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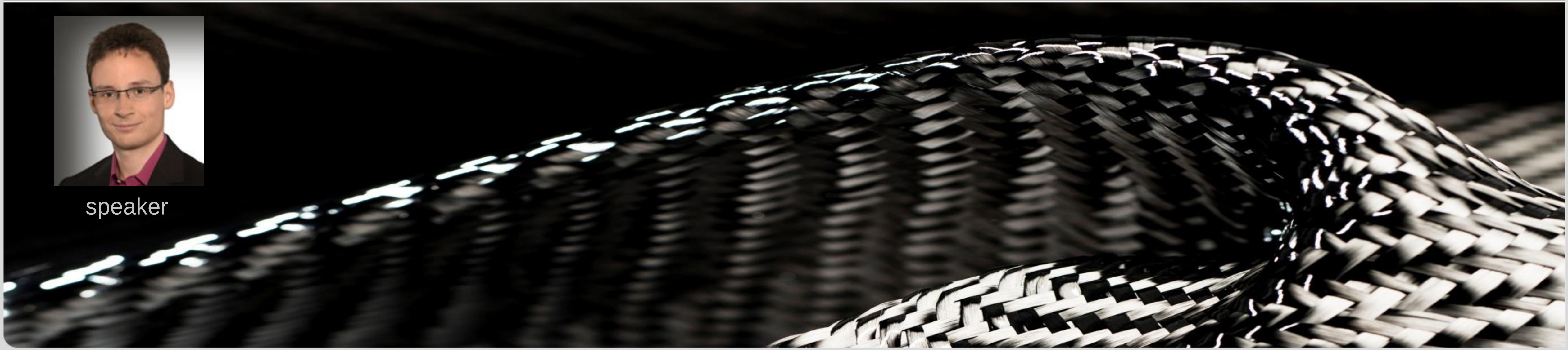
Rapid Determination of Suitable Reinforcement Type in Continuous-Fibre-Reinforced Composites For Multiple Load Cases

Virtual ICCS23 in Porto/Portugal

Clemens Zimmerling[1], Benedikt Fengler[1,2], Haitao Wen[1], Zeyu Fan[1], Luise Kärger[1]

[1]: Karlsruhe Institute of Technology (KIT), Institute of Vehicle System Technology, Karlsruhe, Germany
[2]: Simutence GmbH, Karlsruhe, Germany



speaker

Motivation
Optimising Fibre-Reinforced Composites

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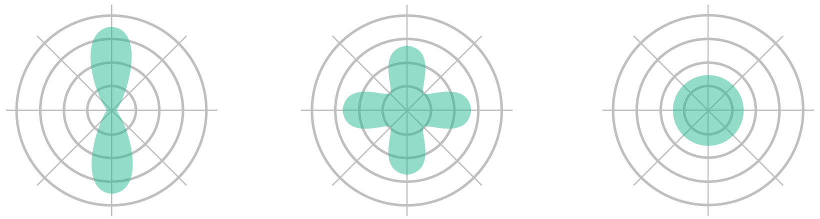
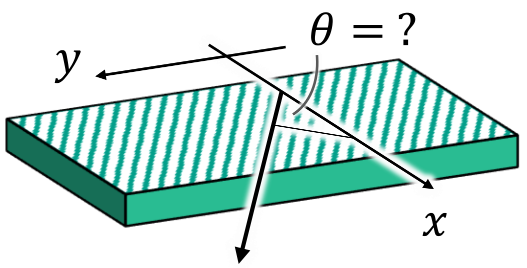
Composite Materials – Structural aspects

- High weight-specific stiffness/strength
- Anisotropic behaviour → requires particular attention



Early phases of component design

- Major design decisions necessary [Kle15]
  - Reinforcement type (uni-/bi-directional vs quasi-isotropic)
  - Material orientation
- Current approaches
  - Analytical, closed-form solutions,
    → limited to simple geometries and load cases
  - Large, complex components require numerical approaches
    → time-intensive numerical optimisation

