Parameter Identification based on quasi-continuous strain data captured by high resolution fiber optic sensing

Parameteridentifikation auf Basis faseroptisch gemessener quasi-kontinuierlicher Dehnungssignale

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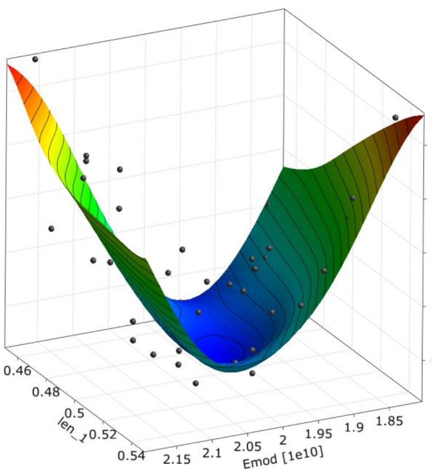
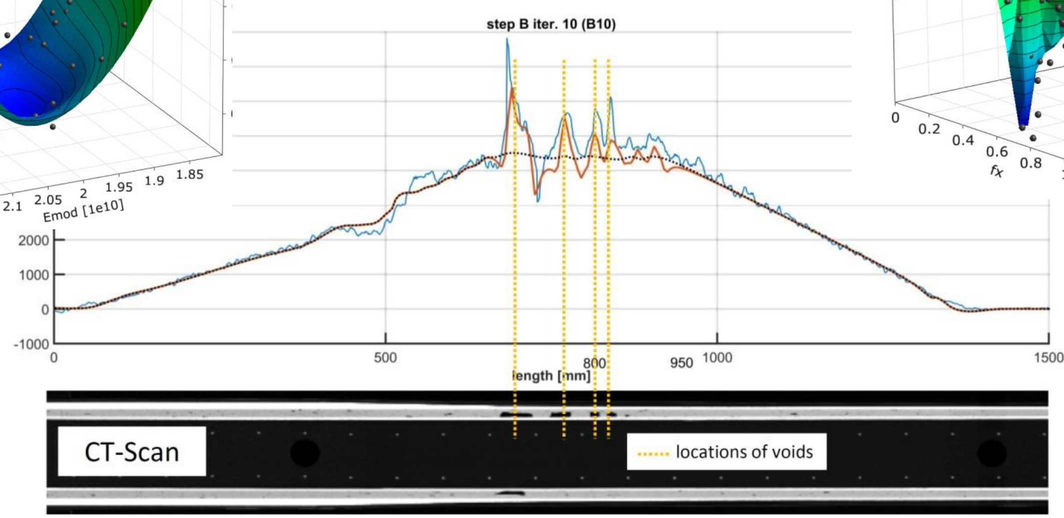
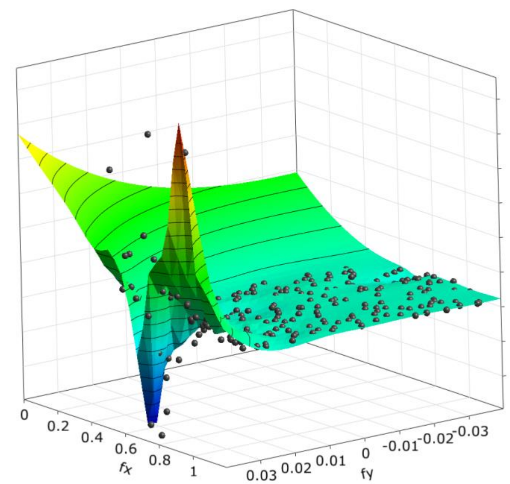
TU Berlin







Parameter Identification based on quasi-continuous strain data captured by high resolution fiber optic sensing

1. Motivation
2. Parameter identification
3. Quasi-continuous strain data
4. Fiber-optic strain measurement
5. Stepwise parameter identification approach
6. Experimental work
7. Summary and outlook

Structural Health Monitoring (SHM)

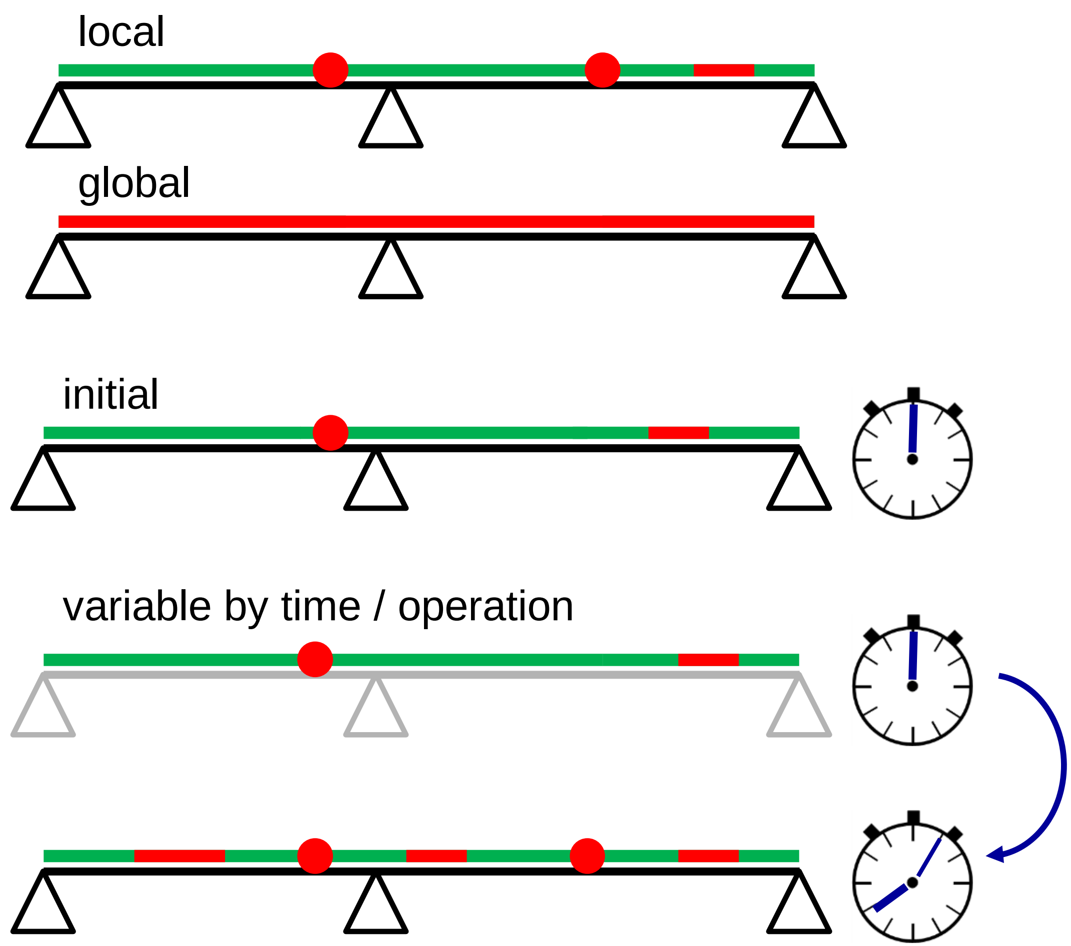
Assessment of structural integrity

1) Capture of inital state / reference state

2) Identification of imperfections and damage

3) Prediction of future state by physically meaningful model

Types of degradation



Basic approach

Structural system

Inputs (loads)

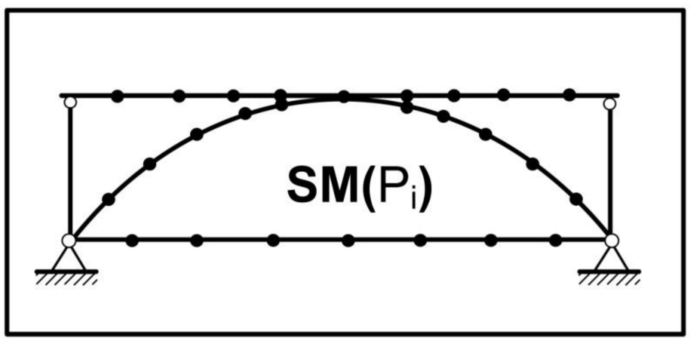
f →

→ $\mathbf{u}_m$

Responses

$\mathbf{u}_m \neq \mathbf{u}_r$

f →



→ $\mathbf{u}_r$

Structural model

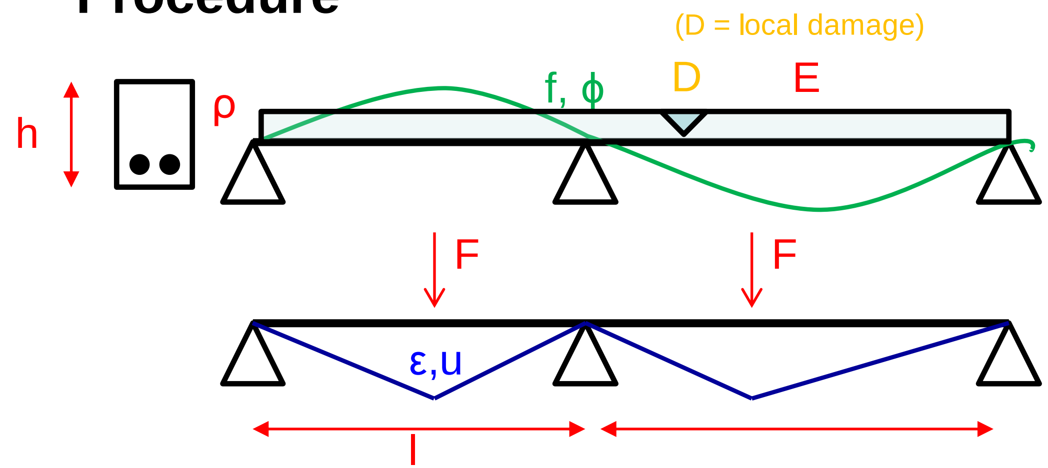
2. Parameter Identification

Procedure

design variables:

global
local

$$\mathbf{p} = \begin{Bmatrix} E \\ h \\ l \\ \rho \\ F \\ D \\ \ldots \end{Bmatrix}$$



system responses:

derived
direct

$$\mathbf{v} = \begin{Bmatrix} f \\ \phi \\ \varepsilon \\ u \\ \ldots \end{Bmatrix}$$

Vector of measured responses

Parameters / design variables

Vector of residuals: $\epsilon_w = \mathbf{W}_v \cdot \epsilon = W_v(v_M - v(p))$

Weighting matrix e.g. identity matrix

Objective function: $f(p) = \sum \epsilon_{wi}^2$

Optimization task: $\min f(p)$

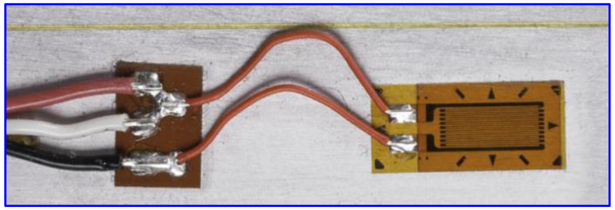
Parameter identification is basically an optimization task which can be performed in many ways

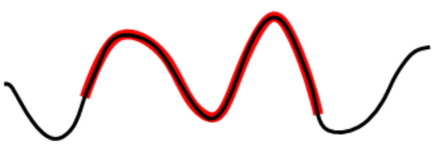
Use OptiSlang

3. Quasi-Continuous Strain Data

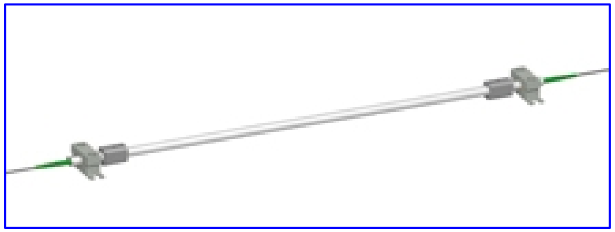
From discrete to quasi-continuous measurement data

Point sensor,
e.g. strain gauge, accelerometer,
temperature sensor,
displacement sensor

