Process Monitoring and Evaluation

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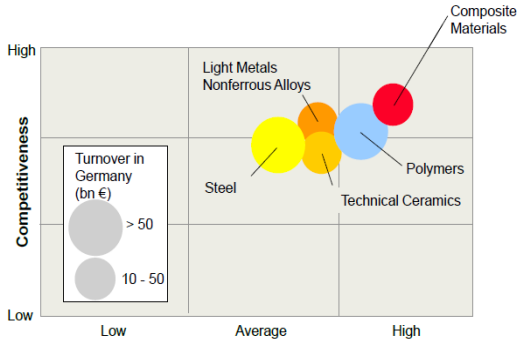
Outline

- Motivation
- Fibre deposition monitoring
- Example for in-situ structural evaluation of fibre deviations during AFP
- Resin infiltration and cure monitoring
- Example for in-situ structural evaluation of process induced distortions
- Conclusion

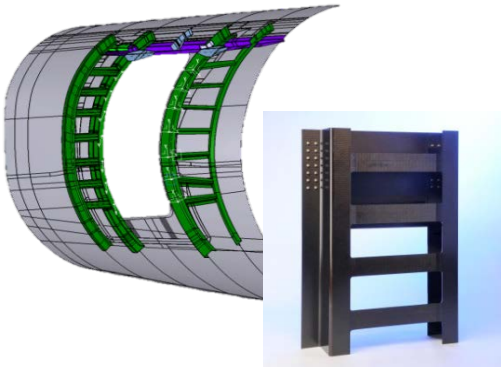
Motivation

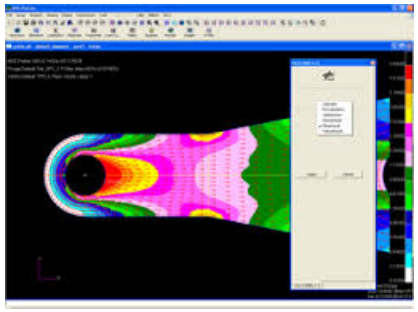
Potentials of Composites

- High weight specific mechanical properties
- Integral Design
- Anisotropic Tailoring
- Function Integration
- …



[VDI-Nachrichten Nr. 37, 2004]



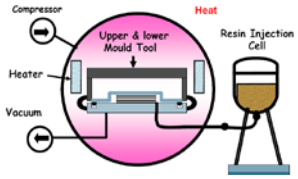


Motivation

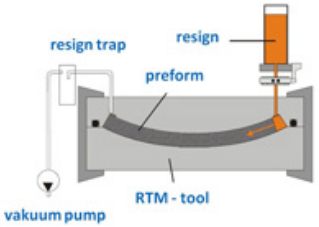
Great variety of composite materials and manufacturing technologies

Pick&place [Schmalz]

AFP [NLR]



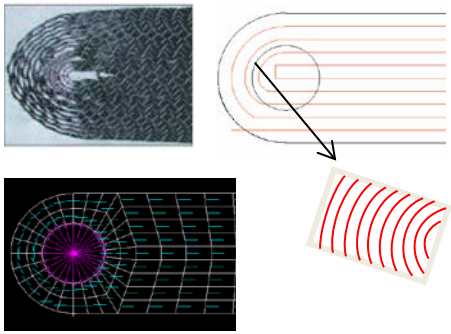
RTI [BAB]



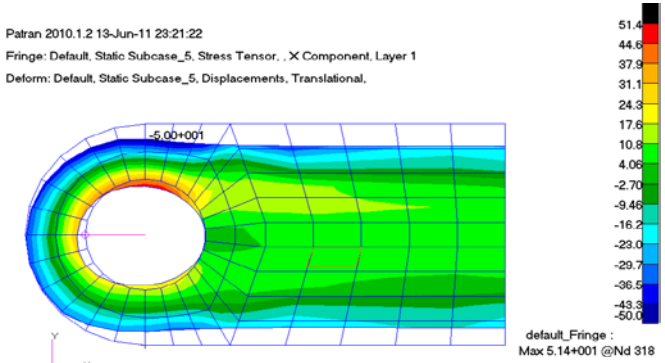
RTM [DLR]

Autoklav [DLR]

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



Fibre orientation resulting from dry fiber placement [DLR]

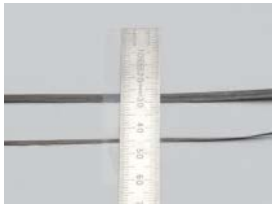


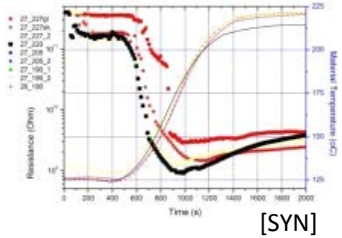
Residual stress in fiber direction [DLR]

Motivation

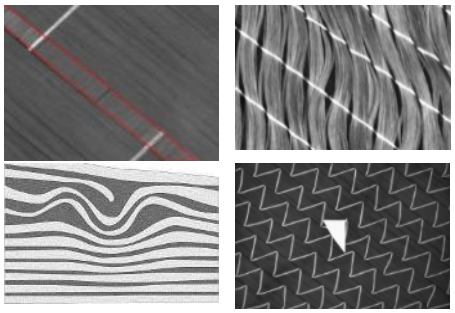
Inevitable uncertainties

- Material properties and tolerances
- Process parameters and tolerances
- Inevitable deviations or faults


[NLR]

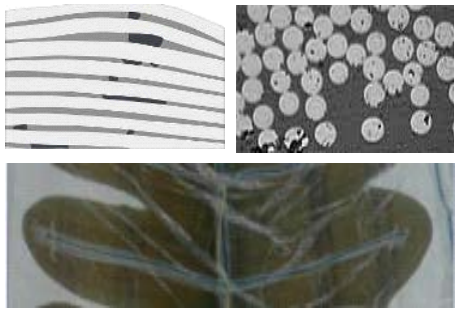

[SYN]

