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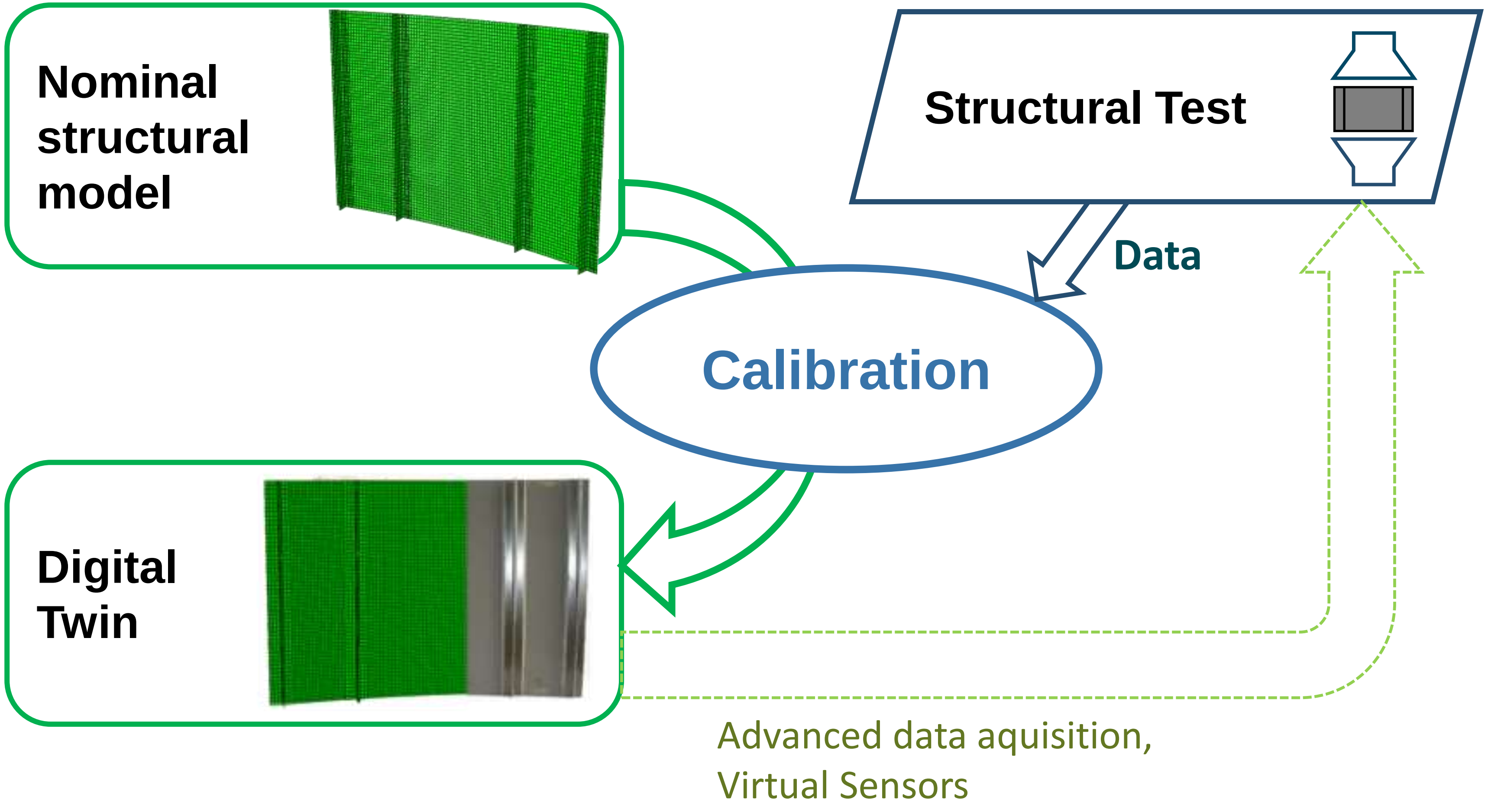
R028 - CALIBRATION OF A DIGITAL TWIN FOR STRUCTURAL TESTING

CompTest2023, 1 June 2023, Girona

Raffael Bogenfeld

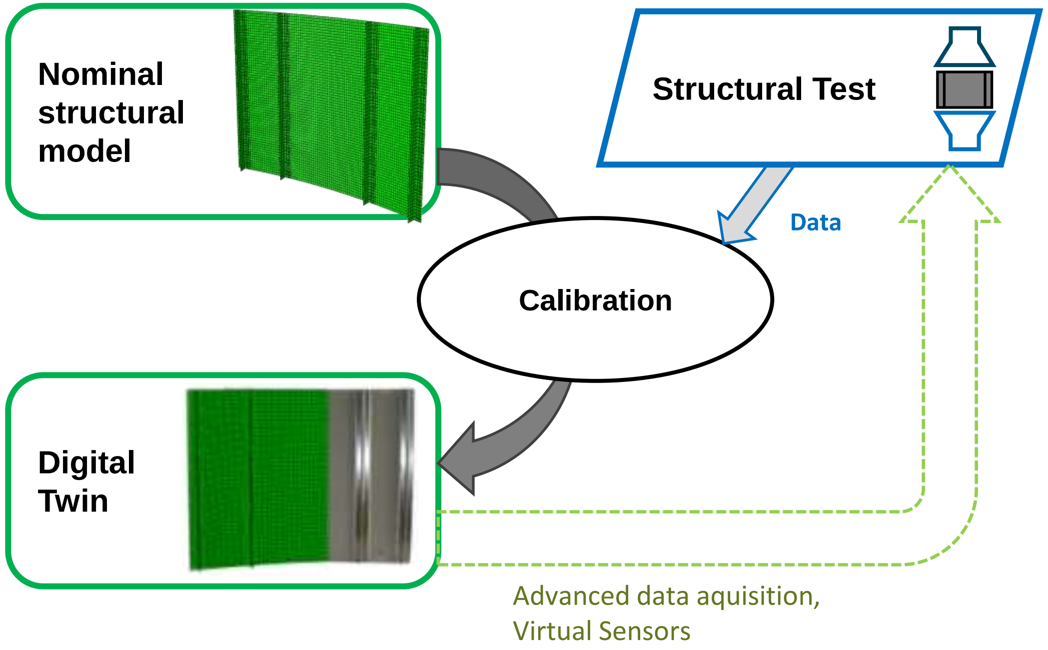
DLR

Model improvement by test data
Basic idea



Model improvement by test data
Required Steps

1. Identification of the uncertainties
   - Parametric uncertainty description
   - Quantification of the uncertainties
2. Study the parameter influence
   - Sensitivity of the nominal model
3. Target variables of the optimization
4. Optimization procedure
5. Validity check

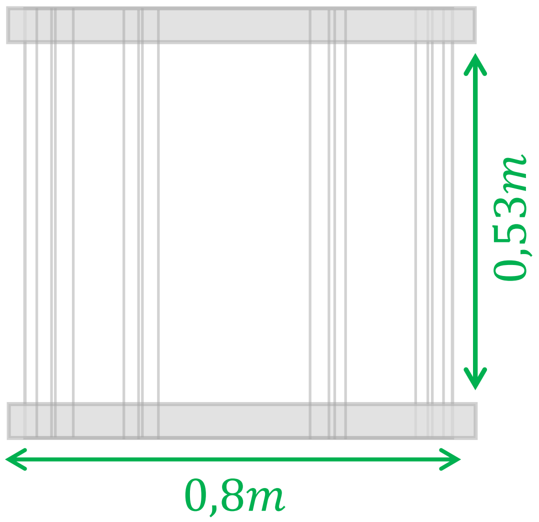


Development Case: stiffened panel

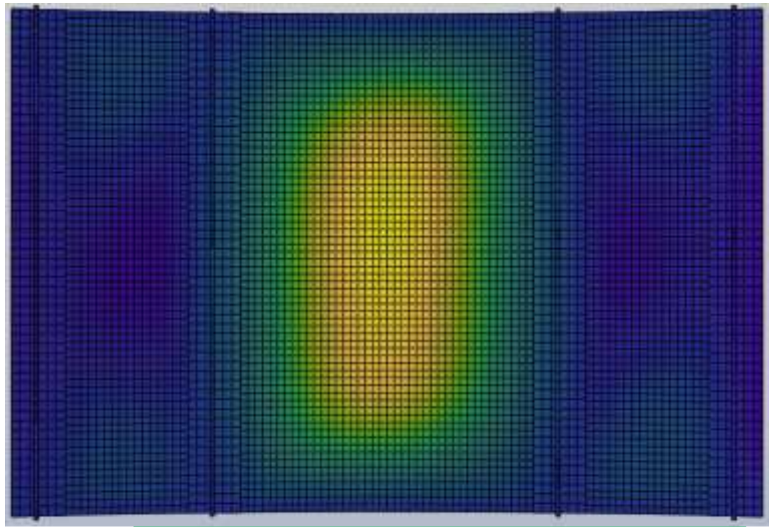
Identification of the uncertainties

- Boundary conditions at the fixtures
- Stringer attachment stiffness
- Geometrical imperfection
- Simplifications of the elastic material parameters
- Load introduction
- Laminate thickness
- Measurement uncertainties

Panel specimen



Out-of-plane Deformation



Test setup

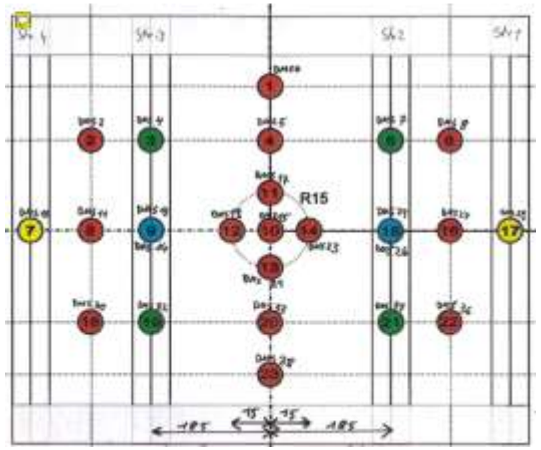
Development Case: stiffened panel
Measured data and deformation