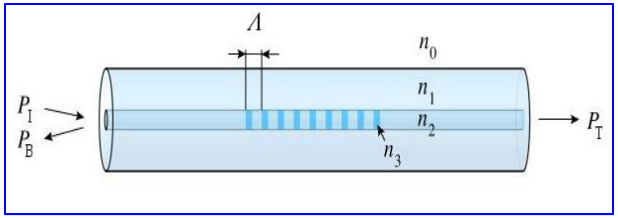


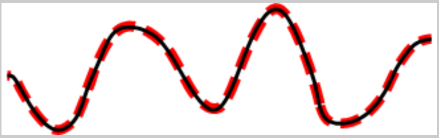


Integrating sensor, e.g. fiber-optic extensometer



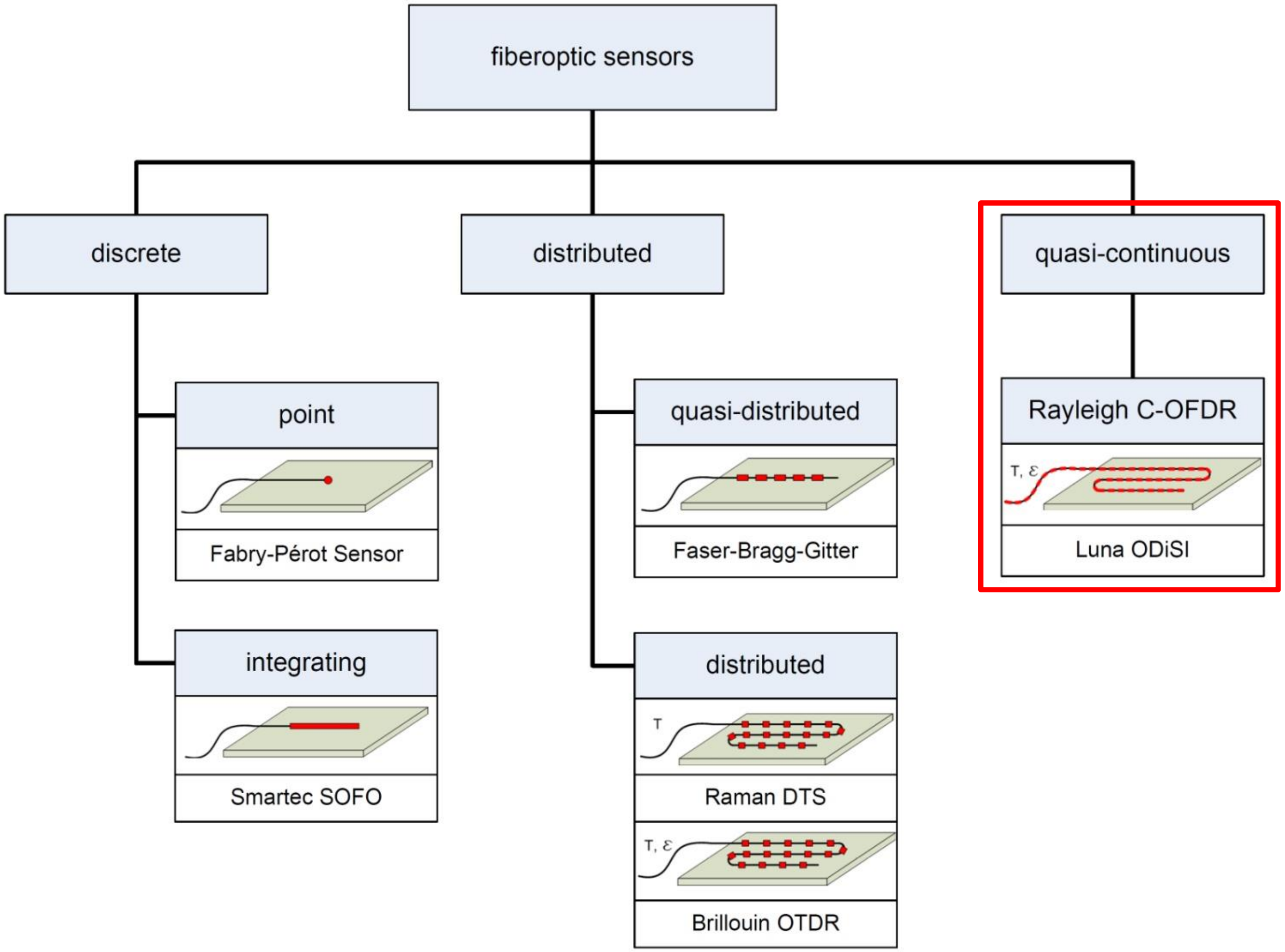
Distributed sensor, e.g. Fiber-Bragg-Grating Sensor



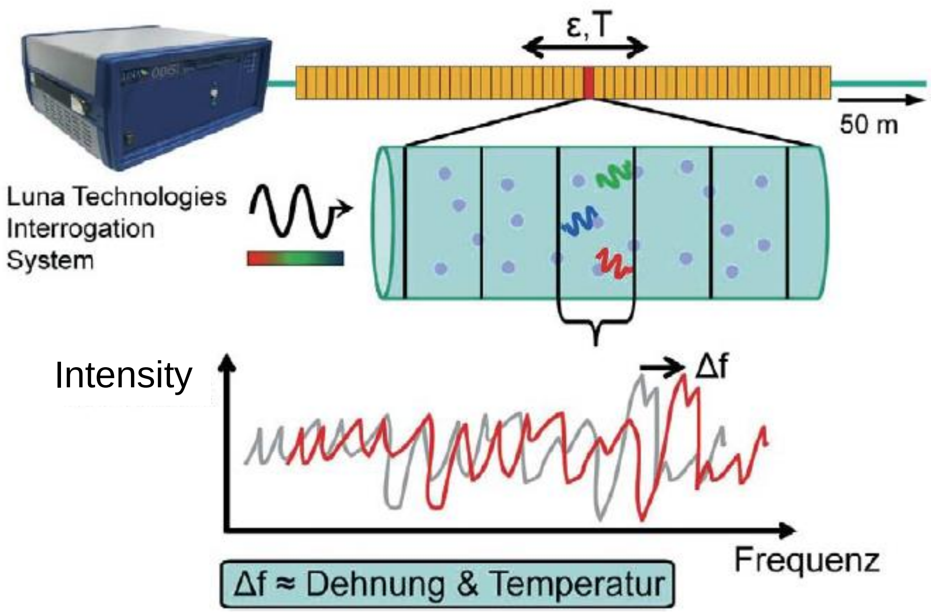


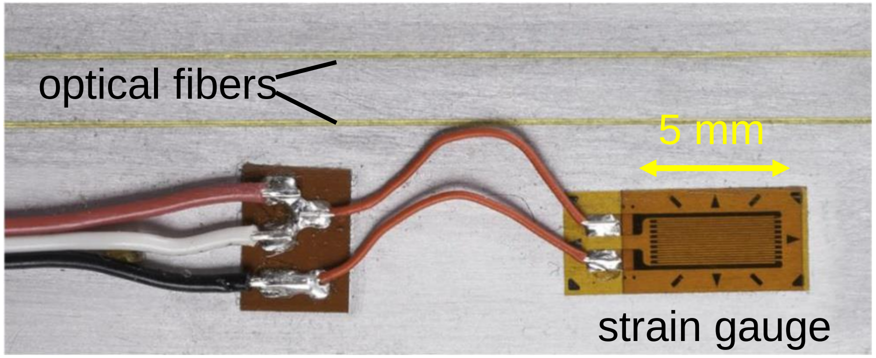
High resolution sensor, e.g.
Rayleigh-based fiber-sensing

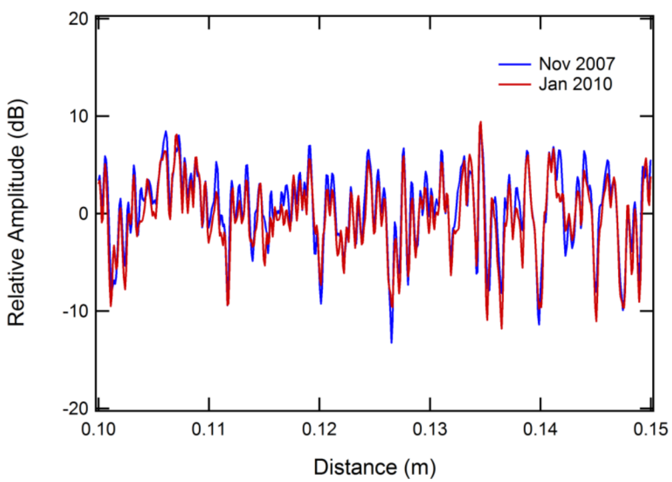
Fiber optic sensing topologies



Principle: Rayleigh-scattering based strain sensing



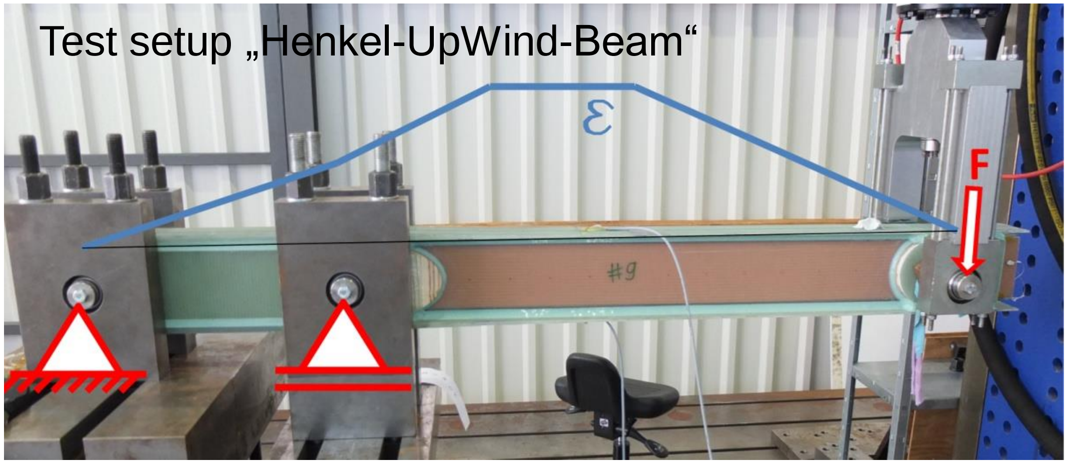


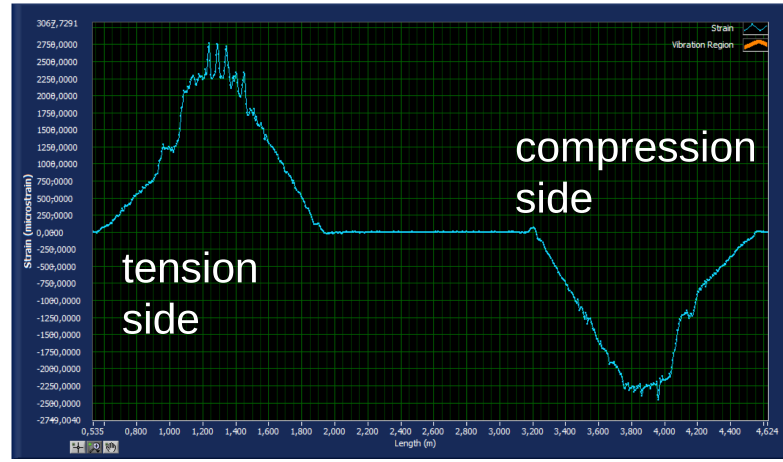


- Rayleigh-backscattering is a stable, fluctuating variation of intensitiy along the fiber – „fingerprint“
- It is caused by fluctuations in the material composition of the optical fiber