Fibre Deposition


[FIBRE, DLR]

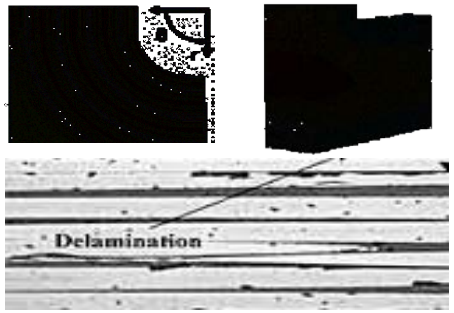
- Fibre orientation
- Waviness
- Gas, Overlaps
- Foreign objects
- …

Resin Infiltration



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

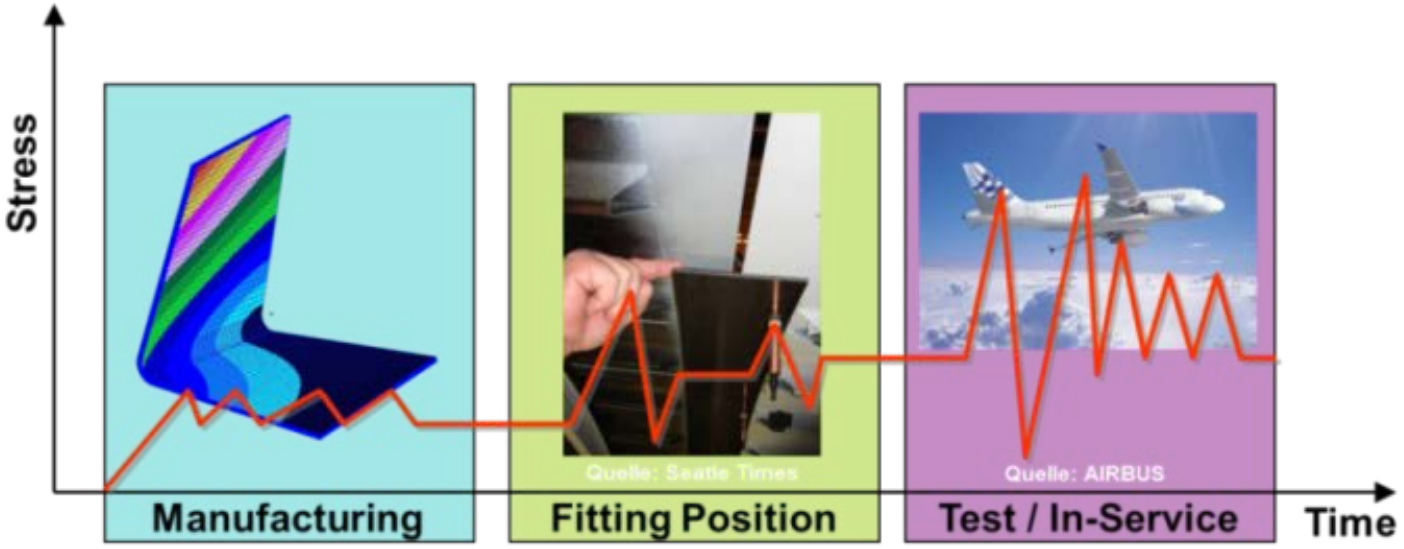
Curing



- Overheating
- Degree of cure variation
- Chemical shrinkage, distortion
- Residual stresses, delamination
- …

Motivation

Effects of process deviations on subsequent assembly and operation



[Spröwitz et al., 2008]

Motivation

Current state-of-the-art tolerance management

- Process design
  - Mainly knowledge based
  - Selected process simulations
  - Conservative composite engineering requirements/ allowable
  - High trade-off between accuracy and efficiency

- Process control
  - Wrt. predefined global (conservative) process tolerances
  - Few sensors within autoclave/ oven, tooling, traveler coupons
  - Not considering actual structural properties

- Resulting in
  - Conservative processing
  - High non-added value costs in case of non-conformities

Motivation

New tolerance management for efficient production requires

- Robust and reliable sensors
  - Low complexity, easy to use
  - Not affecting manufacturing process or structural properties
- Efficient analysis methods
  - Real-time capability
  - Multidisciplinary coupling of process and structural analysis

Potentials

- Increased understanding of materials and processes
- Significant reduction of process time, energy, emissions and costs
- Material savings
- Enhanced NDI
- Less rework and concessions
- Higher exploitation of composites
- Less maintenance effort, increasing life-time
- …

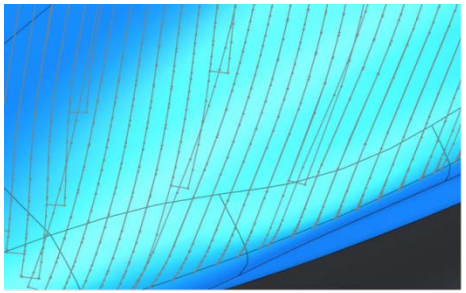
Fibre Deposition Monitoring

Depending on

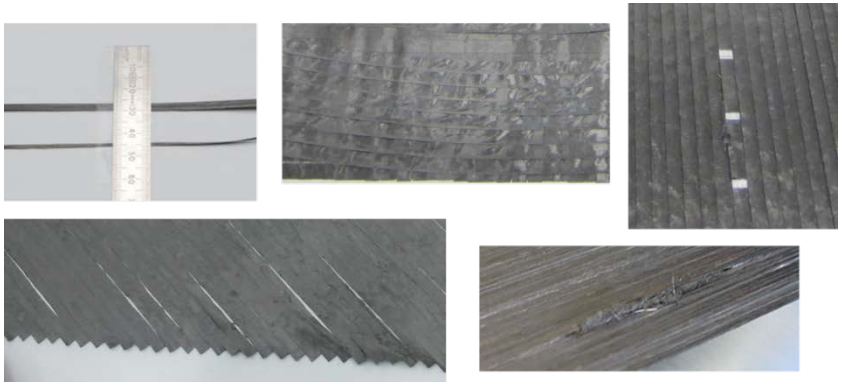
- Part complexity (double curved, inserts, etc.)
- Fibre material (dry or prepreg, tow, tape, fabric, etc.)
- Manfacturing technologies
  (manual layup, pick&place, AFP, winding, etc.)

