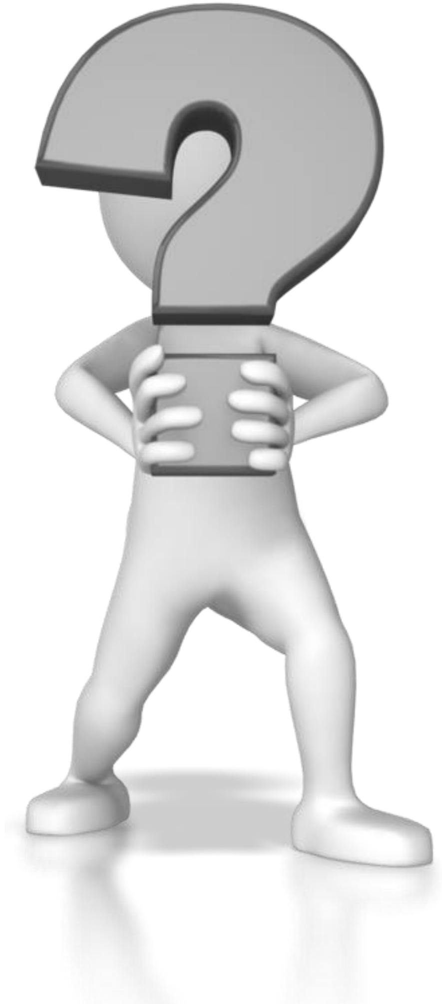
In-situ Evaluation of Laminates with Gaps and Overlaps – Uncertainties in Modelling and Analysis

Falk Heinecke, Tobias Wille
German Aerospace Center (DLR)

DLR

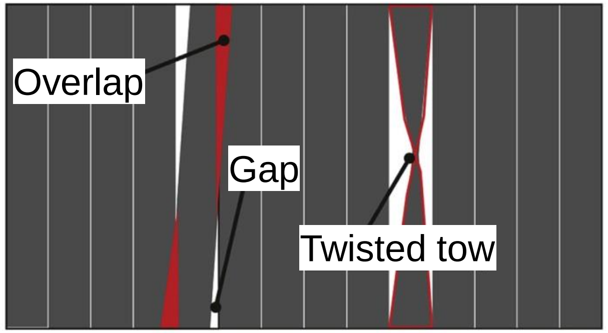
Preparing a Tiramisu



- Ingredients determine the quality of the Tiramisu
  - How to check whether the eggs are still consumable?

Manufacturing a laminate using Automated Fibre Placement (AFP)

- Typical manufacturing induced deviations:

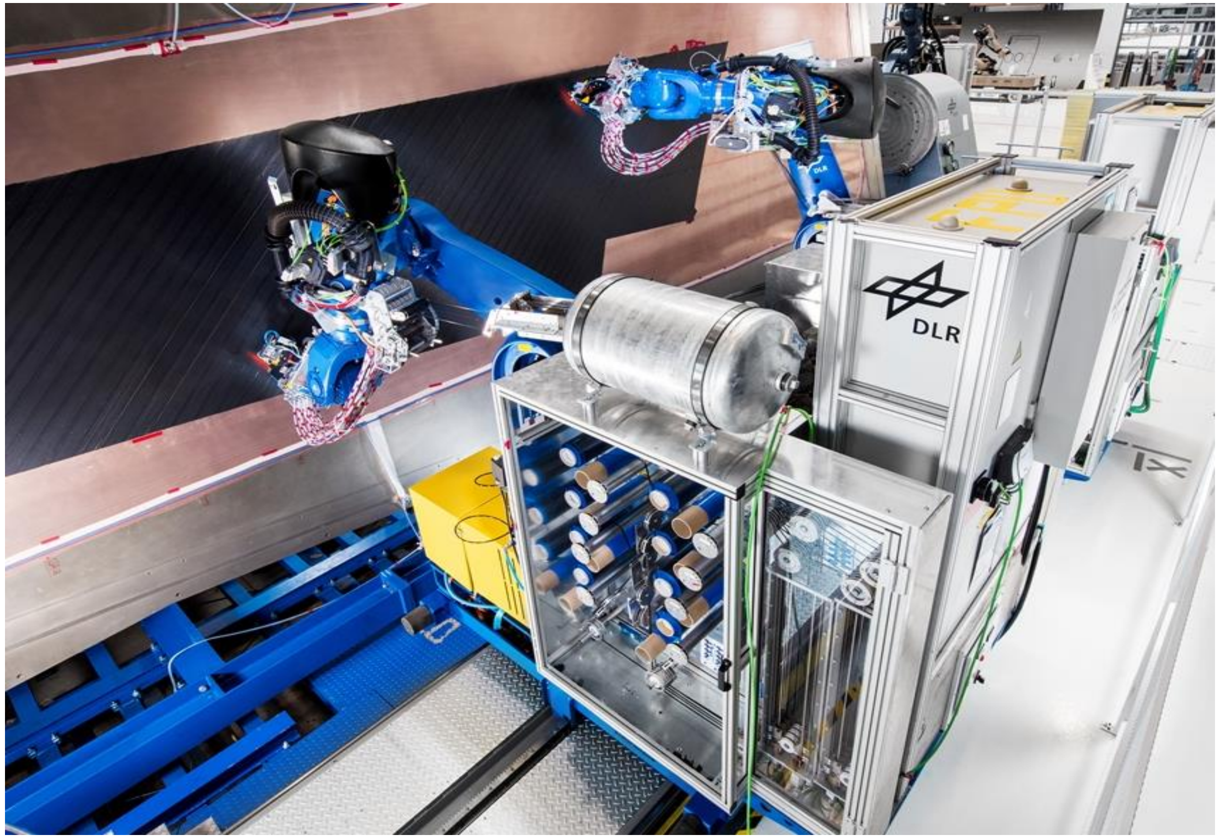


Source:[Denkena2016]

