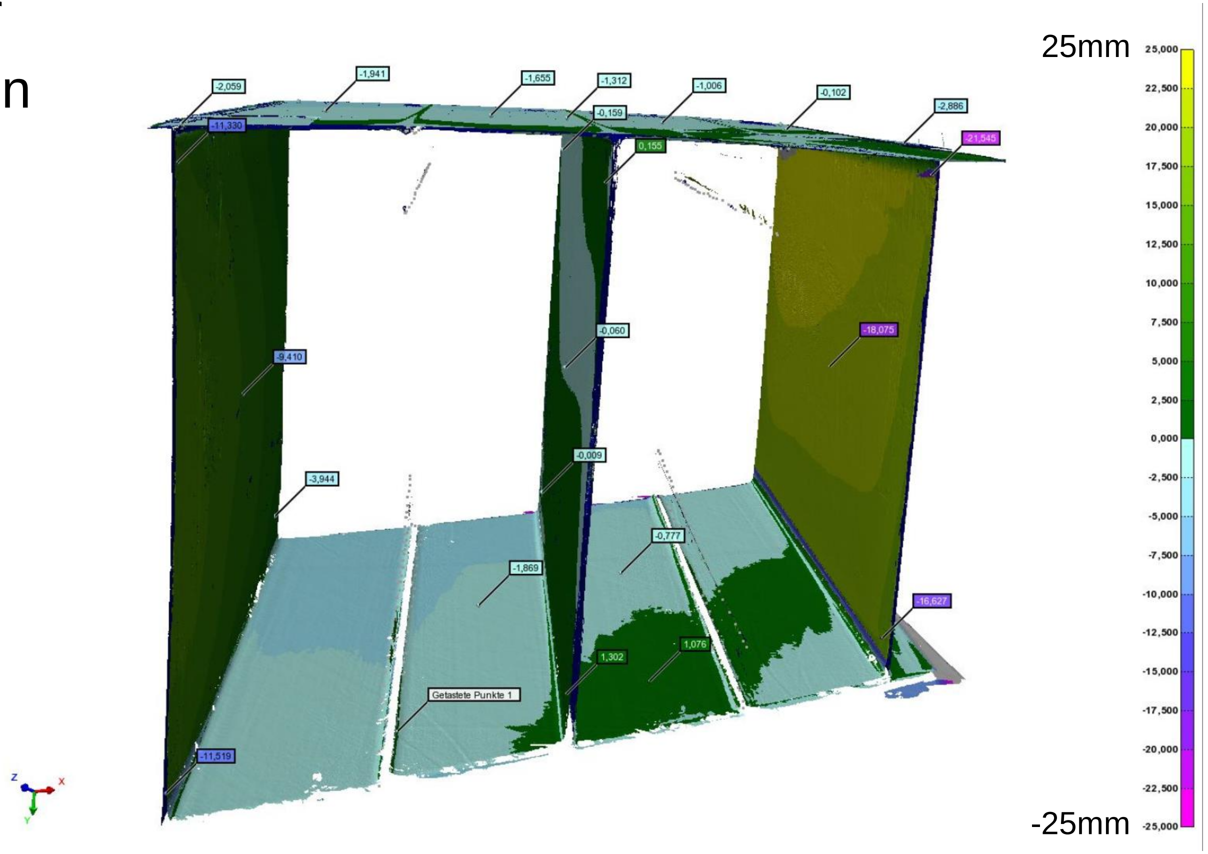
Inhomogeneous temperature leads to:

- Shifts in the development of stiffness
- Regions with different stiffnesses
- Reduction in absolute stiffness

Comparison with DIC Measurements

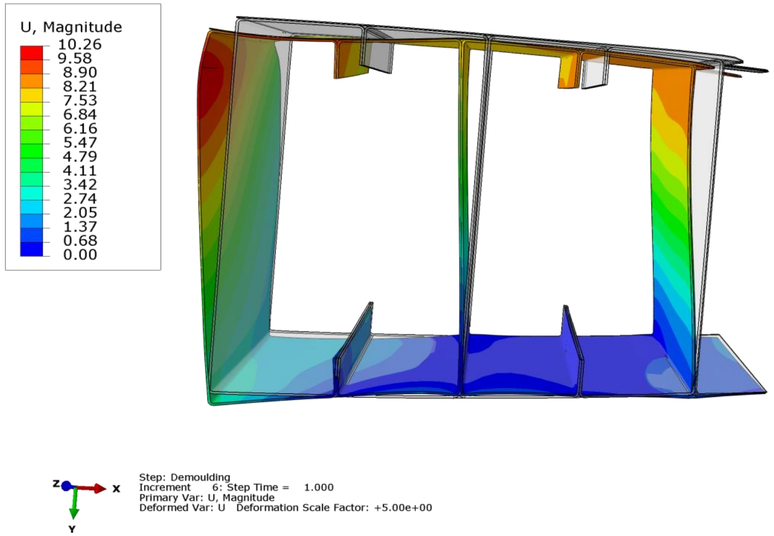
- Correlation of measured and predicted PID
  - Qualitatively identical deformation behavior
  - Real deformations greater than in simulation





Summary and Conclusion

- Introduction of a novel multi-step cure process
- High part deformation observed
- Multi-physic process simulation developed
- Basis are thermomechanical measurements
- Inappropriate tooling design result into inhomogneous curing and caused high part deformations
- Process simulation exhibit significant potentials for improvements



Contact

Thank you for your attention.

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