Physical

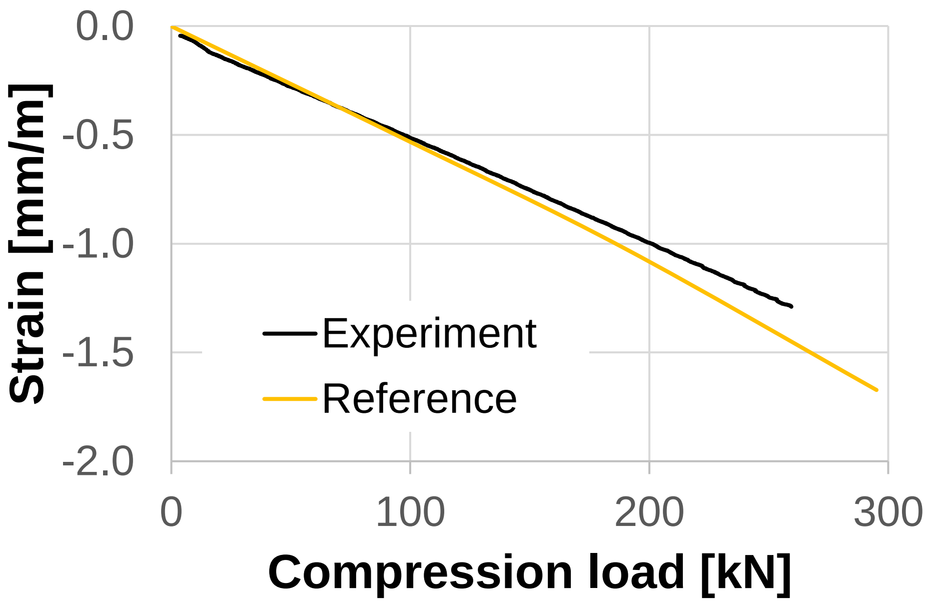
- 30 back-to-back strain gauges
- 3D displacement measurement through ARAMIS DIC

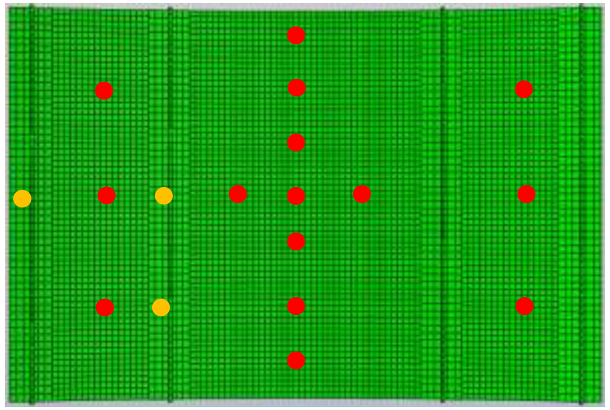
Virtual

- Virtual strain gauges through inverse distance averaging
- Displacements through inverse distance averaging measurements



Physical strain gauge position



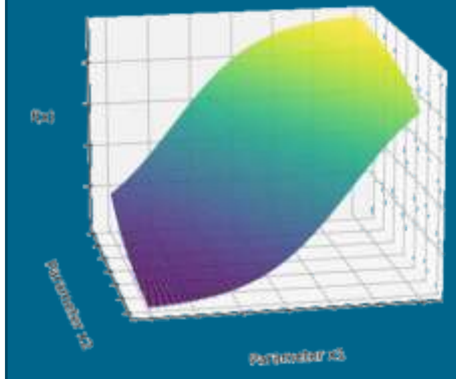


Virtual strain gauge position

Calibration procedure

A non-linear least squares (LSQ) approach

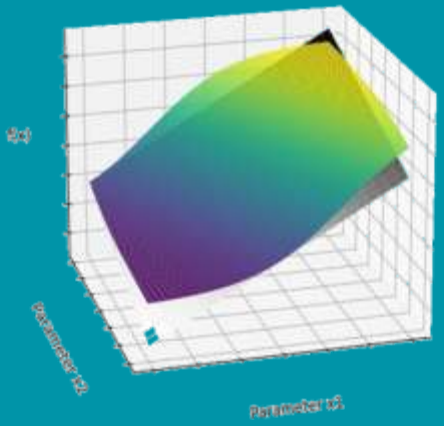
Nonlinear system



$$F(x, \boldsymbol{\beta}^k)$$

F: model
$\boldsymbol{\beta}$: uncertain parameters

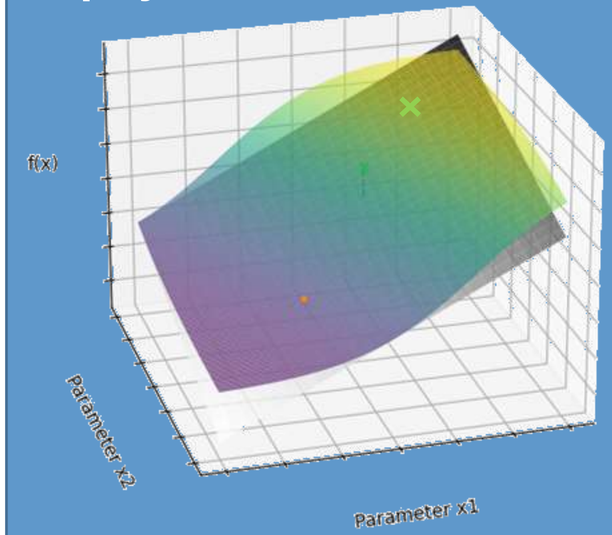
Linearization



$$\boldsymbol{f}^0(\boldsymbol{x}, \boldsymbol{\beta}) = \boldsymbol{F}(\boldsymbol{x}, \boldsymbol{\beta}^0) + \left.\frac{\partial \boldsymbol{F}}{\partial \boldsymbol{\beta}}\right|_{\boldsymbol{\beta}^0} (\boldsymbol{\beta} - \boldsymbol{\beta}^0)$$

f: linearized model through first order taylor approx.

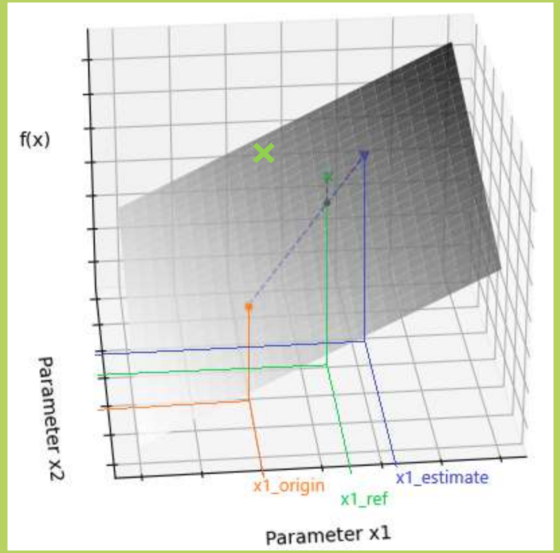
Target values from the physical world



$$\min\left|\left|\boldsymbol{f}(\boldsymbol{x}, \boldsymbol{\beta}) - \boldsymbol{y}\right|\right|^2$$

y: measured target values

Nonlinear LSQ Estimation



$$\Delta\hat{\boldsymbol{\beta}} = \left(\boldsymbol{J}^{0^T}\boldsymbol{J}^0\right)^{-1}\boldsymbol{J}^{0^T}\left(\boldsymbol{y} - \boldsymbol{F}(\boldsymbol{x}, \boldsymbol{\beta}^0)\right)$$

$$\boldsymbol{\beta}^0 + \Delta\hat{\boldsymbol{\beta}} = \boldsymbol{\beta}^1$$

Calibration procedur

Nonlinear Least Squares

- Full computation time:

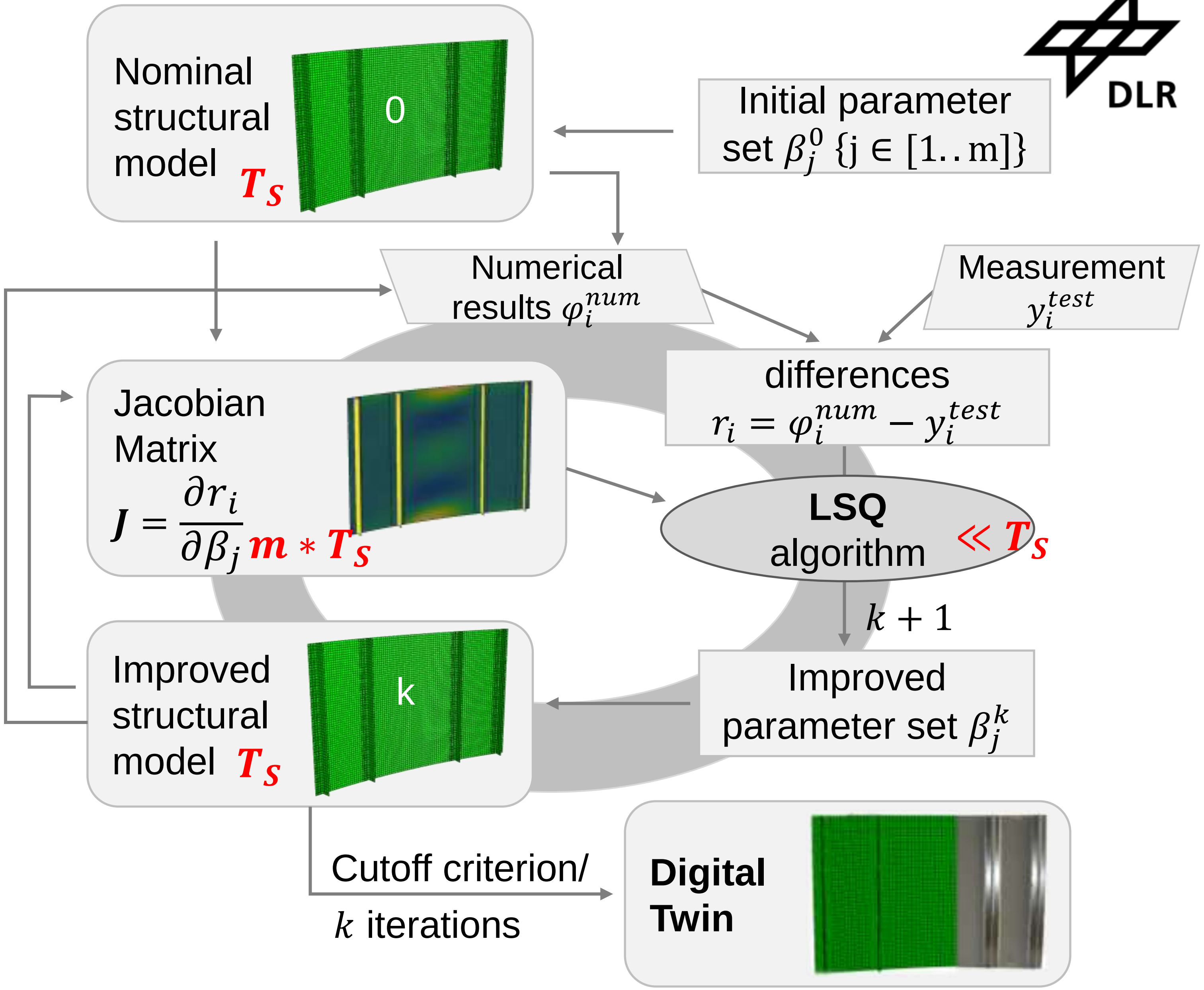
$T_{total} = T_s \cdot (1 + (m+1) \cdot K)$