- AFP cycle time distribution:

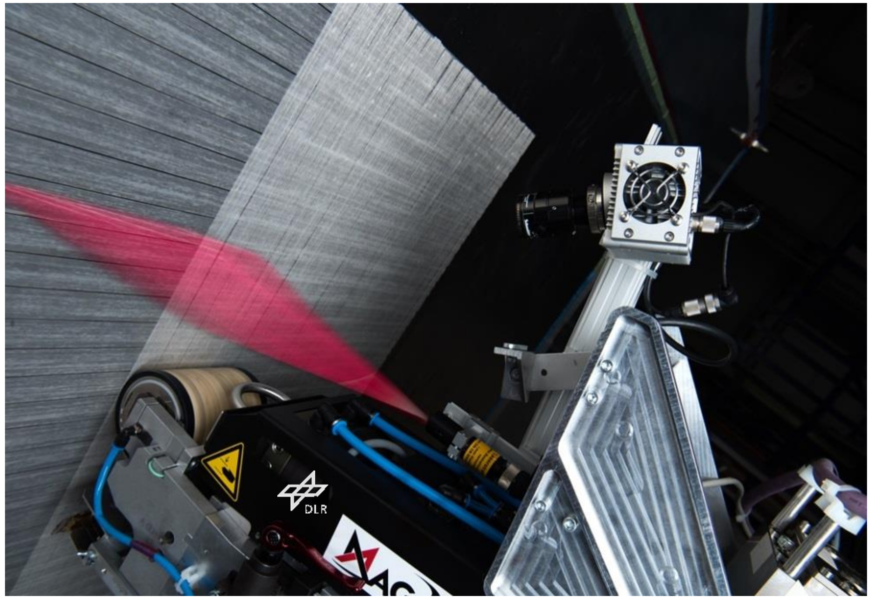
41% Inspection & rework
32% Layup
27% Anything else

Source: according to [Rudberg2014]



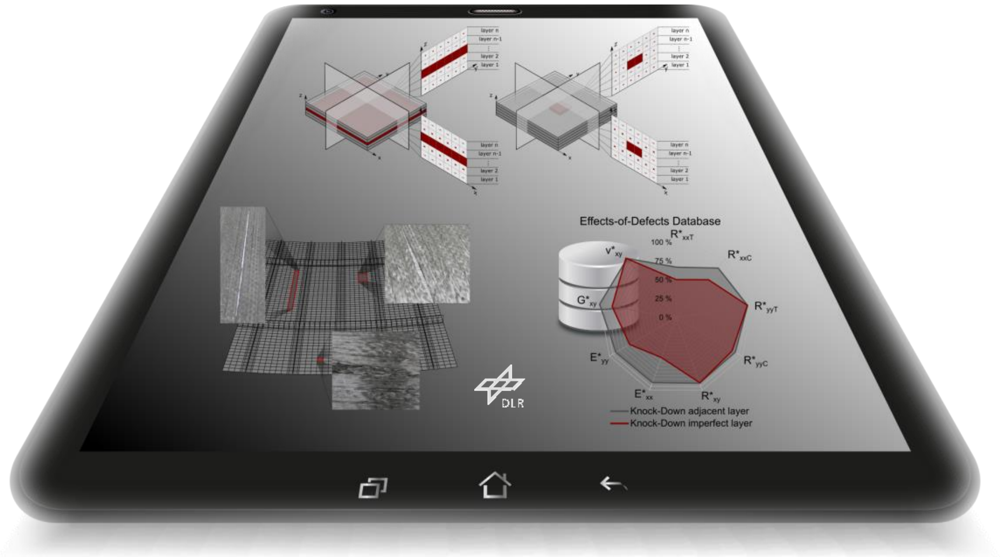
In-situ evaluation of laminates – The enablers

Online monitoring



- Realtime capable measurement systems and algorithms
  - Instead of manual inspection

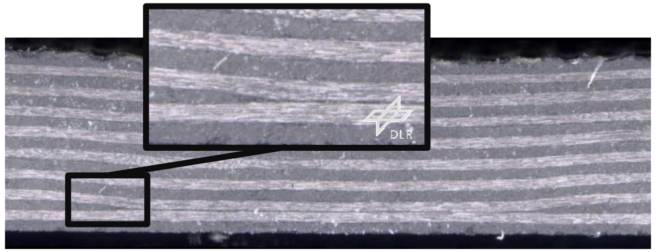
In-Situ evaluation and assessment tools



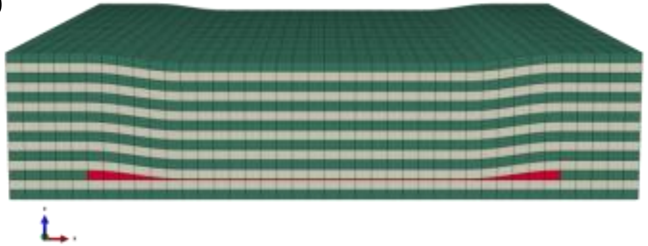
- Realtime capable evaluation systems and algorithms
  - Instead of conservative composite engineering requirements/ allowables