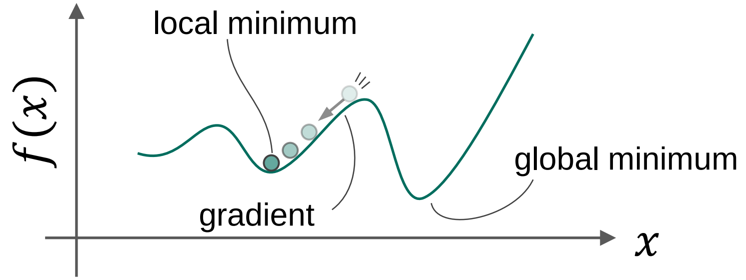


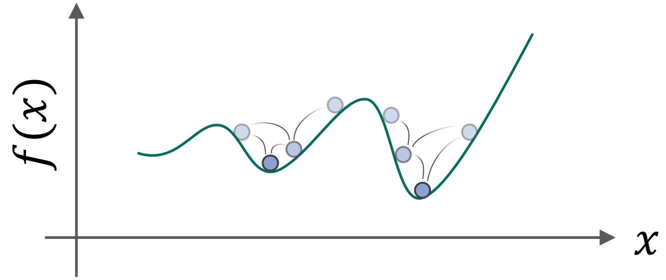
Motivation

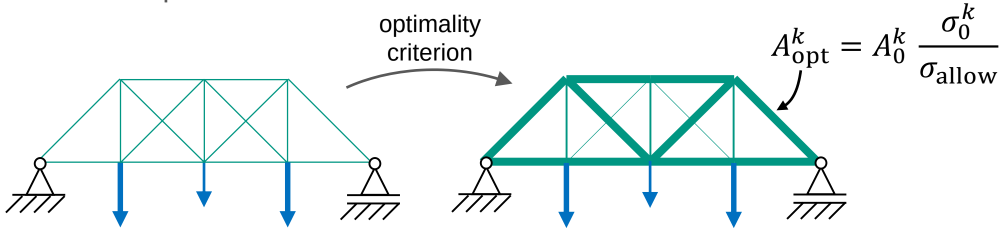
Optimising Fibre-Reinforced Composites

Popular optimisation approaches

- Gradient-based, e.g. topology optimisation [Sig11]
  - generally fast (few iterations)
  - local optima, categorial variables
- Gradient-free, e.g. evolutionary algorithms [Sig11]
  - global optima
  - generally many iterations
- Optimality-criterion, e.g. *fully-stress-design*
  - potentially extremely fast (ideally 1 iteration)
  - definition of optimality-criteria difficult







Approach

Overview and current limitation

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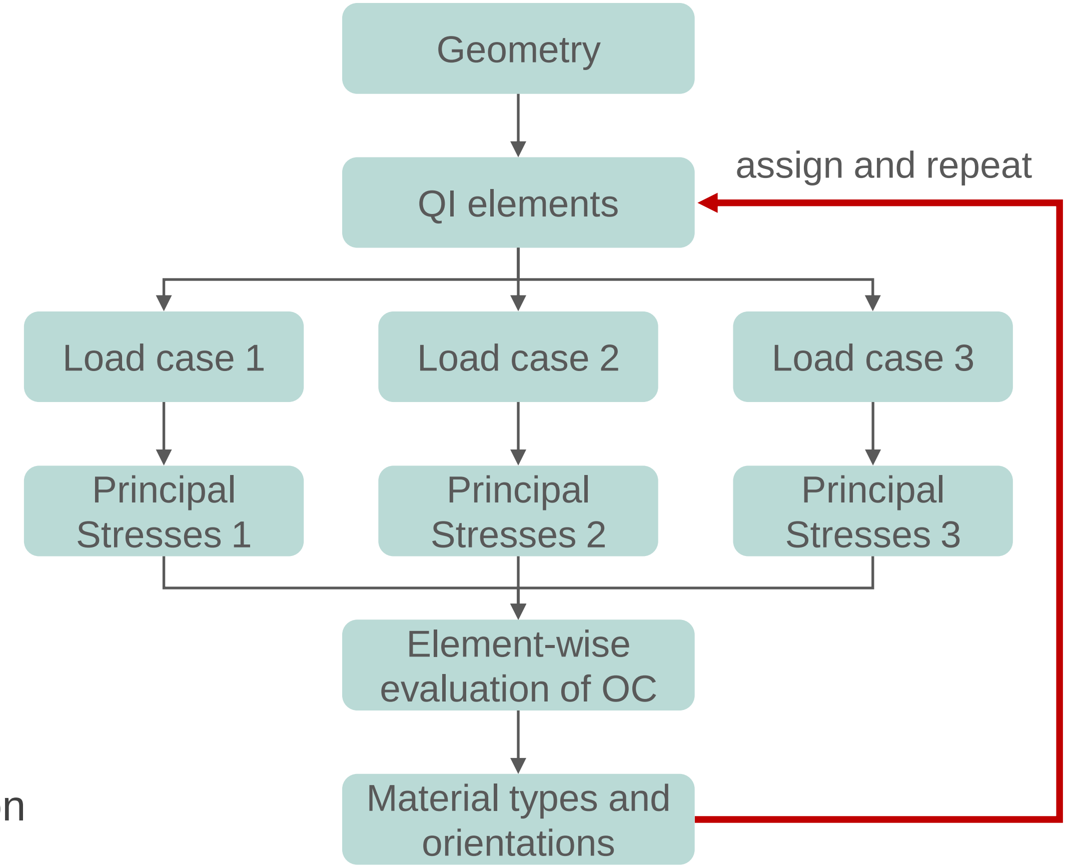
Previous work

