TOWARDS A DIGITAL TWIN FOR THE ASSESSMENT OF MANUFACTURING EFFECTS ON THE STRUCTURAL PERFORMANCE OF AIRCRAFT STRUCTURES MADE FROM AUTOMATED FIBER PLACEMENT

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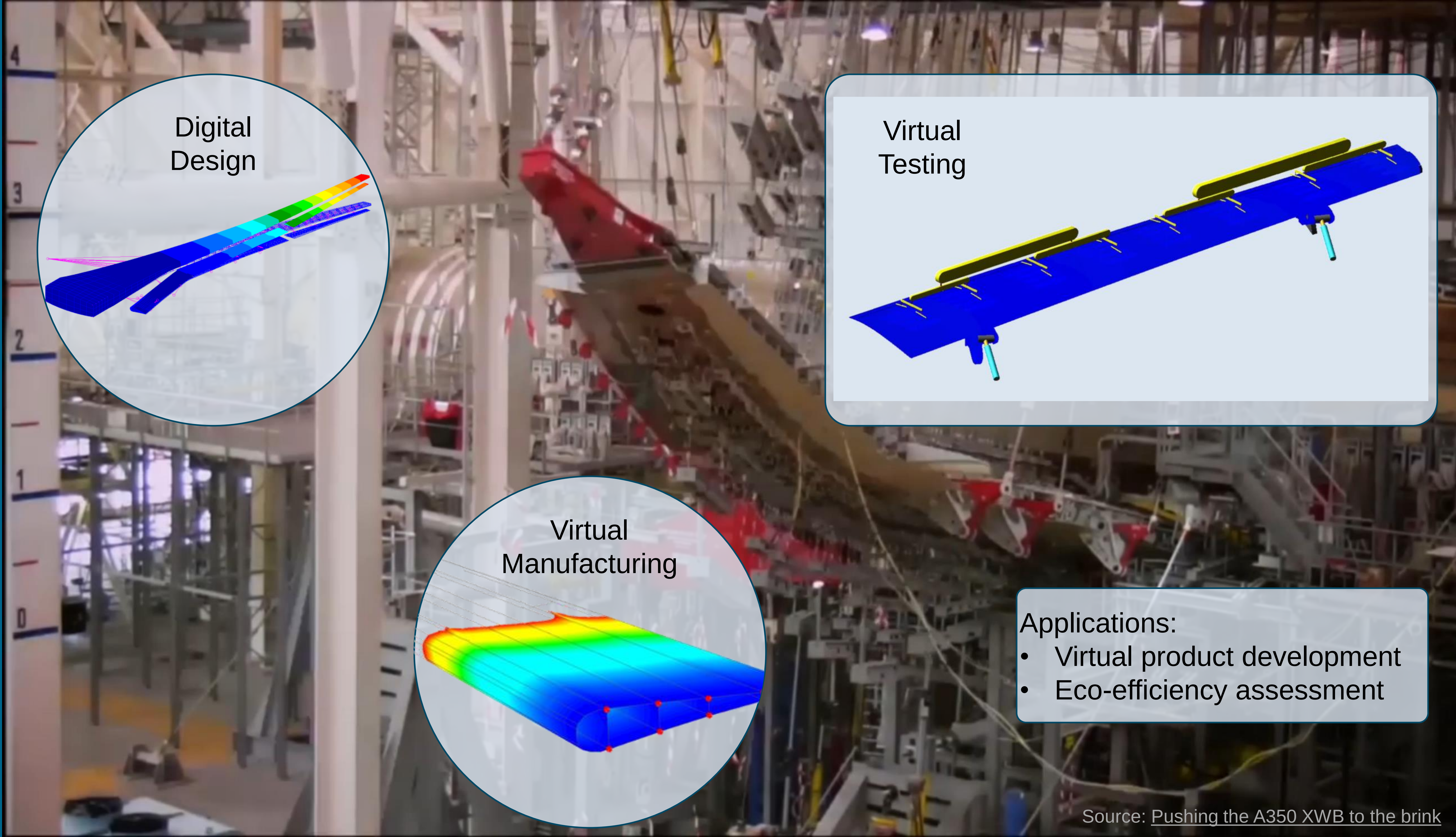
Imagine…

Source: Pushing the A350 XWB to the brink

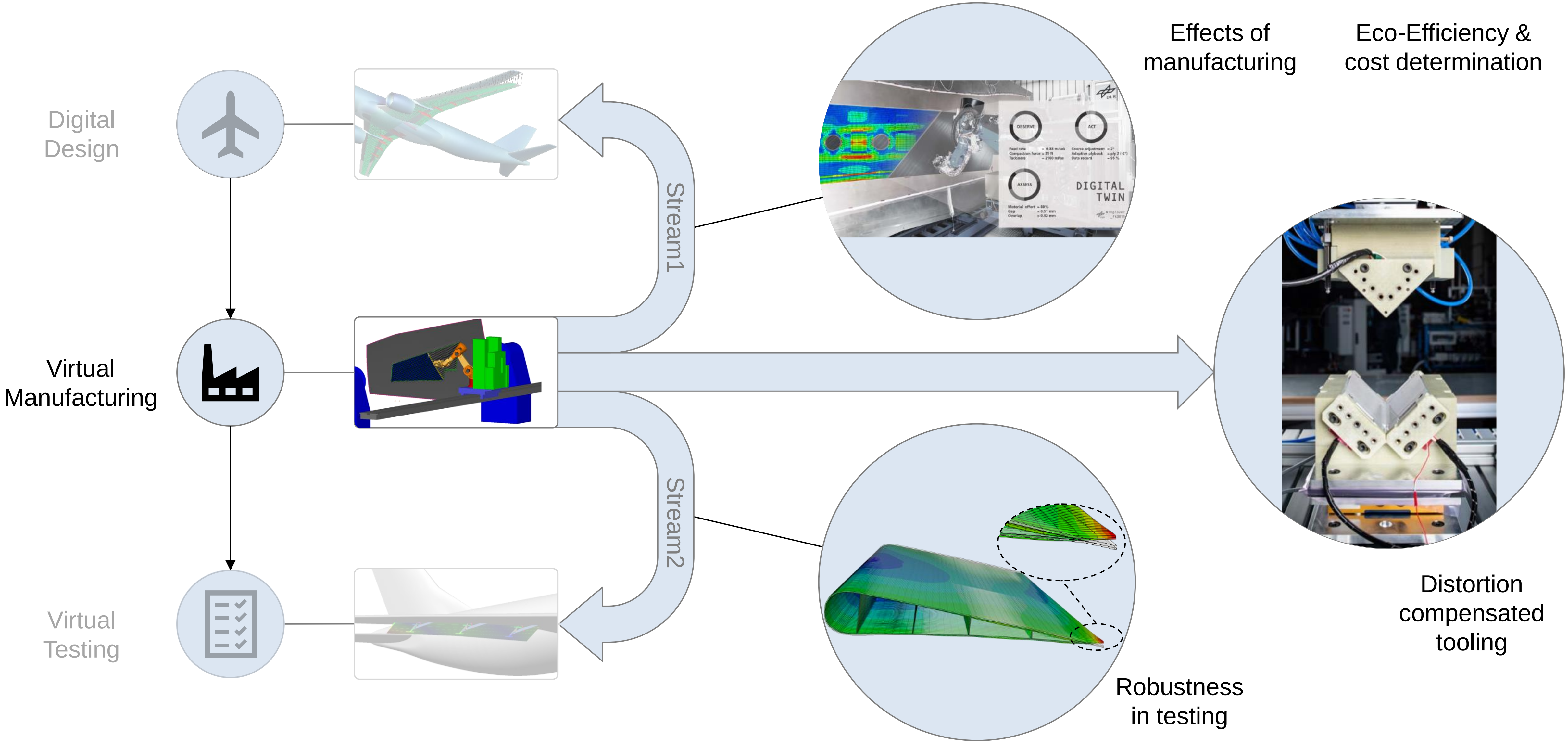


Applications:
- Virtual product development
- Eco-efficiency assessment

Source: Pushing the A350 XWB to the brink


DLR Virtual Product House @ HB
www.dlr.de/vph
Inputs
Digital Design
Virtual Manufacturing
Virtual Testing
Virtual Certification
As designed
As built
As tested
Common Source
Software Engineering

