# STRUCTURAL EVALUATION OF PROCESS INDUCED DEVIATIONS DURING COMPOSITE LAYUP AND CURING

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**FULLCOMP Workshop – *Novel Developments in Failure Analysis of Composite Materials and Structures***
Hannover, 30th July 2018


DLR

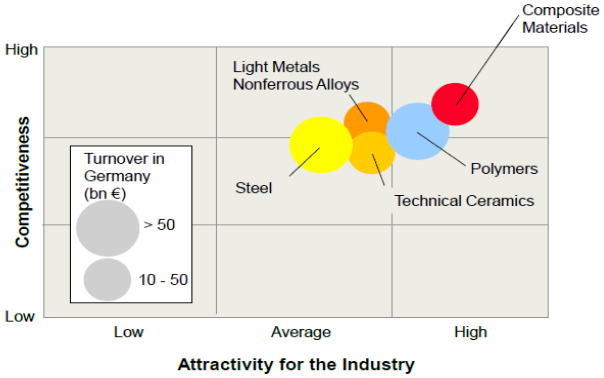
# Outline

- Introduction
- Probabilistic process simulation
- Effects of defects
- In-situ structural evaluation during fibre deposition
- In-situ structural evaluation of process induced distortions

# Introduction

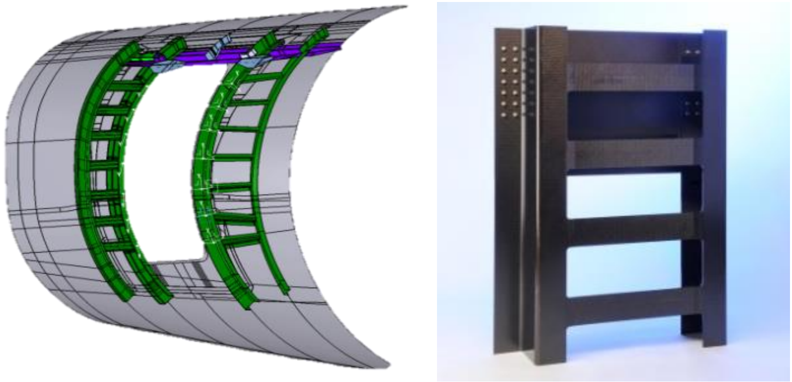
- Well known potentials of composites, such as

High weight specific mechanical properties



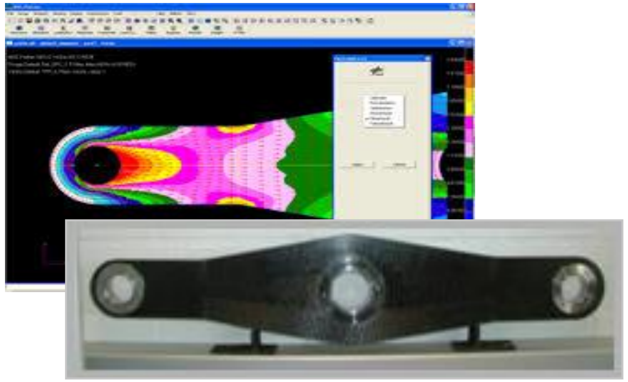

[VDI-Nachrichten Nr. 37, 2004]

Integral Design



[Integral manufactured letter structure, CRUVA project]

Anisotropic Tailoring



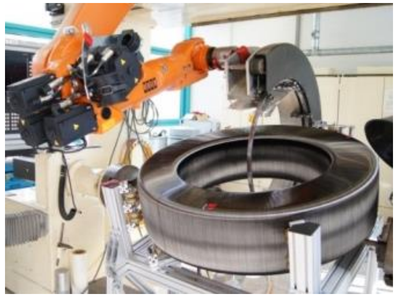
[HTP connection beam, MAAXIMUS project]

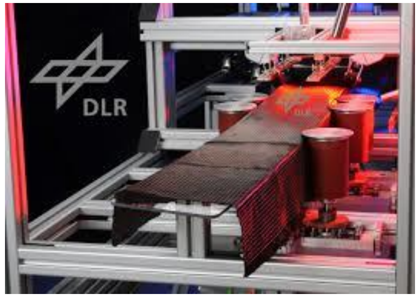
Function Integration

[SHM integrated door surround structure, SARISTU project]

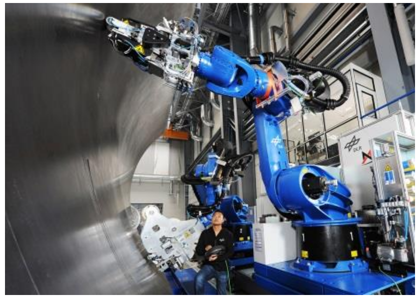
# Introduction

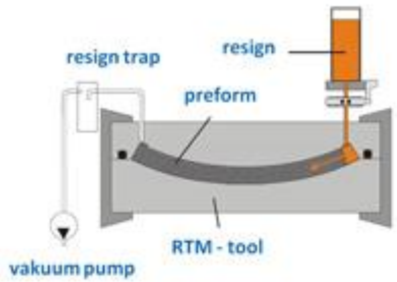
- Great variety of composite materials and manufacturing technologies, such as


Winding



Preforming (COPRO® Technology)

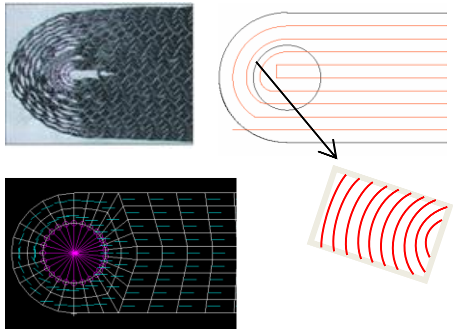

Automated Fibre Placement

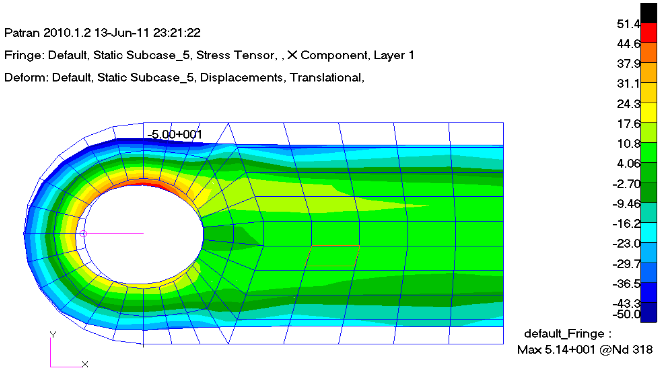


Resin Transfer Moulding


Autoclave

- Property development during manufacturing, depending on material systems, process technology, process parameters

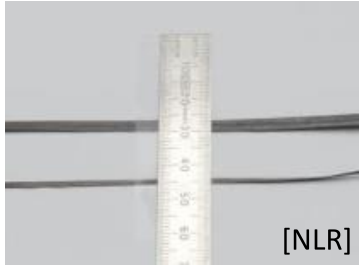

Fibre orientation resulting from tailored fibre placement



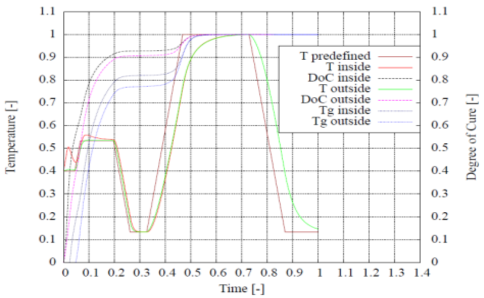
Residual stress in fiber direction after curing

# Introduction

- Remaining uncertainties
  - Material properties and tolerances
  - Process parameters and tolerances



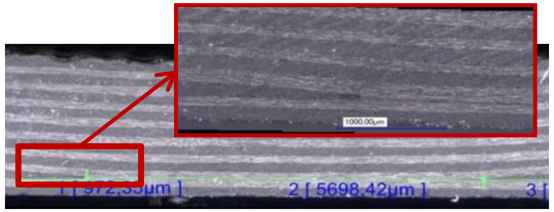
Tow width variation



Temperature distribution

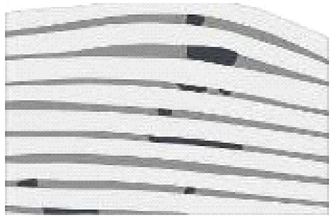
- Inevitable deviations or faults

## Fibre deposition



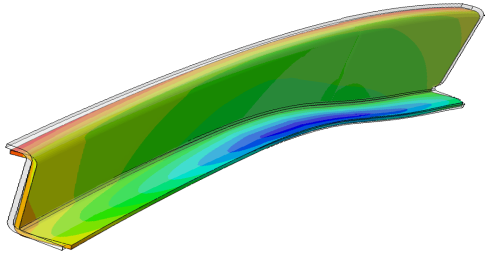

- Fibre orientation
- Waviness
- Gaps, overlaps
- Folds, twists
- Foreign objects
- …