- Reduced computation time

$T_{red} = T_s \cdot (1 + m + K)$

- Stiffened panel
  - $\mathrm{m} \approx 15,\ \mathrm{K} \approx 10\ ,\ \mathrm{T_s} \approx 1\mathrm{min}$
  - $T_{Total\_panel} \approx 2{,}5h$
  - $T_{red\_panel} \approx 0{,}3h$

- Fuselage Section
  - $\mathrm{m} \approx 50,\ \mathrm{K} > 10\ ,\ \mathrm{T_s} \approx 2h$
  - $T_{Total\_barrel} > 1000h$
  - $T_{red\_barrel} \approx 120h$



Computation times

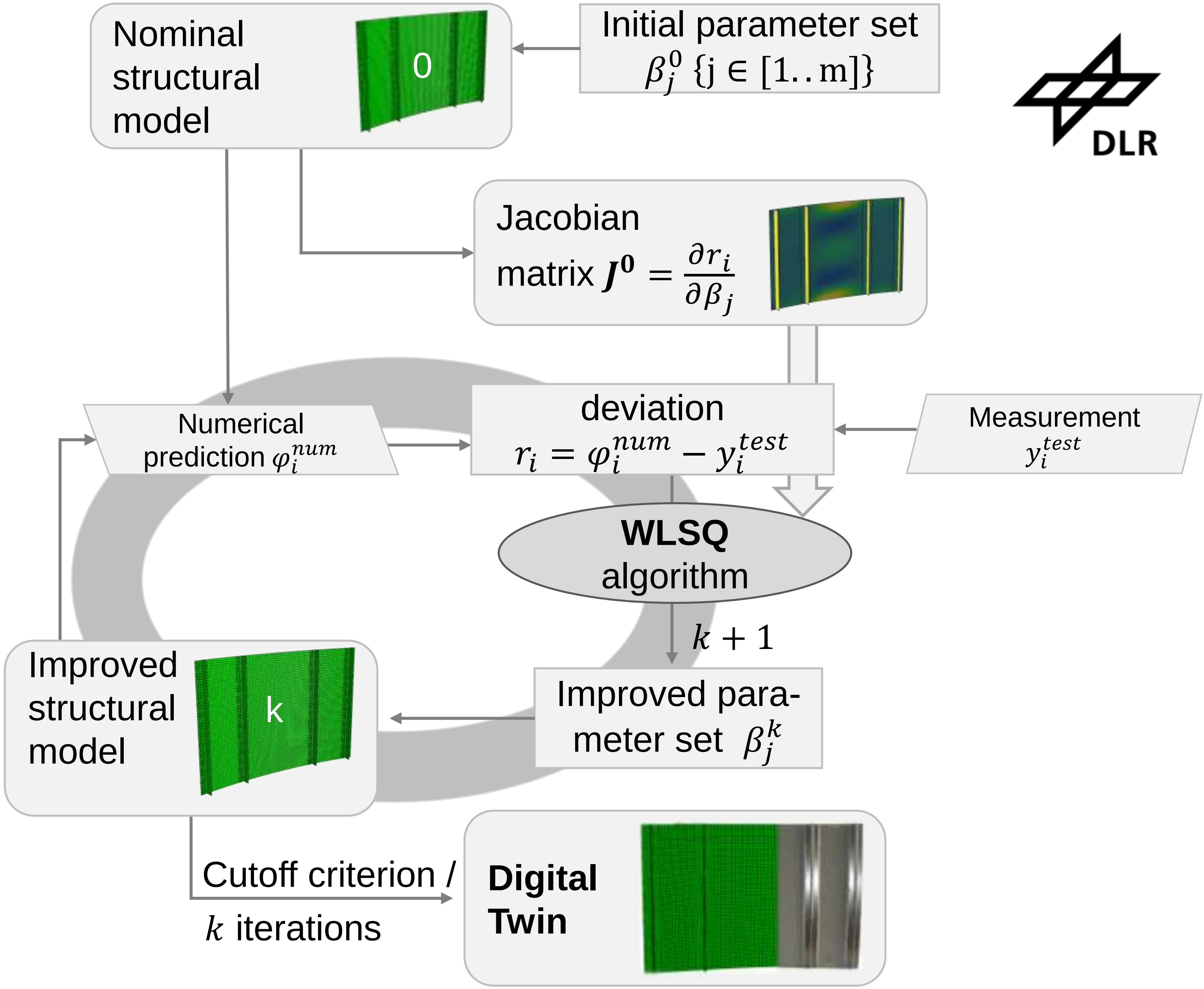
Calibration procedur

Nonlinear Least Squares

- Pre-calculation of the Jacobian matrix

$J^k = J^0$; assumption: $\left(\frac{\partial^2 r_i}{\partial \beta_j \beta_l}\right)_{j,l=1 \ldots m} \Rightarrow \mathbf{0}$

- damped LSQ (Levenberg Marquardt)
  → reduces the improvement step with per increment
- Sequential LSQ: Different groups of parameters are optimized in separate loops
- WLSQ: weight is chosen according to the sensitivity of an output variable toward the active parameter set

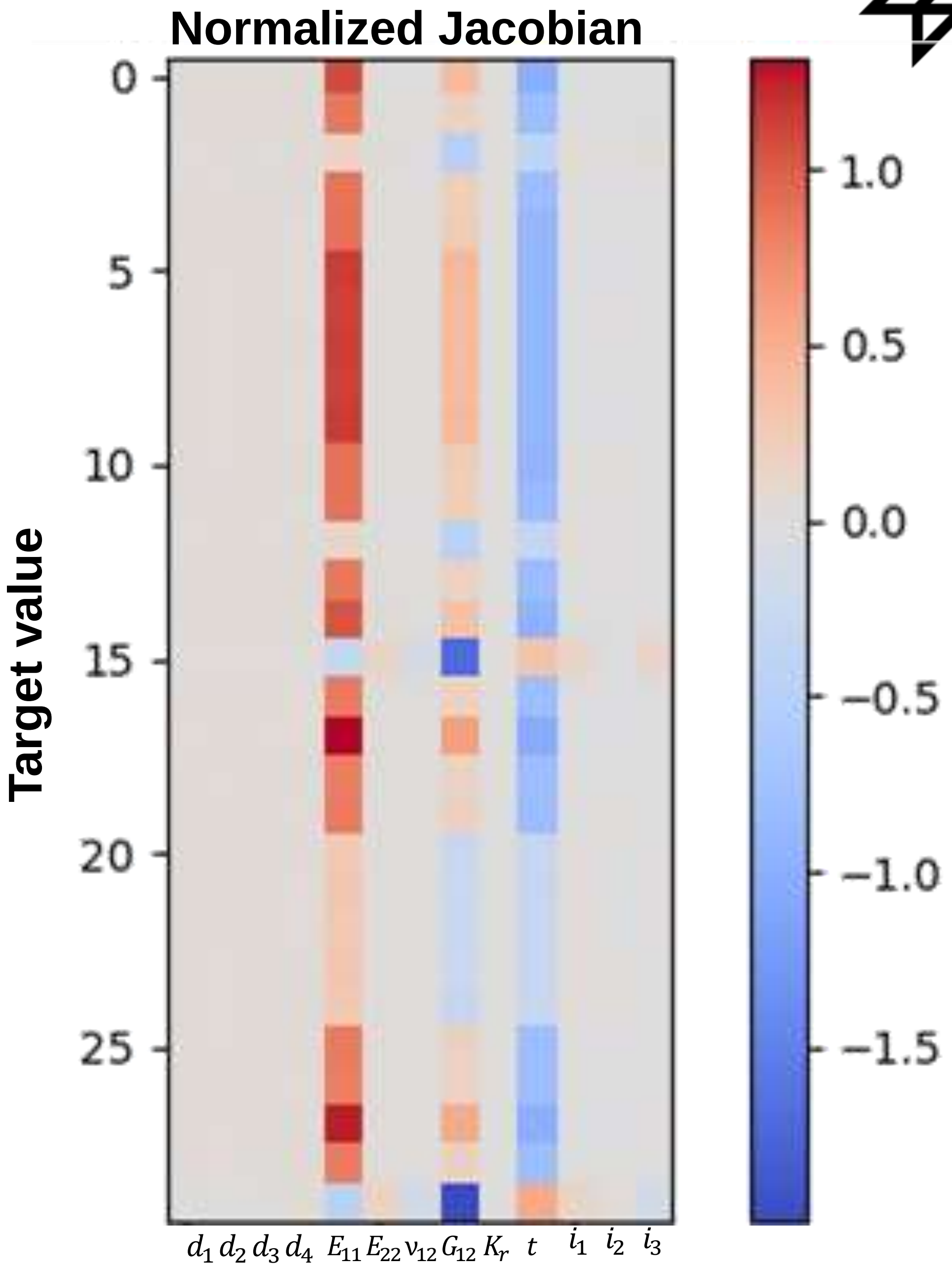


Calibration parameters
Visualization of the sensitivity

- Significant uncertainties
  - Elastic parameter
    - E11 (due to differing tension/compression values)
    - G12 (linearized value)
  - t laminate thickness
  - Attachment stiffness of the stiffeners
  - Rotational stiffness at the panel boundary
  - Geometrical imperfections

- Any skalar value in the model could be included as a parameter
- Normalized Jacobian:

$$\frac{Percentage\ of\ output\ difference}{Percentage\ of\ parameter\ difference}$$