Particular features to be identified and evaluated

- Global and local fibre orientation
- Ply/ patch/ tow boundaries
- Misplacement
- Thickness
- Gaps and overlaps
- Twisted tows
- Splicing
- In-plane/ out-of-plane waviness
- Foreign objects
- …



Geometrical induced features during AFP [Gerrits et al., NLR]

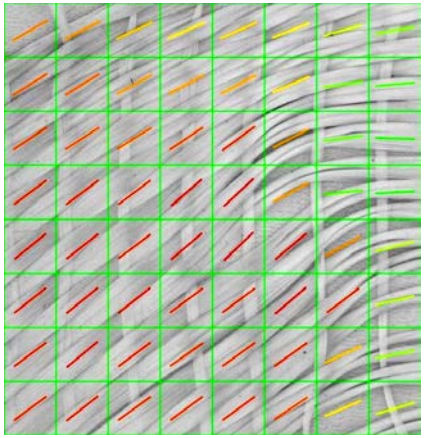


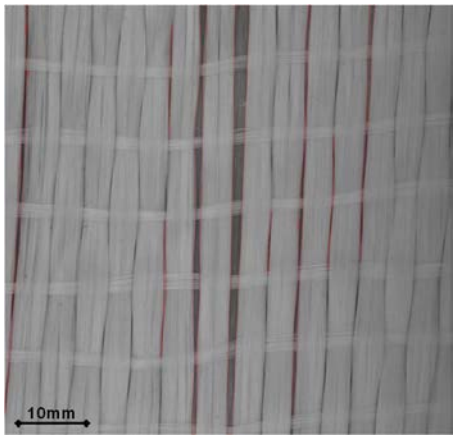
Typical defects during AFP [Gerrits et al., NLR]

Fibre Deposition Monitoring

Fibre monitoring by 2D image analysis

- Image quality depending on camera (lens, sensor), illumination, speed and fibre material
- Analysis of features depending on image quality and data analysis software



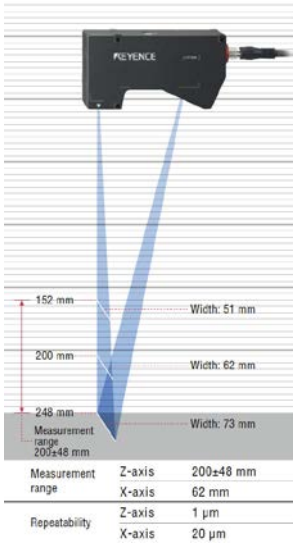


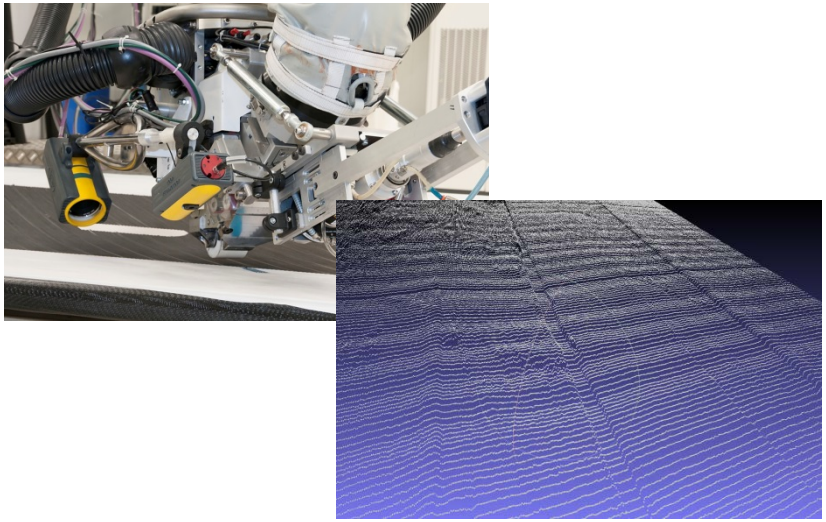
Suspension blade measured with diffuse light cone from Faserinstitut Bremen at Hutchinson [Miene et. al]

Fibre Deposition Monitoring

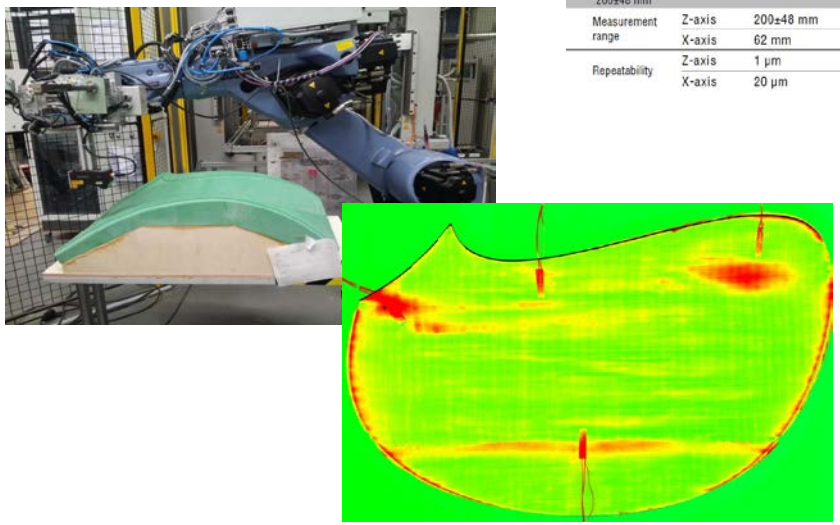
Fibre monitoring by 3D laser triangulation

- Thickness profile measurement
- Data analysis (reference plane, strip stitching, smoothing, feature identification)





Wing Cover measured by Loop Technology during AFP at NLR [Redman et al.]