Virtual Manufacturing
Potentials



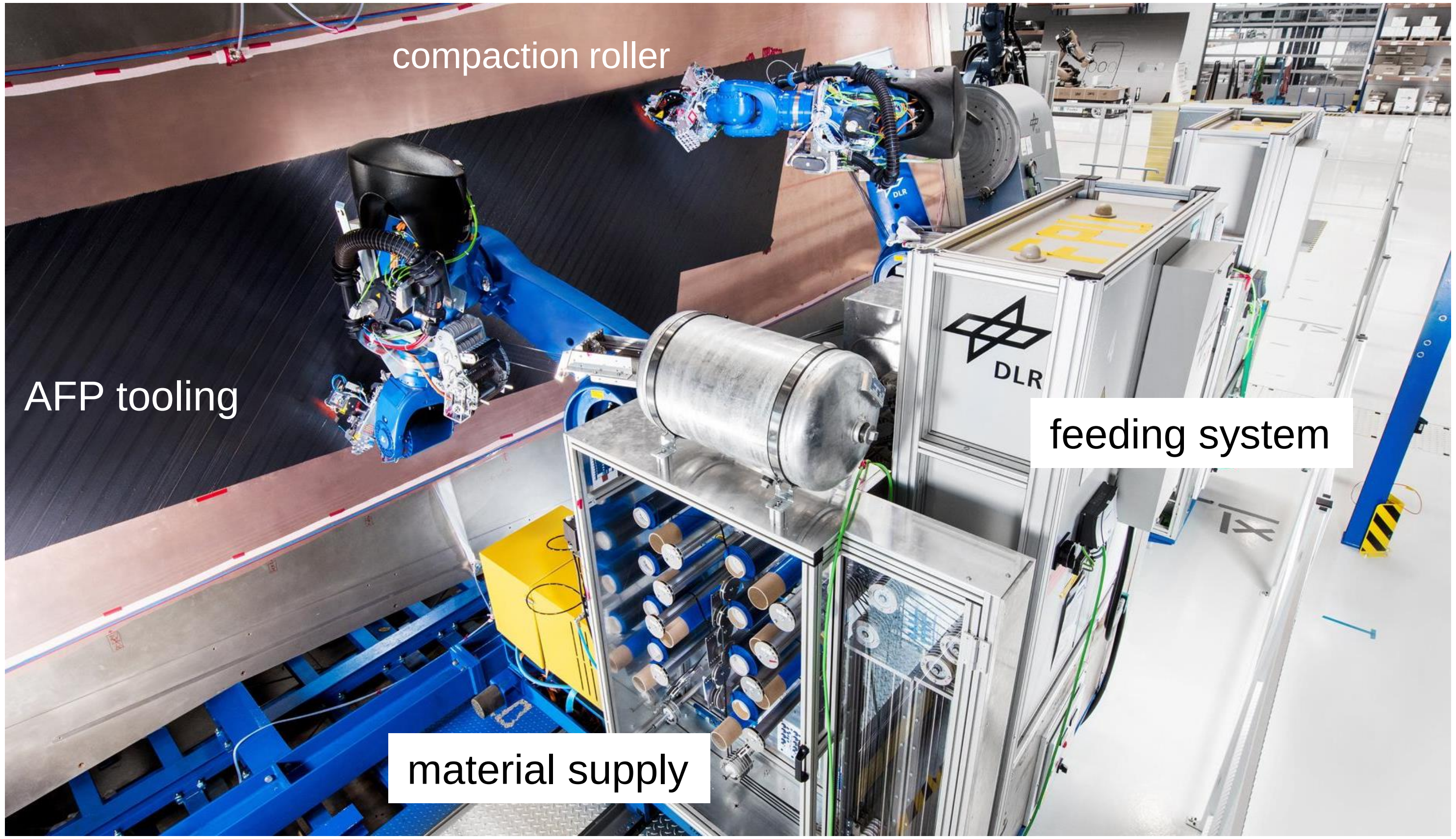
AFP-Manufacturing

- Automated Fibre Placement (AFP) process aims to produce large aicraft structure like wing skins

- Placement of „tows“ layer per layer

- complex process favor different types of manufacturing effects

How to handle/ predict the structural behaviour in presence of such effects?



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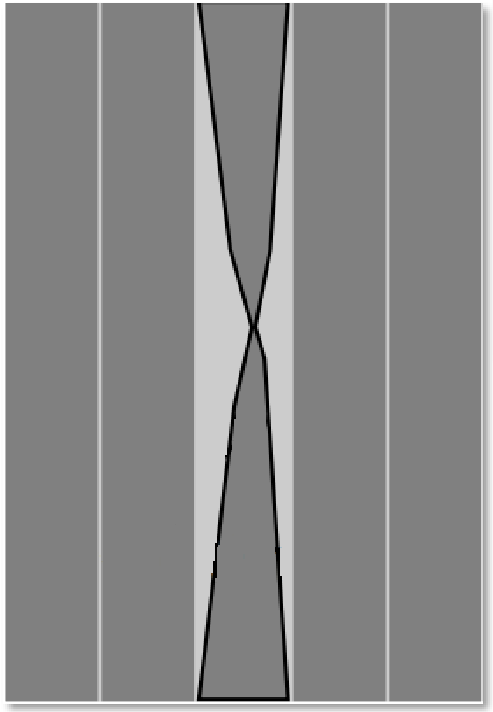
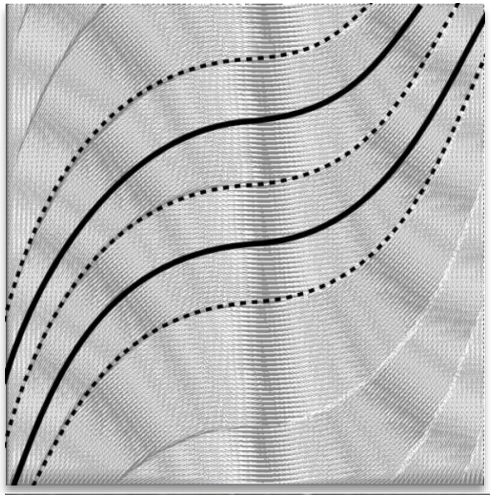
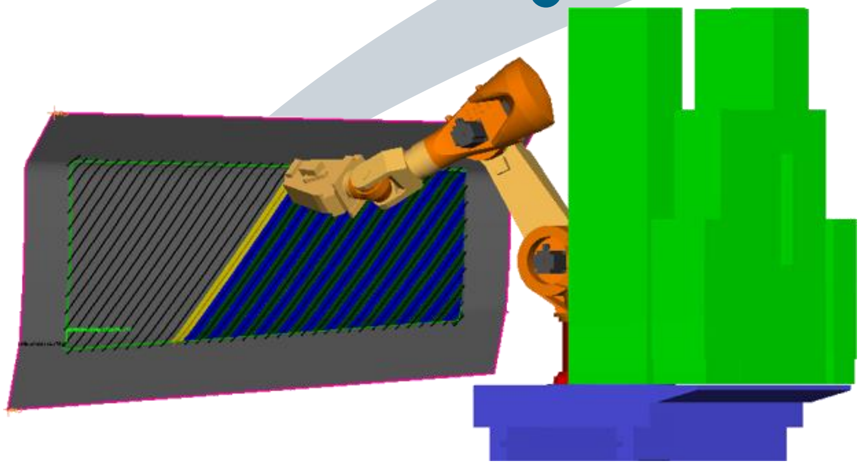


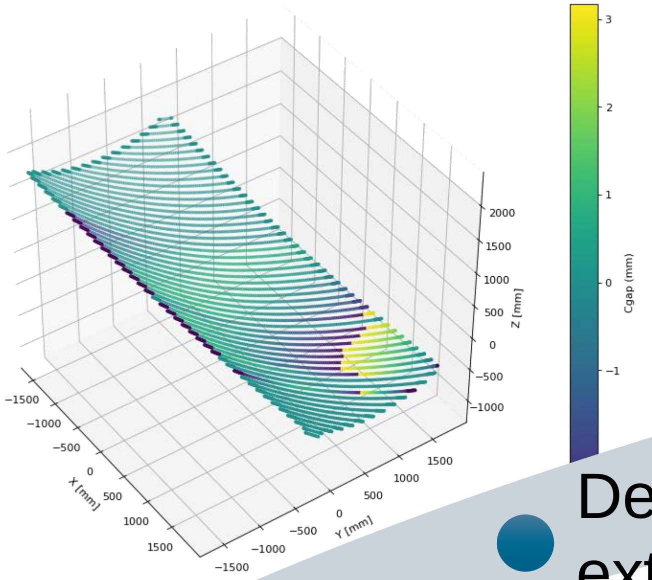


courtesy of the NLR

Evaluation approach

AFP Simulation





Defect geometry extraction


```
"defectConfigurations": [
    {
        "type": "gap",
        "subtype": "straight",
        "shape": {
            "width": 3.171627,
            "length": 26.5889
        },
        "material": "R_8551-7",
        "affectedPlies": [
            1
        ],
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    },
```
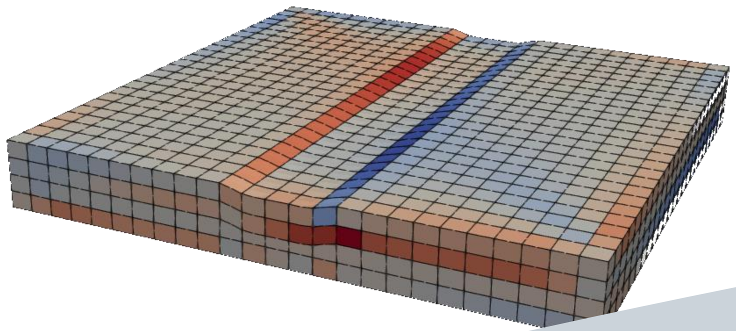
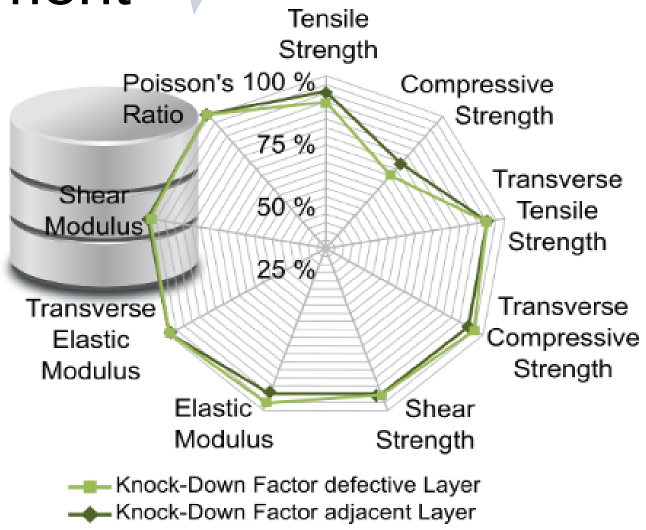
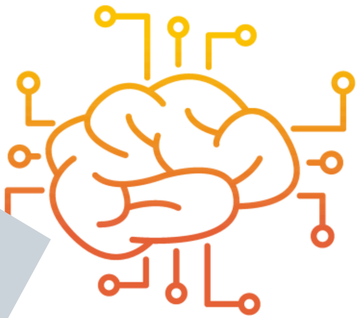