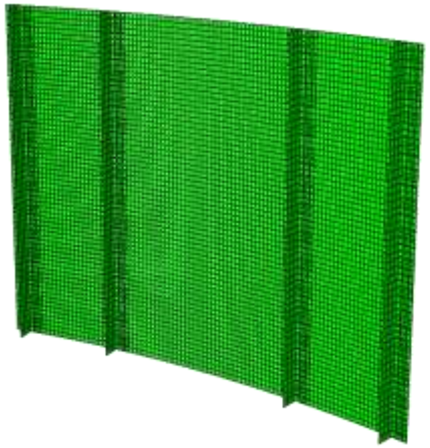


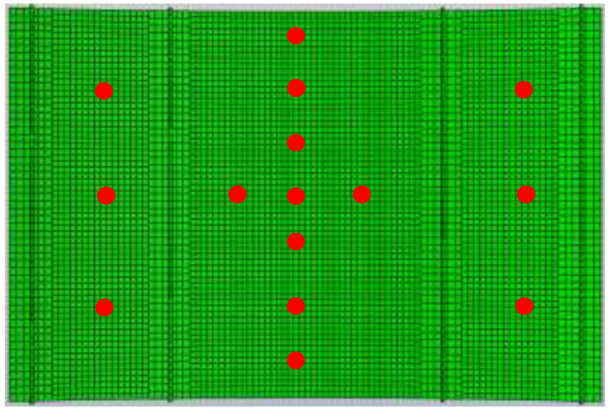
Results: FE-based calibration

Reference simulation with different parameter set

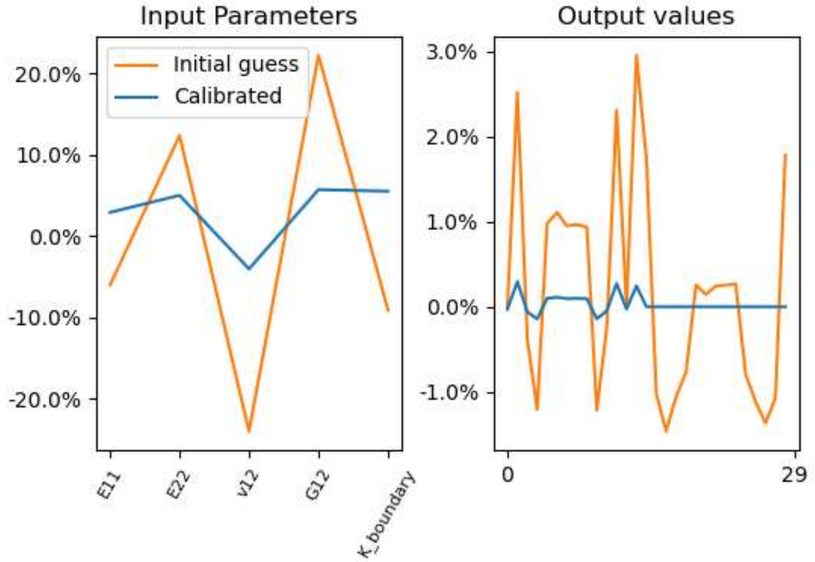
Calibration point: F = 200 kN

Parameter set	E11	E22	v12	G12	K
Guess	156000	9090	0.228	5500	1000
Real Value	166000	8090	0.3	4500	1100
Intial Guess (relative)	94%	112%	76%	122%	91%
Initial guess error (relative)	**-6%**	**12%**	**-24%**	**22%**	**-9%**
Calibration result (absolute)	170800	8490	0.288	4756	1160
Calibration result (relative)	103%	105%	96%	106%	105%
Result error	**3%**	**5%**	**-4%**	**6%**	**5%**

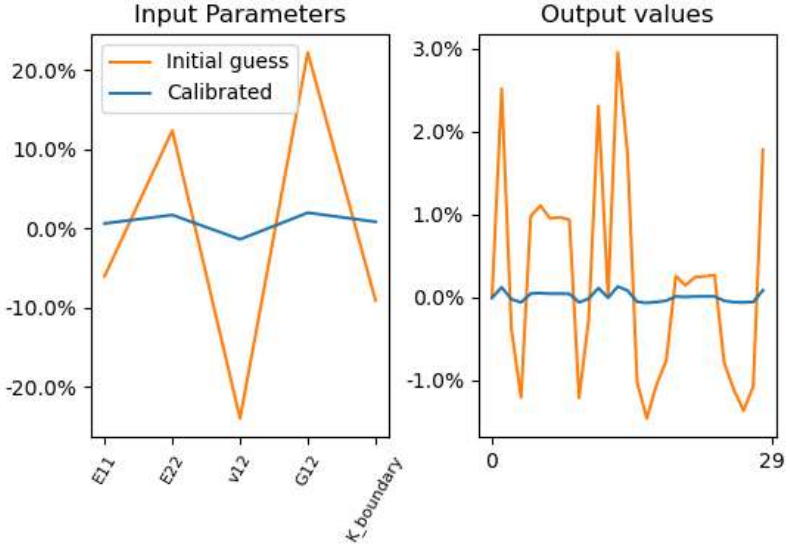




Single Iteration (k=1)



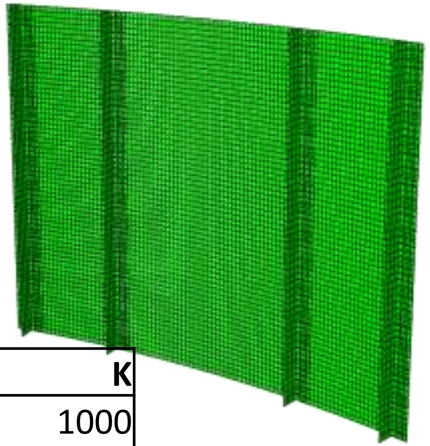
Three Iterations (k=3)

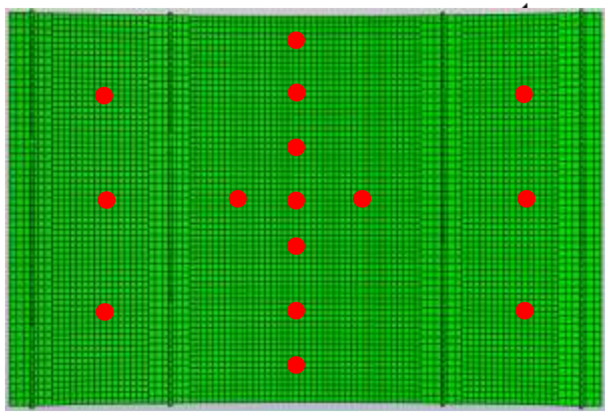


Results: FE-based calibration

Different measured values

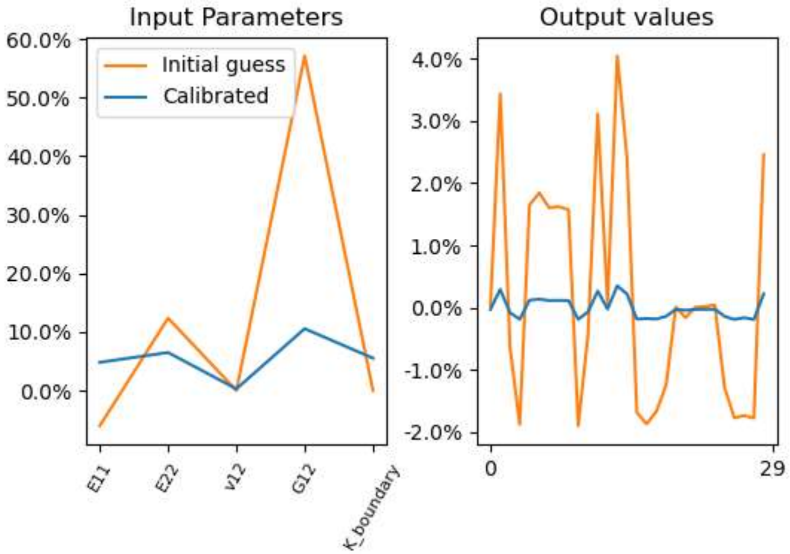
Calibration point: F = 200 kN



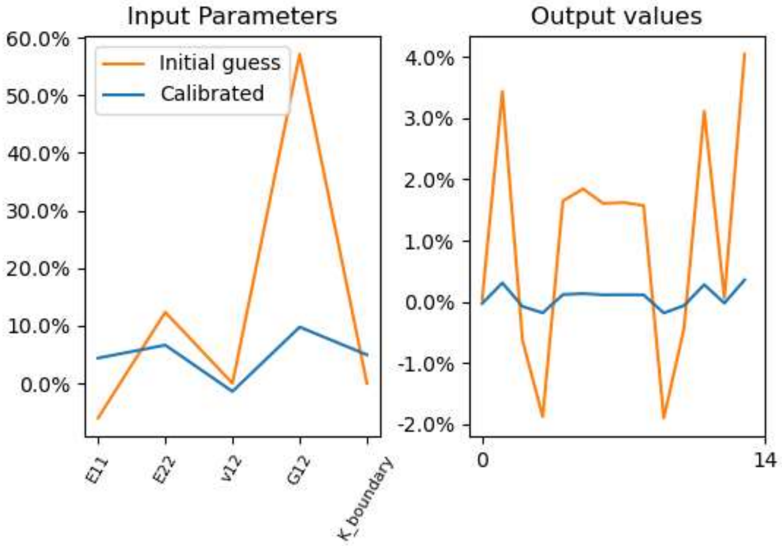


Parameter set	E11	E22	v12	G12	K
Guess	156000	9090	0.228	5500	1000
Real values	166000	8090	0.228	3500	1055
Initial values (relative)	94%	112%	100%	157%	95%
Initial guess error (relative)	-6%	12%	0%	57%	-5%
Results (outside) k=3	173200	8627	0.224	3840	1049
Results (inside) k=3	181000	9180	0.22	3971	1072
Results (both sides) k=3	173000	8615	0.228	3870	1160