Alle Bilder: Quelle: Luna Technologies

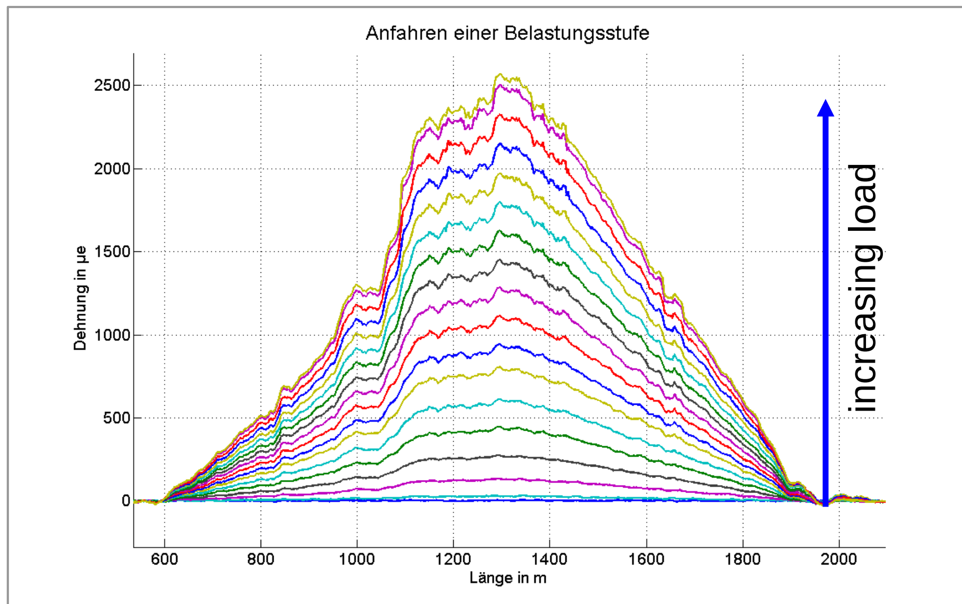
4. Fiber-Optic Strain Sensing

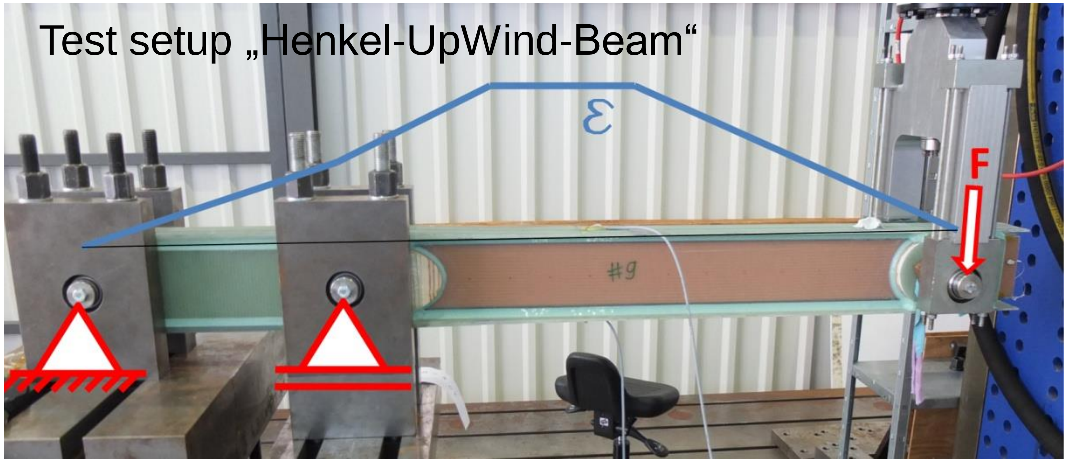


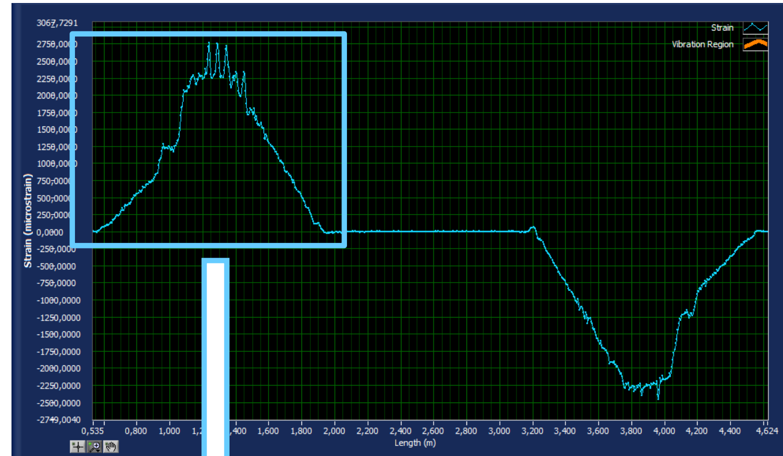


ODiSI System (Luna Technologies):

- Fiber length max. 10 m / 50 m
- Spatial resolution 1,25 mm / 5 mm
- Noise level 20 µε / 5 µε
- Measurement rate 23,5 Hz / 50 Hz
- max. measurable strain ca. 1%







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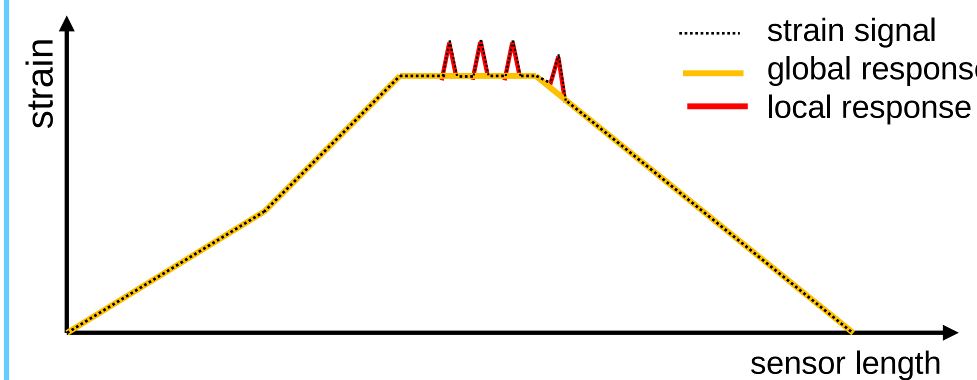
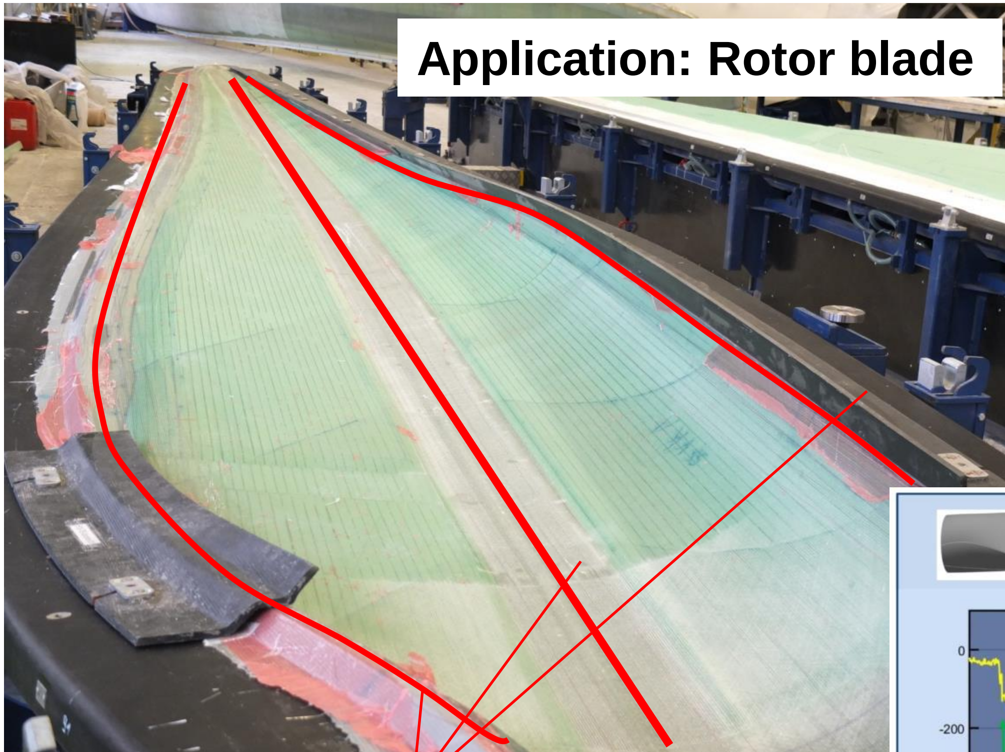
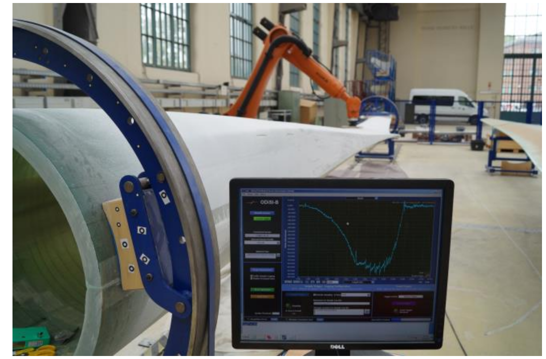


The quasi-continuous strain signal contains global and local information !

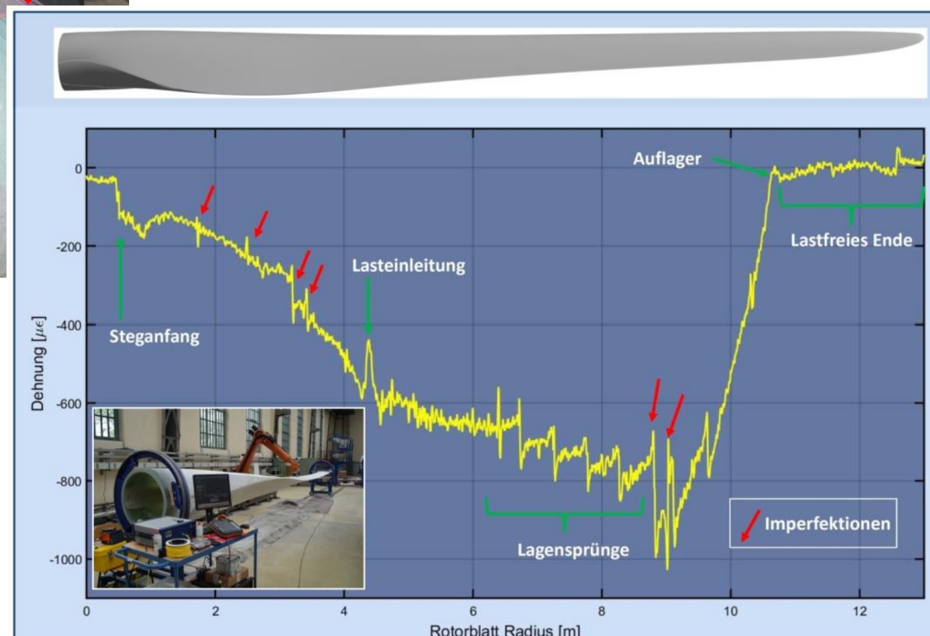


Strain in the fiber along the spar cap due to bending load and beam-like support



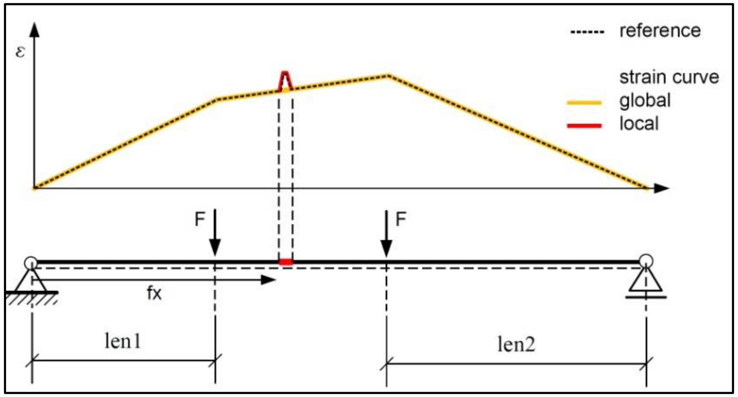
Sensor positions:

- Leading and trailing edge
- Spar caps



Interpretation of measured signal

Quasi-continuous strain signal

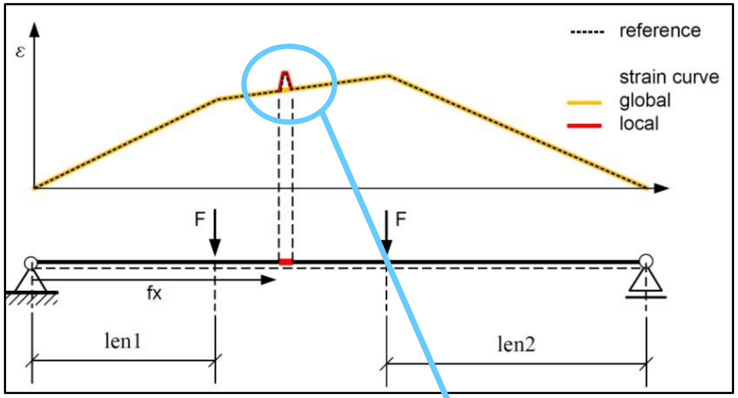


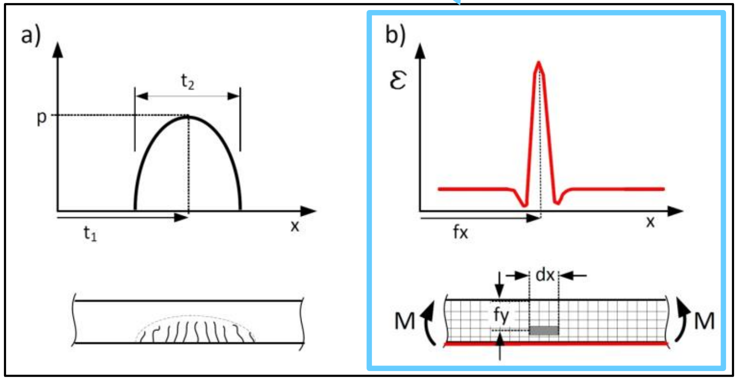
<u>*Classic* parameter identification approach:</u>

- Local properties (e.g. Young's modulus) variable in each element
- Very large space of unknowns: $n = m^k$
- Different kinds of value / resolution types for loacl and global parameters

5. Stepwise Parameter Identification Approach

Quasi-continuous strain signal

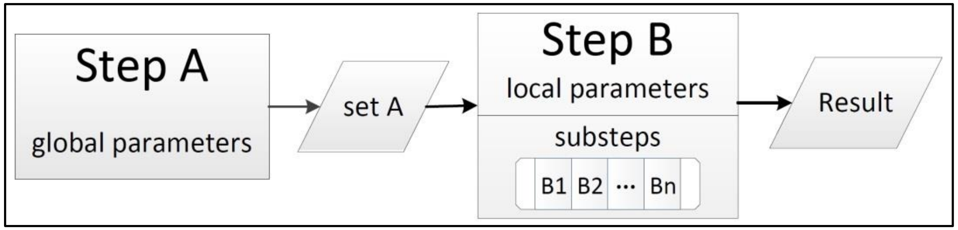




Damage function (analytical)

Shape function (FE-Model)

Solution: Stepwise approach:



First step: Identification of global parameters

Step A

Second step: Identification of local parameters

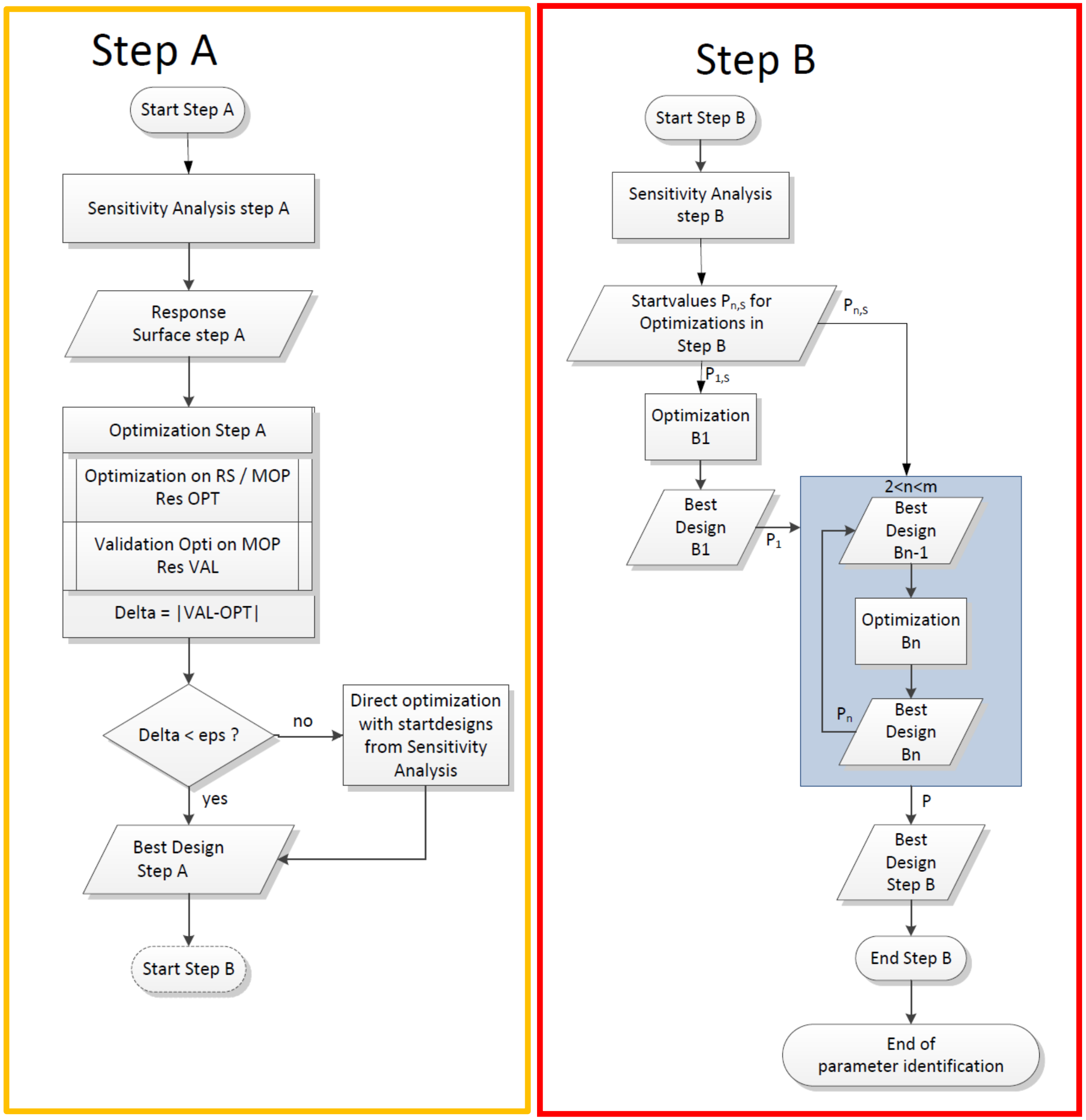
- Introduction of shape functions covering effect of local discontinuity (b)
- Basis: Damage functions for concrete (a) (Teughels and De Roeck 2005)
- Iterative identification of local discontinuities in substeps

Step B

5. Stepwise Parameter Identification Approach

Identification of global parameters

Reference state for Step B

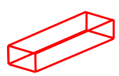


Reference state from Step A

Completely identified parameter set

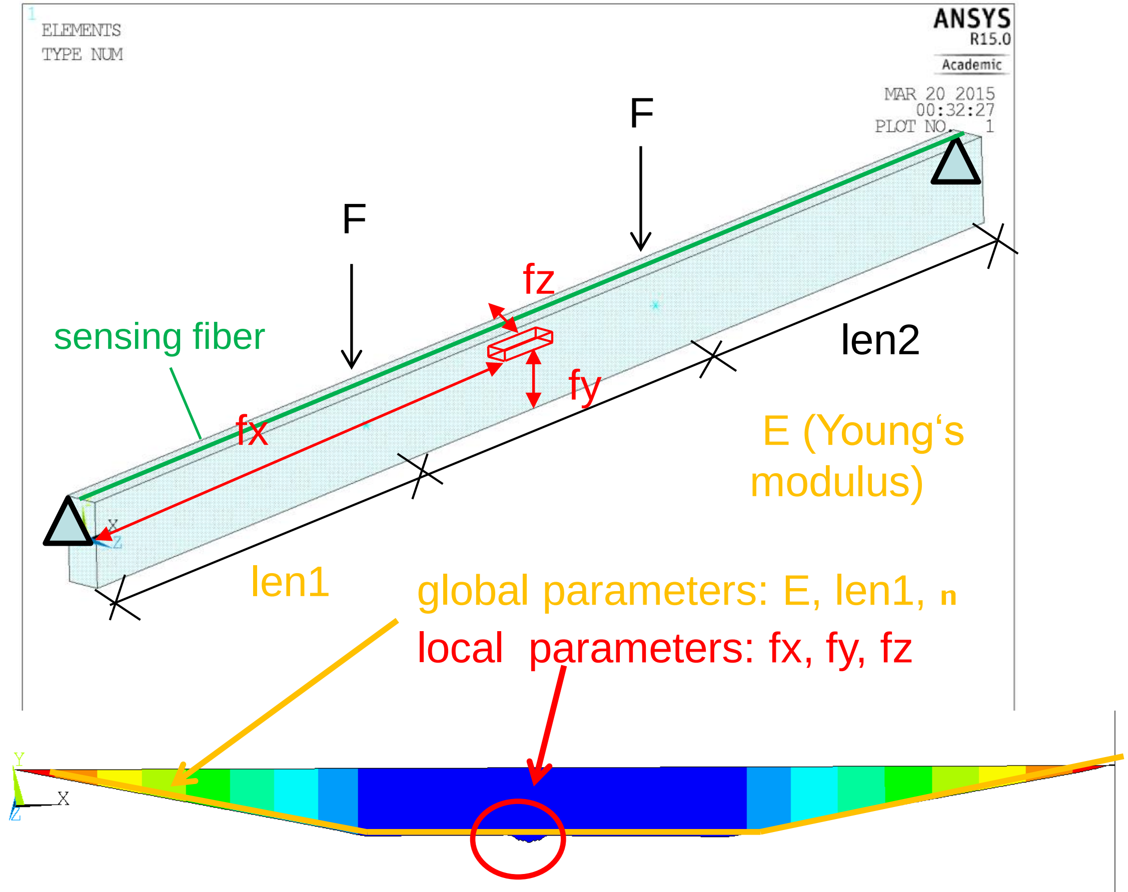
Simulation example

- Global portion of strain signal
  - due to global parameters E, len1, n
  - large influence on objective function
  - obscuring local effects
  - parameters of continuous distribution type
- Local portion of strain signal
  - due to local parameters fx, fy, fz of disturbance



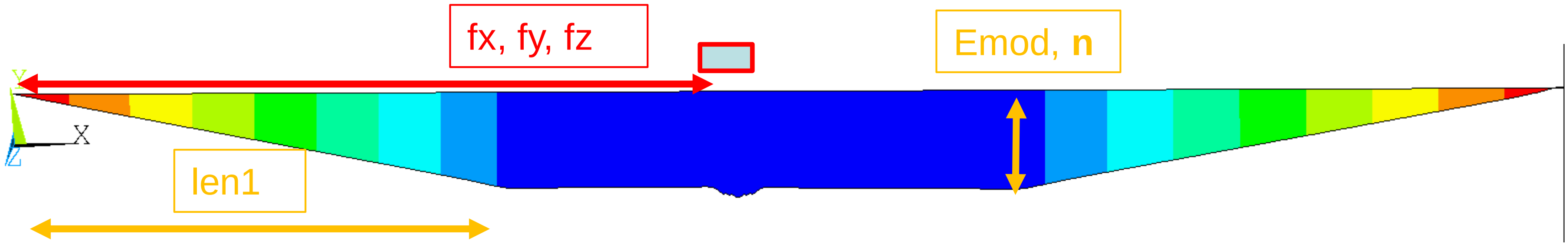
  - location assumed to be unknown
  - parameters mesh-dependent and therefore of discrete type
- Separation of parameters
  - E, len1, n - Step A
  - fx, fy, fz – Step B

Beam in 4-point bending test (FE-Simulation)