Ship Propeller measured by Faserinstitut Bremen [Miene et al.]

Fibre Deposition Monitoring

During measurement

- Feature storage within manufacturing database and digital life data sheet
- Direct feedback to CAD/CAE for detailed structural analysis possible

Measures in case of deviations

- Remove foreign objects
- Ply correction in case of wrong orientation, misplacement, waviness, etc.
- Remove splices, fill in tows
- Add/ remove ply or core for thickness adjustment
- (Stop process)

Impact

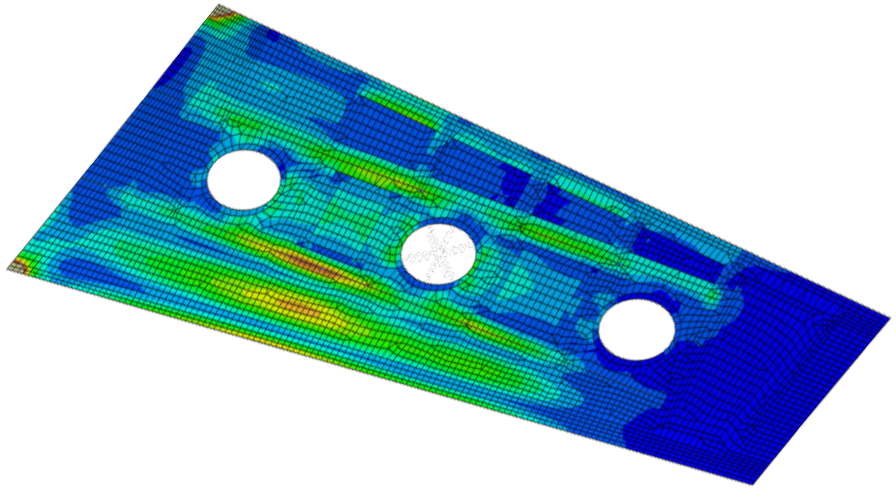
- In-situ NDI (fibre architecture)
- Less conservatism required (engineering + manufacturing)
- Earliest correction to save waste of subsequent manufacturing steps
- Increased robustness for subsequent processes (e.g. reproducible runners and permeability during infiltration)

Fibre Deposition Monitoring

Challenges

- Sensor robustness under environmental conditions
  (e.g. illumination, speed, vibrations)
- Sensor system integration into manufacturing environment
  (fibre deposition machine, work flow, software, database)
- Robust defect identification also for interacting defects
- Handling of material and process particularities, e.g. debulking
- Big data issues
- Real-time data analysis

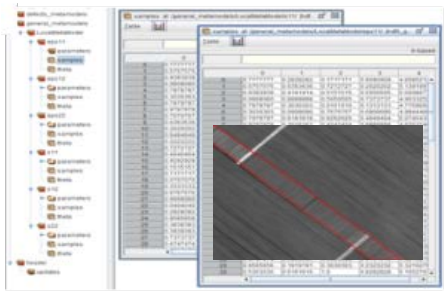
Example:
In-situ structural evaluation of fibre deposition of a composite wing (ECOMISE project)

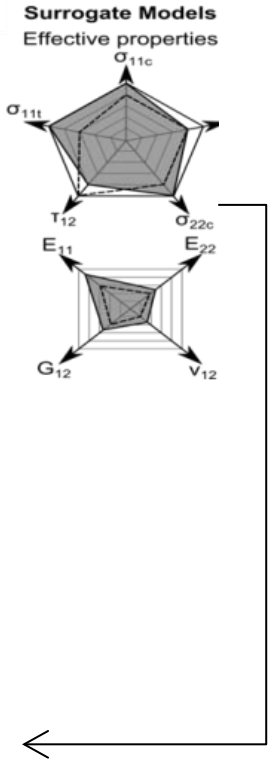


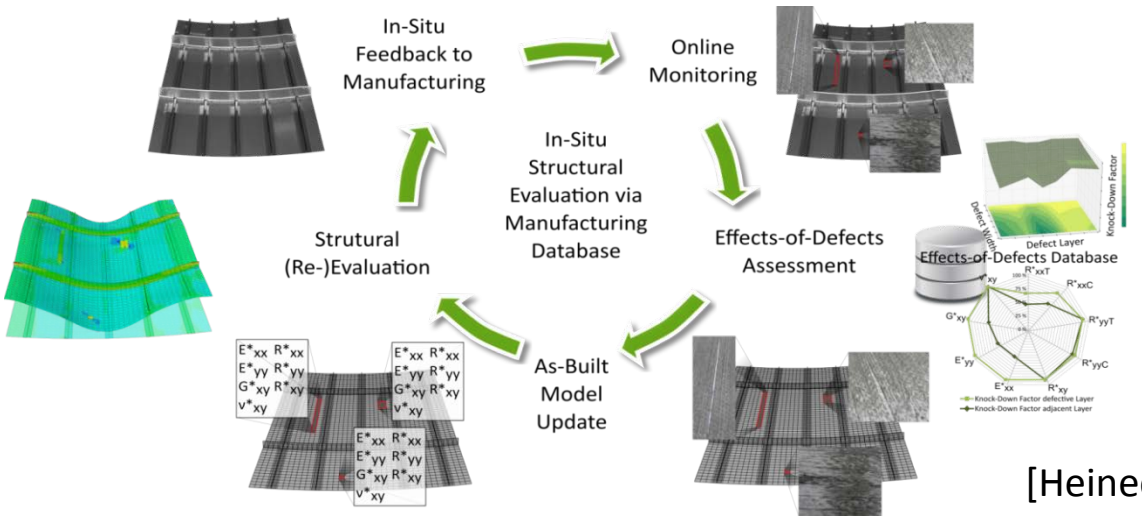
In-Situ Structural Evaluation during AFP