Numerical defect assessment

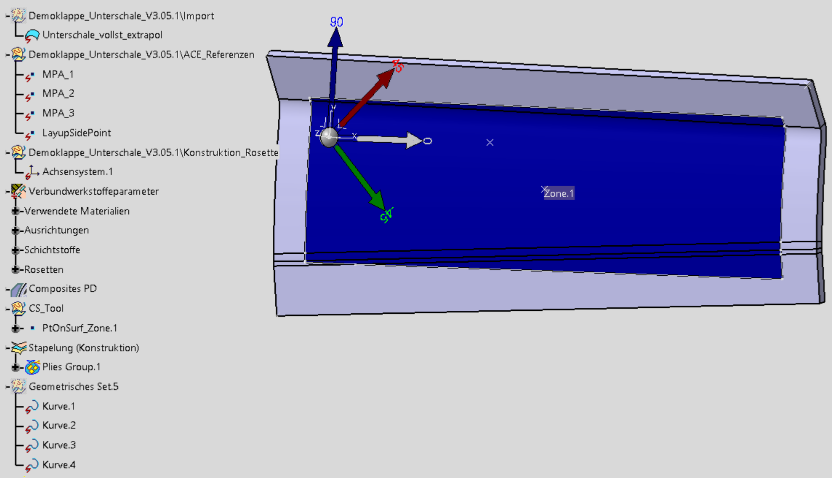




Virtual AFP-Process

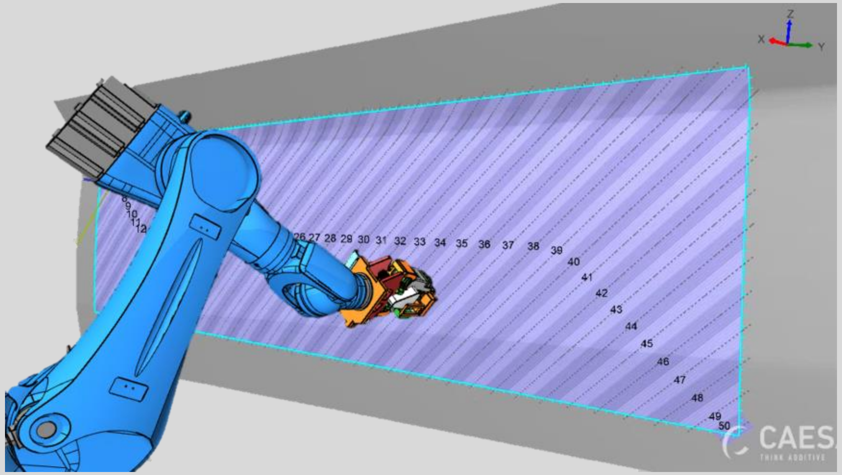
Information chain

CAD



- Mold | Part Geometry
- Laminate Design | Stacking
- Ply Contours
- References

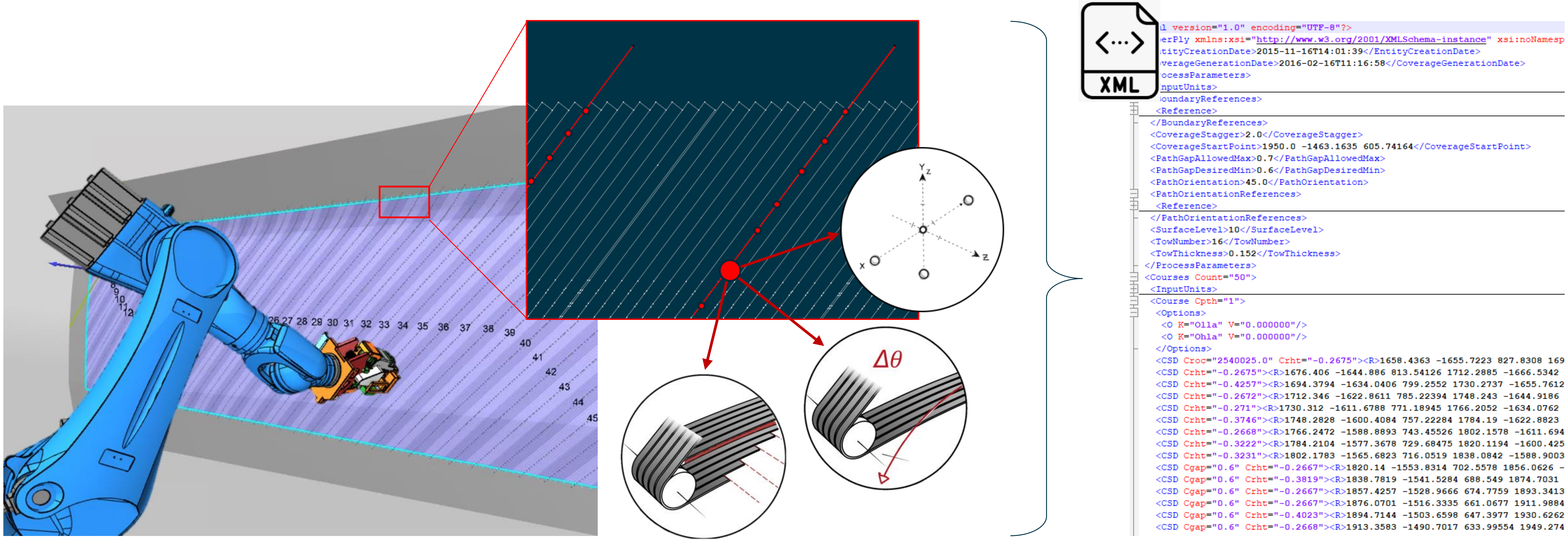
CAM | Offline Programmierumgebung



- Layup- & Process-Parameters
- Layup Pathes
- Coverage Analysis
- Post Processing