## Resin infiltration



- Fibre volume variation
- Pores
- Resin rich areas
- Air entrapments
- …

## Curing



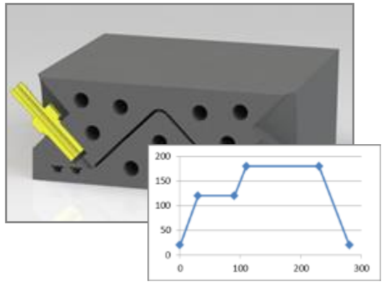
- Overheating
- Degree of cure variation
- Chemical shrinkage, distortion
- Residual Stresses
- Delamination
- …

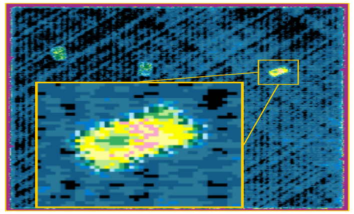
# Introduction

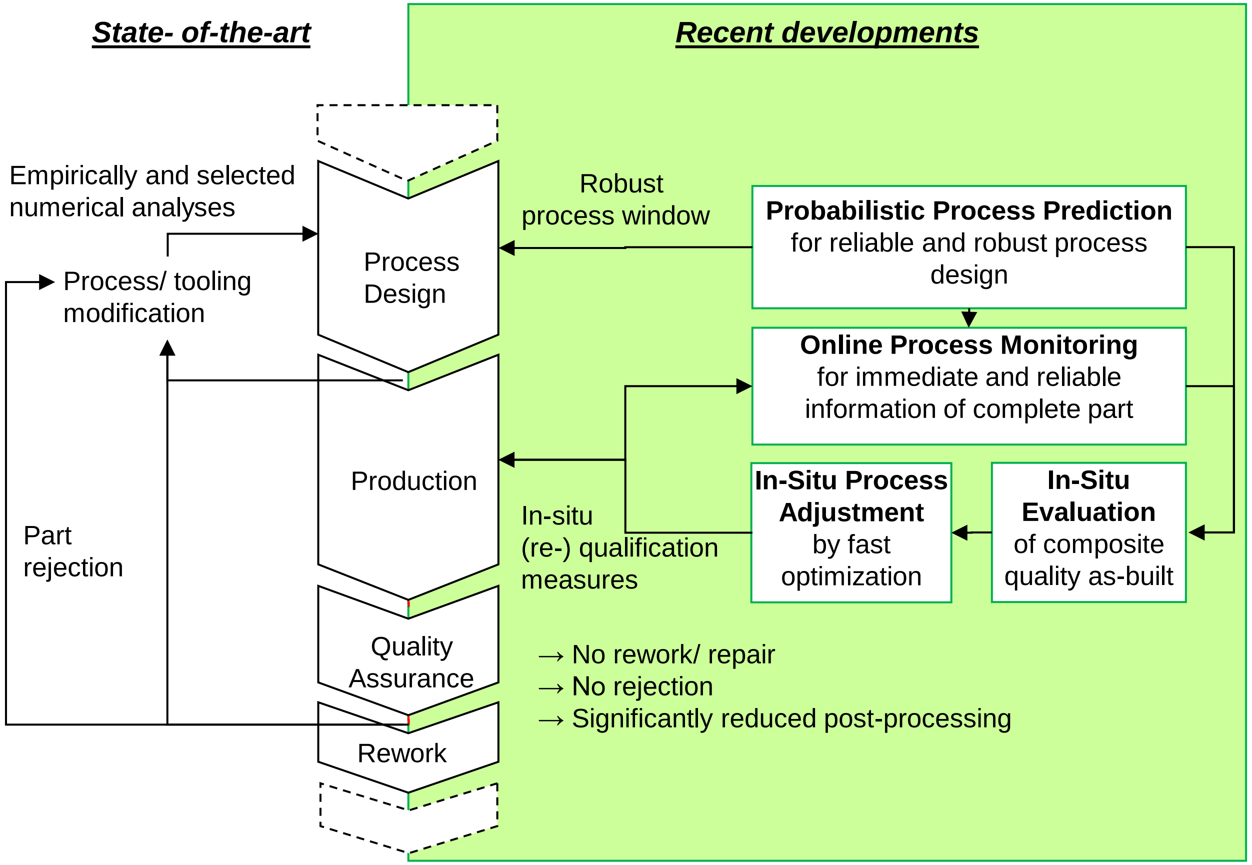
- Careful tolerance management required
  - Definition of composite engineering requirements (CER) and allowables (trade-off between accuracy and efficiency during production)
  - Quality assurance methods wrt. predefined tolerances
    - Process (temperature, pressure, cure, …)
    - Part (visual inspection, ultrasonic testing, geometry, …)
    - Actual structural properties analysed in case of particular non-conformities
  - High non-added value costs due to NDT effort or non-conformities

# Introduction

- Developments of composite process chains






[Wille et al.: ECOMISE overview, ECOMISE public workshop, 2016]

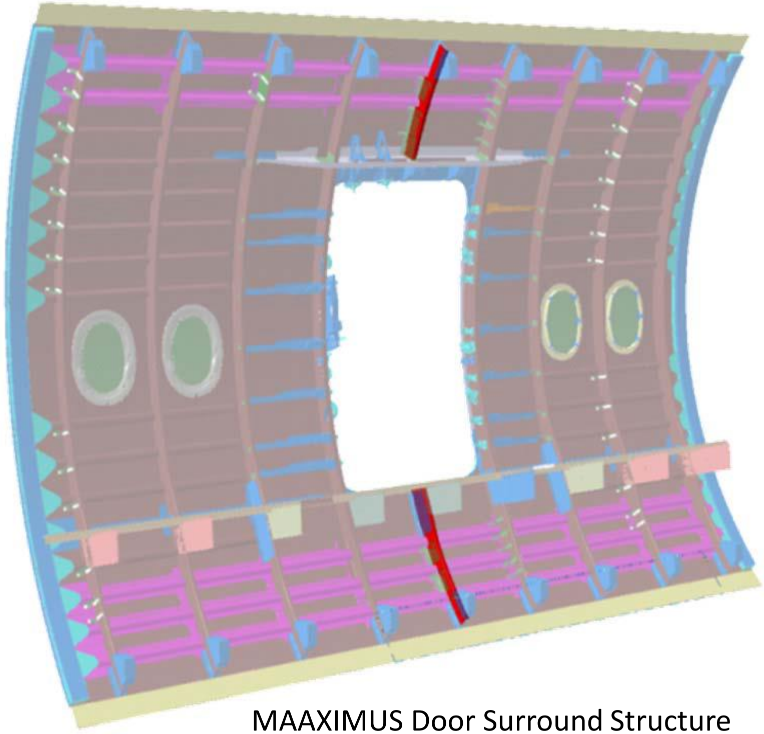
# Introduction

- Advanced methods under development and implementation
  - Probabilistic process simulation
  - Enhanced effects-of-defects analyses
  - Online process monitoring
  - In-situ structural evaluation of deviations

} Serving Digital Twin

# Probabilistic Process Simulation

- Prediction of process induced distortions for robust tool design



MAAXIMUS Door Surround Structure
(AID, 12/2014)

[Liebisch et al.: Probabilistic process simulation to predict process induced distortions of a composite frame, CEAS Aeronautical Journal, 2018]

# Probabilistic Process Simulation

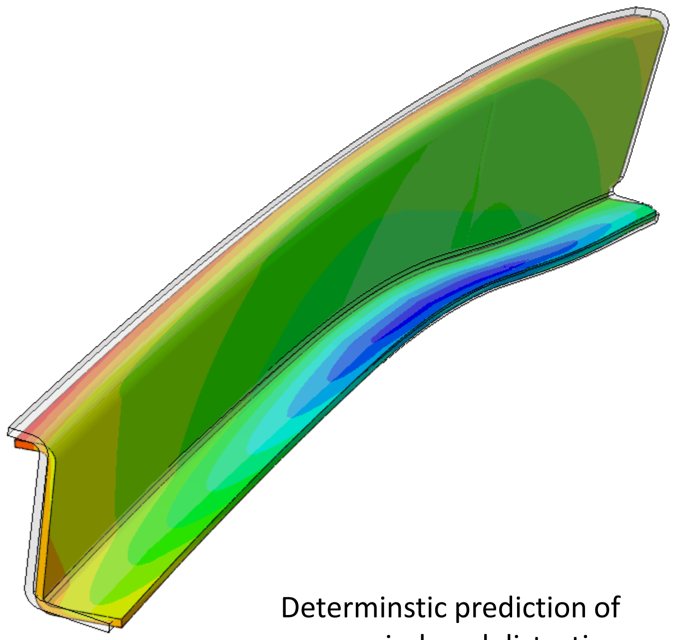
- Deterministic numerical analysis of composite curing