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

In-situ evaluation of laminates – Uncertainty factors

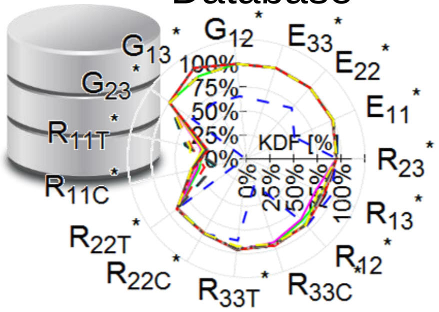


Transfer from Reality to Model



Transfer from Model to KDF

Effects-of-Defects Database

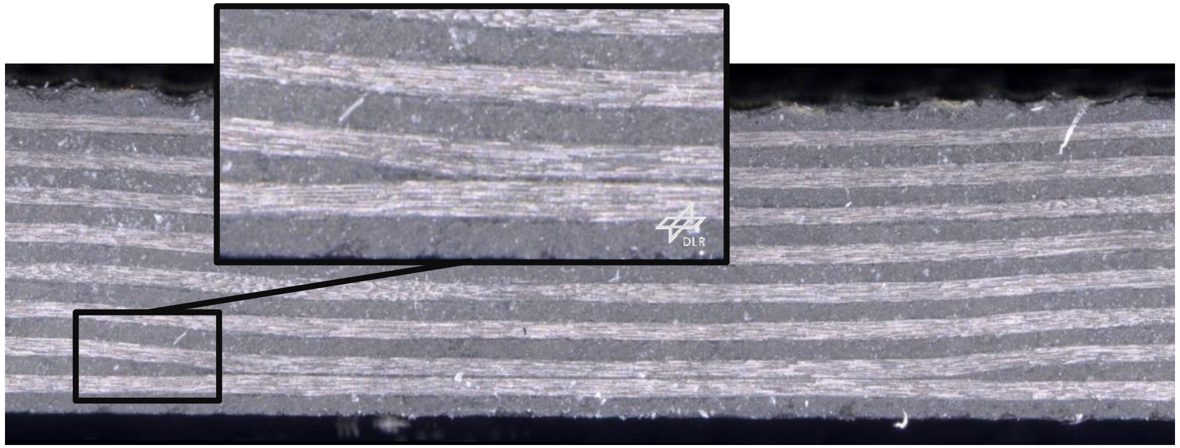


- From Reality to Phenomenology:
  - Which simplifications are valid?
  - Which assumptions are valid?

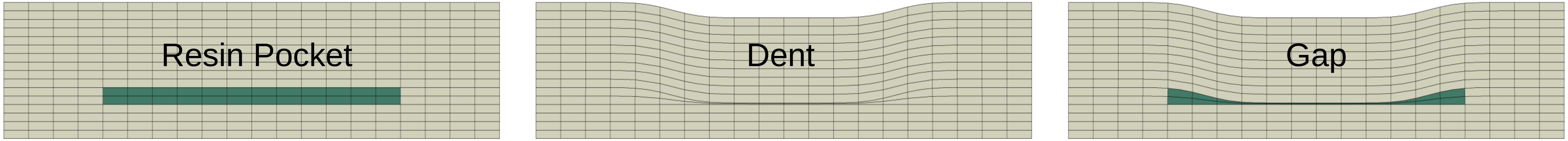
- From Phenomenology to Modelling:
  - Which boundary conditions to use in model?
  - Which failure criterion to use in model?
  - How to transfer the high-fidelity result into a simple Knock-Down-Factor (KDF)?

Transferring „real“ world into model world – From Reality to Phenomenology

- What happens after fibre deposition?
  - Influence of subsequent manufacturing process steps [Hassan2017,Belnoue2017]