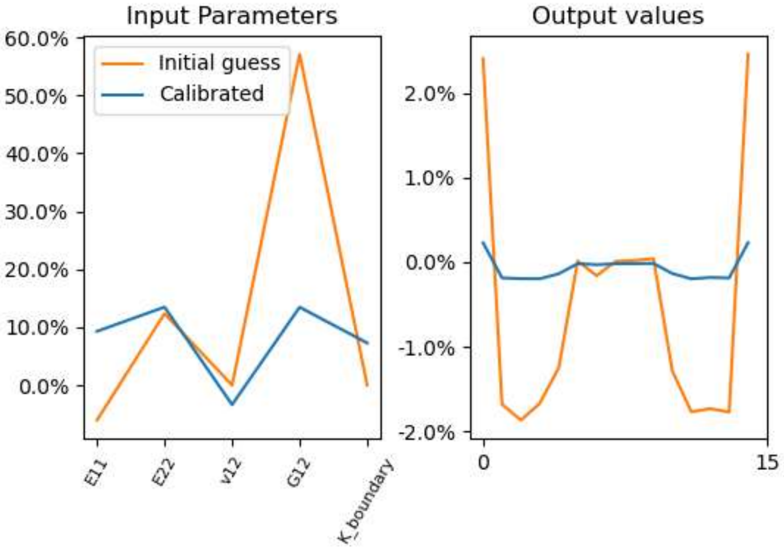
30 strains from both sides



15 strains on outer skin

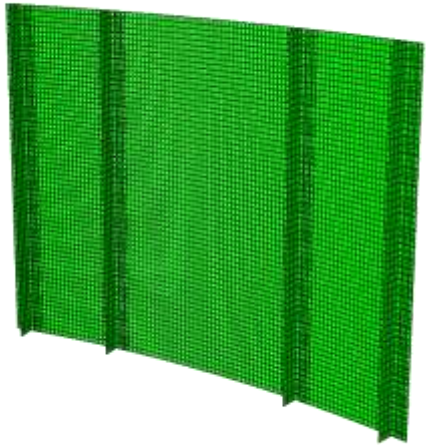


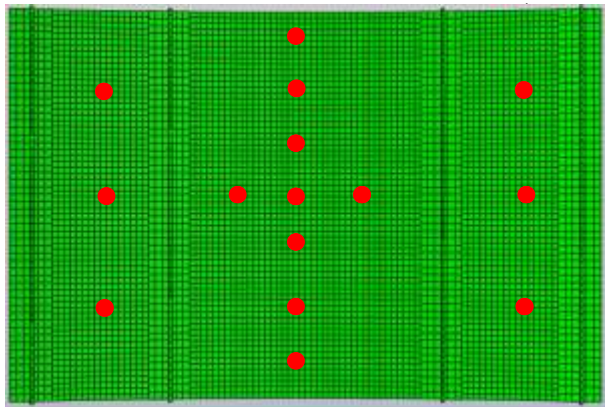
15 strain on inner skin



Results: FE-based calibration

Incompatible parameter sets

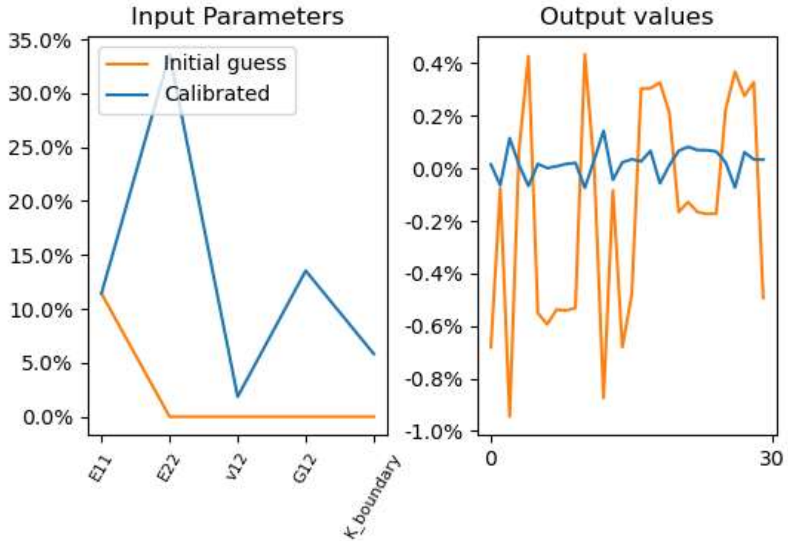




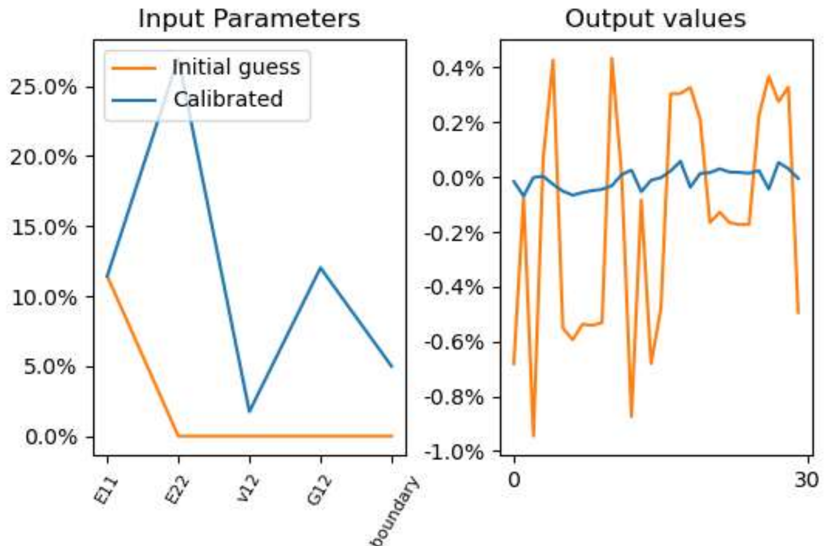
Calibration point: F = 200 kN

Zu schätzende Parameter	E11	E22	v12	G12	K
Guess	156000	9090	0.228	5500	1000
Real Value	140000	9090	0.228	5500	1000
Anfangswert (rel)	111%	100%	100%	100%	100%
Initial guess error (relative)	**11%**	**0%**	**0%**	**0%**	**0%**
Results k=3	156000	11540	0.23	6161	1049
Results k=1	156000	12143	0.23	6244	1058
Results (relative) k=3	111%	134%	101%	114%	106%
Fehler im Ergebnis k=3	**11%**	**34%**	**1%**	**14%**	**6%**

Single iteration (k=1)

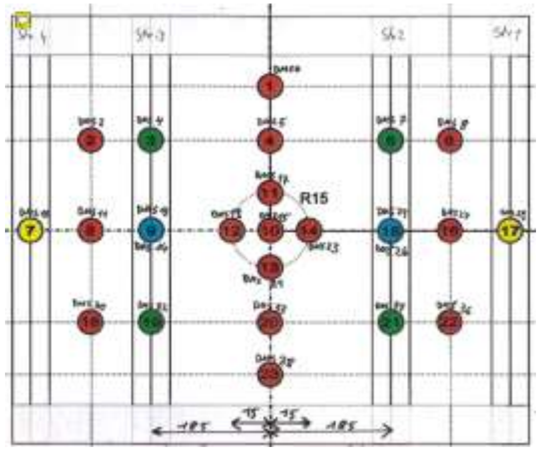


Three iterations (k=3)