Procedure

1. Prior to manufacturing
   - Investigation of effects-of-defects
   - Database and surrogate modeling
2. During manufacturing
   - Online process monitoring
   - Feedback of online fibre measurment
   - Structural model update and assessment





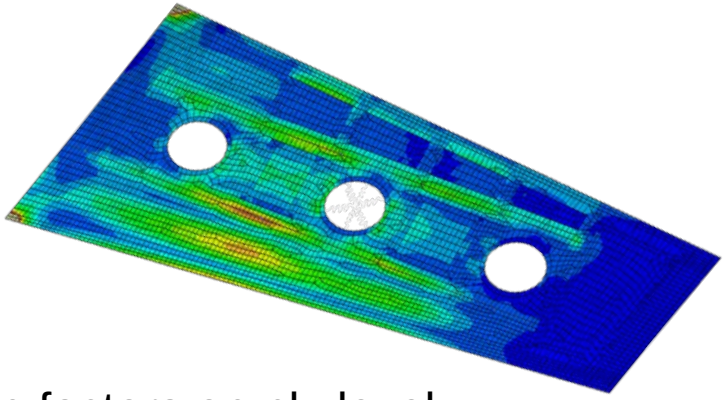


[Heinecke et al., DLR]

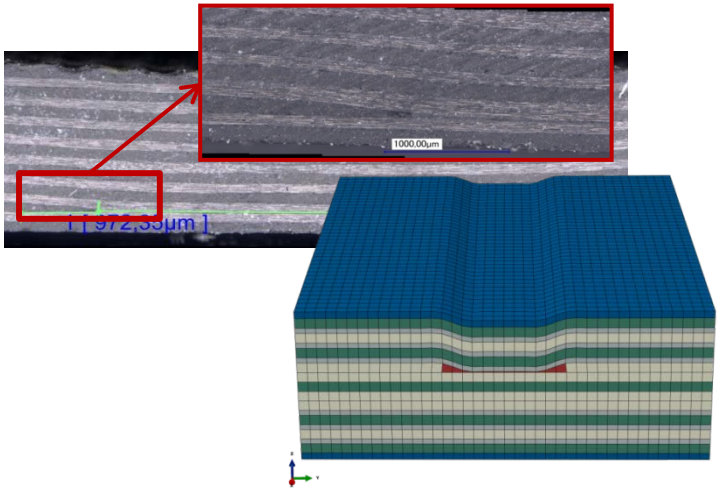
In-Situ Structural Evaluation during AFP

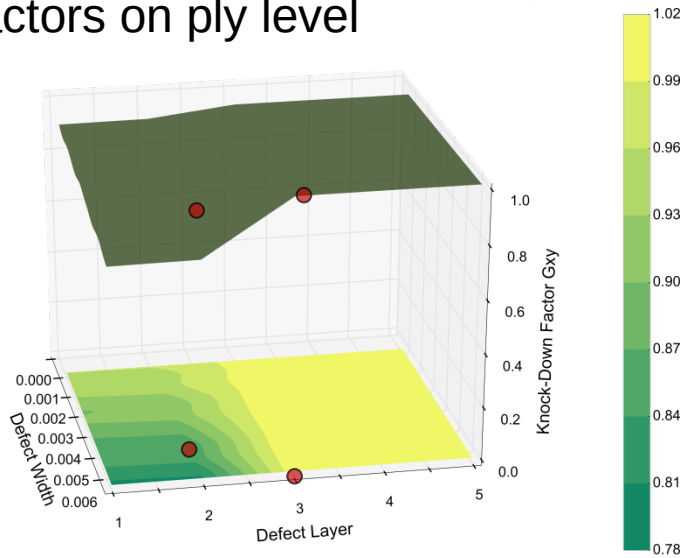
Industrial application (1. step, offline)

- Nominal design and analysis (without defects)



- Effect-of-defect analysis and surrogate models for knock-down factors on ply level



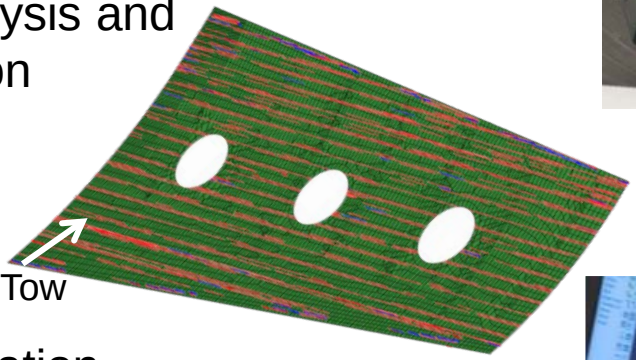


[Heinecke et al., DLR]

In-Situ Structural Evaluation during AFP

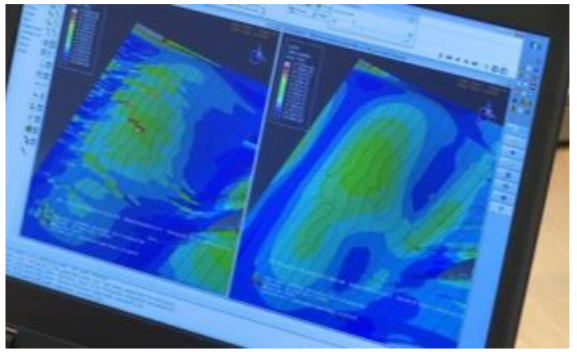
Industrial application (2. step, online)

- Process monitoring
  - Laser triangulation
  - In-situ profile analysis and defect identification



Measurement with Loop System at NLR

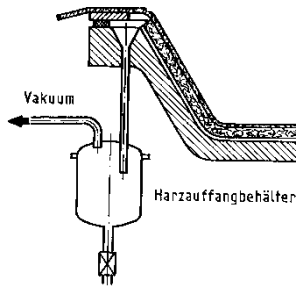
- In-situ structural evaluation
  - In-situ model update and structural re-analysis
  - Comparison with initial design and requirements