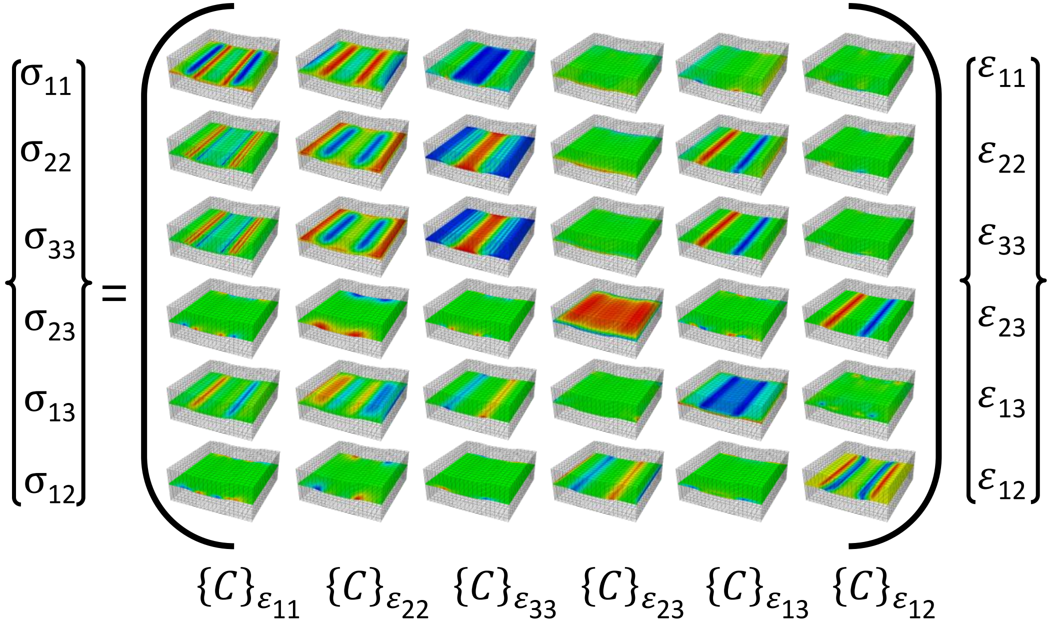
- Which geometry characteristics are relevant?
  - Influence of modelling approaches (e.g. Defect Layer Method [Fayazbakhsh2013])



Transferring „real“ world into model world – From Phenomenology to Modelling

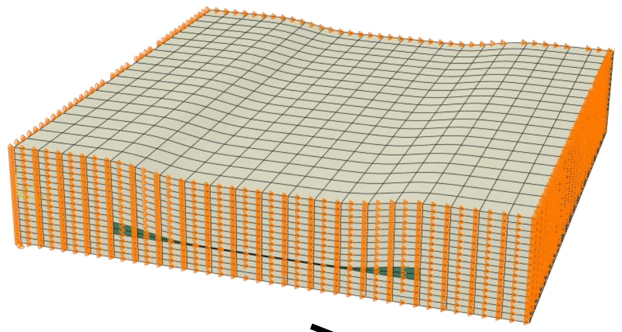
Stiffness Homogenization

- Classical boundary value problem
- Volume-averaging stresses and strains



Strength Homogenization

- Material effort (M) calculated from failure criterion
- Evaluation of local stresses (no averaging)



$$KDF_{E11} = \frac{E_{11}^{defective}}{E_{11}^{pristine}}, \ldots \qquad KDF_{R_{11}} = \frac{M_{R_{11}}^{defective}}{M_{R_{11}}^{pristine}}, \ldots$$

Stiffness Homogenization – From Phenomenology to Modelling

- Homogeneous displacement BC's ("plane-remains-plane" [Xia2006]) used for numerical homogenization (FE-Model)

Engineering Constants	**Resin Pocket (KDF)**			**Dent (KDF)**			**Gap (KDF)**		
	Reuss-Model	FE-Model	Voigt-Model	Reuss-Model	FE-Model	Voigt-Model	Reuss-Model	FE-Model	Voigt-Model
E_x	23%	98%	98%	27%	96%	102%	26%	95%	101%
E_y	21%	81%	81%	24%	87%	92%	23%	80%	85%
E_z	74%	96%	97%	79%	95%	100%	77%	93%	99%
G_{xy}	25%	98%	98%	31%	98%	104%	28%	98%	103%
G_{xz}	92%	95%	111%	102%	102%	122%	99%	99%	122%
G_{yz}	88%	92%	105%	98%	96%	113%	94%	93%	110%
ν_{xy}	50%	120%	120%	30%	112%	104%	38%	119%	119%
ν_{xz}	122%	92%	92%	129%	99%	122%	126%	96%	98%
ν_{yz}	124%	100%	100%	130%	99%	113%	128%	99%	99%

Voigt-Model (iso-strain)

$$[C_{lm}]^V = \sum_{i=1}^{n} v_i [C_{lm}]^i$$

Reuss-Model (iso-stress)

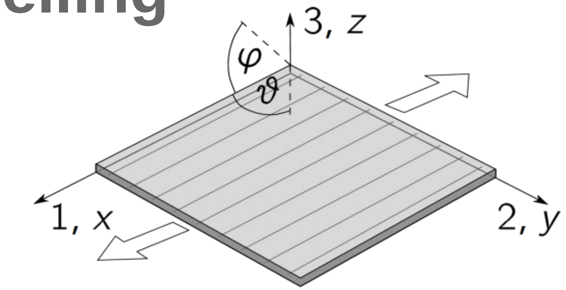
$$[C_{lm}]^R = \left[\sum_{i=1}^{n} v_i [S_{lm}]^i\right]^{-1}$$