1) Heat Transfer Analysis
   (incl. cure model, exothermal reaction, thermal interaction)
   → Degree of cure & $T_g$ fields
   → Temperature fields

2) Structural Analysis
   (incl. thermal and chemical shrinkage, viscoelasticity, tool-part interaction)
   → Distortions
   → Residual Stresses

3) Nominal tool geometry compensation

→ No information about probabilistic distribution or robustness
→ Efficient method required for large parameter space



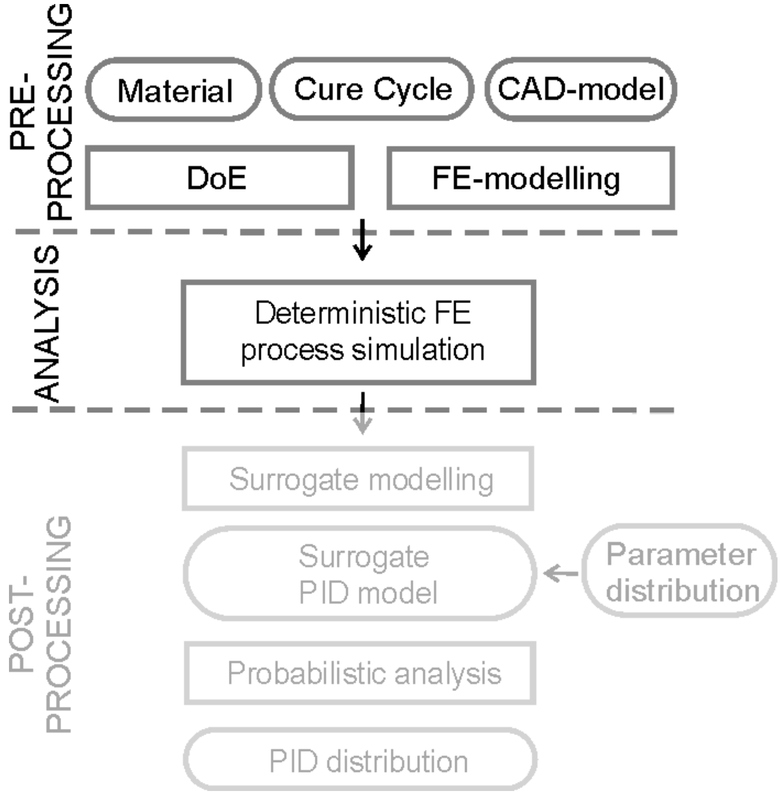
Determinstic prediction of
process induced distortion

[Liebisch et al.: Probabilistic process simulation to predict process induced distortions of a composite frame, CEAS Aeronautical Journal, 2018]

# Probabilistic Process Simulation

- Probabilistic analysis procedure (1/2)
  - Sensitivity analysis, definition of area of interest/ parameter space
  - Design of Experiments, e.g. Latin Hypercube Design with Maximin method
  - FE analysis for e.g. 50 design points

| Parameter | range | μ | $\sigma_{abs}$ | $\sigma_{rel}$ [%] |
|---|---|---|---|---|
| ***material uncertainties*** | | | | |
| $CTE_L$, [ppm/K]* | -0.5…0.5 | 0.0 | 0.167 | - |
| $CTE_T$, [ppm/K]* | 27.2…40.8 | 34.0 | 2.167 | 6.67 |
| resin shrinkage [%] | 2.49…3.73 | 3.11 | 0.208 | 6.67 |
| point of gelation [%] | 50.0…70.0 | 60.0 | 3.3 | 5.55 |
| ***process deviations*** | | | | |
| Cure temp. [°C] | 150…160 | 155 | 1.33 | - |
| Cure time [min] | 200…220 | 210 | 3.33 | - |
| Cooling time [min] | 25…120 | 60 | 10 | - |



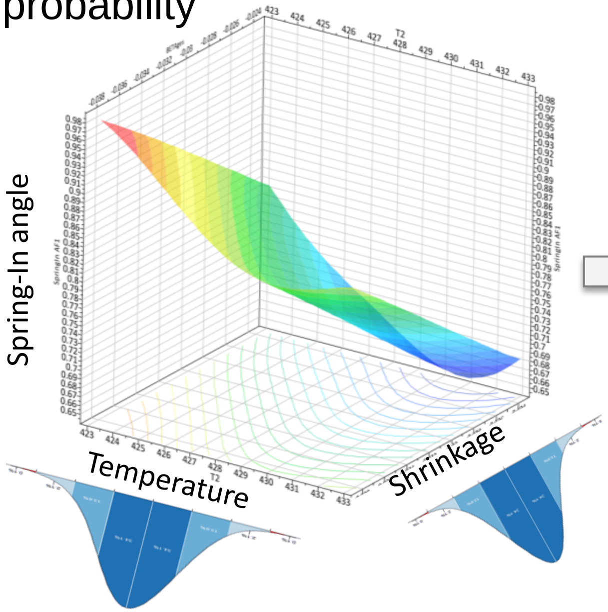

[Liebisch et al.: Probabilistic process simulation to predict process induced distortions of a composite frame, CEAS Aeronautical Journal, 2018]

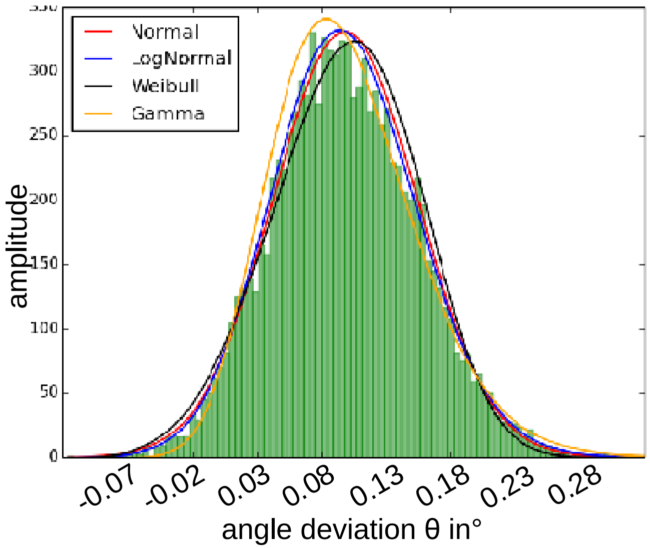
# Probabilistic Process Simulation

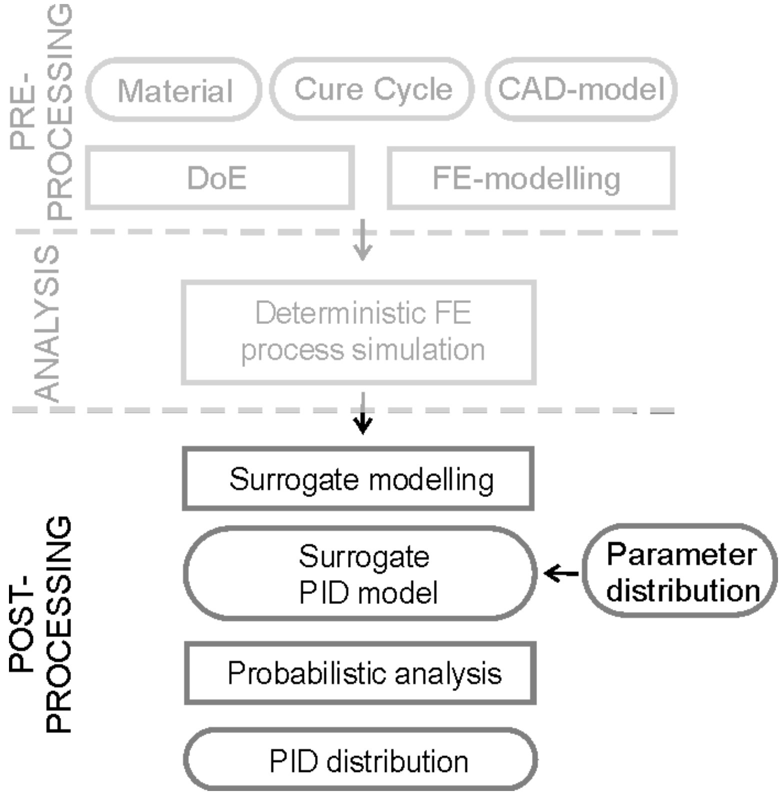
- Probabilistic analysis procedure (2/2)
  - Surrogate model derivation, e.g. Kriging method and cross validation for evaluating predictive quality

$$PID = f(CTEL, CTET, \beta_R, GP, Tcure, tcure, t_{cool})$$

  - Monte Carlo simulation (100.000 points) for deriving confidence interval and probability