Export

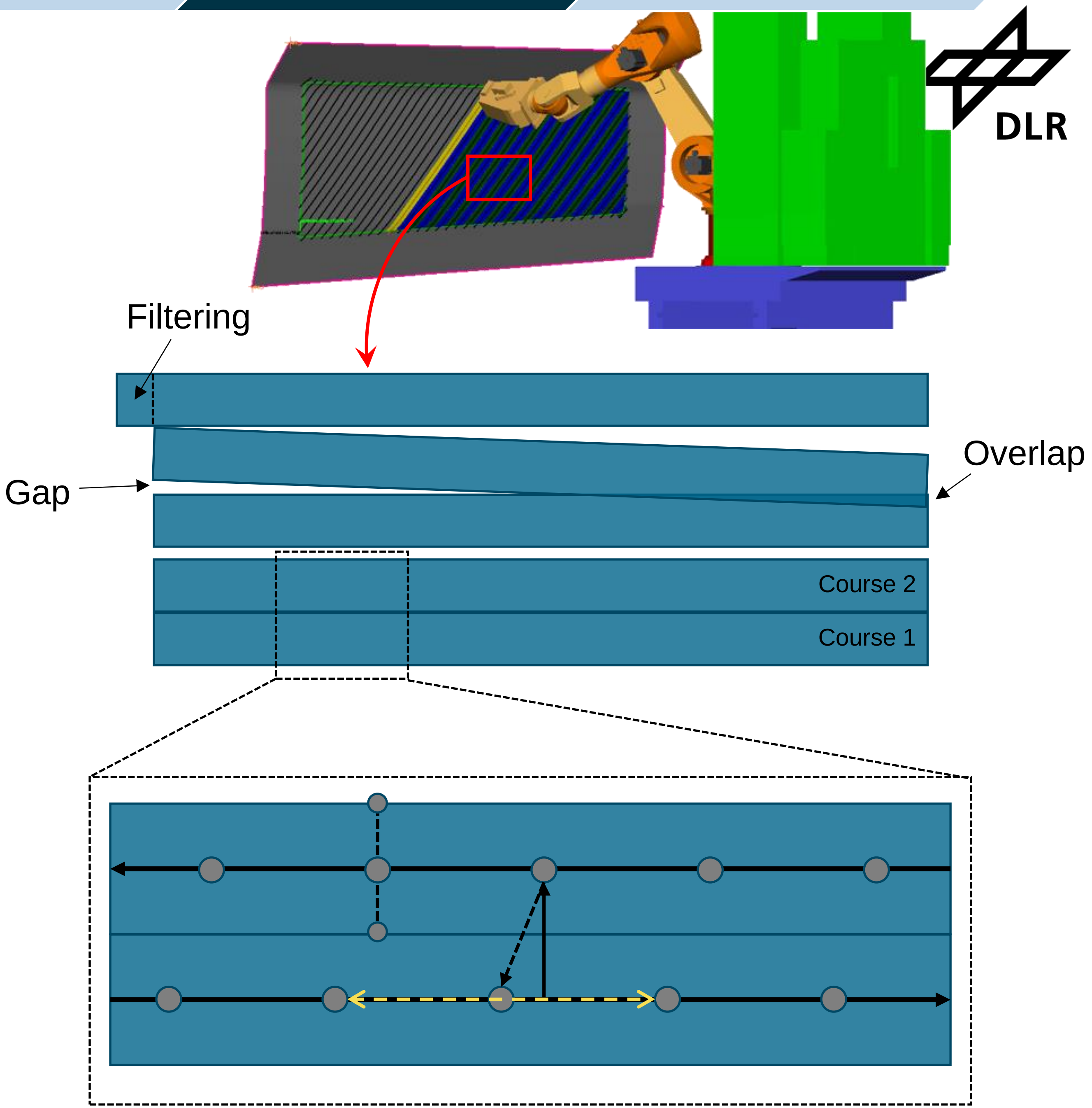
Virtual AFP-Process



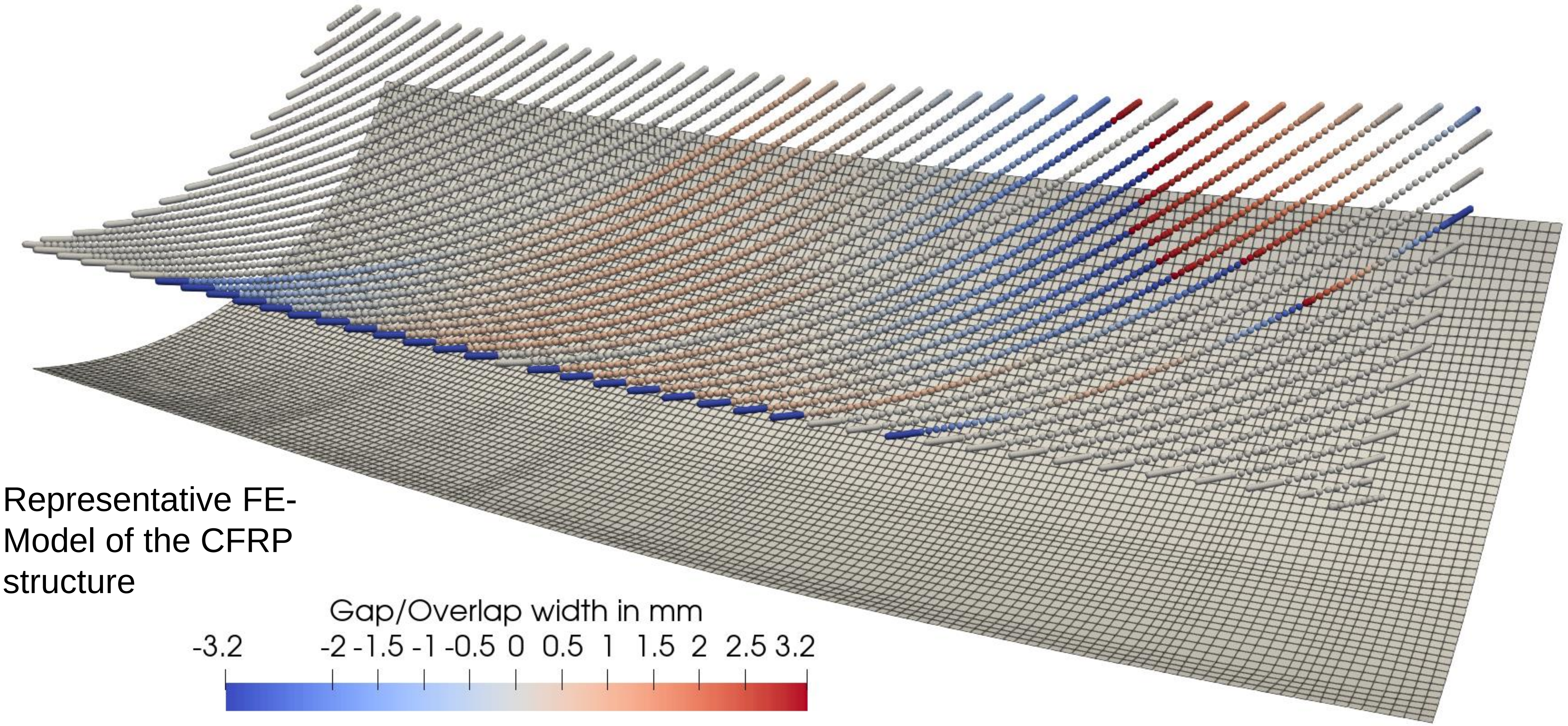
- **Centerline Geometry:** centerline coordinates of each material path
- **Local fiber orientation:** pointwise deviations of the deposited fiber angle from the nominal layup
- **Steering radius:** local steering radius at every point along the path
- **Edge geometry:** pointwise coordinates of both material edges corresponding to each centerline location

Defect geometry extraction

- ACES simulation output read as .xml
- Retrieve discretized course points, directions and normal
- Remove out of bounds areas
- Identify nearest point on last course
- Find orthogonal and calculate distance
- Compare with allowed tolerances
- Extract defect information