Stiffness Homogenization – The essence

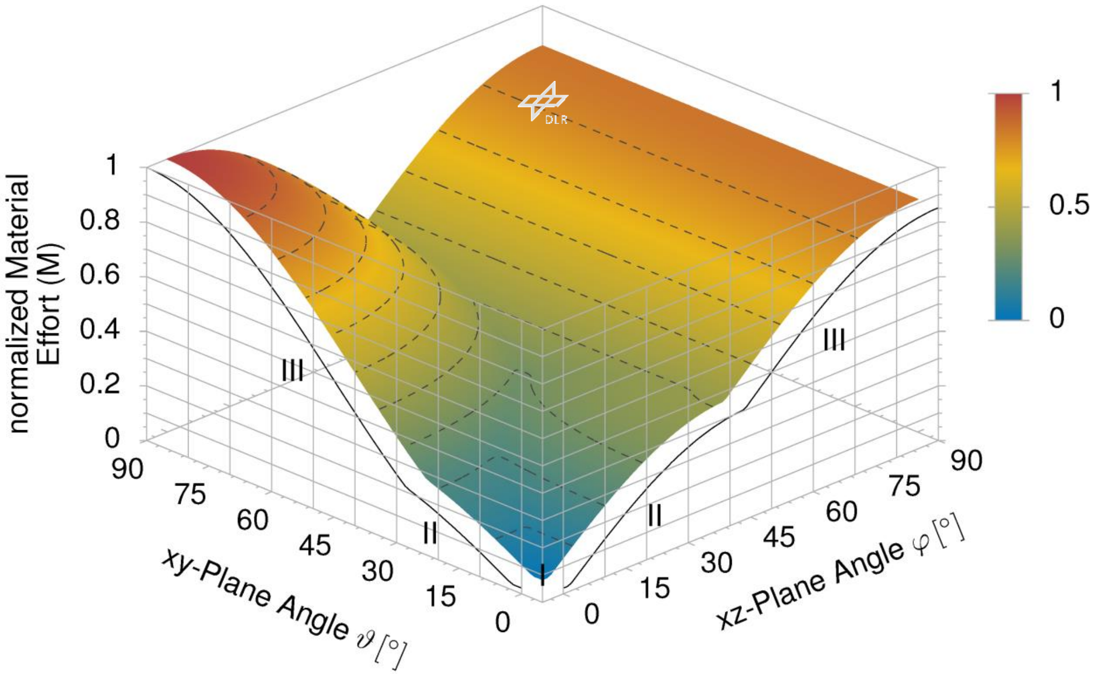
- Negligible influence from modelling approach…
  - …Depending on modelling approach – Maximum 8% Variation in Results

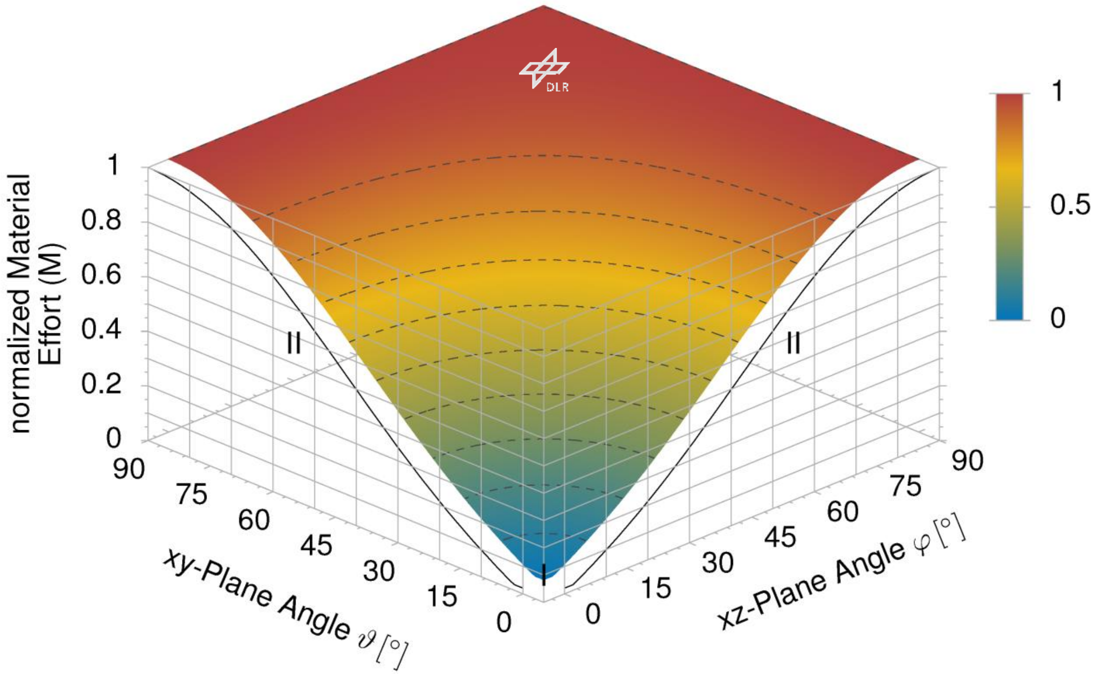
- Homogeneous displacement boundary conditions provide “iso-strain-like” results…
  - …in contrast to periodic displacement boundary conditions or stress boundary conditions [Glüge2013]