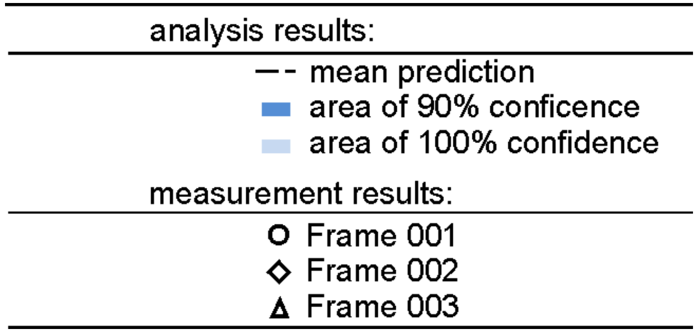



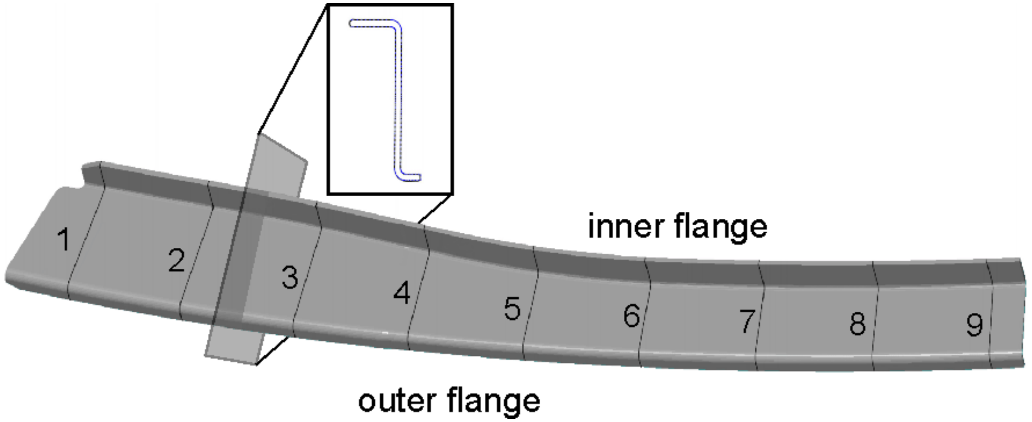



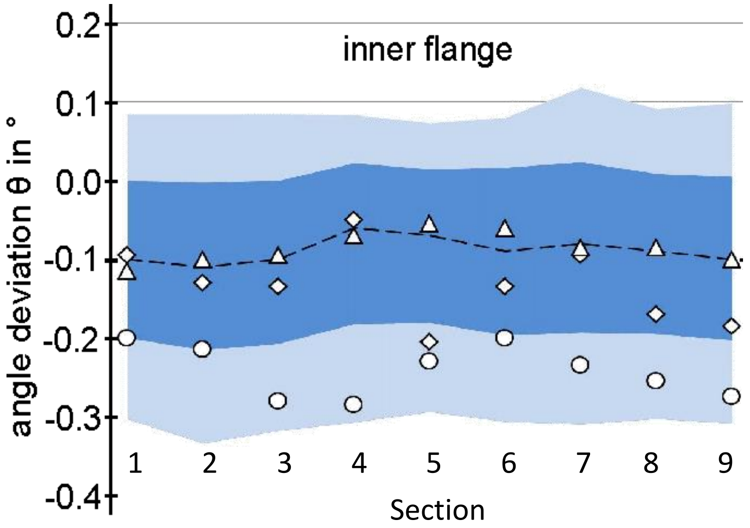

[Liebisch et al.: Probabilistic process simulation to predict process induced distortions of a composite frame, CEAS Aeronautical Journal, 2018]

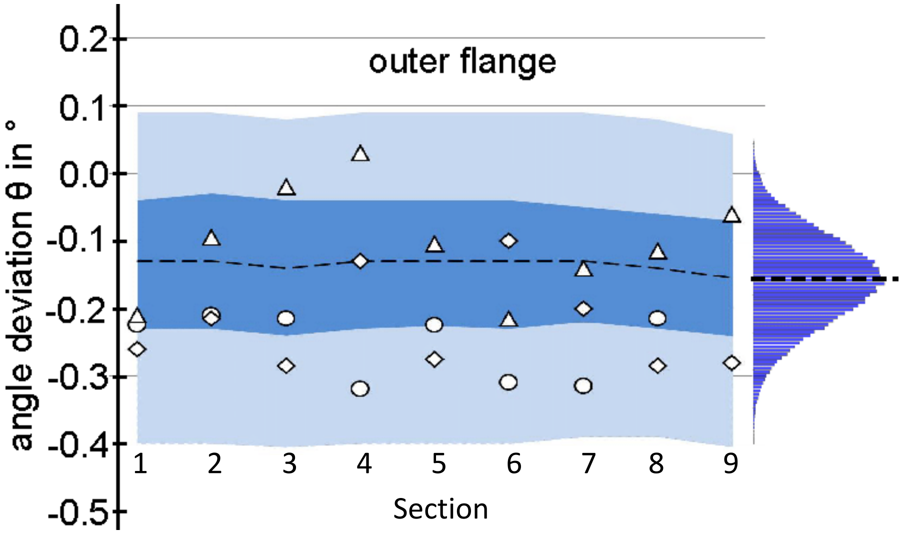
# Probabilistic Process Simulation

- Validation




[Liebisch et al.: Probabilistic process simulation to predict process induced distortions of a composite frame, CEAS Aeronautical Journal, 2018]

# Effects of Defects Analysis

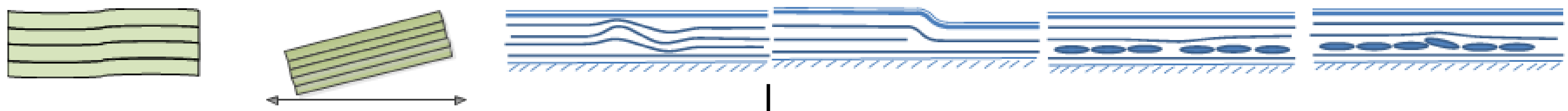
- Defect characterisation depending on defect types, e.g. for AFP process
  - Misc. causes for deviations from design to manufacturing

Part complexity | Steering | Course Deviation | Tow Width

  - Misc. types of manifestation

Fibre curvature/ in-plane ondulation | Fibre angle deviation | Out-of-plane fibre ondulation | Ramp | Gap | Overlap

Mainly 2D effect | Mainly 3D effect | 2D-3D effect



  - Misc. types of effects

Stiffness Variation | Strength Variation | Laminate Thickness Variation | Laminate Stacking Variation | Fiber Volume Fraction Variation

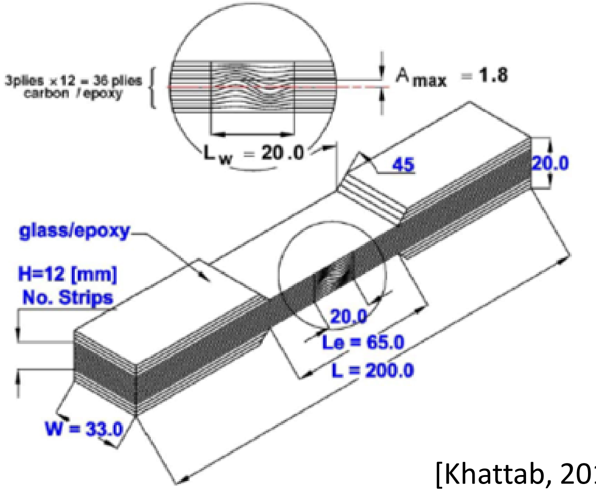
[Heinecke: In-Situ Structural Evaluation, ECOMISE Public Workshop, 2016]

# Effects of Defects Analysis

- Methods to determine knock-down factors (KDF)

**Experimental**

- Mostly component cut-out specimens
- Supplementary coupon specimens with artificial defects
- Limited statistical assurance
- Extremely high costs
- Derivation of conservative KDF functions (lower bound)