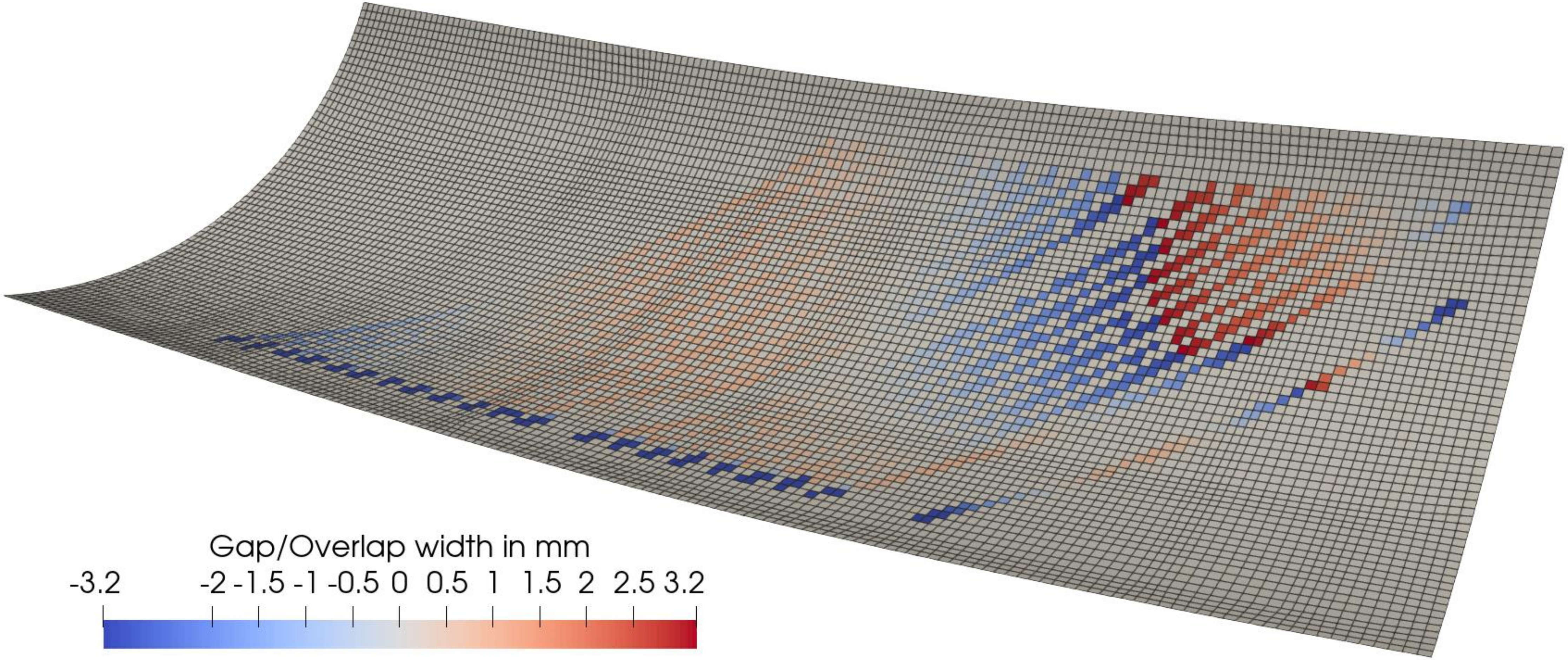


Mapping of defect data to structural model



Representative FE-Model of the CFRP structure

Mapping of defect data to structural model



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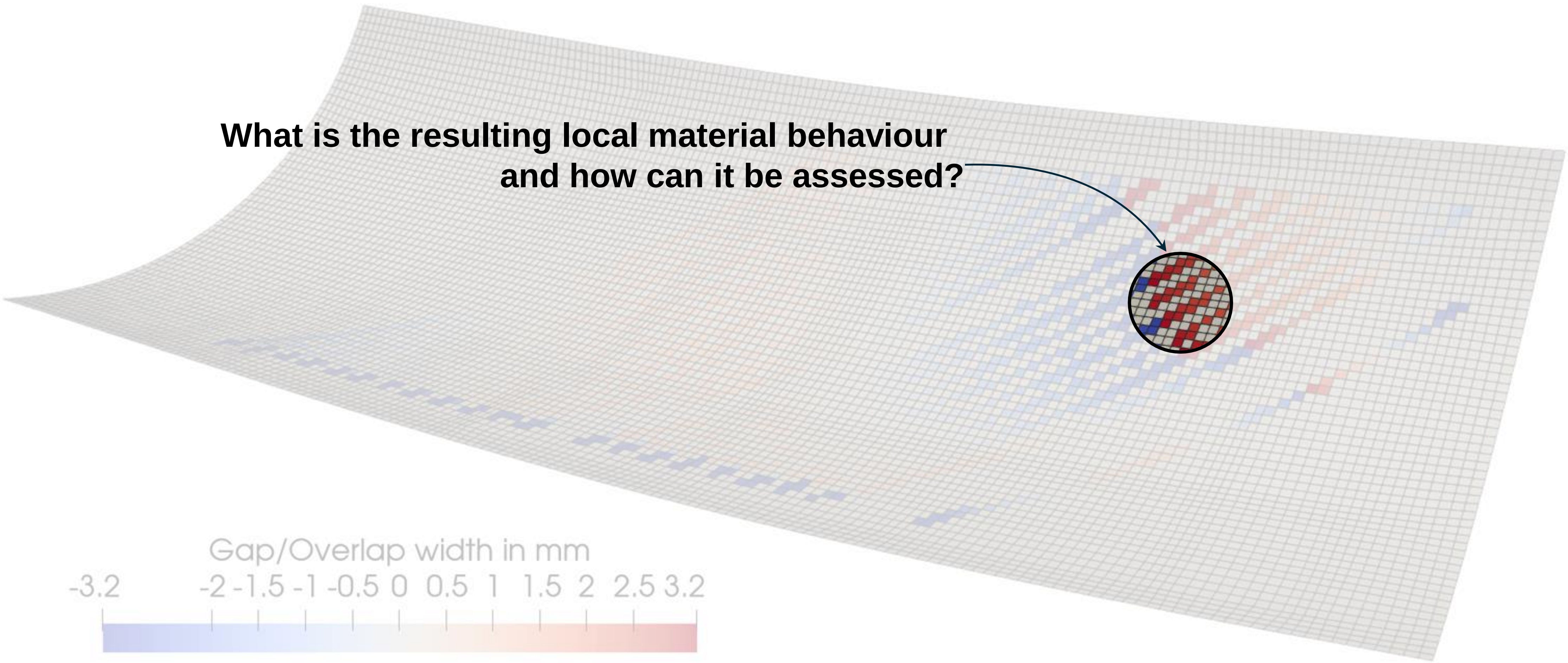
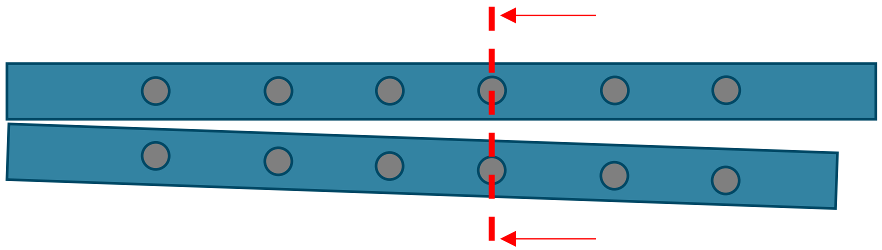


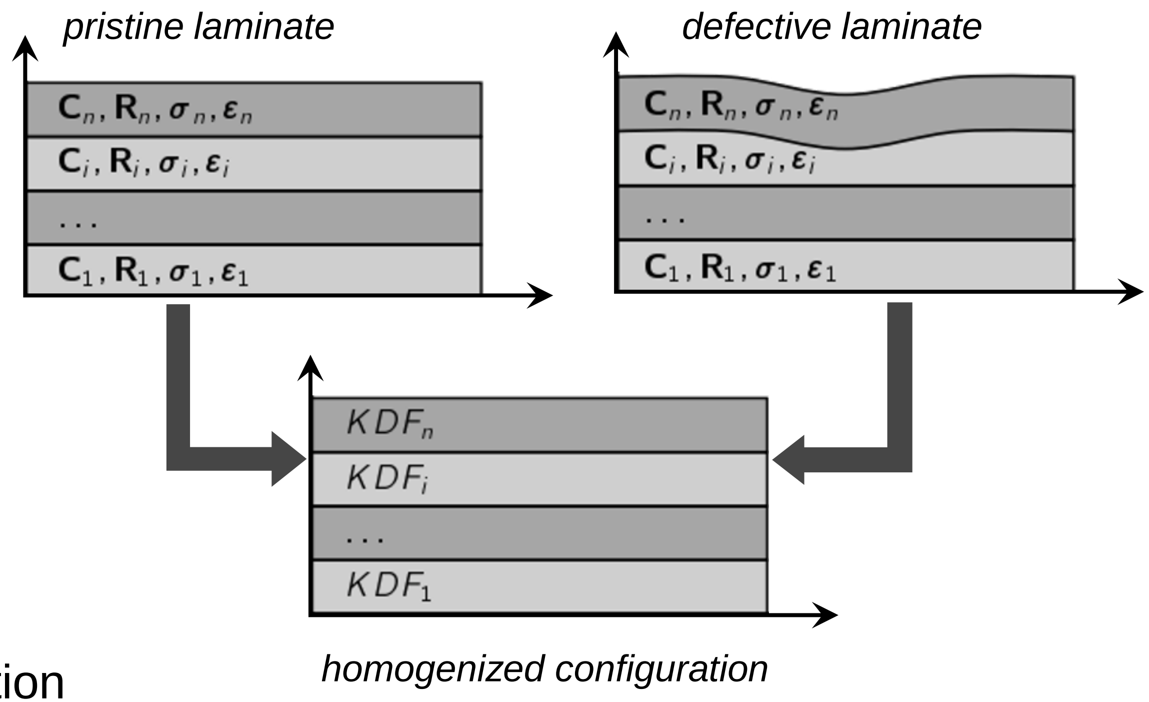
Numerical defect assessment



- appropriate methods for strength and stiffness determination needed
- observation: imperfections often affect not only one layer but also neighboring layers (e.g. through stress localization)

analytical vs. numerical

accuracy issues ⟷ *time-consuming*



Presented approach :

- assessment of material degradation based on homogenization approach
- use of parametrized 3D-FE-models for determination of so-called „**K**nock-**d**own **f**actors“ (KDF)
- models on the mesoscale (laminate) level provide the homogenized structural response from boundary conditions applied on the macroscale (structural level)

Numerical defect assessment
Strength assessment

- Linear-elastic material model
- effect of defects estimated using elaborated failure criteria

$$f(\sigma, \boldsymbol{R}) = FI$$

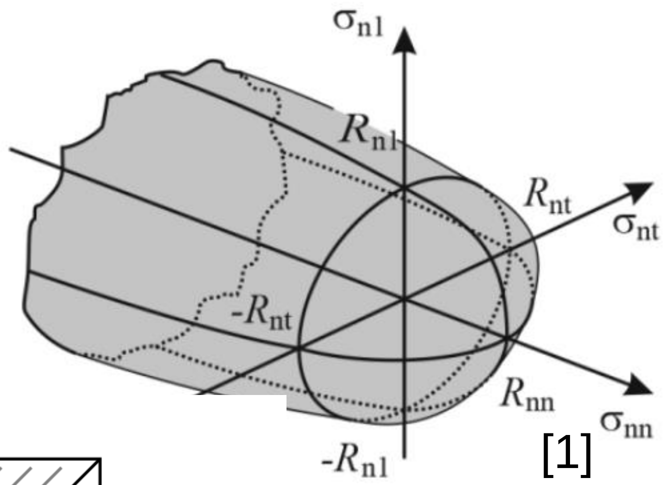
FI … Versagensindex
σ … Spannungszustand
$\boldsymbol{R}$ … nominelle Festigkeit

- in case of $FI = 1$ → damage initiation
- For each stress vector there is a scalar $f_R(\sigma)$:

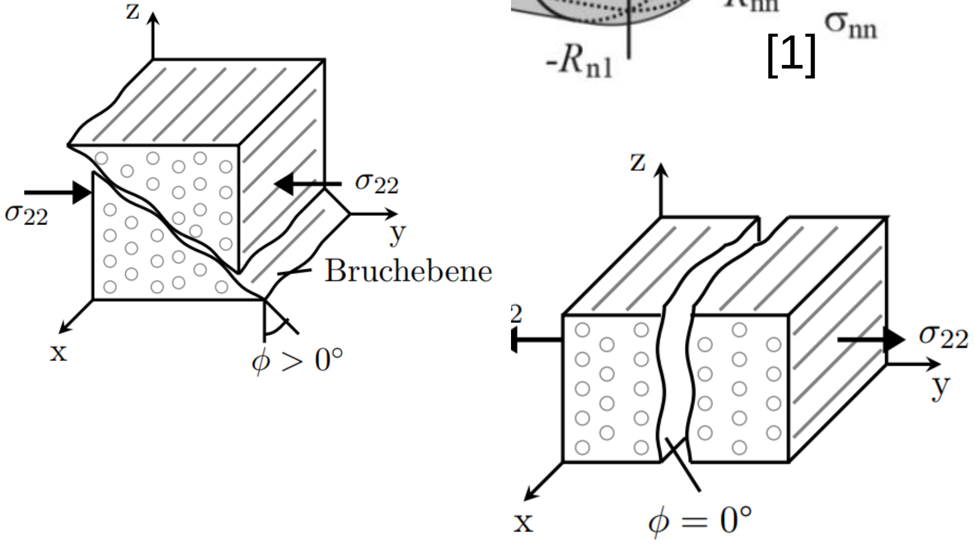
$$f(f_R(\sigma), \sigma, \boldsymbol{R}) = 1$$