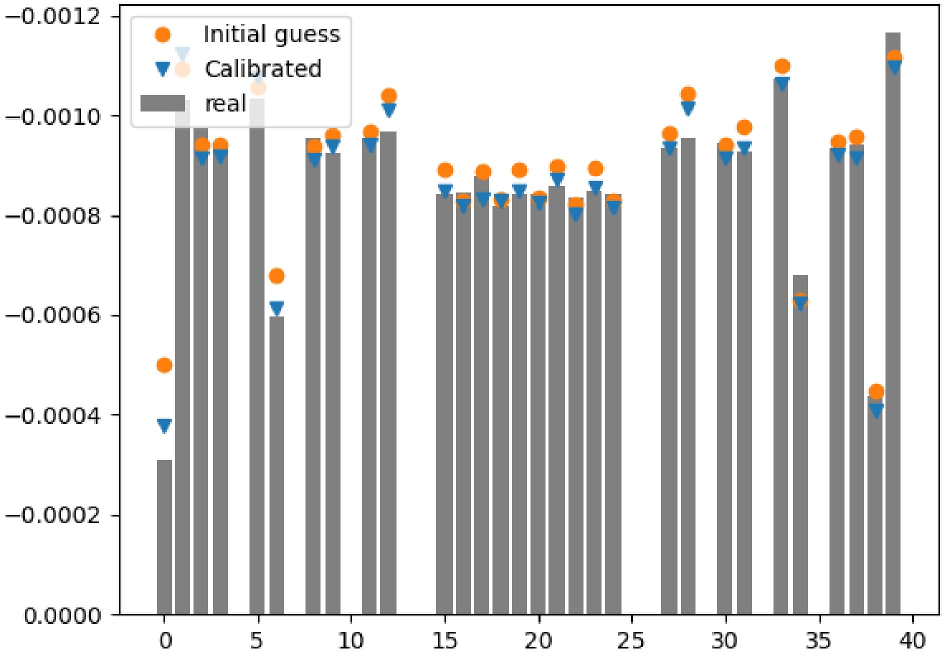
Results: Experiment-based calibration

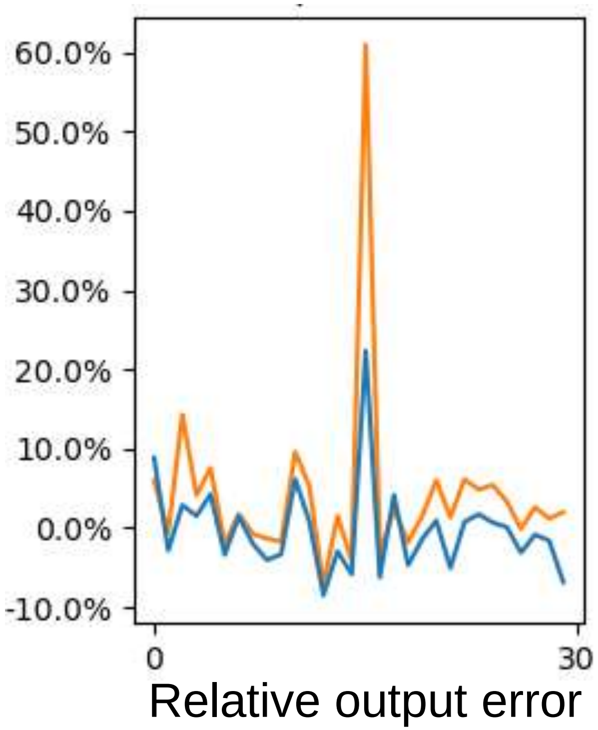
A real digital twin

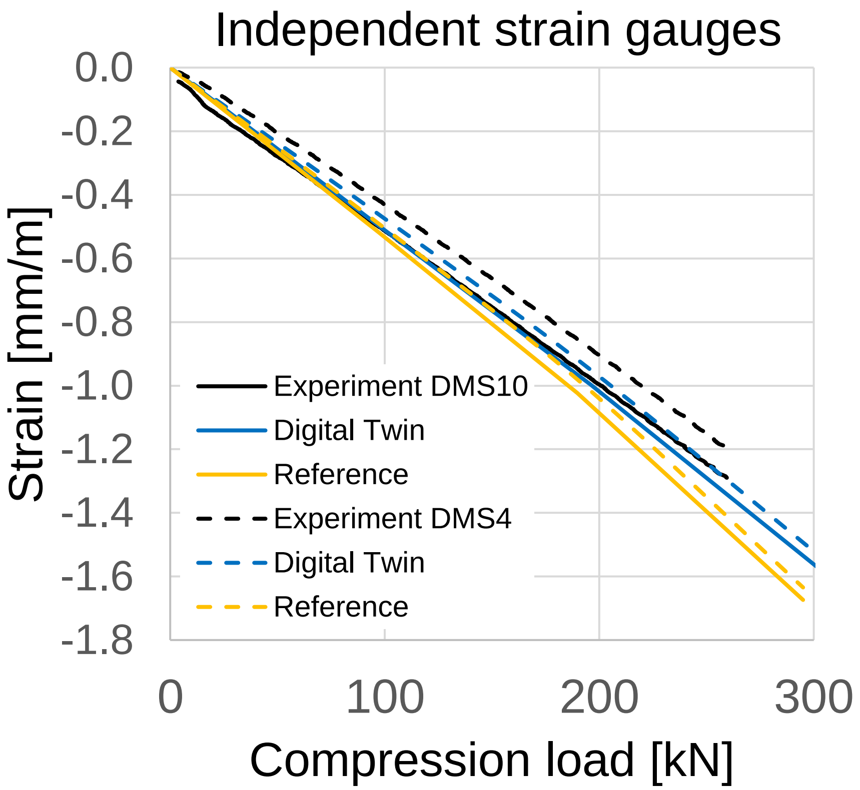


Comparison is only possible with output values

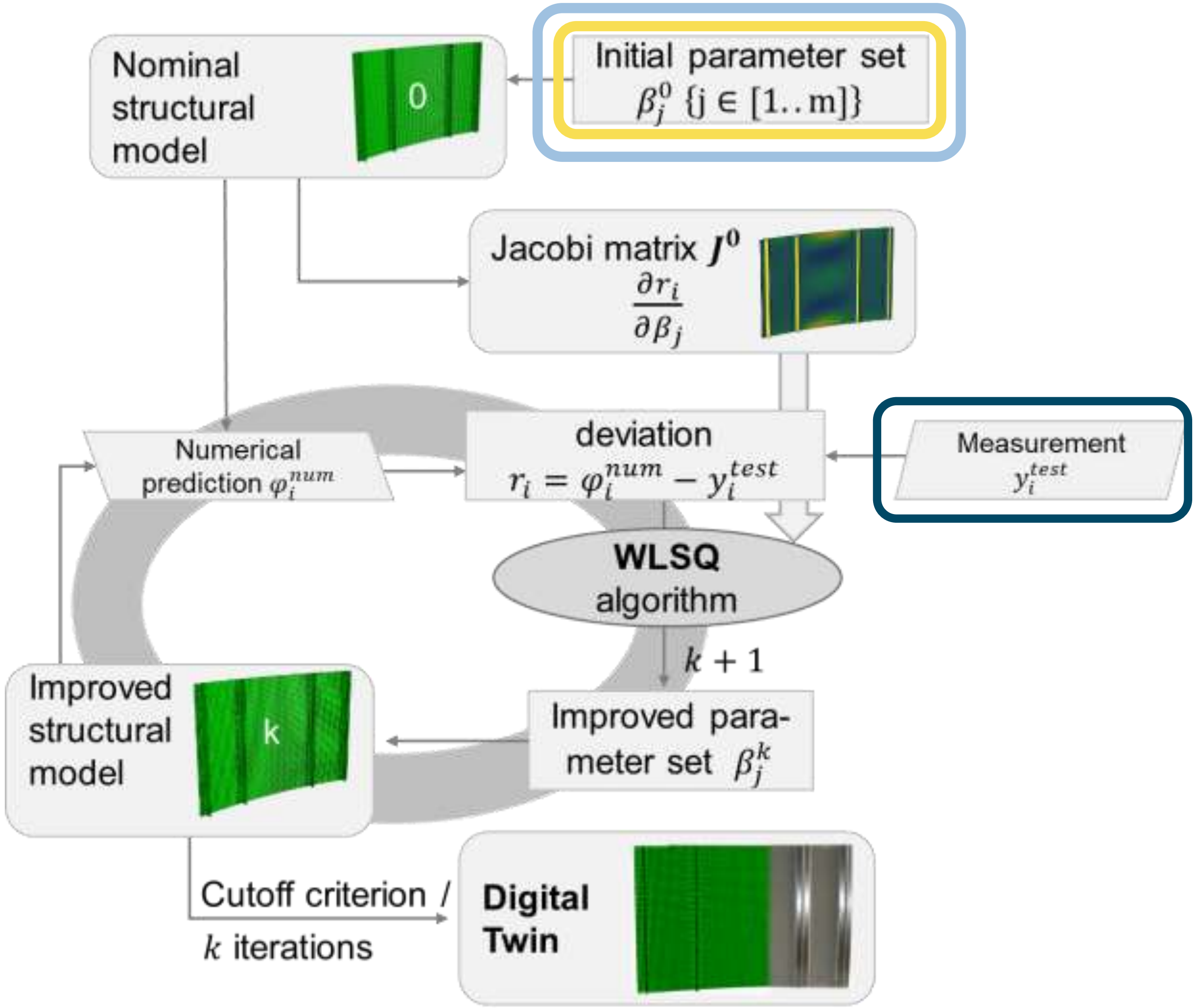
	E11 [Mpa]	G12 [Mpa]	K_rot [Nmm/rad]	imperfect mode1	imperfect mode3
Initial	156000	5500	500000	1	1
Final	167112	4641	586500	0.36	0.178



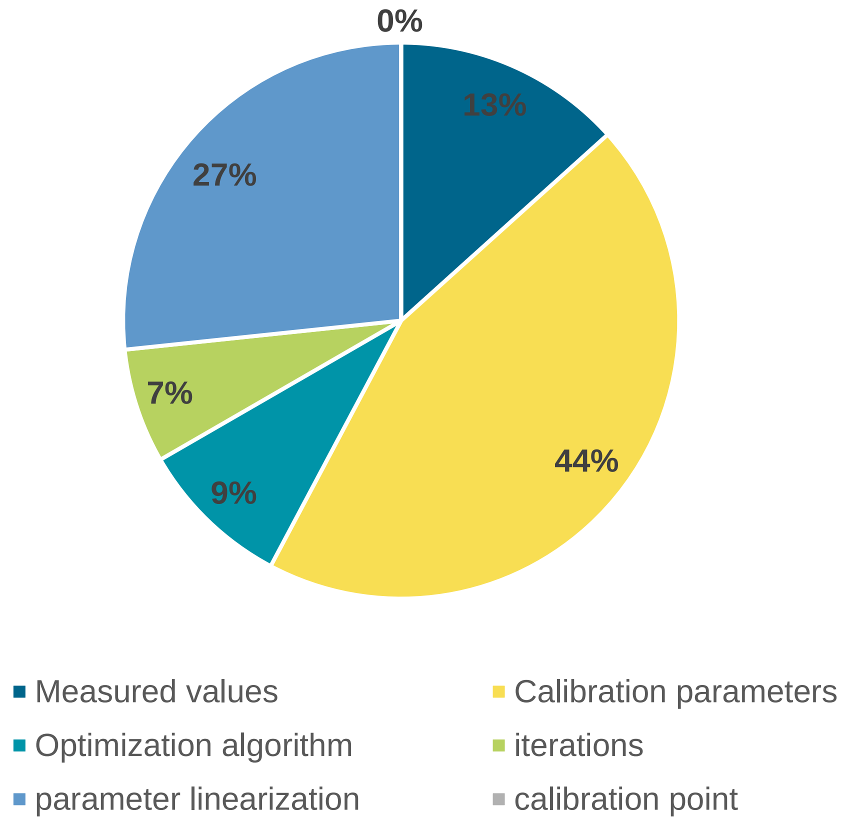




Review
Advantages and disadvantages of the proposed procedure

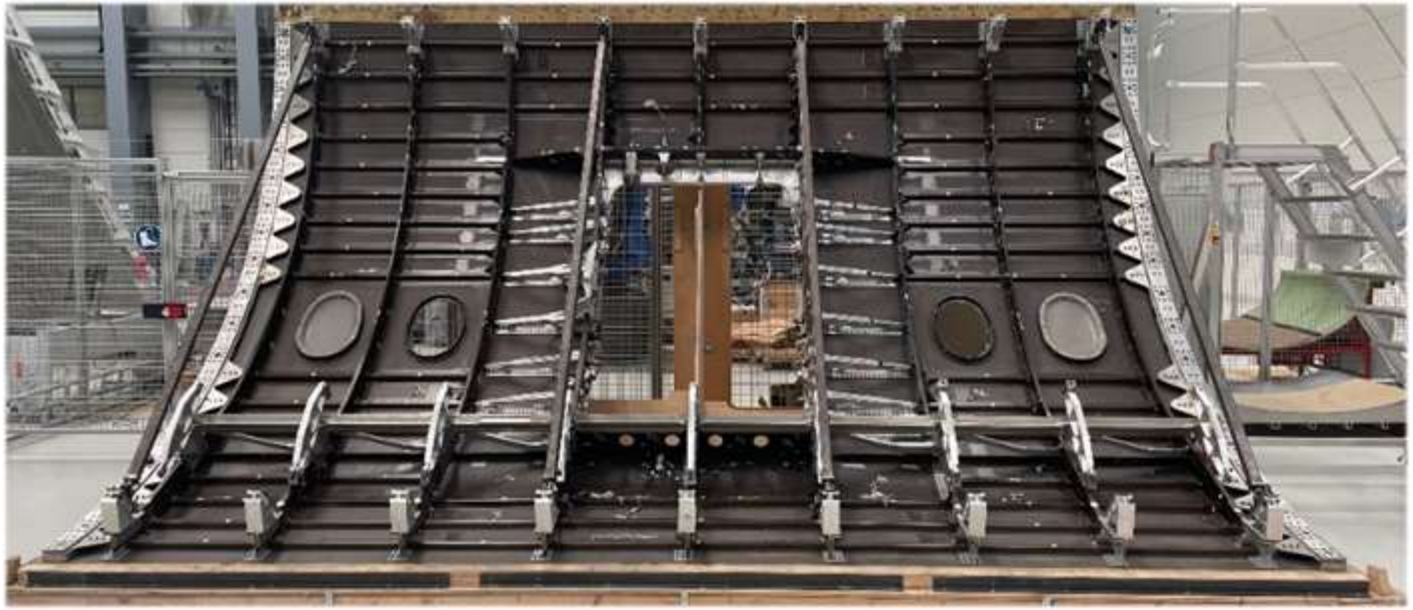


Comparison of the relative influence of different factors to the accuracy of the calibration