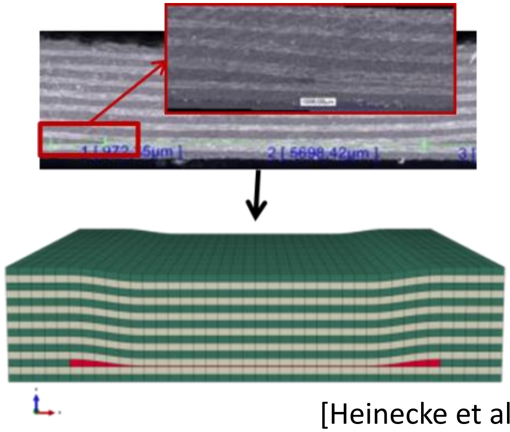



[Khattab, 2013]

Validation

**Numerical**

- 2D/3D FEM models
- Homogenisation of material properties considering load redistribution
- Separated and combined defect analysis
- Model validity to be proven (e.g. fidelity, failure criteria)
- Derivation of distinct KDF functions

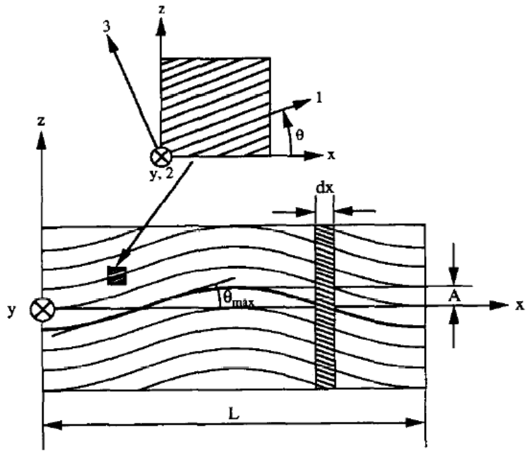


[Heinecke et al., 2018]

Verification

**Analytical**

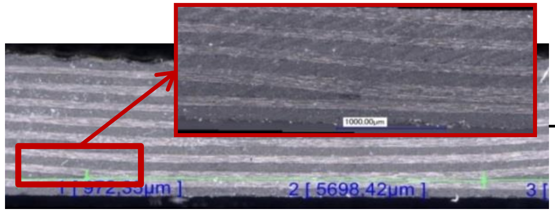
- Determination of stiffness and strength
- Limited application on laminate level
- Simplified/ idealized defects
- Derived properties and KDF for subsequent numerical analyses on laminate/ component level



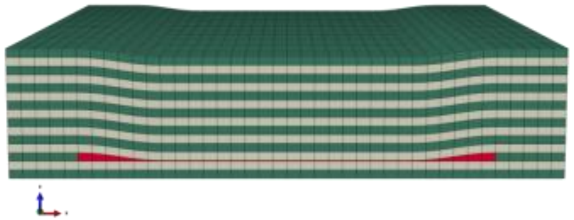

[Hsiao and Daniel, 1996]

# Effects of Defects Analysis

- Transferring „real“ world into model world

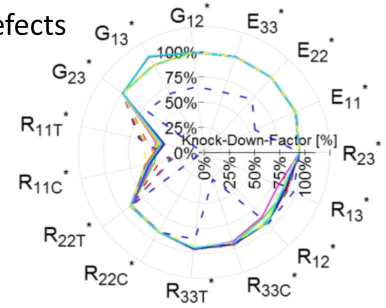



Transfer from
Reality to Model



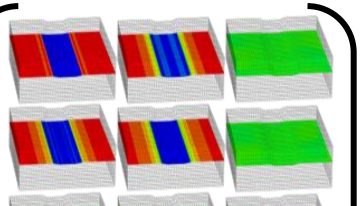
Transfer from
Model to KDF

Effects-of-Defects
Database




- Homogenisation approach to determine layer-wise KDFs of the defective laminate by averaging the stress and strain response from unit load cases

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} = \Bigg( \text{[image]} \Bigg) \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \end{Bmatrix}$$



$\{Q\}_1 \quad \{Q\}_2 \quad \{Q\}_3$

$$\longrightarrow \begin{pmatrix} Q_{11} & Q_{12} & Q_{13} \\ Q_{21} & Q_{22} & Q_{23} \\ Q_{31} & Q_{32} & Q_{33} \end{pmatrix} \longrightarrow \boldsymbol{KDF_{E11}} = \frac{\{\boldsymbol{E_{11}}\}^{\boldsymbol{n}}_{\boldsymbol{defective}}}{\{\boldsymbol{E_{11}}\}^{\boldsymbol{n}}_{\boldsymbol{pristine}}}, \ldots$$

- Calculation of strength KDFs by relating failure indices of defective and pristine layers $\boldsymbol{KDF} = \dfrac{\boldsymbol{FI^{defective}}}{\boldsymbol{FI^{pristine}}}$

[Heinecke et al.: In-situ structural evaluation during the fibre deposition process of composite manufacturing, CEAS Aeronautical Journal, 9:123–133, 2018]

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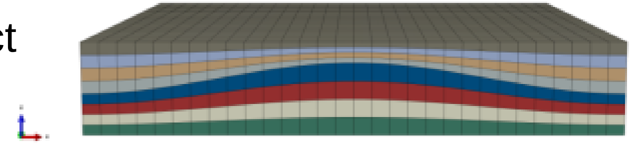
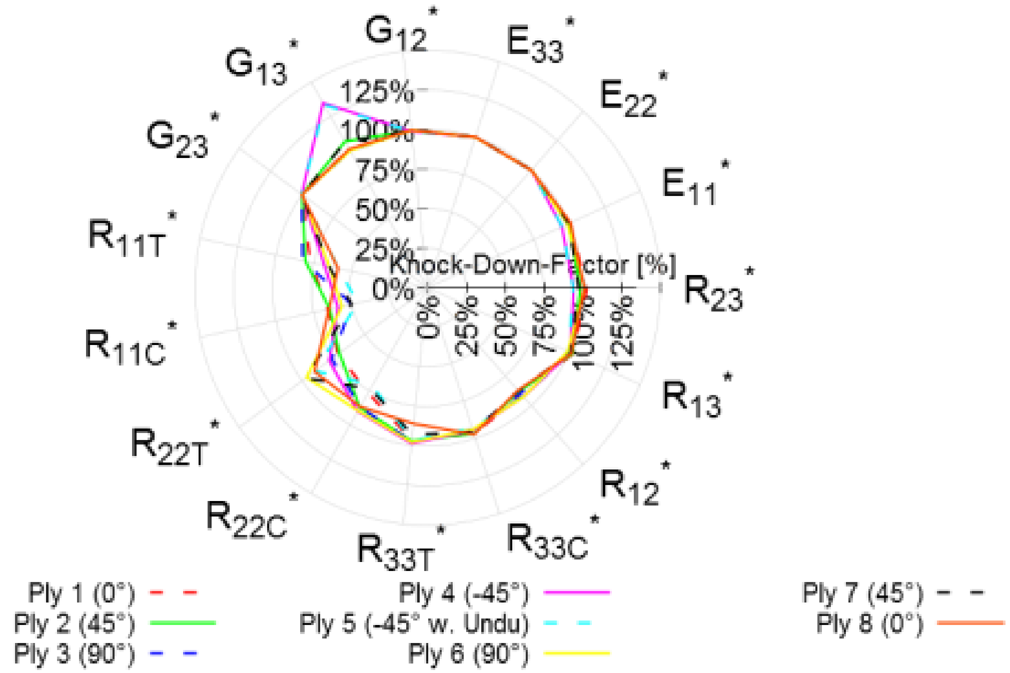
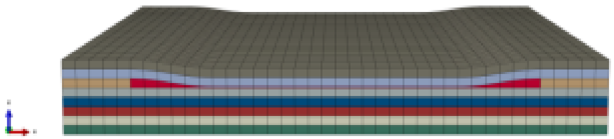
# Effects of Defects Analysis