Homogenization of Strength – From Phenomenology to Modelling

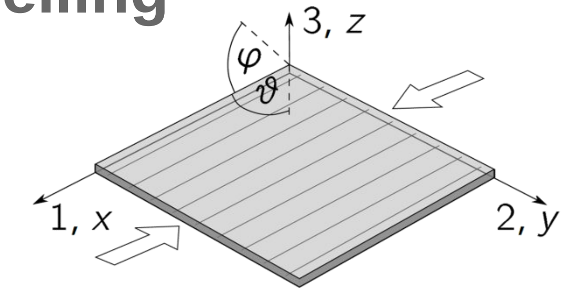


- Strength properties: Pre-preg Hexply IM7/8552
- Uniaxial tensile stress – Limit Stress versus Puck 3D
- Failure mode switches – I: Fibre fracture; II & III: Interfibre fracture

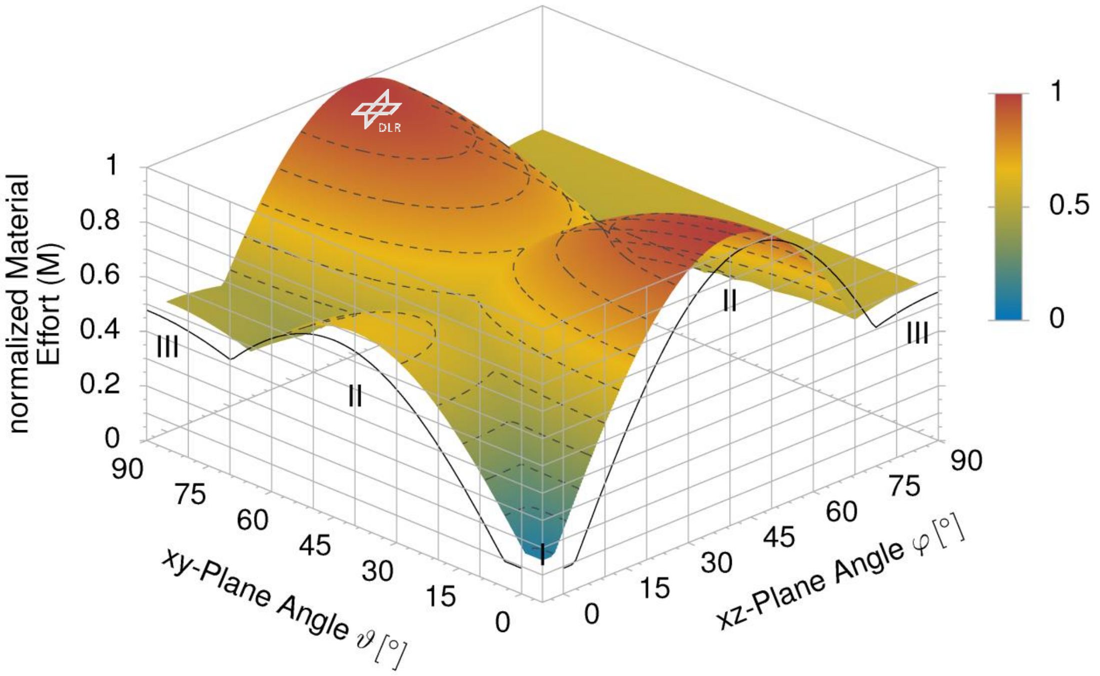


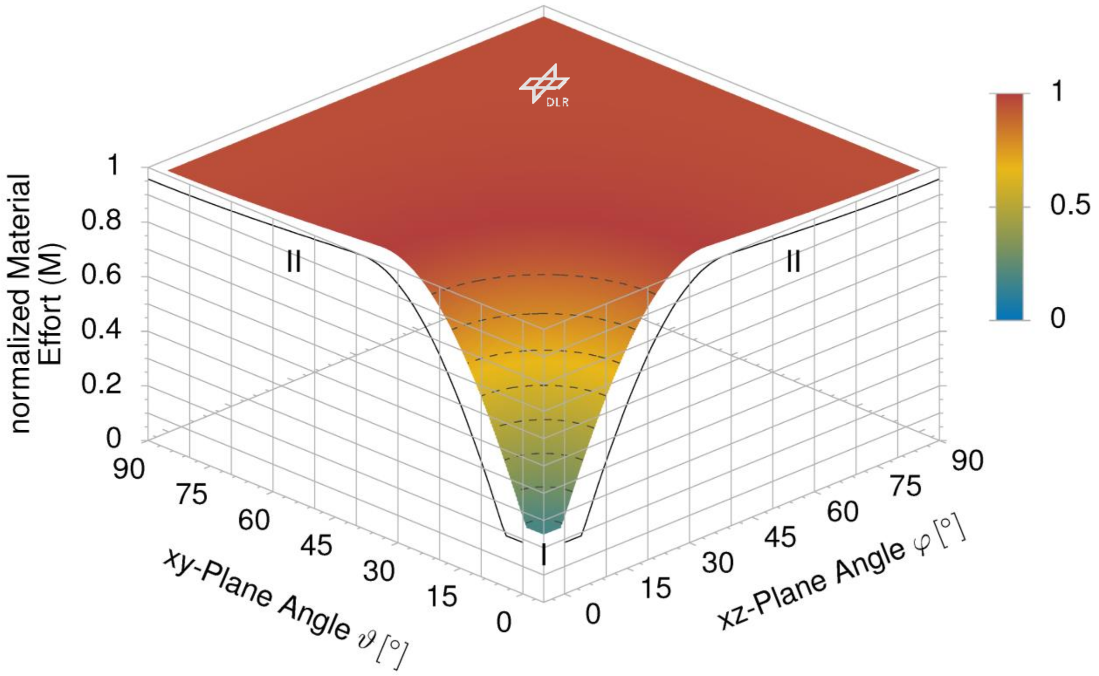


Homogenization of Strength – From Phenomenology to Modelling



- Strength properties: Pre-preg Hexply IM7/8552
- Uniaxial compression stress – Limit Stress versus Puck 3D
- Failure mode switches – I: Fibre fracture; II & III: Interfibre fracture