Strain signal in virutal sensing fiber

5. Stepwise Parameter Identification Approach



	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range		Range plot
4	Emod	Optimization	2.1e+10	☐	REAL	Continuous	1.8e+10	2.2e+10	
5	fy1	Optimization	0	☑	REAL	Ordinal discrete by value	-0.04; -0.035; -0.03; -0.025; -0.02; -0.01; 0; 0.01; 0.02; 0.025; 0.03; 0.035; 0.04		
6	fy2	Optimization	0	☑	REAL	Ordinal discrete by value	-0.04; -0.035; -0.03; -0.025; -0.02; -0.01; 0; 0.01; 0.02; 0.025; 0.03; 0.035; 0.04		
7	fy3	Optimization	0	☑	REAL	Ordinal discrete by value	-0.04; -0.035; -0.03; -0.025; -0.02; -0.01; 0; 0.01; 0.02; 0.025; 0.03; 0.035; 0.04		
8	fz1	Optimization	0	☑	REAL	Ordinal discrete by value	-0.01; 0; 0.01		
9	fz2	Optimization	0	☑	REAL	Ordinal discrete by value	-0.02; -0.01; 0; 0.01; 0.02		
10	fz3	Optimization	0	☑	REAL	Ordinal discrete by value	-0.02; -0.01; 0; 0.01; 0.02		
11	len_1	Optimization	0.5	☐	REAL	Continuous	0.45	0.55	
12	len_3	Optimization	0.53	☑	REAL	Continuous	0.45	0.55	
13	Nue	Optimization	0.32	☐	REAL	Continuous	0.27	0.33	
14	nx1	Optimization	60	☑	INTEGER	Ordinal discrete by index	[0-140];		
15	nx2	Optimization	60	☑	INTEGER	Ordinal discrete by value	[0-140];		
16	nx3	Optimization	60	☑	INTEGER	Ordinal discrete by index	[0-140];		

Parameter | Start designs | Criteria | Simplex | Other | Result designs

Definition of the model's parameters in OptiSlang

☐ Prefer parameter from slot

global, continuous

local, discrete

(parameter set for 3 iterations in step B)

Objective function: Minimum of sum of least squares

```
! -------- Parameter  ---------
breite = 0.04
hoehe = 0.1
laenge = 1.5
len_1 = 0.48
len_3 = 0.53
len_2 = laenge-len_1-len_3

! ------- Vernetzung ------
```

Step A: Portion of strain signal with low influence of local effects preferred:

f_a = min(S(eps1i – eps1i_ref)² + S(eps2i – eps2i_ref)²)

Step B: Whole signal evaluated:

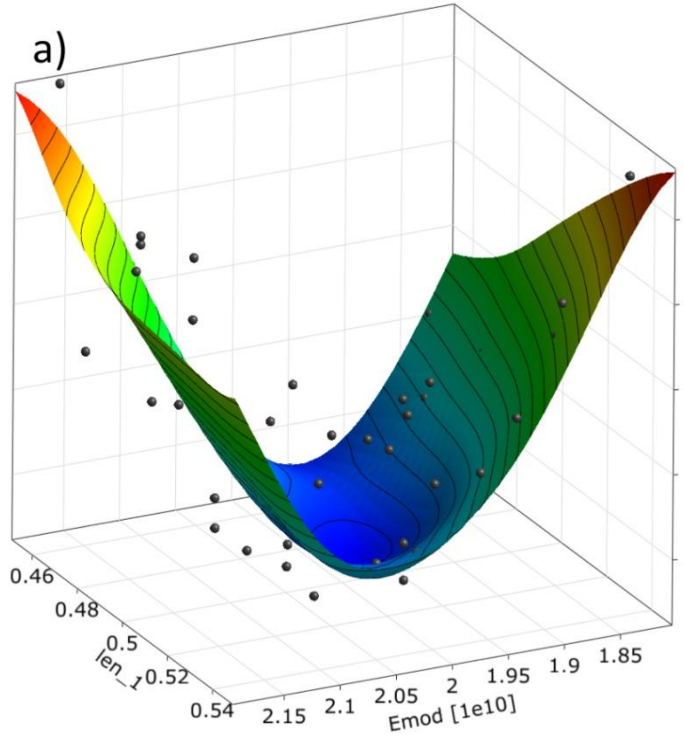
f_b = min(S(epsi – epsi_ref)²)

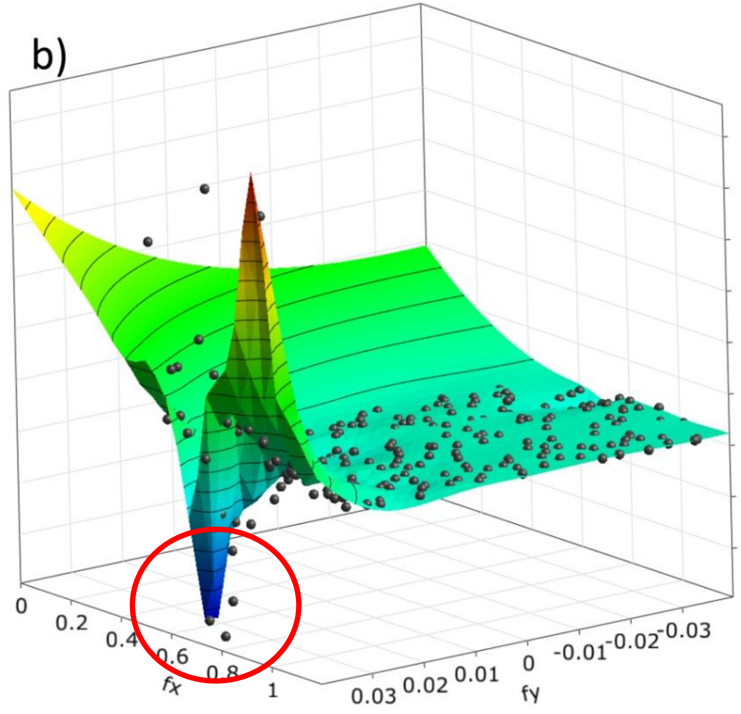
Visualization of optimization characteristic by MOP / RS

Evaluation of sensitivity analysis

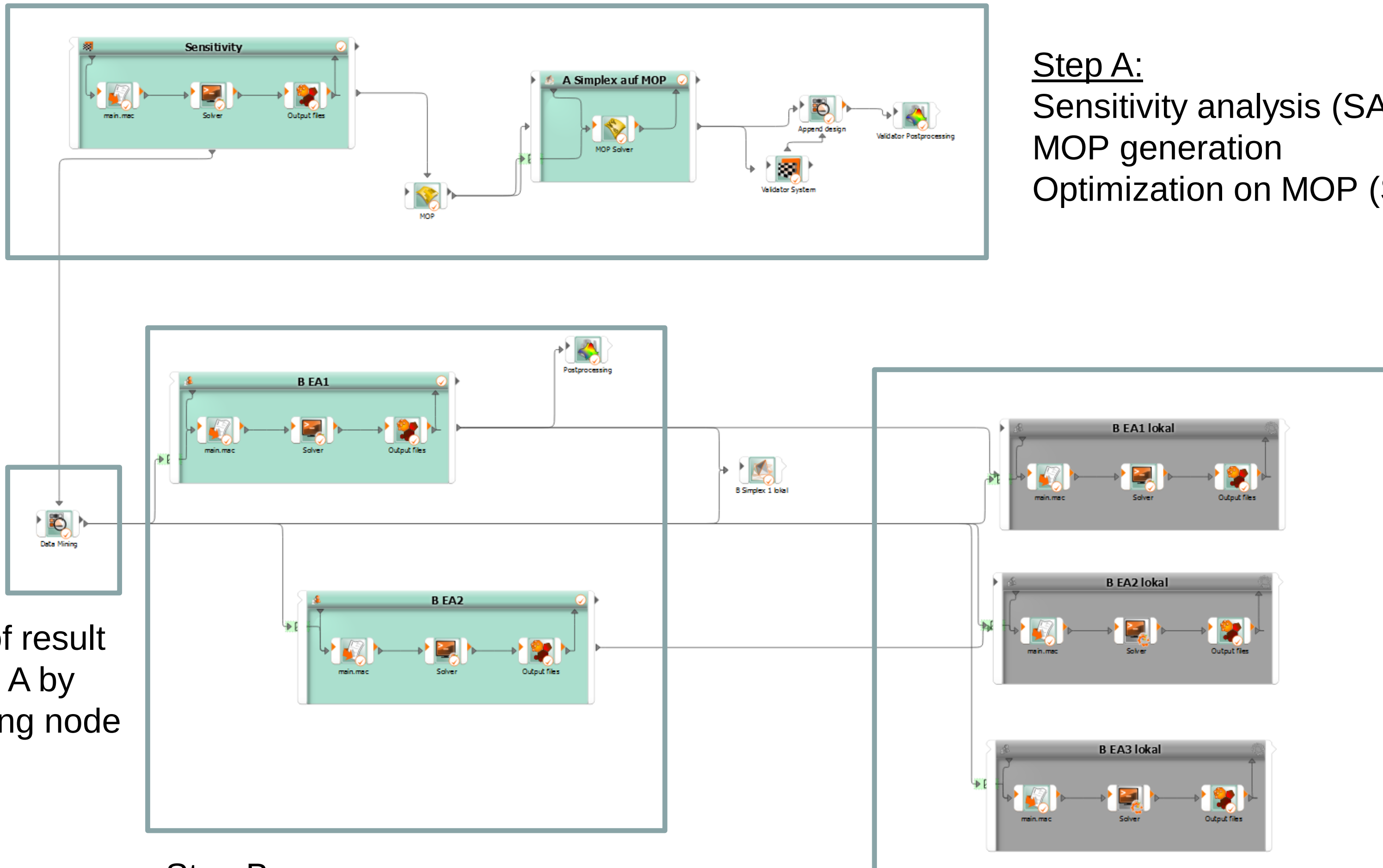
Step A: Smooth and convex RS

Step B: sharply bounded minimum





Implementation in OptiSlang



Step A:
Sensitivity analysis (SA)
MOP generation
Optimization on MOP (Simplex)

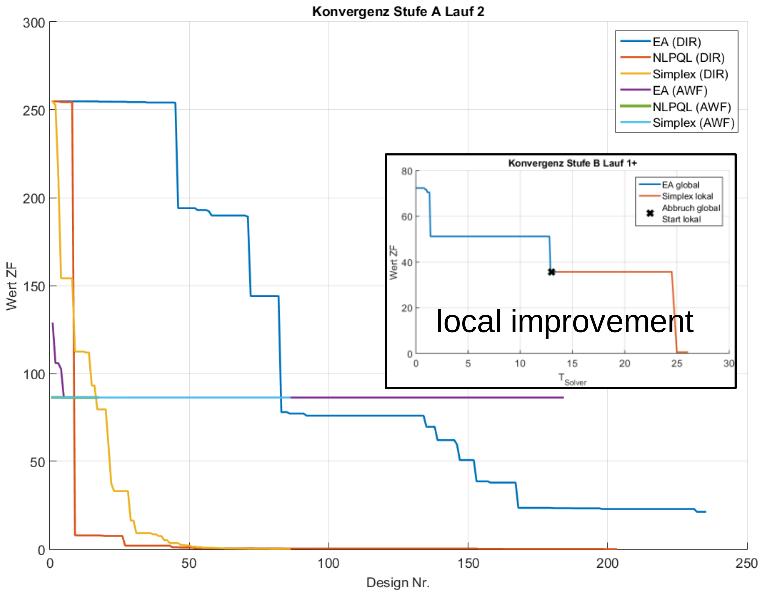
Capture of result from Step A by Data Mining node