Next steps

- MAAXIMUS barrel section
- Detection of local degradation
- Validation of model accuracy by virtual sensors



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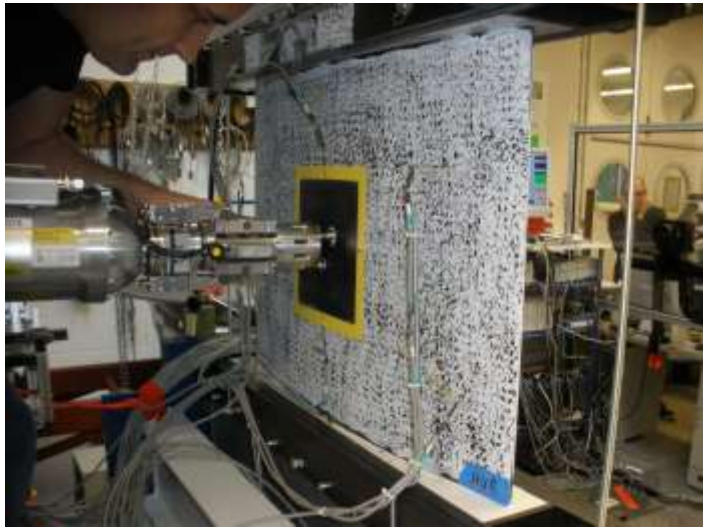
Thank you!

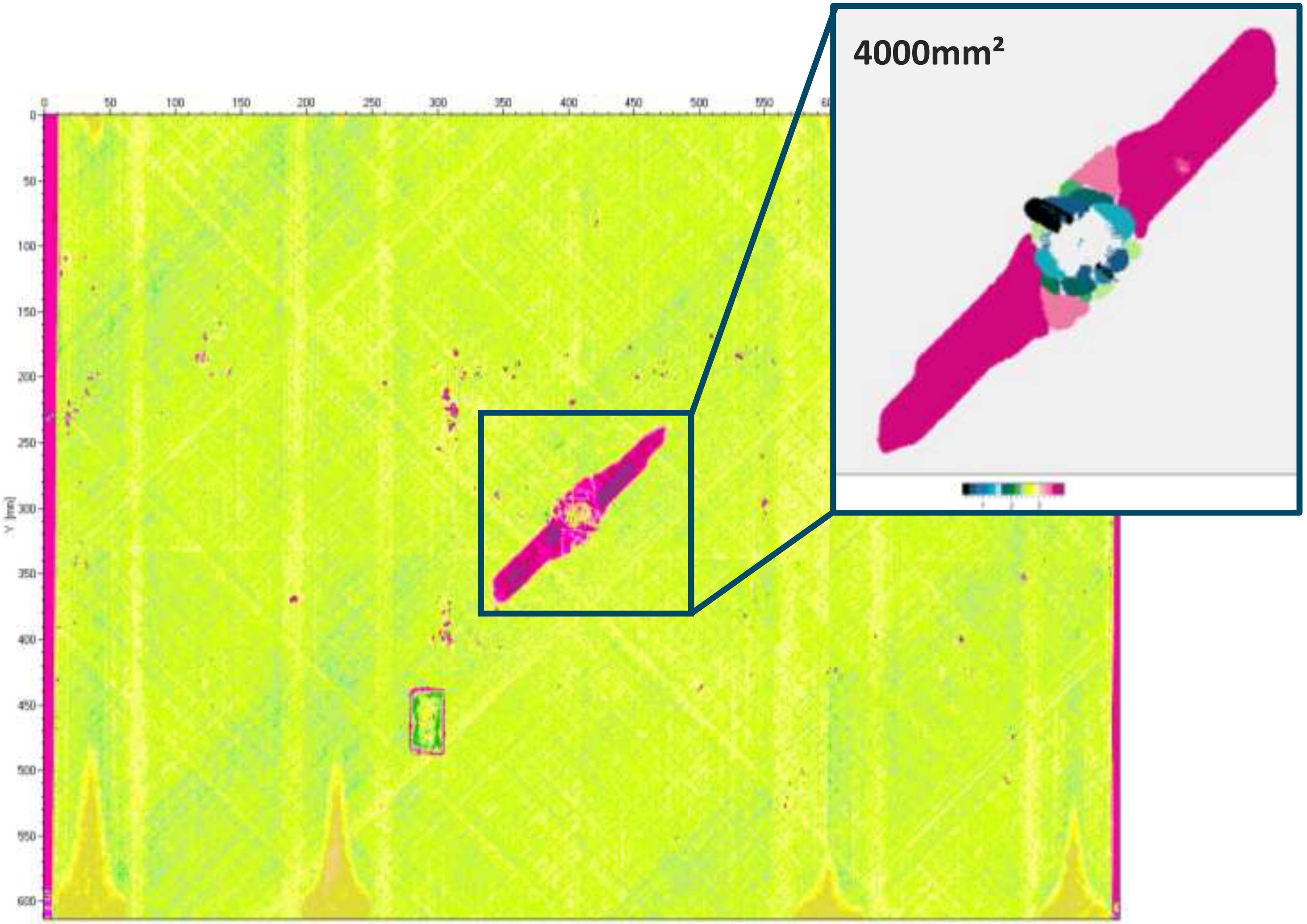
Dr.-Ing Raffael Bogenfeld
raffael.bogenfeld@dlr.de

DAMAGE LOCALIZATION

Impact damage on the stiffened panel
Properties of the damage

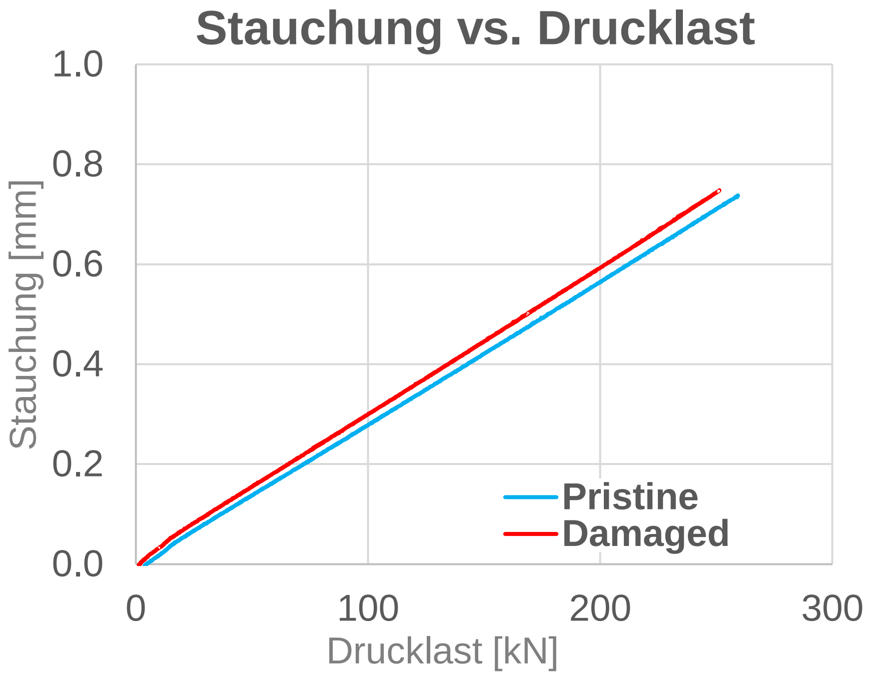
- Gasgun impact 140J
  - Supported from behind
  - Central position
- Damage
  - 4000mm² projected delamination
  - symetrical damage
  - delamination differs per interface
  - Fiber fracture on the impact side