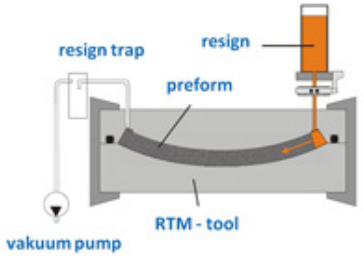
In-situ structural evaluation during AFP [Heinecke et al., DLR]

Resin Infiltration and Curing Monitoring

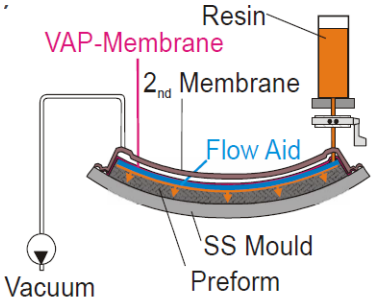
Typical infiltration and curing technologies for dry fibres and prepreg



Vacuum bagging

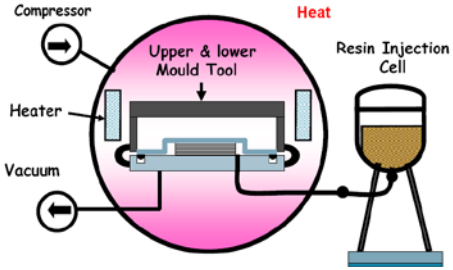


RTM

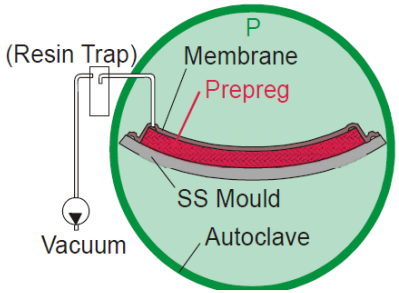


VAP

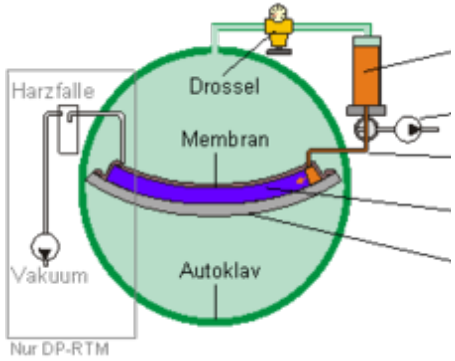
...



RTI



Autoclave



DP-RTM

Resin Infiltration and Curing Monitoring

Monitoring systems required for

- Fast ramp-up through early and efficient identification of issues
- Sensor-based process optimization (e.g. during curing)
- Verification and validation
- Quality control

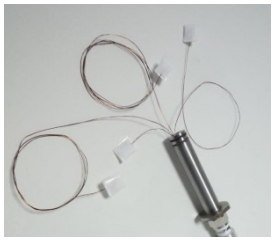
Parameters to be monitored

- Temperature
- Viscosity
- Pressure
- Amount of resin infiltrated
- Flow front, velocity and shape, air entrapments
- Degree of cure, point of gelation, glass transition
- Thickness/ fibre volume content and floating/ sliding
- Strain, stress
- Geometry

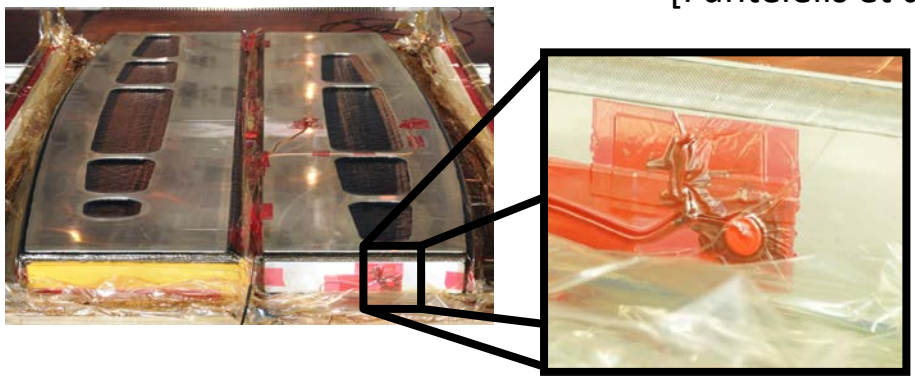
Resin Infiltration and Curing Monitoring

Typical resin/ composite monitoring systems

- Thermocouples, thermography
- Pressure sensors
- Dielectric sensors
- Electrical resistance sensors
- Ultrasonic sensors
- Fibre optical sensors
- Digital image correlation



Electrical resistance sensors from Synthesites [Pantelelis et al.]



Ultrasonic sensor system from DLR [Liebers et al.]

Resin Infiltration and Curing Monitoring

During measurement

- Feature storage within manufacturing database and digital life data sheet
- Direct feedback to online process simulation and optimization possible

Measures in case of deviations

- Adjust temperature profile
- Adjust pressure
- Open/ close valves
- Stop process

Impact

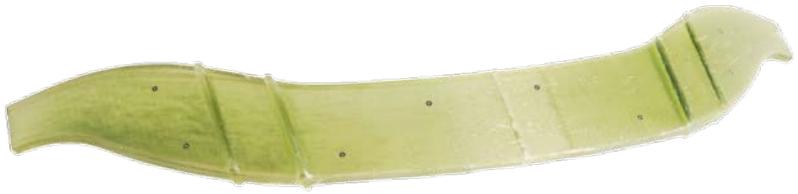
- In-situ NDI (filling, Tg, degree of cure, etc.)
- Reduction of process time and cost
- Increased understanding of materials and processes as well as efficient root cause analysis in case of deviations