Step B:
Optimization with EA

Step B:
Local improvement with EA

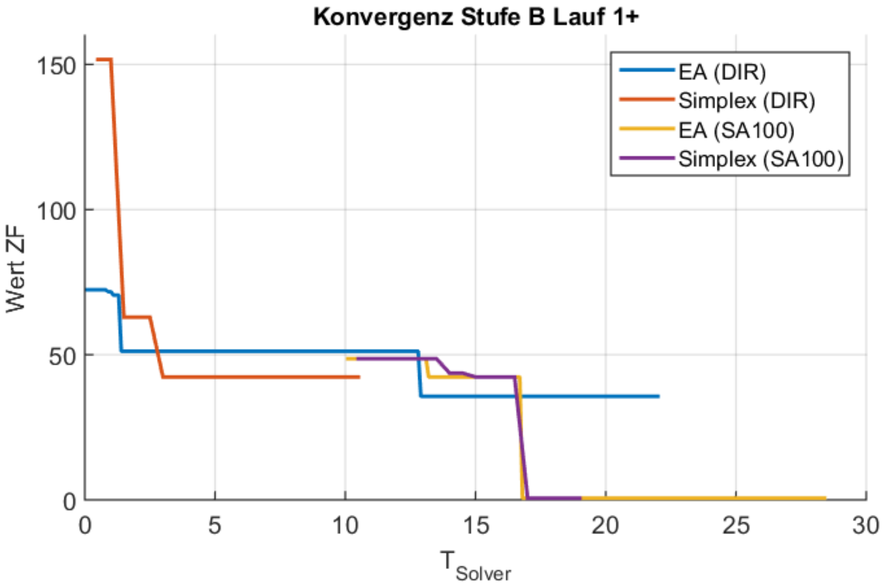
Performance

Step A



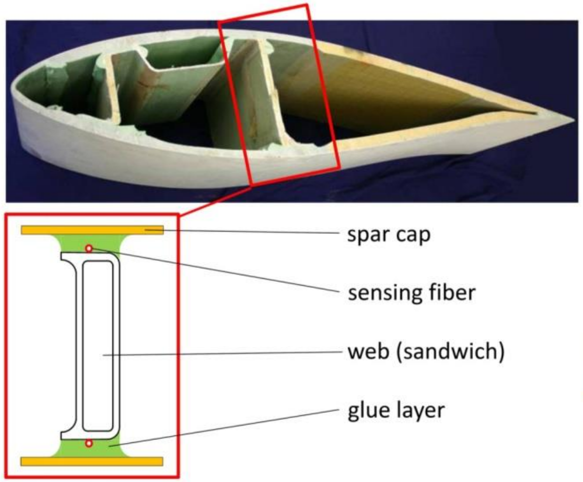
- Fastest convergence for NLPQL
- Simplex comparable to NLPQL
- EA needs many solver calls but allows for parallel solver runs
- Local improvement of EA result by Simplex is best solution

Step B

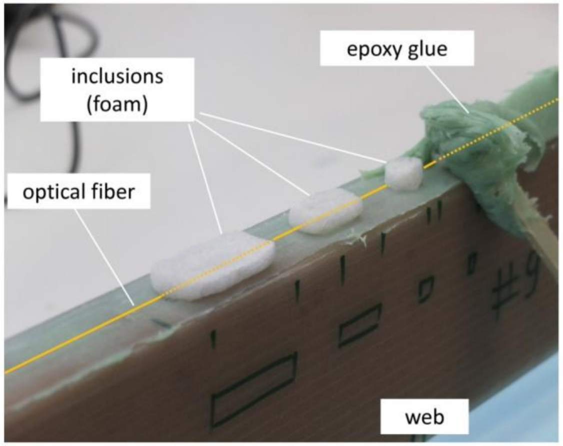


- Gradient-based algorithms not feasible due to discrete parameters
- Best results when combining start values from SA with local optimization settings
- All local parameters identified correctly by EA and Simplex with SA

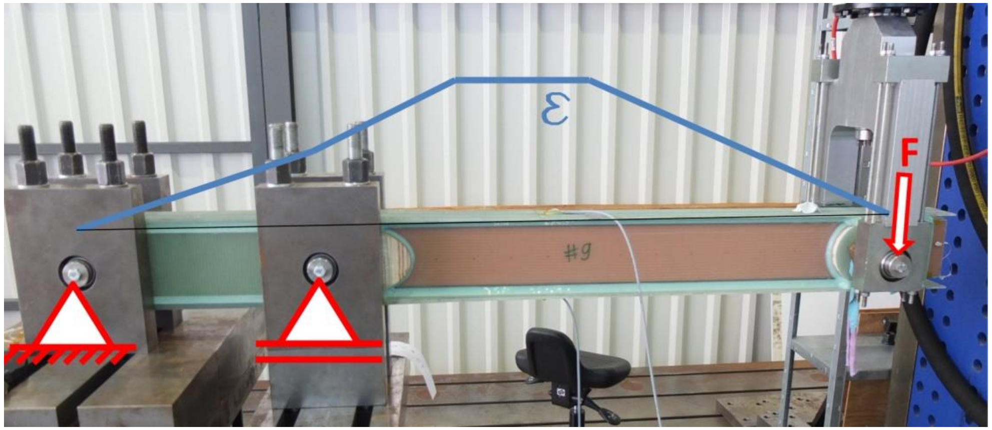
Sub-component of rotor blade structure in test setup „Henkel-UpWind-Beam“ (Fraunhofer IWES)



Definition of sub-component



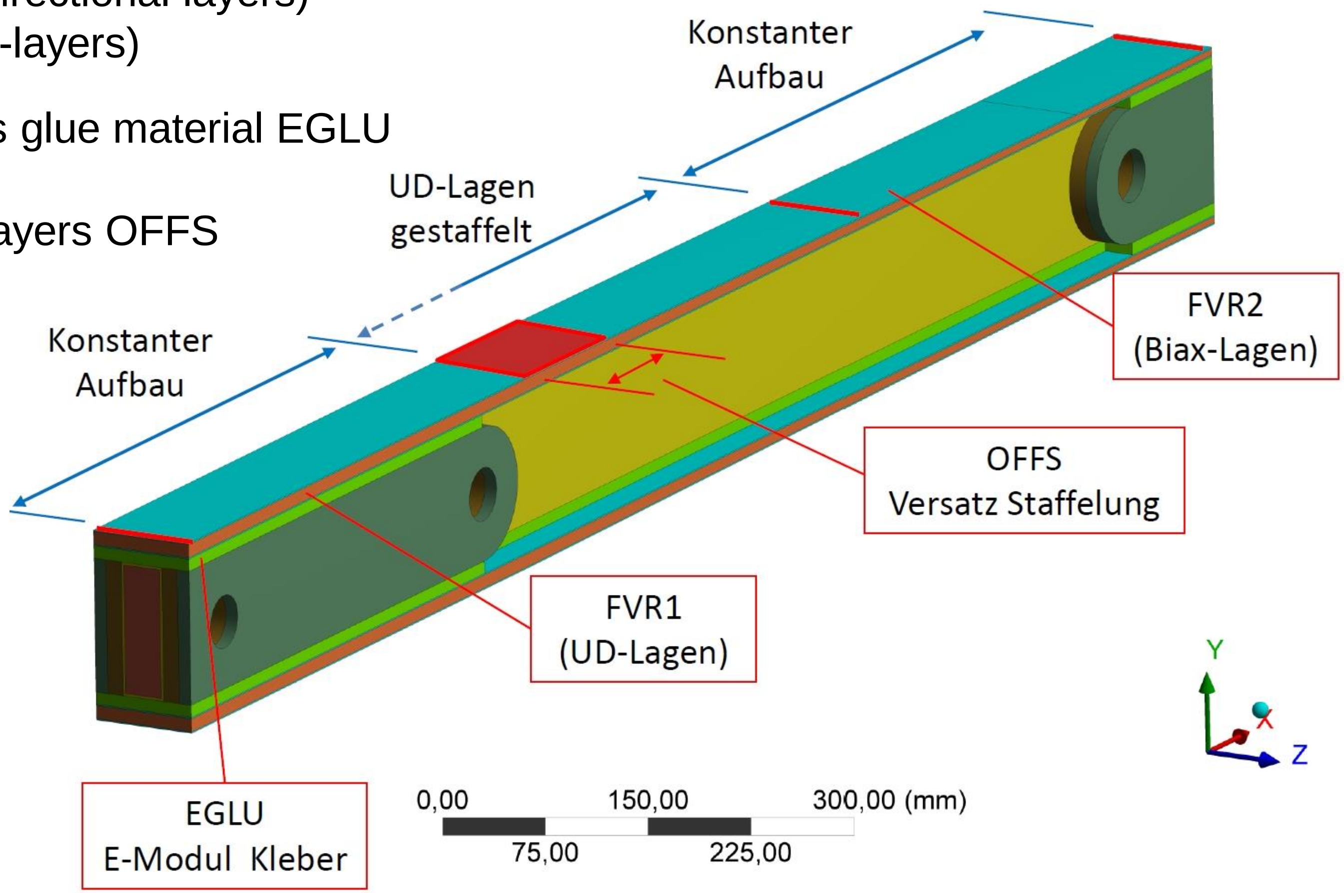
Sensing fiber and artificial defects in glue layer



Test setup: Support conditions, load and strain signal

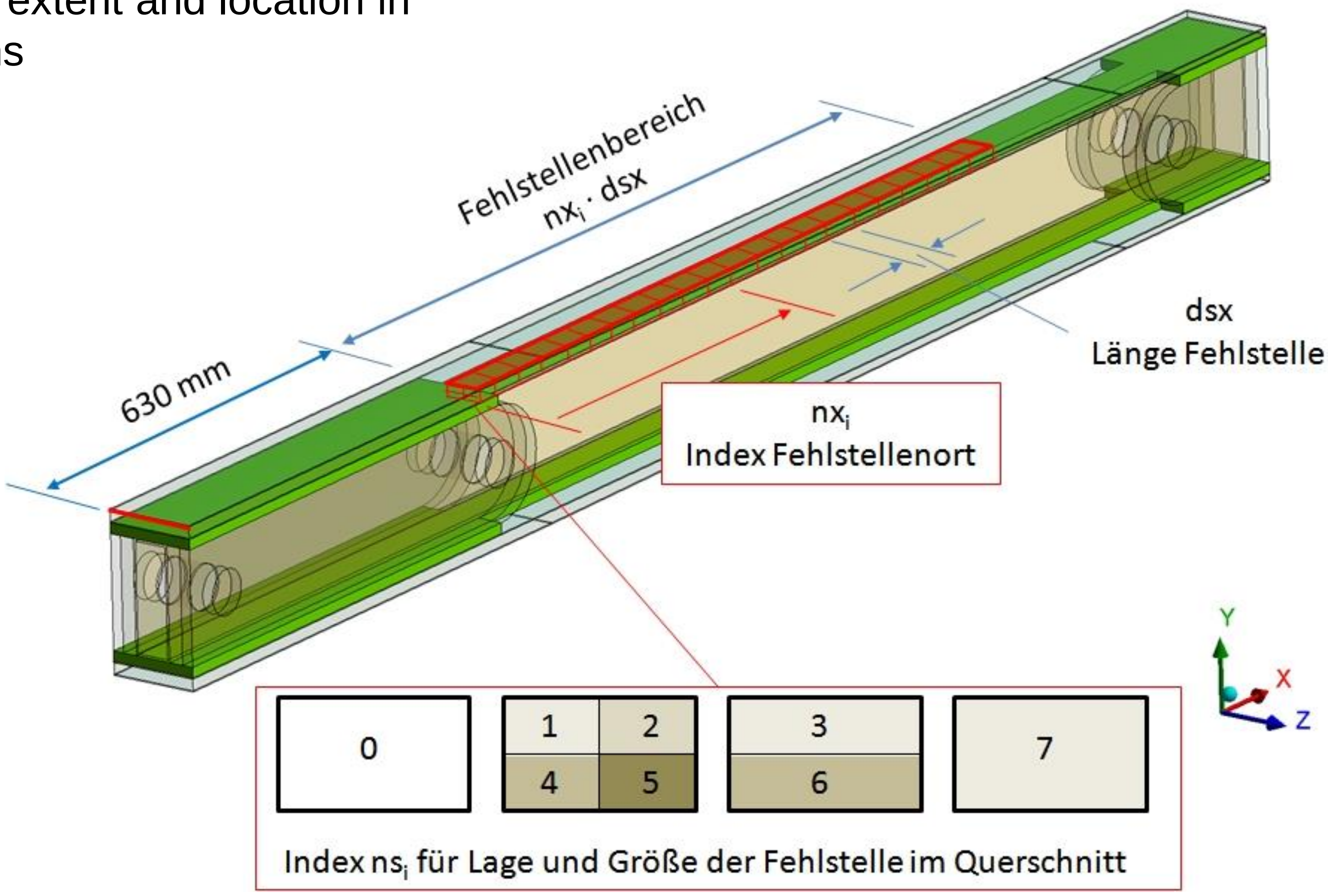
Definition of model parameters in step A:

- Stiffness determining parameters for GFRP-components
    - FVR1 (unidirectional layers)
    - FVR2 (biax-layers)
- Young‘s modulus glue material EGLU
- Offset spar cap layers OFFS