Homogenization of Strength – Laminate failure

- Linear static analysis combined with First-Ply-Failure approach used to compare pristine failure versus defective failure

Strength	**Resin Pocket (KDF)**				**Dent (KDF)**				**Gap (KDF)**			
	Homog. BC's		In-Plane BC's		Homog. BC's		In-Plane BC's		Homog. BC's		In-Plane BC's	
	Limit Stress	Puck	Limit Stress	Puck	Limit Stress	Puck	Limit Stress	Puck	Limit Stress	Puck	Limit Stress	Puck
R_{11T}	93%	98%	91%	99%	84%	84%	58%	50%	95%	84%	94%	52%
R_{11C}	99%	99%	94%	76%	92%	92%	46%	49%	91%	91%	45%	48%
R_{22T}	83%	83%	75%	78%	86%	86%	79%	84%	81%	81%	70%	77%
R_{22C}	83%	92%	79%	78%	88%	88%	76%	76%	82%	82%	79%	79%
R_{33T}	92%	92%	92%	92%	93%	93%	93%	93%	92%	92%	92%	92%
R_{33C}	92%	70%	92%	70%	93%	91%	93%	76%	92%	63%	92%	63%
R_{12}	90%	90%	90%	90%	97%	97%	94%	87%	88%	87%	88%	85%
R_{13}	85%	84%	80%	78%	70%	70%	74%	73%	90%	86%	87%	82%
R_{23}	84%	83%	83%	82%	94%	89%	94%	89%	89%	85%	88%	88%

Strength Homogenization – The essence

- Depending on combination of modelling approach and boundary conditions…
  - …Significant influence from failure criterion – Up to 20% Variation in Results
  - …Significant influence from boundary conditions – Over 30% Variation in Results

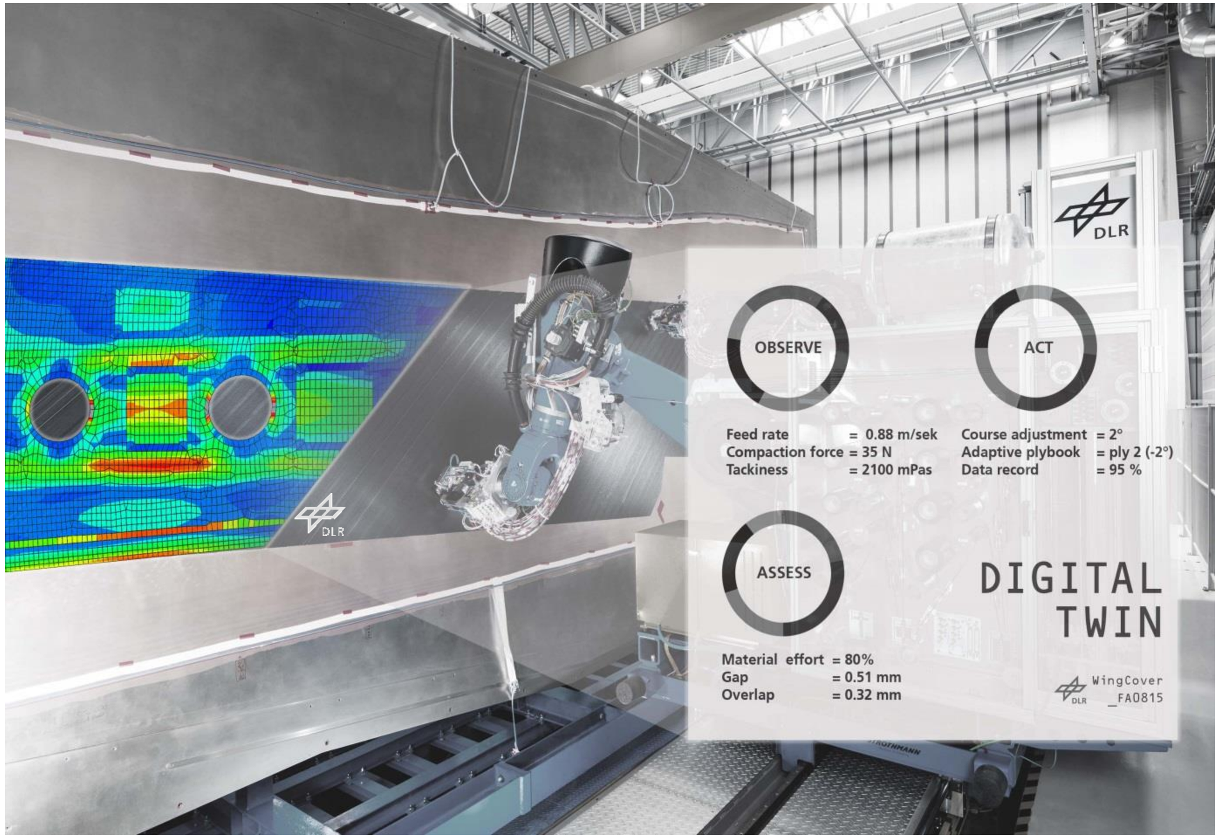
- Significant influence from modelling approach
  - Fibre undulation is failure driving [Garnich2005, Hsaio1996]