- Due to $f_R(\sigma) = \infty$ for $\sigma = 0$, inverse $M = \frac{1}{f_R(\sigma)}$ is used
- Layerwise estimation of KDF:

$$\boldsymbol{KDF_i} = \frac{\boldsymbol{M_i^{ref}}}{\boldsymbol{M_i^{def}}} = \frac{\boldsymbol{f_R^{def}(\sigma_i)}}{\boldsymbol{f_R^{ref}(\sigma_i)}}$$



[1]

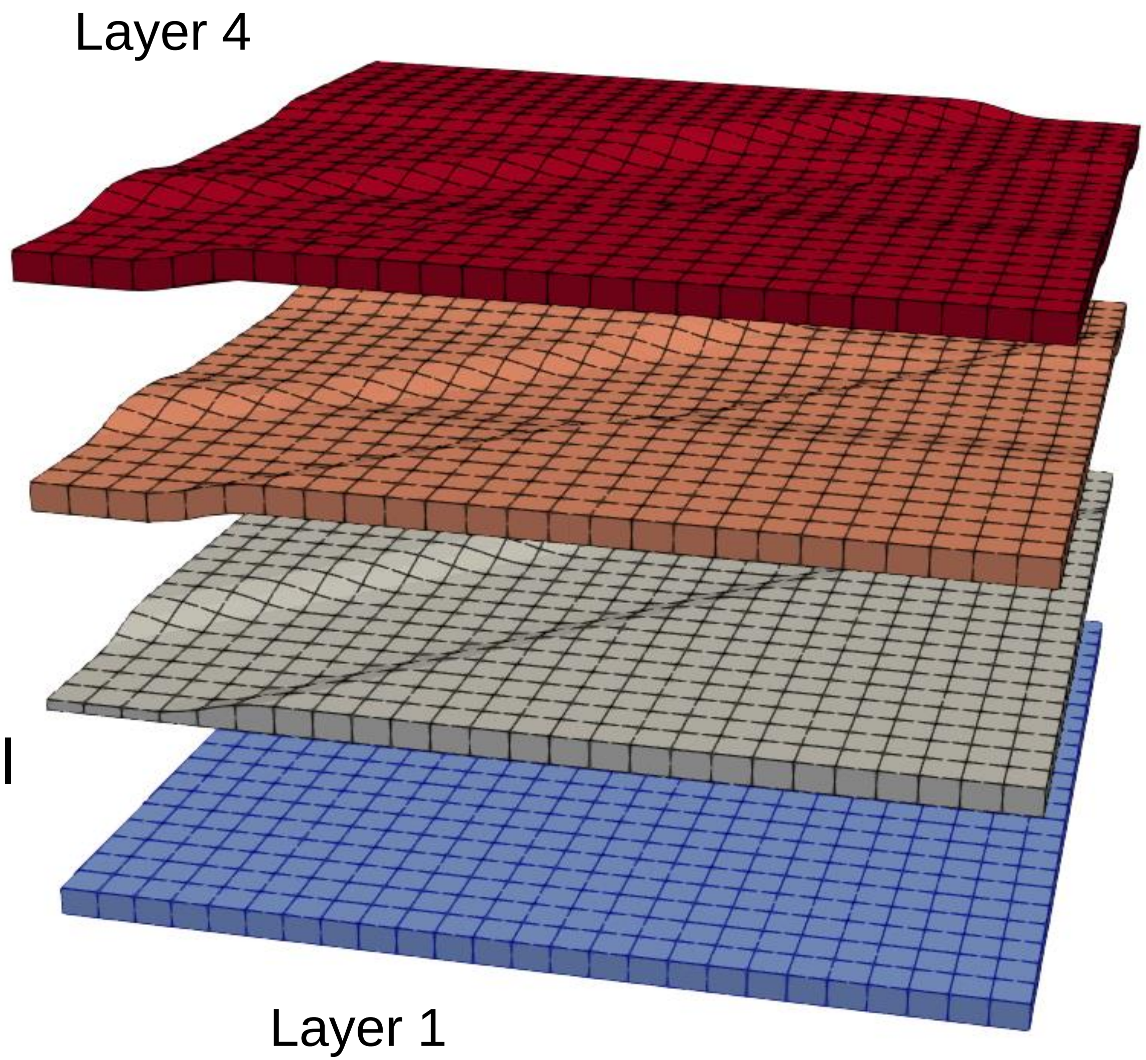


[1] Findeisen et.al: USER'S MANUAL OF PUCK ANALYSIS TOOL, IWM Report V1195/2022

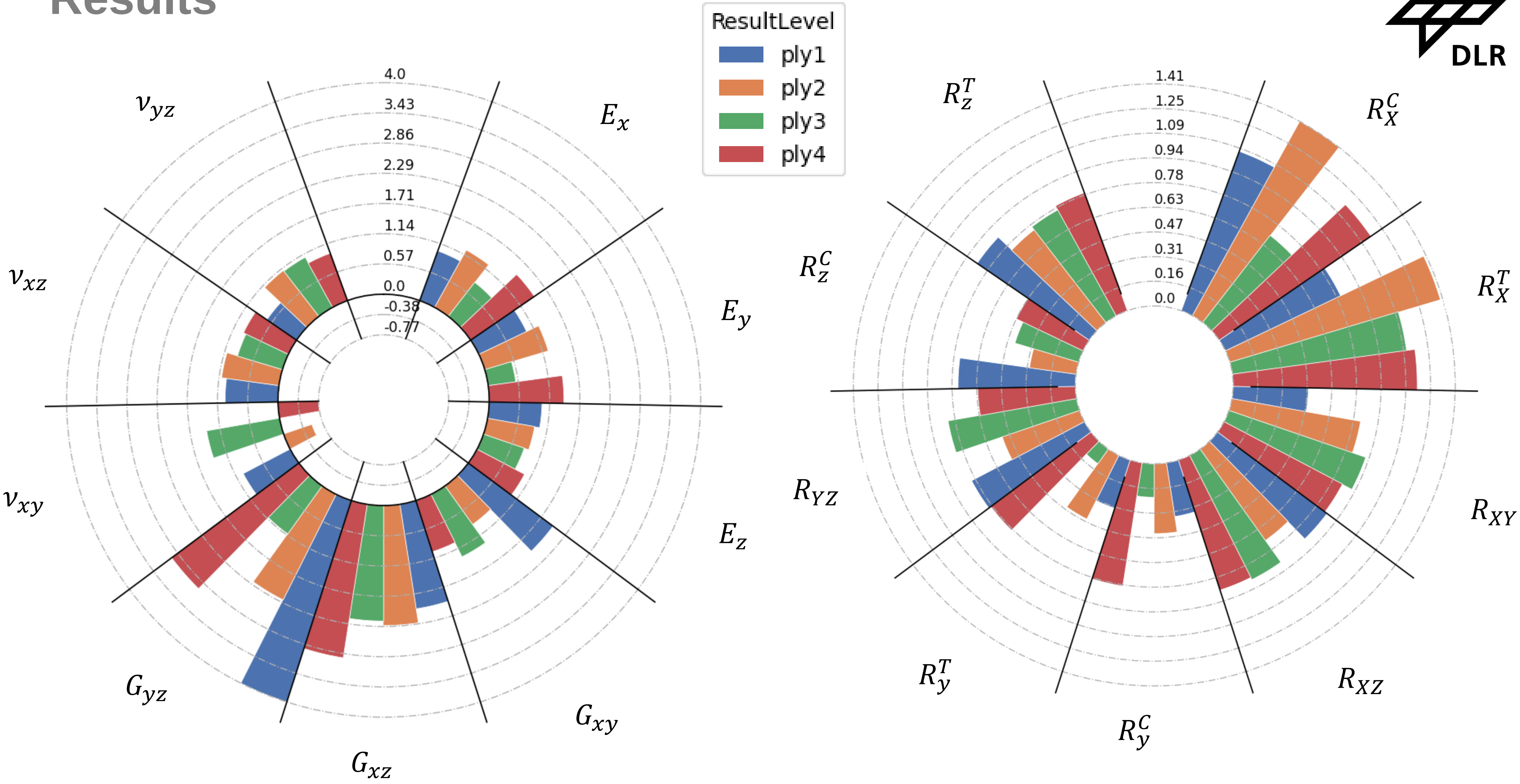
Results
Model description

- UD-Material: IM7/8551-7
- Layer orientations:
  [0°, 45°, 90° , -45 °]
- Layer thickness: 0.3 mm
- Quadratic ansatz function in FE-Model
- Puck criterion used as strength assessment function