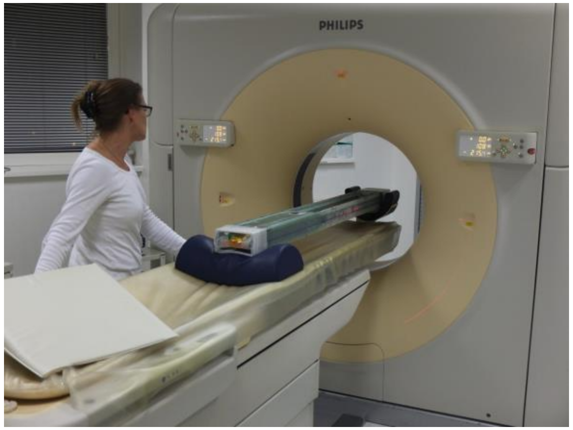
Definition of model parameters in step B:

- Location of local defect nx
- Index of defect extent and location in cross section - ns

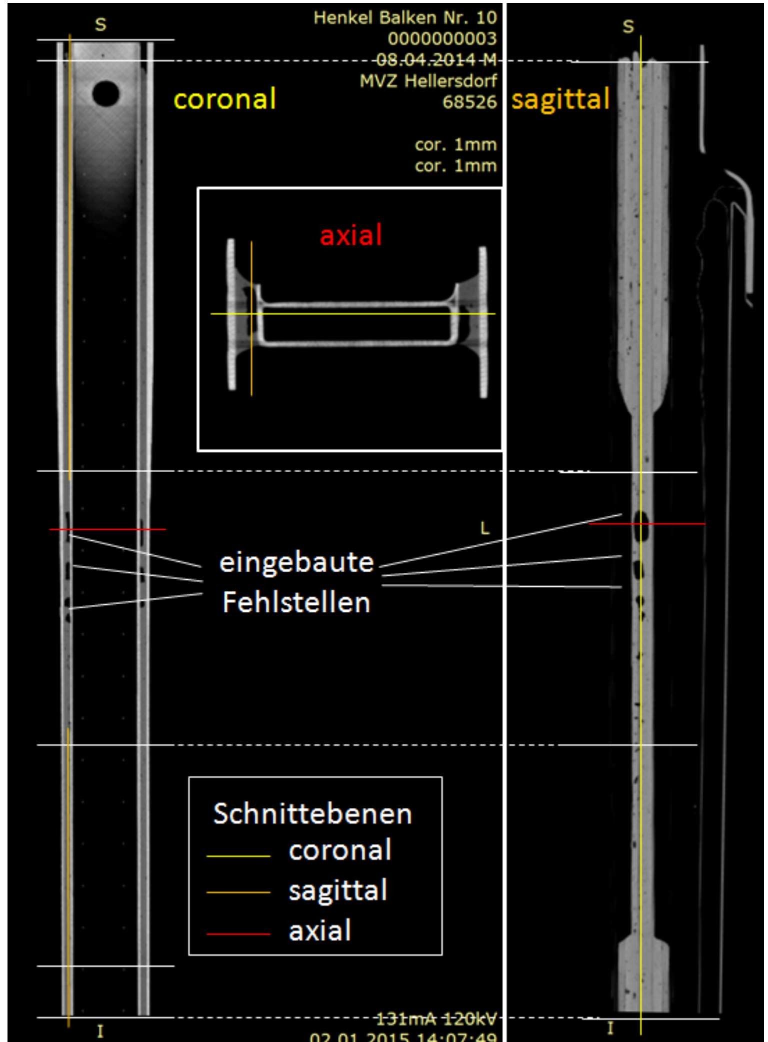


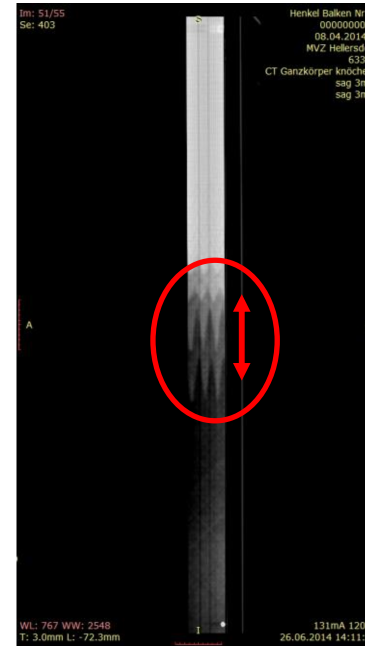
Local imperfections

global imperfections



CT-scans are used to evaluate parameter identification results



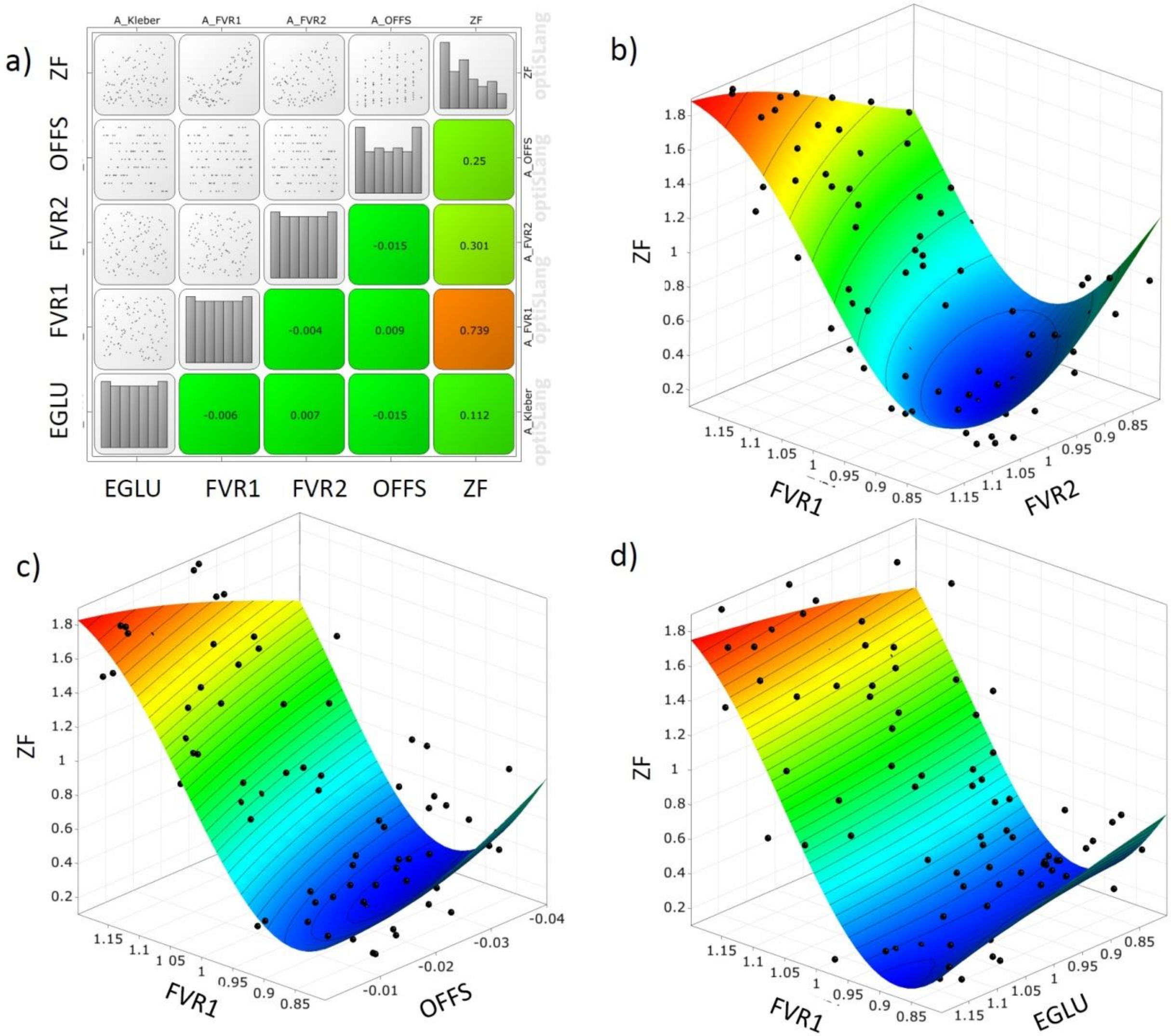


Tapered GFRP-layers in spar caps

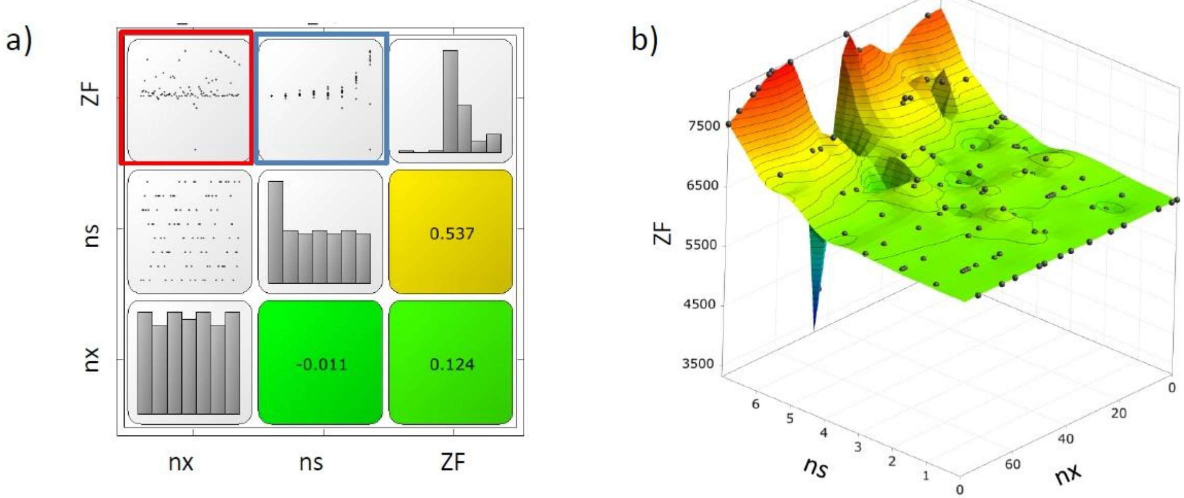
Artificial defects as well as unintendet voids are visible in CT-scan