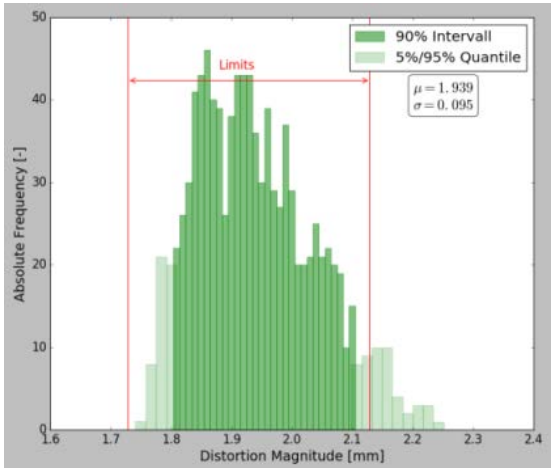
Resin Infiltration and Curing Monitoring

Challenges

- Effective sensor network (multiple sensors and multiple purpose)
- Sensor robustness under environmental conditions
- Accessibility within closed tools, autoclave
- Part damage by contacting or integrated systems
- Sensor and material model calibration considering uncertainties
- Real-time data and process analysis as well as forecast

Example:
In-situ structural evaluation of of process induced distortions of a composite suspension blade (ECOMISE project)

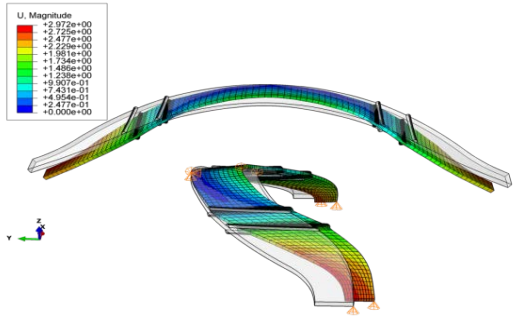




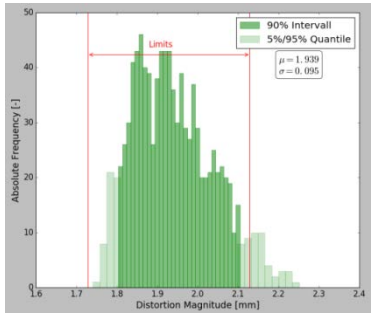
In-situ evaluation of process induced distortions

Procedure

1. Prior to Manufacturing
   - Process and sensitivity analysis
   - Surrogate modeling for in-situ process simulation and evaluation



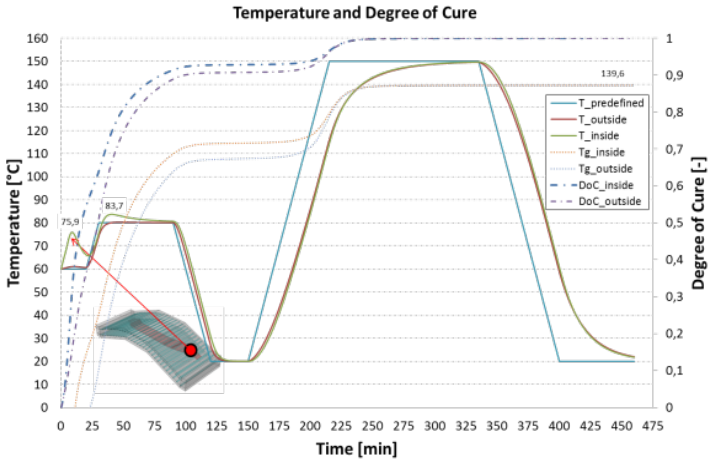
1. During Manufacturing
   - Online process monitoring
   - In-situ evaluation and process adjustment

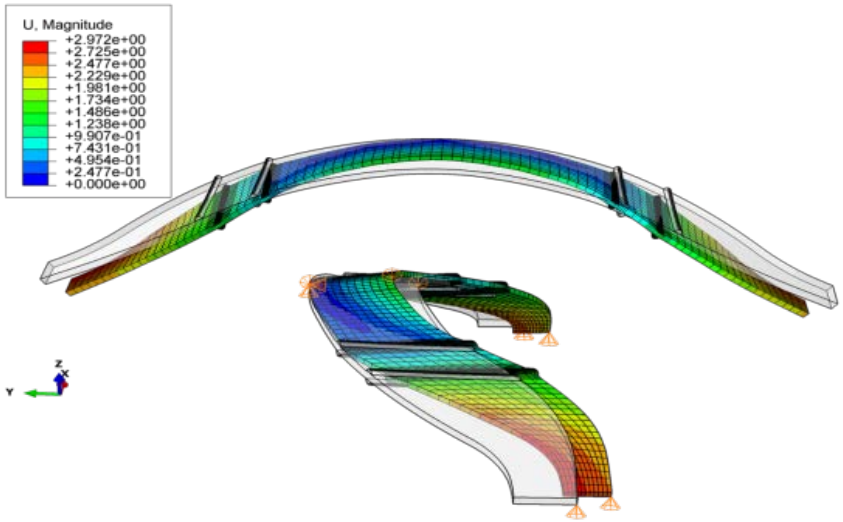


In-situ evaluation of process induced distortions

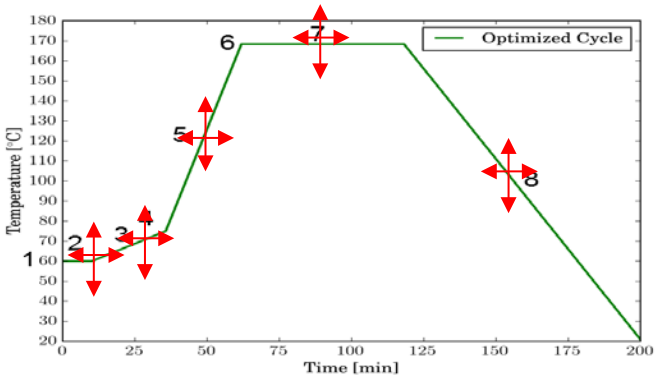
Industrial application (1. step, offline)