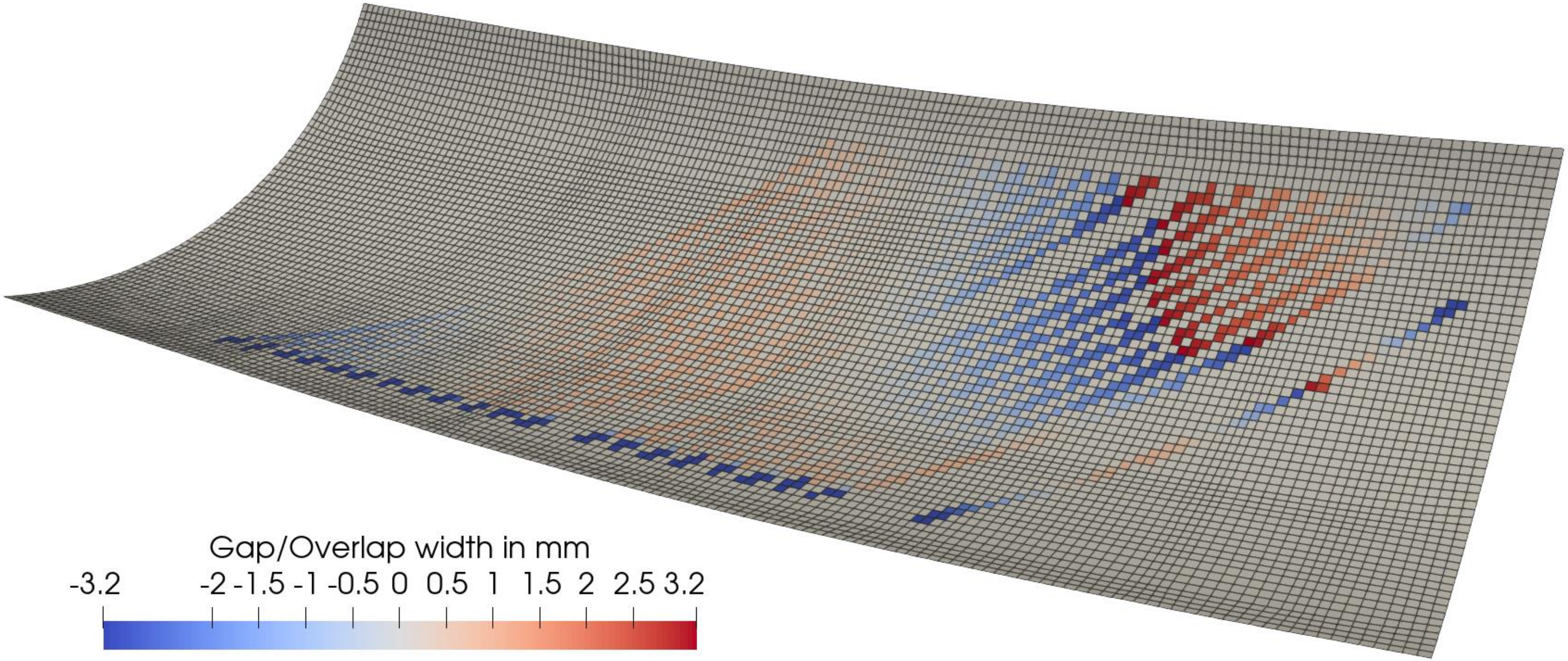
FE-Mesh



Results


ResultLevel
ply1
ply2
ply3
ply4
4.0
3.43
2.86
2.29
1.71
1.14
0.57
0.0
-0.38
-0.77
E_x
E_y
E_z
G_{xy}
G_{xz}
G_{yz}
ν_{xy}
ν_{xz}
ν_{yz}
1.41
1.25
1.09
0.94
0.78
0.63
0.47
0.31
0.16
0.0
R_X^C
R_X^T
R_{XY}
R_{XZ}
R_y^C
R_y^T
R_{YZ}
R_Z^C
R_Z^T

KI-based prediction



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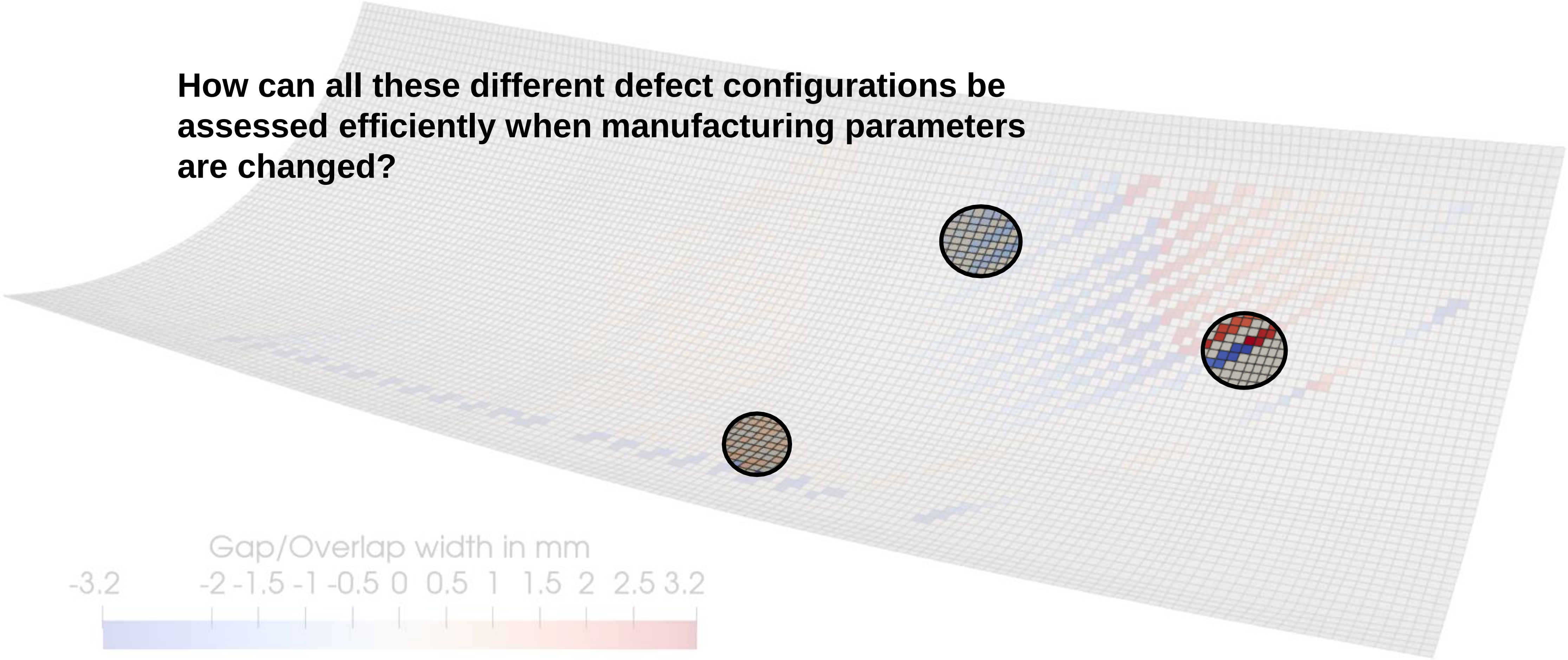


KI-based prediction

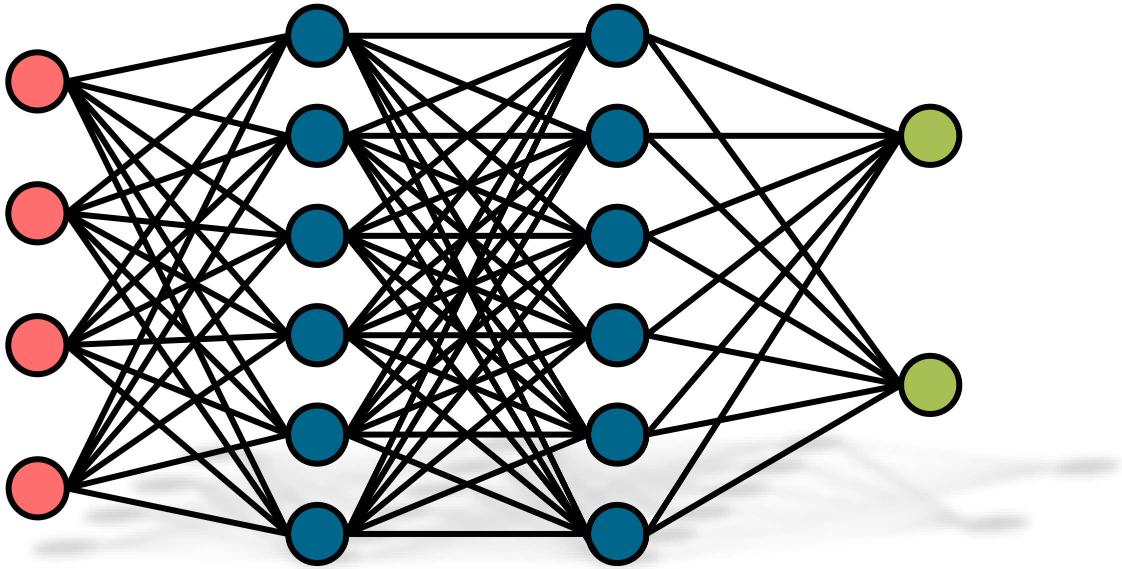
- KDF estimation for local material deviation based on neural networks
- Model trained for fixed UD-material and number of laminate plies

Input layer

Hidden layers

Output layer

gap
geometry
parameters
(width +
amplitude)



KDF
for all plies
and material
properties

KI-based prediction

DETACT

DLR KPI-VORHERSAGE

MODELLIERUNG

TRAININGSDATEN

WOHER KOMMEN DIE TRAININGSDATEN?