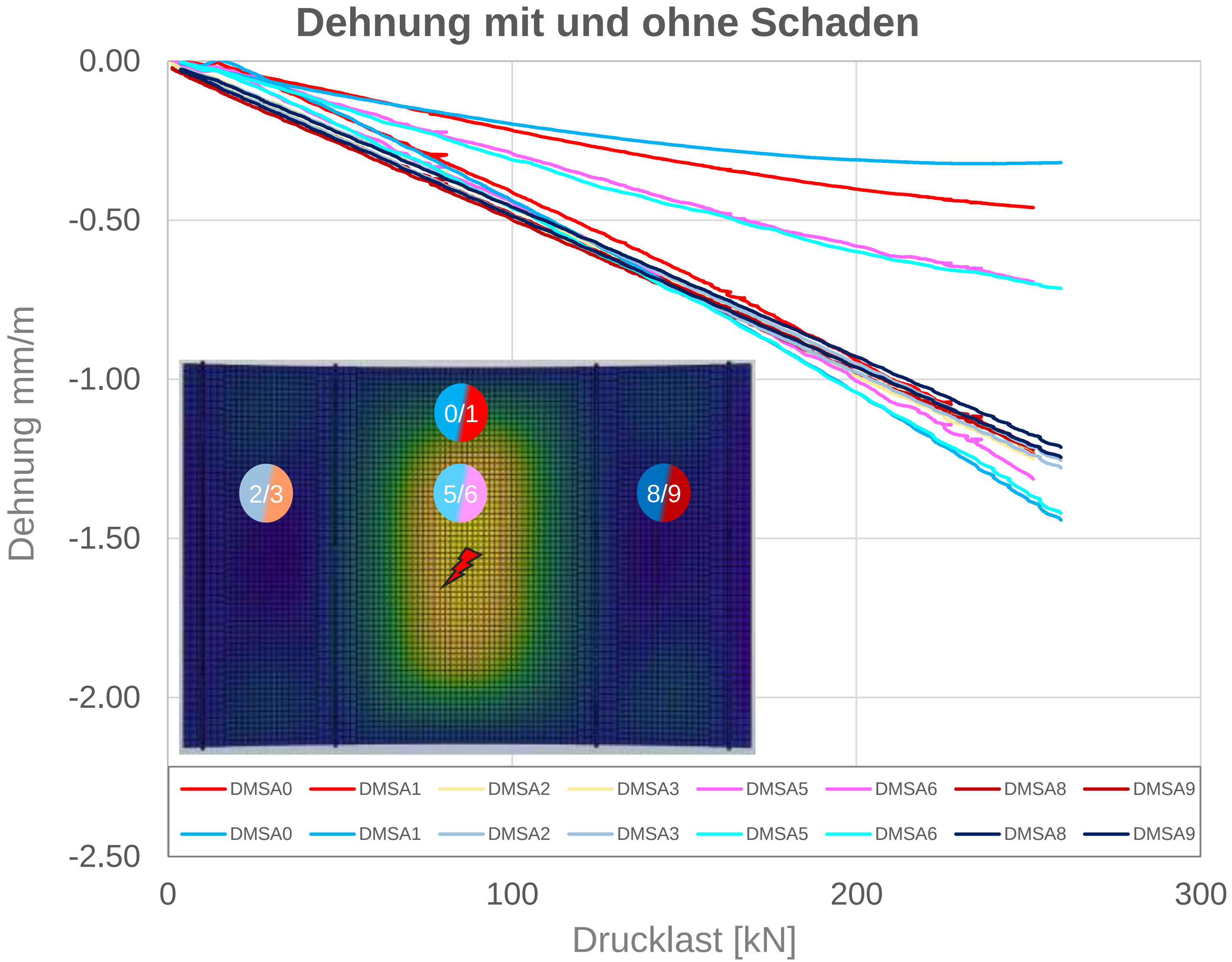




Impact damage on the stiffened panel

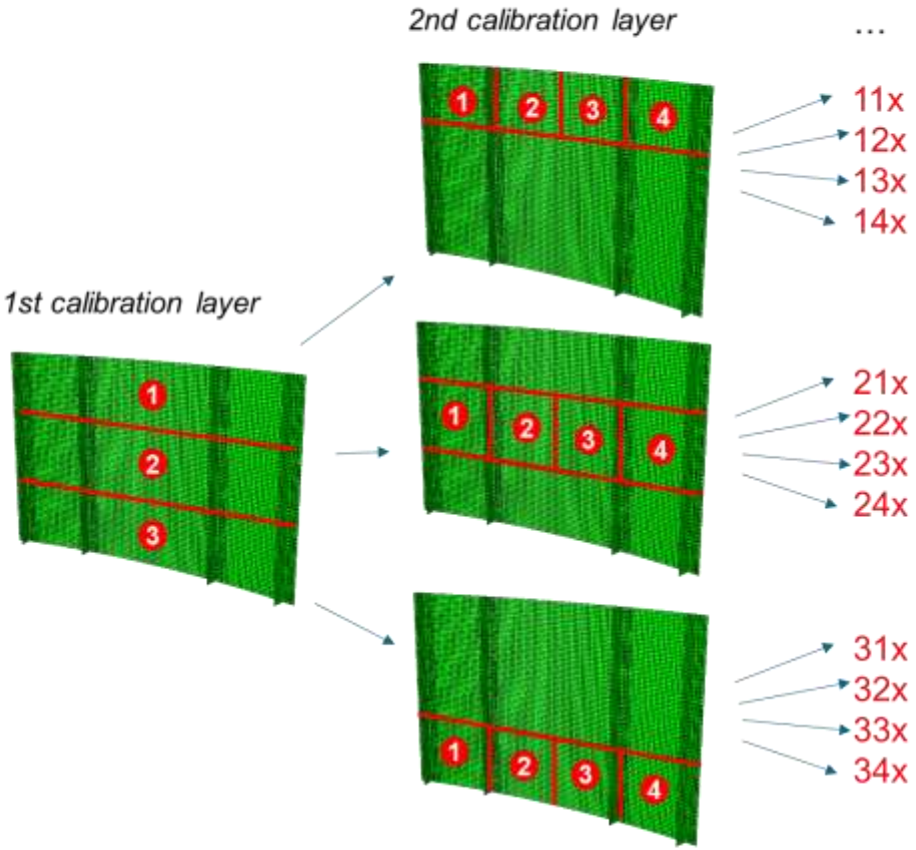
Influence of damage to the compression test





Impact damage on the stiffened panel
Degradation localization through refinement

- Hirarchical division of the structure into subdomains
- Probability based approach to find the most likely region of degradation
- References only for horizontal and vertical refinement sections
  → unhandy in terms of storage and computational effort
- Sensitivity of the local stiffness is very low
  → Even a 4000mm² is hardly detectable and likely leading to an implausible optimization

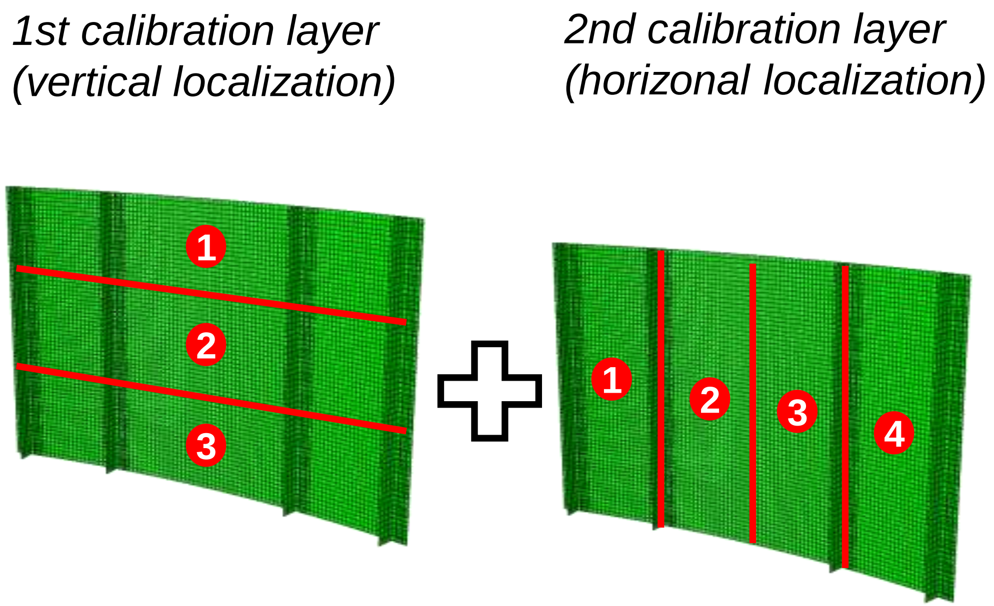


Impact damage on the stiffened panel

Grid-based degradation localization

- Each refinement requires its own reference
  → unhandy in terms of storage and computational effort

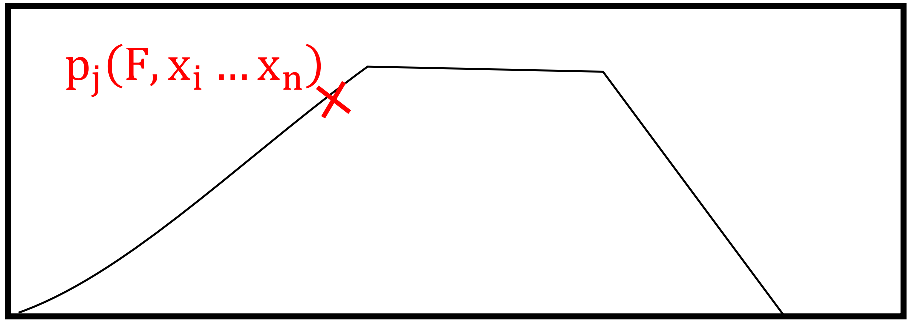
- Sensitivity of the local stiffness is very low
  → Even a 4000mm² is hardly detectable and likely leading to an implausible optimization



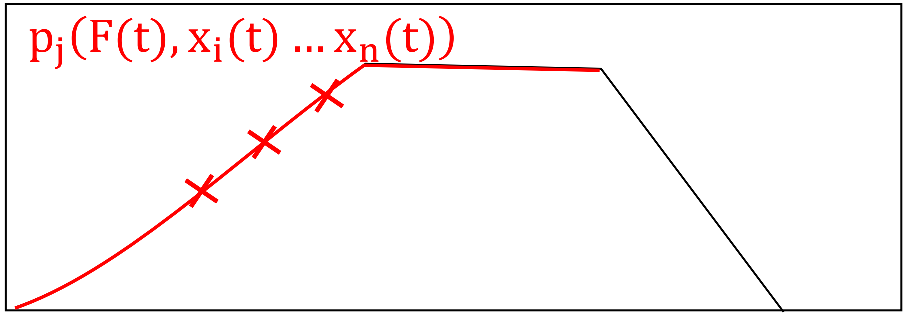
Calibration procedure

Reference data aquisition

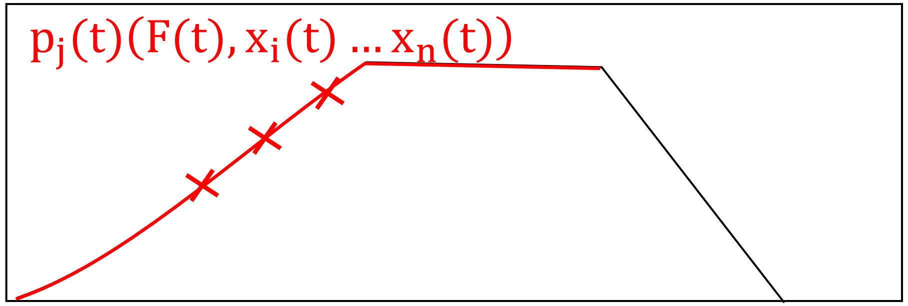
1. **Point-based calibration**
   - Selection of an individual loading point for the calibration



2. **History-based calibration**
   - Inclusion of the entire load path or a subsection from it for the calibration



3. **Nonlinear history-based calibration**
   - Der gesamte Belastungspfad, oder ein Teil davon wird in die Kalibrierung einbezogen
   - Parameter $p_j(t)$ sind keine skalaren Kennwerte sondern Funktionen



→ Compression force as independent variable