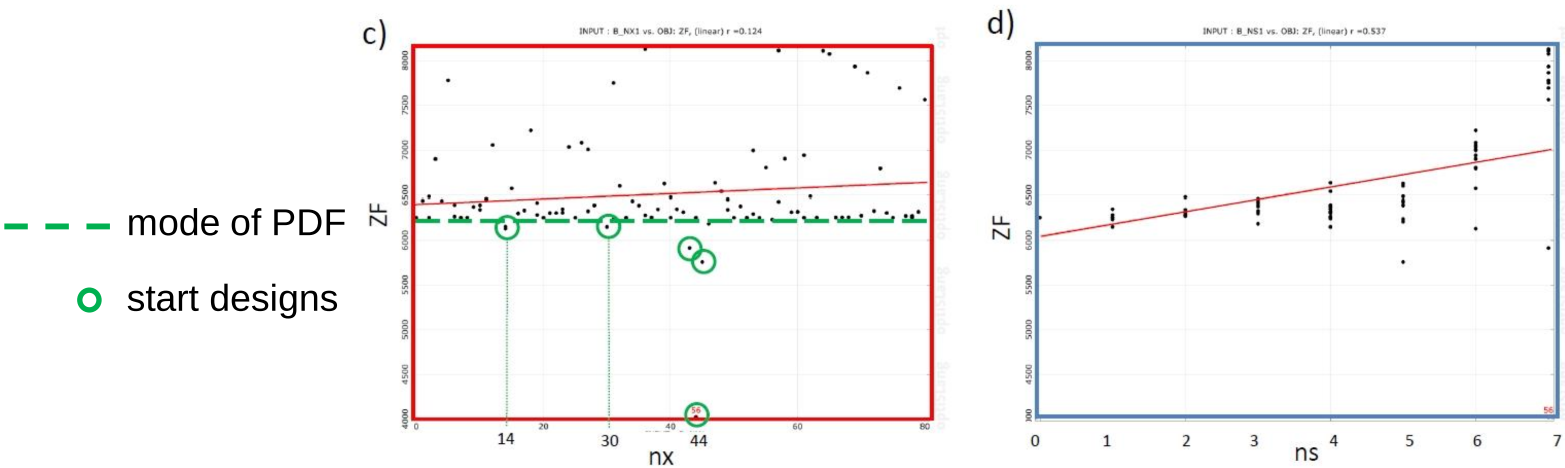
6. Experimental Work

Correlation matrix and MOP in Step A



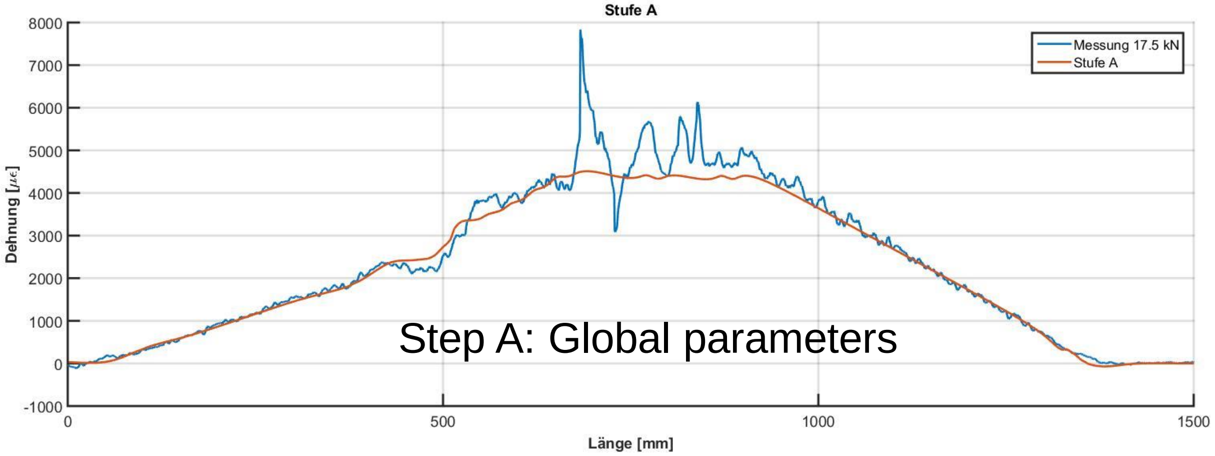
Correlation matrix (a) and MOP (b) in Step B



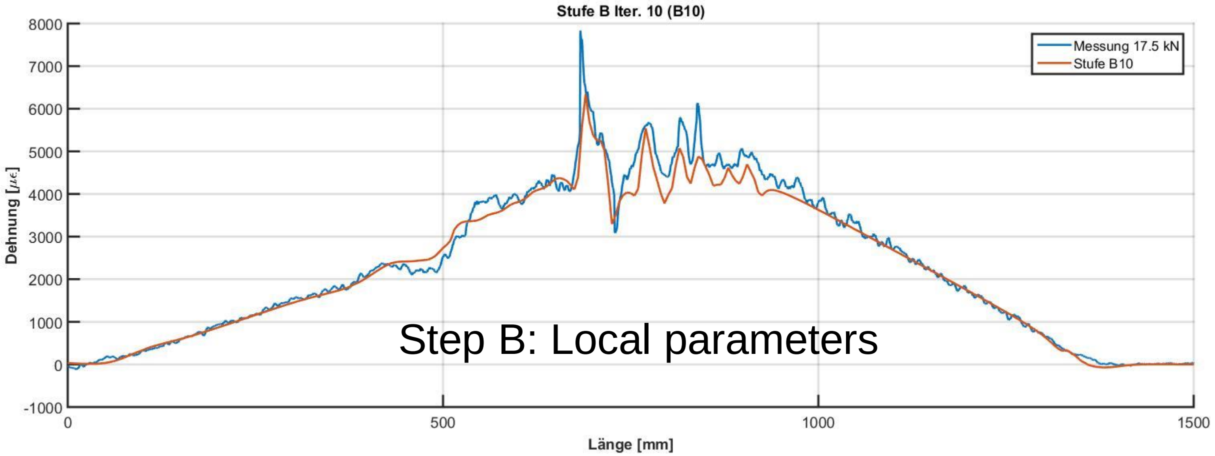


Anthill plot for x-.location nx (c) and defect index ns (d)

Results



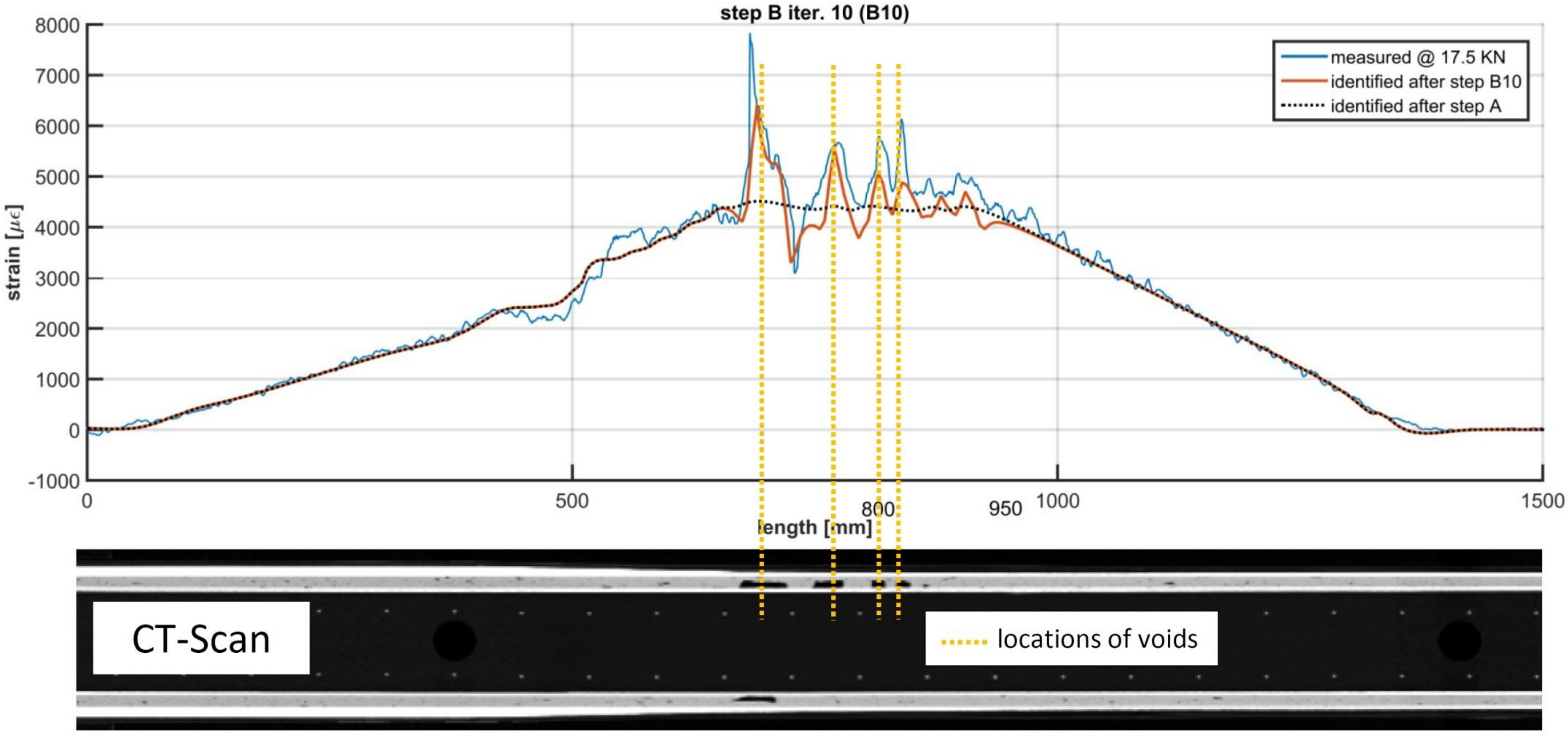
Step A: Global parameters



Step B: Local parameters

Results

Comparison of identified voids with CT-scan



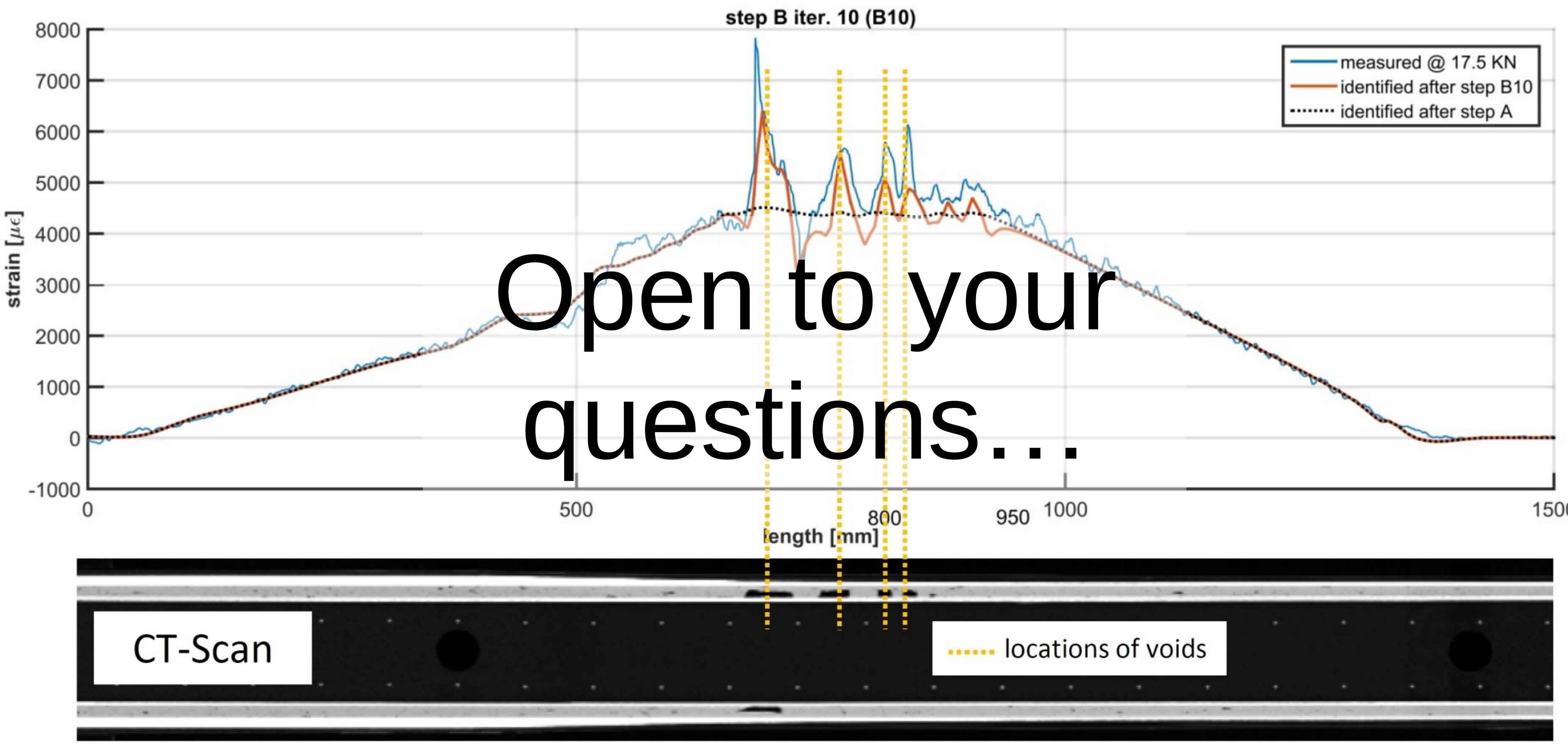
Summary:

- Stepwise parameter identification approach for strategic evaluation of quasi-continuous strain data
- Signal capturing by high-resolution fiber optic sensing system
- Determination of global and local parameters
- Efficient optimization task due to grouping of parameters by physical meaning and distribution type
- Successfull application to „real-world“ experimental setup

Outlook:

- Enhancement of efficiency (optimization algorithms, settings)
- Application / extension to dynamic sytems
- Software integration

Open to your questions…



Special thanks to: Fraunhofer IWES, Fa. Polytec, MVZ Hellersdorf