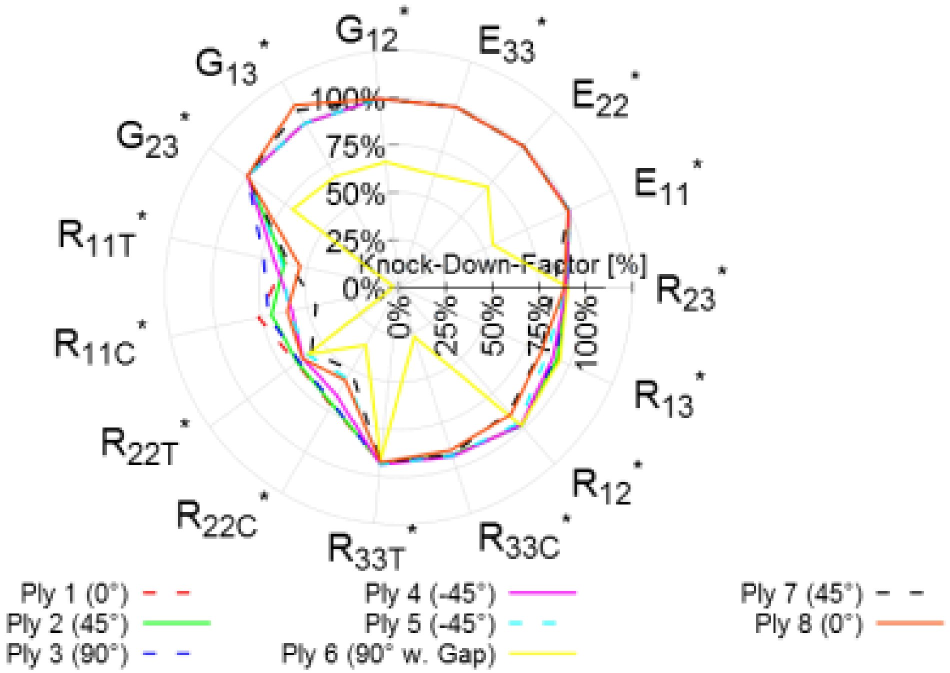
- Examples
  - Undulation defect (A/L = 0,0625)






  - Gap defect (6mm width)





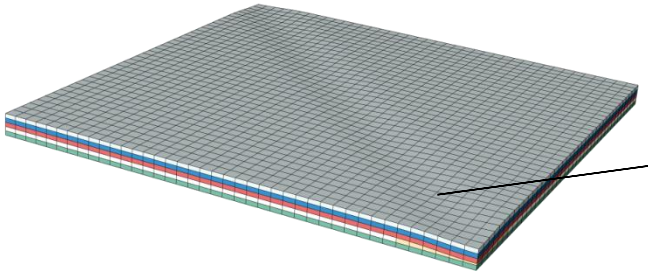

[Heinecke et al.: In-situ structural evaluation during the fibre deposition process of composite manufacturing, CEAS Aeronautical Journal, 9:123–133, 2018]

# Effects of Defects Analysis

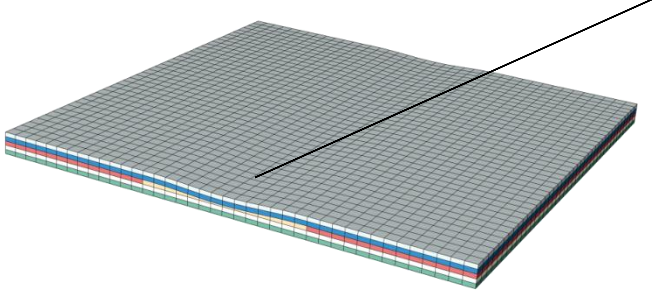
- Derivation of KDF functions (e.g. Kriging) of laminate property within defect parameter space

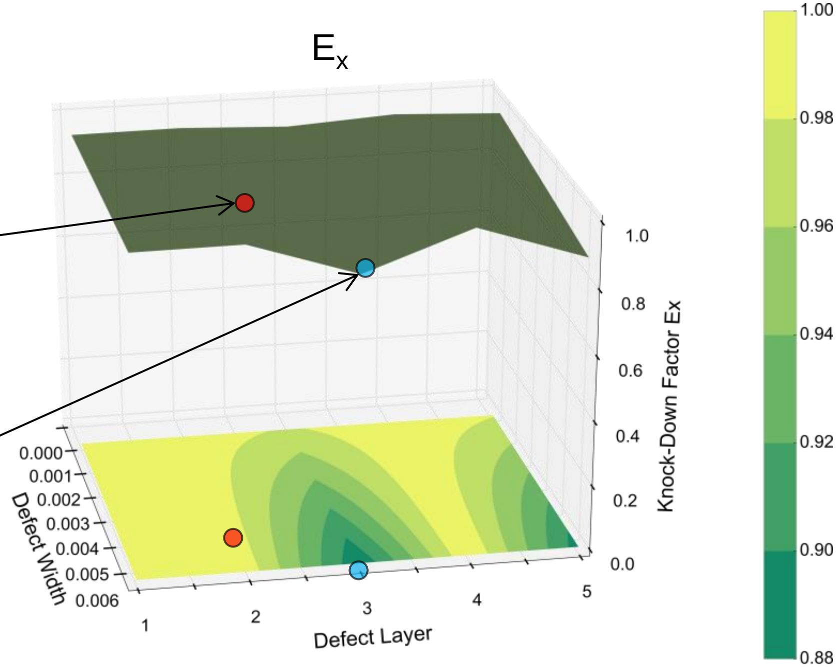
Example: [-45°, 45°, 0°, 90°, 0°] laminate with