- (•) Sampling des aktuellen Gesamtdatenbestands
- ( ) aktueller Gesamtdatenbestand
- ( ) aktuell gefilterter Datenbestand
- ( ) Import (json-Upload)

ANTEIL DER TRAININGSDATEN

0,8

✓ TRAININGSDATEN BESTÄTIGEN UND VERARBEITEN

KPI-VORHERSAGEPARAMETER

KPI First Ply Failure RxxT | KPI First Ply Failure RxxC | KPI First Ply Failure RyyT | KPI First Ply Failure RyyC | KPI First Ply Failure RzzT | KPI First Ply Failure RzzC | KPI First Ply Failure Rxy | KPI First Ply Failure Rxz | KPI First Ply Failure Ryz

MODELLE BERECHNEN

MODELLEVALUATION

WOHER KOMMEN DIE TESTDATEN?

- (•) Sampling (Rest)
- ( ) Gesamtdatenbestand
- ( ) Filter-Rest
- ( ) Import (json-Upload)

✓ TESTDATEN BESTÄTIGEN, VERARBEITEN UND EVALUIEREN

MODELLE AUSWERTEN

- ( ) Fehlermaße
- ( ) KPI-Landkarte (Autoencoder-Code)
- (•) Vorhersage-Tabelle

VORHERSAGE-TABELLE HERUNTERLADEN (CSV)

Datenauswahl | Datenanalyse | Modellierung

MODELL	ID	KPI FIRST PLY FAILURE RXXT	KPI FIRST PLY FAILURE RXXC	KPI FIRST PLY FAILURE RYYT	KPI FIRST PLY FAILURE RYYC	KPI FIRST PLY FAILURE RZZT	KPI FIRST PLY FAILURE RZZC	KPI FIRST PLY FAILURE RXY	KPI FIRST PLY FAILURE RXZ	KPI FIRST PLY FAILURE RYZ
Autoencoder mit Nachbarschaft 1	id_1	0.98	1.00	0.99	1.00	0.99	0.98	0.97	0.94	0.97
	id_2	0.98	1.00	0.99	1.00	0.99	0.98	0.97	0.94	0.97
	id_3	0.89	0.94	0.98	1.00	0.99	0.96	0.93	0.89	0.95
	id_4	0.71	0.74	0.97	1.00	0.98	0.89	0.82	0.81	0.87
	id_5	0.71	0.74	0.97	1.00	0.98	0.89	0.82	0.81	0.87
	id_6	1.01	1.00	0.98	0.97	1.00	1.00	0.99	0.98	0.99
	id_7	1.01	1.00	0.98	0.97	1.00	1.00	0.99	0.98	0.99
	id_8	1.01	1.00	0.98	0.97	1.00	1.00	0.99	0.98	0.99
	id_9	0.36	0.59	0.94	0.86	0.95	0.23	0.87	0.50	0.69
	id_10	0.72	0.73	0.93	0.86	0.95	0.24	0.85	0.64	0.75
	id_11	0.72	0.73	0.93	0.86	0.95	0.24	0.85	0.64	0.75
	id_12	0.47	0.81	0.99	0.99	0.97	0.96	0.97	0.81	0.97
	id_13	0.45	0.68	1.06	1.06	0.94	0.94	1.04	0.84	1.01
	id_14	0.45	0.68	1.06	1.06	0.94	0.94	1.04	0.84	1.01
	id_15	0.37	0.28	0.37	0.28	0.79	0.22	0.27	0.66	0.66
	id_16	0.37	0.28	0.37	0.28	0.79	0.22	0.27	0.66	0.66
	id_17	0.91	0.94	0.86	0.75	0.96	0.76	0.87	0.94	0.90
	id_18	0.94	0.93	0.94	0.93	0.96	0.89	0.65	0.92	0.92
	id_19	0.98	0.99	0.38	0.82	0.96	0.44	0.81	0.88	0.88
	id_20	0.94	0.97	0.36	0.58	0.92	0.39	0.69	0.71	0.72
	id_21	0.94	0.97	0.36	0.58	0.92	0.39	0.69	0.71	0.72
	id_22	1.00	0.91	0.64	0.77	0.92	0.80	0.50	0.87	0.71
	id_23	0.81	0.98	0.97	0.90	0.97	0.97	0.88	1.02	1.02
	id_24	0.20	0.19	0.20	0.19	0.64	0.21	0.34	0.46	0.46
	id_25	0.17	0.16	0.17	0.16	0.65	0.20	0.29	0.60	0.60
	id_26	0.17	0.16	0.17	0.16	0.65	0.20	0.29	0.60	0.60
	id_27	0.87	0.83	0.88	0.83	0.90	0.87	0.85	1.02	1.01
	id_28	0.91	0.95	0.90	1.00	0.95	0.67	0.93	0.90	0.88
	id_29	0.77	0.85	0.80	0.76	0.91	0.47	0.79	0.75	0.86

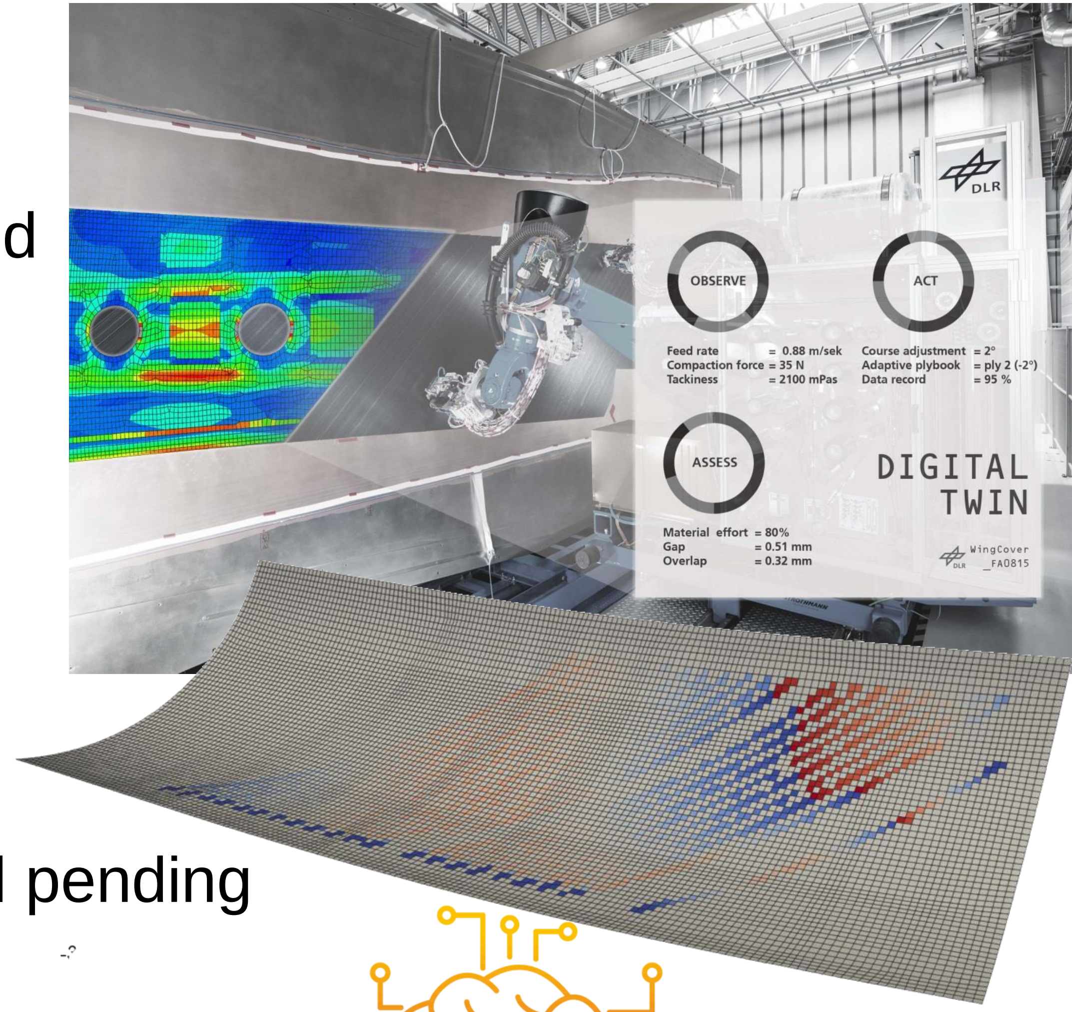
Summary and Outlook

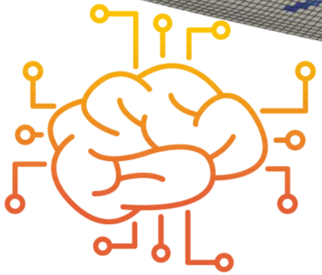
- further steps towards a digital-twin for the assessment of CFRP structures manufactured by AFP prozesses achieved

- Focus on virtual design and manufacturing, easily adoptable for quality assurance issue in production phases

- Assessment of AFP effects on structural level pending

- further efforts on AI assissted evaluation in future project





THANK YOU FOR YOUR ATTENTION

Contact

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Impressum

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