Key messages

- Reasonable choice of a model:
  - Accuracy versus complexity – Not because it is always done this way

- Don’t struggle with uncertainties
  - They are everyway – Try to identify their sources and influence

- In-situ evaluation of laminates means also effectiveness:
  - The adequate model to accomplish the purpose



Questions and comments are very welcome!

“What makes modelling and scientific inquiry in general so painful is uncertainty. Uncertainty is not an accident of the scientific method, but its substance.”

A. Saltelli

Contact:

Falk Heinecke
Phone: +49 531-295-2312
Email: falk.heinecke@dlr.de

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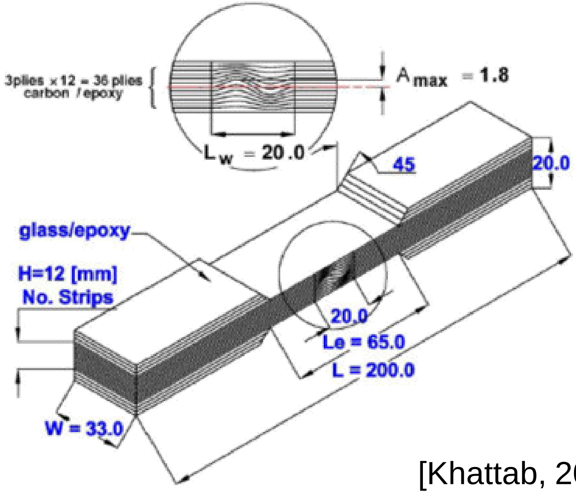
Backup

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)

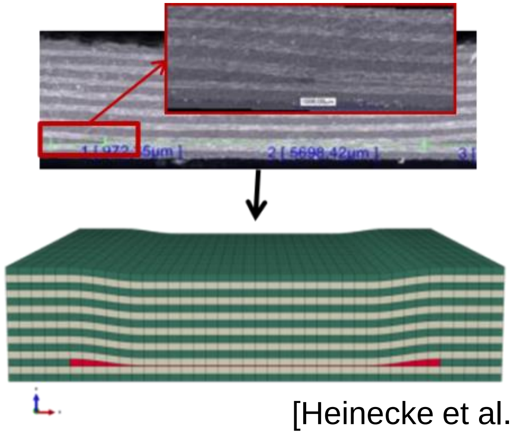


[Khattab, 2013]

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

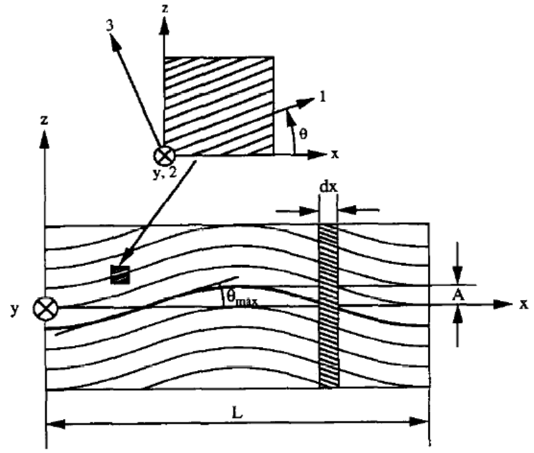


[Heinecke et al., 2018]

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

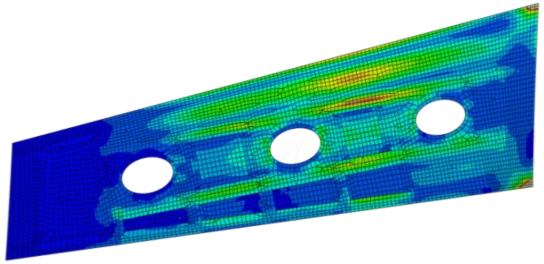


[Hsiao and Daniel, 1996]

In-situ evaluation of laminates – In a nutshell

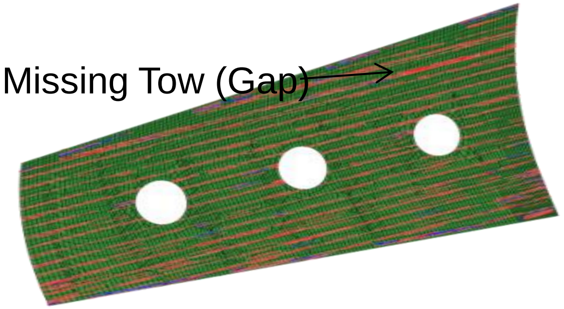
- **Demonstration on Wing Cover [Heinecke2018]:**

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)