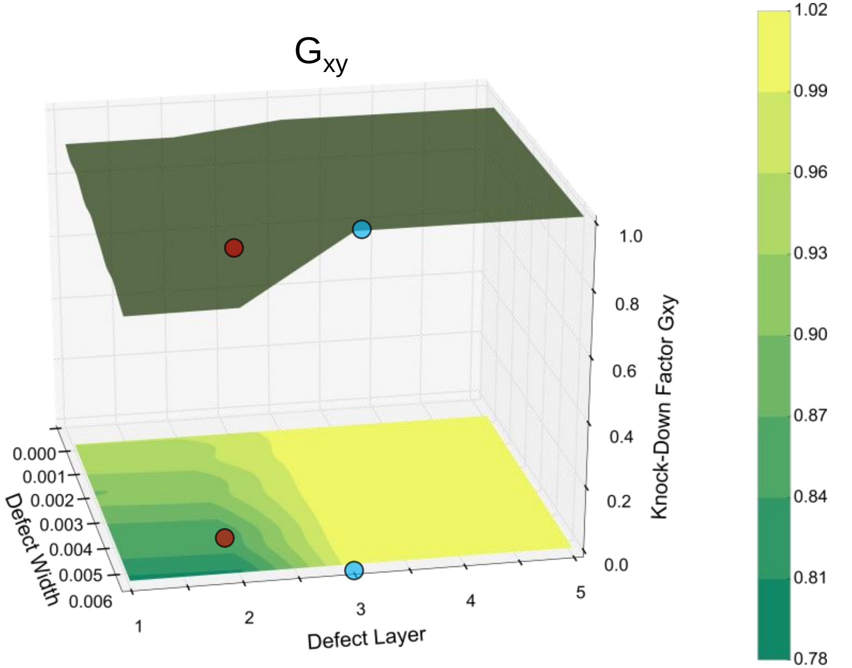
- Gap in 2nd layer



- Gap in 3rd layer



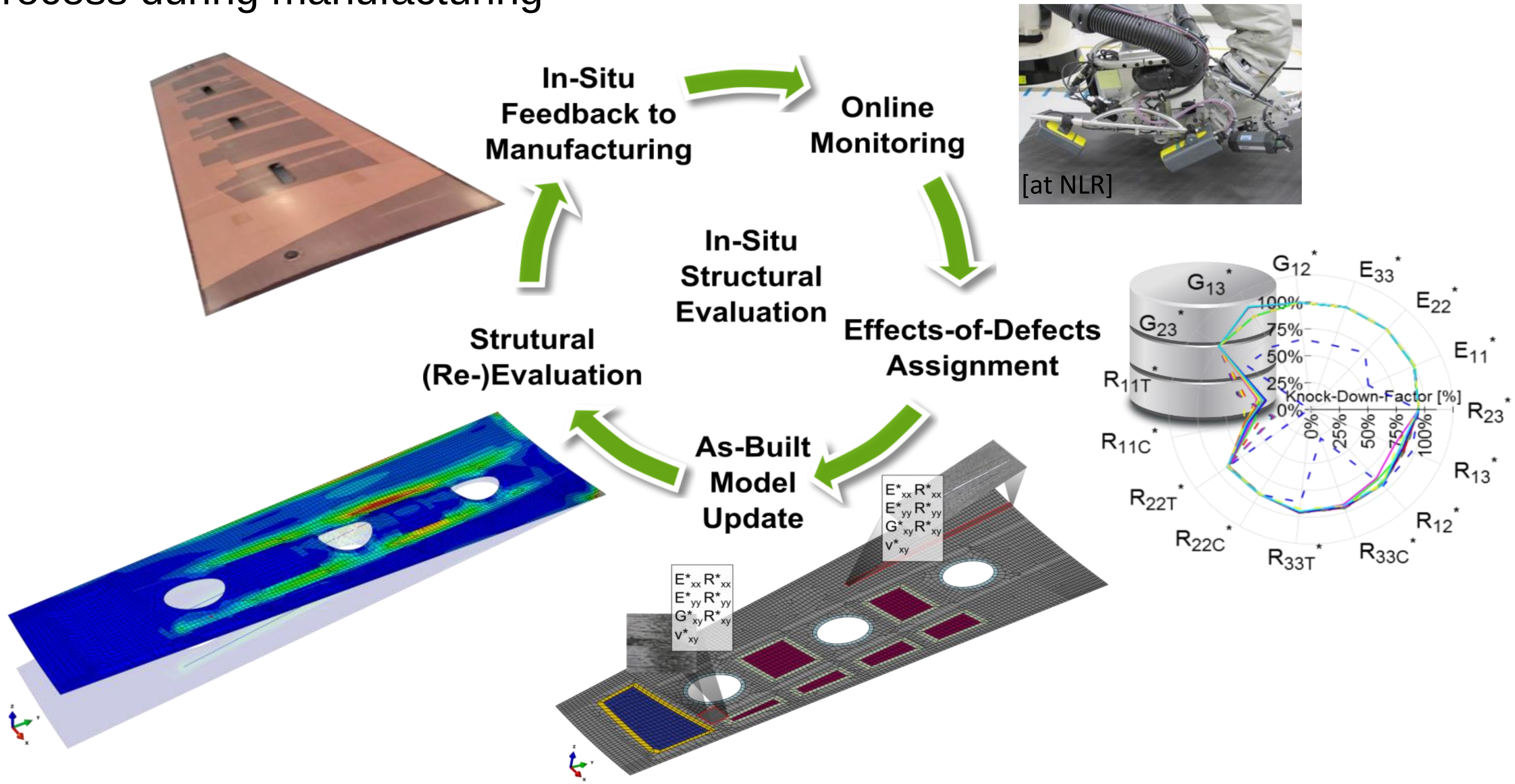



[Heinecke et al.: In-situ structural evaluation during the fibre deposition process of composite manufacturing, CEAS Aeronautical Journal, 9:123–133, 2018]

# In-situ structural evaluation during fibre deposition

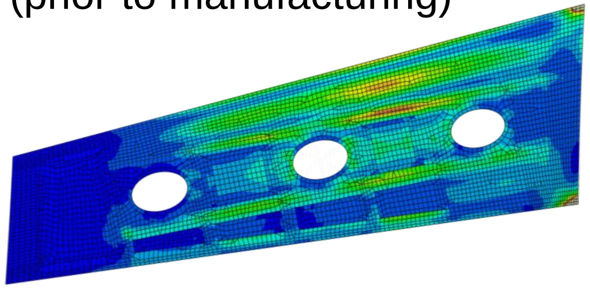
- Effects of defects analysis completed prior to manufacturing
- Assessment process during manufacturing




[Heinecke et al.: In-situ structural evaluation during the fibre deposition process of composite manufacturing, CEAS Aeronautical Journal, 9:123–133, 2018]

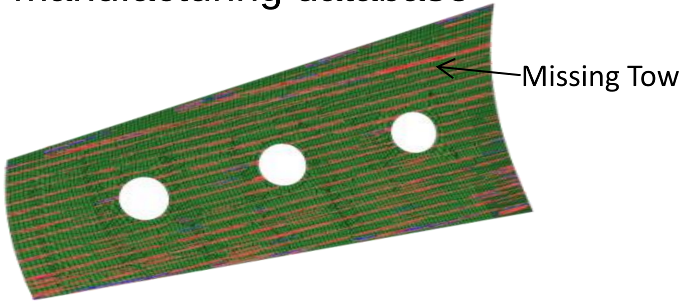
# In-situ structural evaluation during fibre deposition

- Example: Demonstration on Wing Cover
  1. Nominal design and analysis (prior to manufacturing)



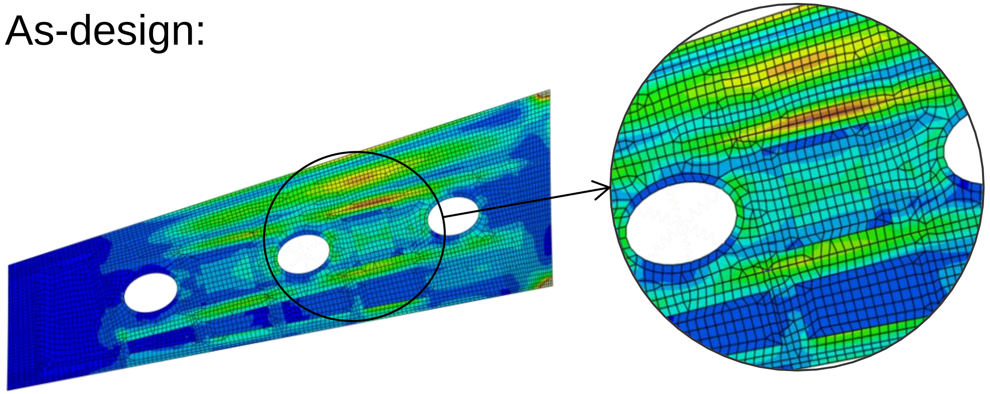
  2. AFP manufacturing incl. online measurement


  3. In-situ data transfer of defects to manufacturing database

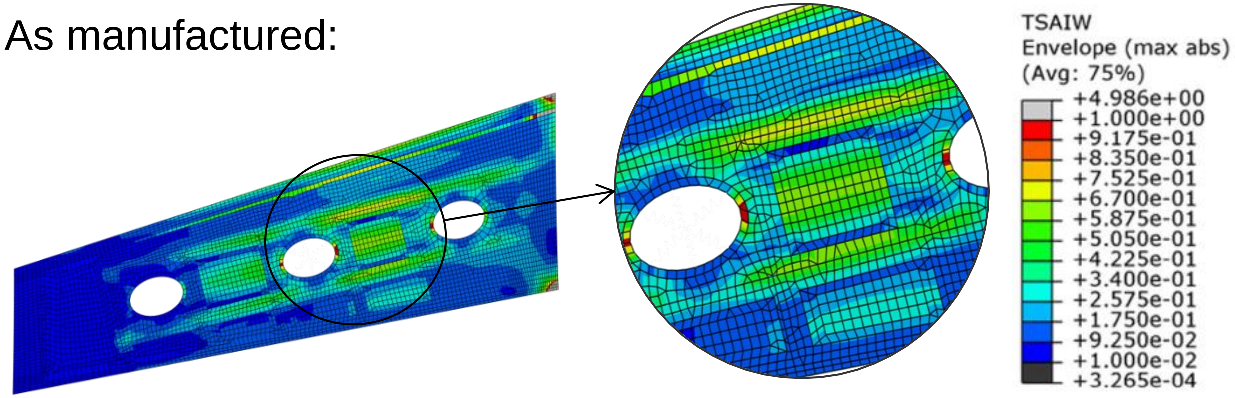



  4. In-situ mapping of material properties, model update and structural as-built analysis (re-evaluation)

As-design:



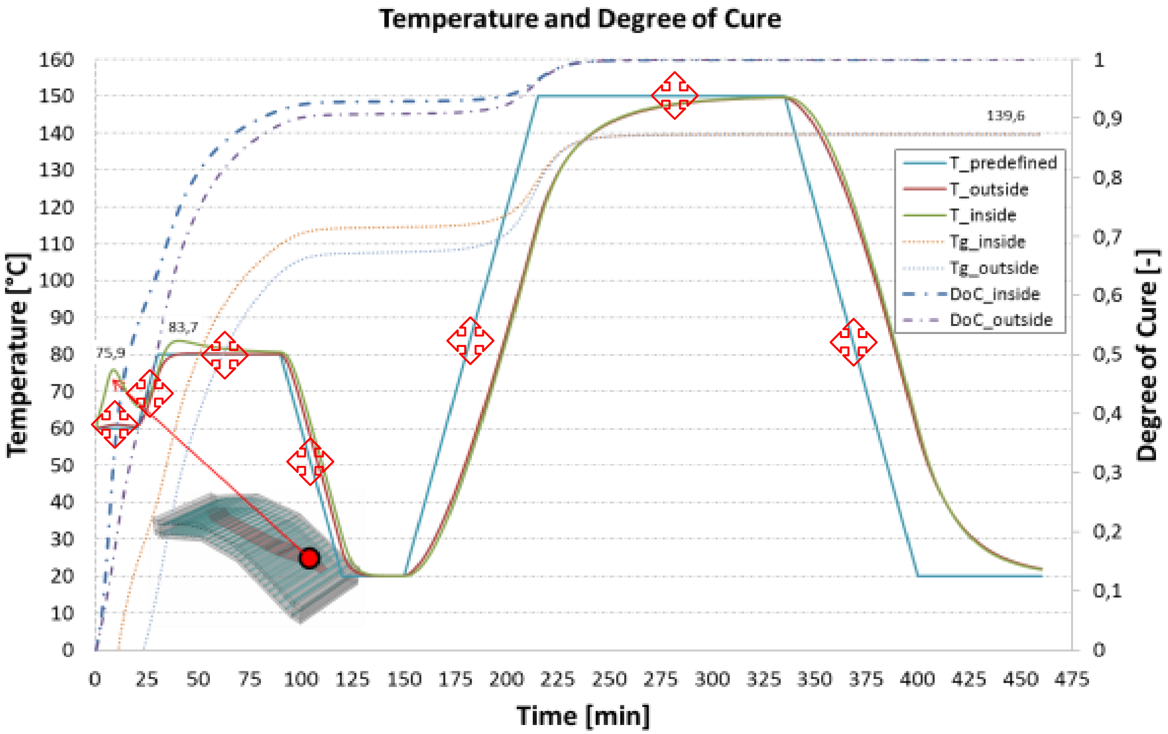
As manufactured:

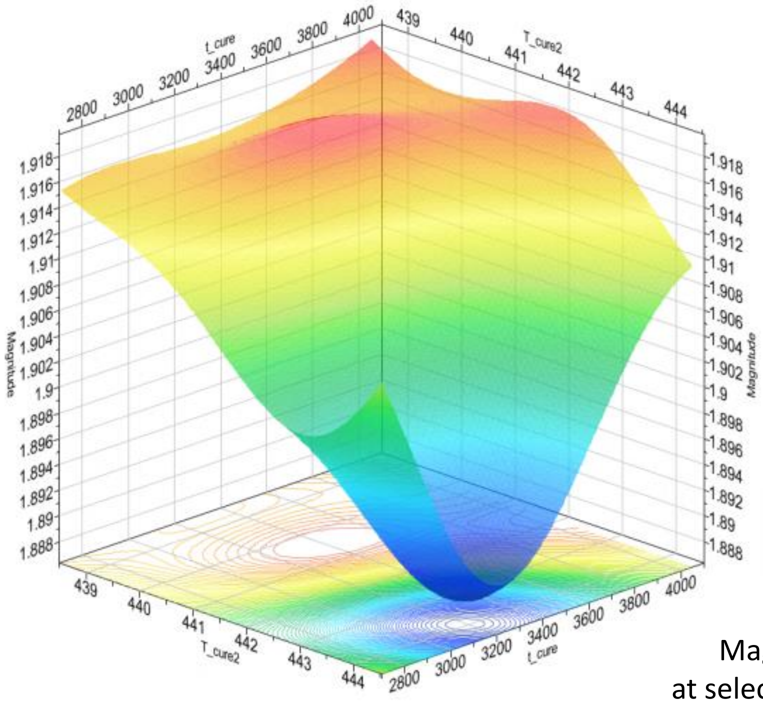


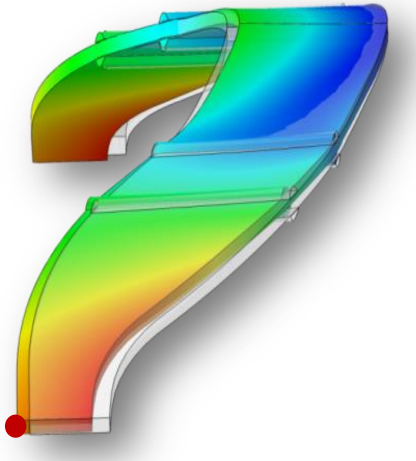

[Heinecke et al.: In-situ structural evaluation during the fibre deposition process of composite manufacturing, CEAS Aeronautical Journal, 9:123–133, 2018]

# In-situ structural evaluation during curing

- Prior to manufacturing
  - Analysis of manufacturing process and structural requirements
  - DoE for varying material and process parameters
  - Surrogate models of part distortion and residual stresses



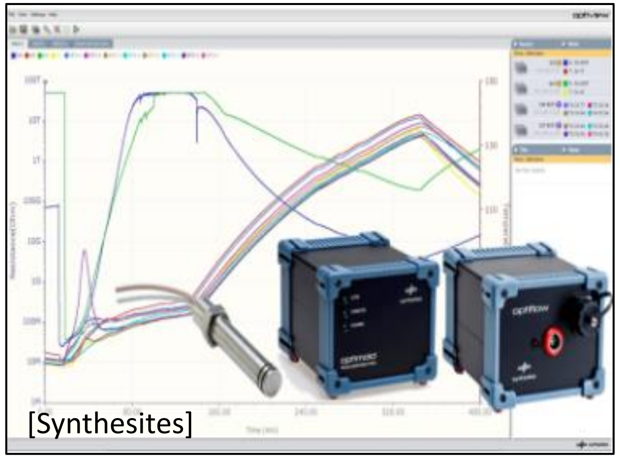



Magnitude of distortion [mm]
at selected point of interest at t_final

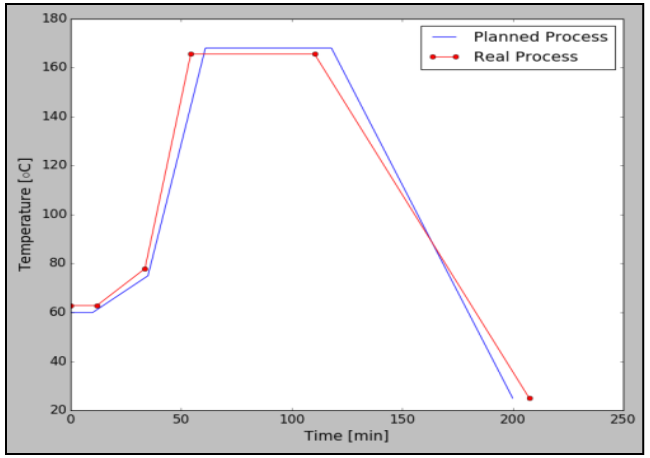
[Hein et al.: Prediction of process-induced distortions and residual stresses of a composite suspension blade, ISCM, 2016]

# In-situ structural evaluation during curing

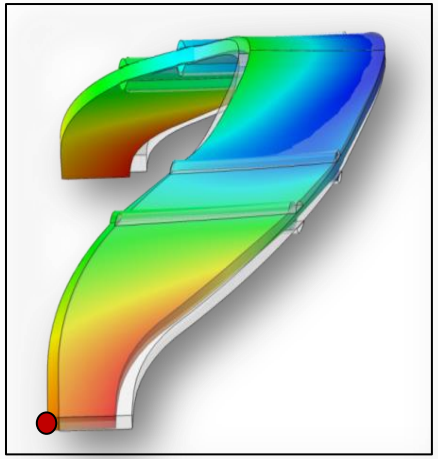
- During curing
    1. Process monitoring
    2. In-situ feedback of on sensor data (temperature) and model update
    3. In-situ process analysis and prediction of final distortion
    4. In-situ evaluation with respect to structural requirements



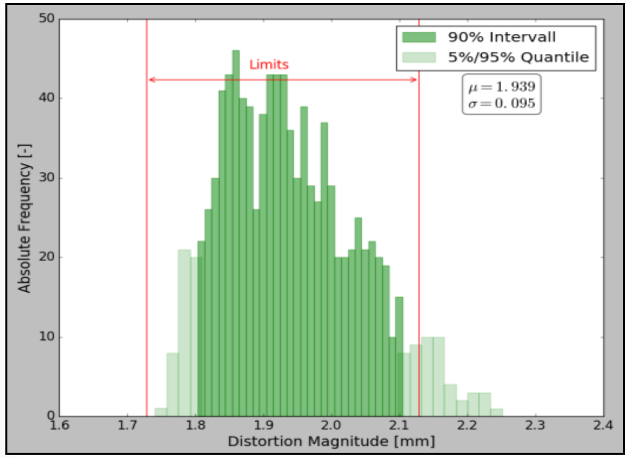

1. Temperature, cure monitoring




2. As-is cure cycle update with sensor data at time t_i



3. Prediction of distortion at time t_final




4. Tolerance check wrt. final process induced distortions

[Hein et al.: Prediction of process-induced distortions and residual stresses of a composite suspension blade, ISCM, 2016]

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