- Curing and distortion simulation





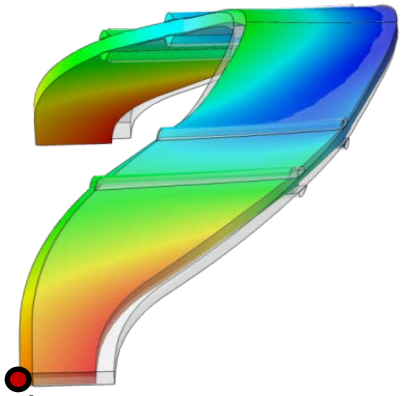
- MaxiMin-Design for varying material and process parameters,
- Evaluation of material & process dependency



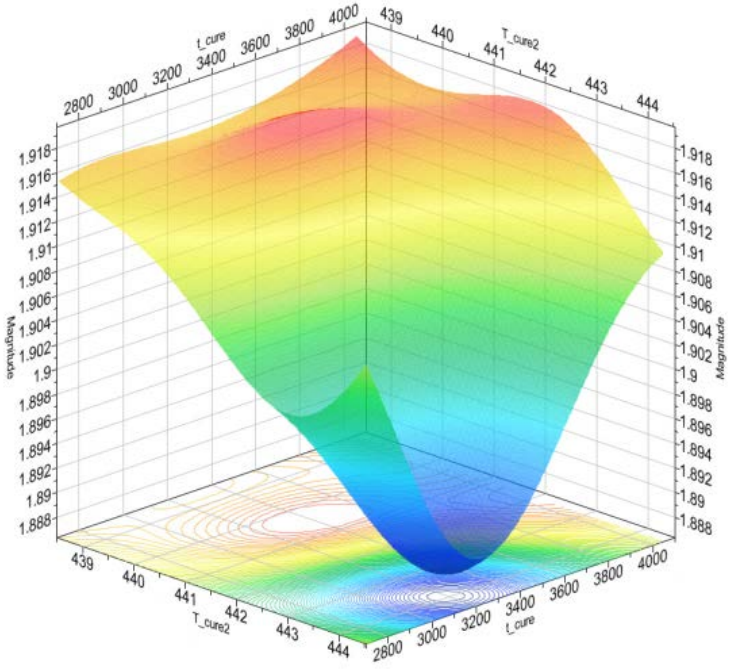
In-situ evaluation of process induced distortions

Industrial application (1. step, offline, cont.)

- Surrogate modeling of process induced distortion (Kriging and RBF), capturing variations of material and process parameters, e.g.
  - Coefficient of thermal expansion
  - Tool temperature
  - Injection time
  - Time dependent cure cycle
  - …



Distortion

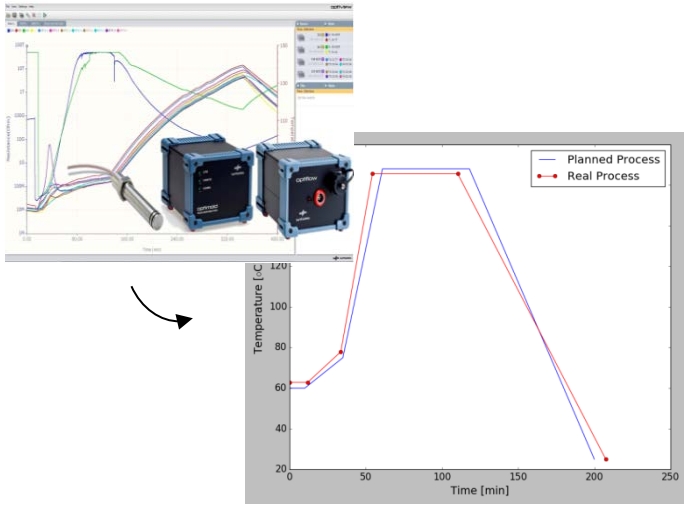


Surrogate modeling [Hein et al.]

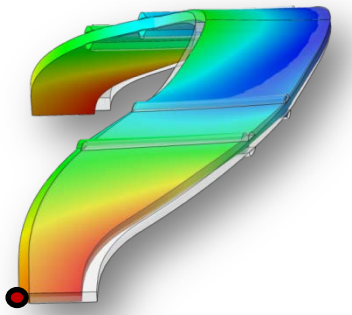
In-situ evaluation of process induced distortions

Industrial application (2. step, online)

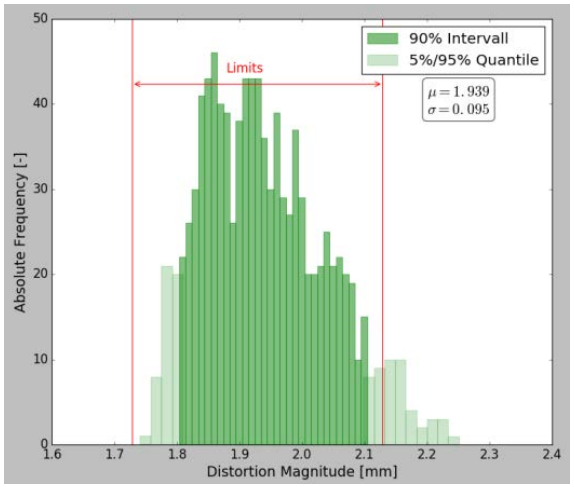
- In-situ feedback of sensor data (temperature) and model update
- In-situ distortion or stress analysis and evaluation wrt. requirements



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



Prediction of distortion or stress at time t_final



Tolerance check wrt. final process induced distortions

[Hein et al.]

Conclusion

Variety of monitoring and evaluation systems available and under development (suited for different materials, manufacturing processes, parameters)

Increasing acceptance and application through industrial demonstrations

Enabling

- Increased phenomenological understanding, efficient root cause analysis
- Early defect detection and enhanced NDI
- Enhanced tolerance management and process control
- Semi-automated feedback to structural analysis for enhanced evaluation

Impacts

- Fast ramp-up by less manufacturing trials
- Minimum cycle time and cost
- Reduced material and energy consumption as well as emissions
- Reduced concessions near to zero

Thank You

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