- Numerous approaches towards laminate optimisation, most concentrate on numerical optimisation
- Zink et al.: *Anisotropy Analysis* [Zin16,Zin17]
  - Optimality criterion (OC) based on principal stresses
  - Identify component regions suitable for FRP
  - Recommends material-type and -orientation

Current limitation

- Change of material behaviour and orientation alters stress distribution and thereby optimum material distribution
- Iterations necessary until convergence



Workflow during *anisotropy analysis* [Zin16,Zin17]

Approach
Optimality criterion | Visualisation

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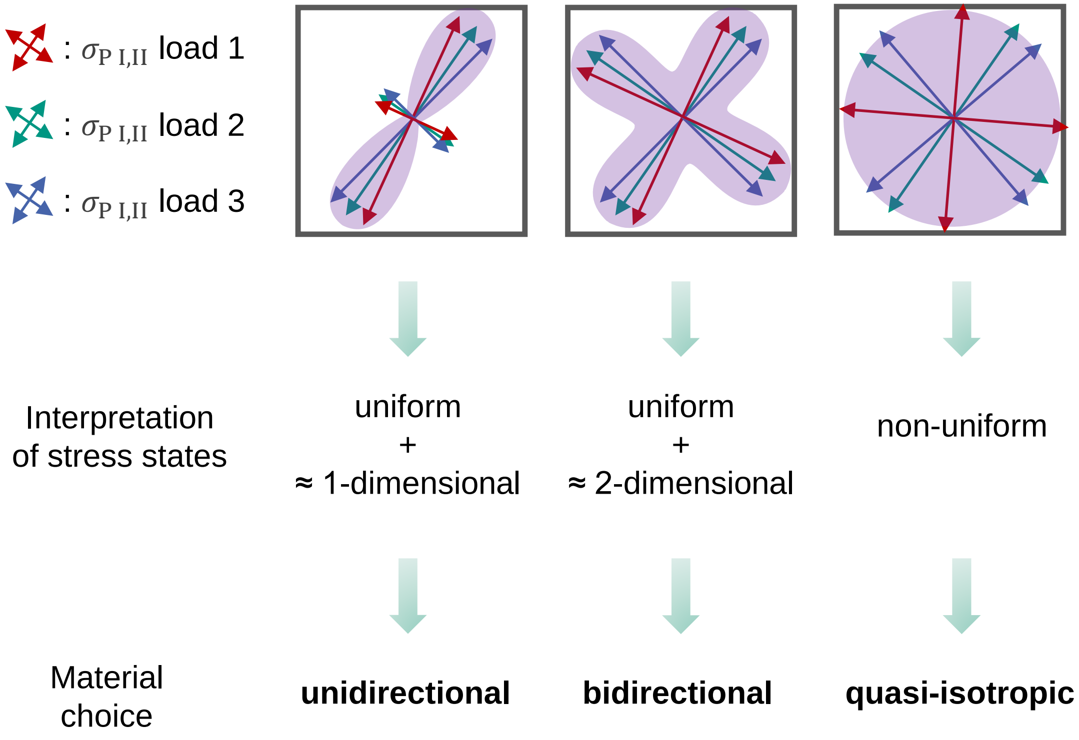
Optimality Criterion for elements

- Maximum stiffness :
  Alignment of material orientations
  with principal stresses $\sigma_{\mathrm{P\ I,II}}$ [Luo98]
- Multiple load cases:
  Consider variability of across load cases



Available material types

- unidirectional
- bidirectional
- quasi-isotropic

Approach

Optimality criterion | Formal evaluation example

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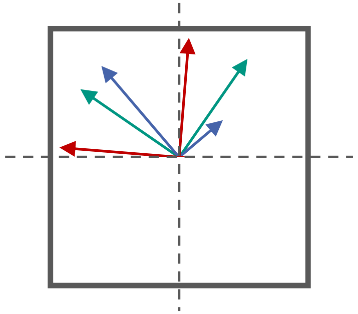
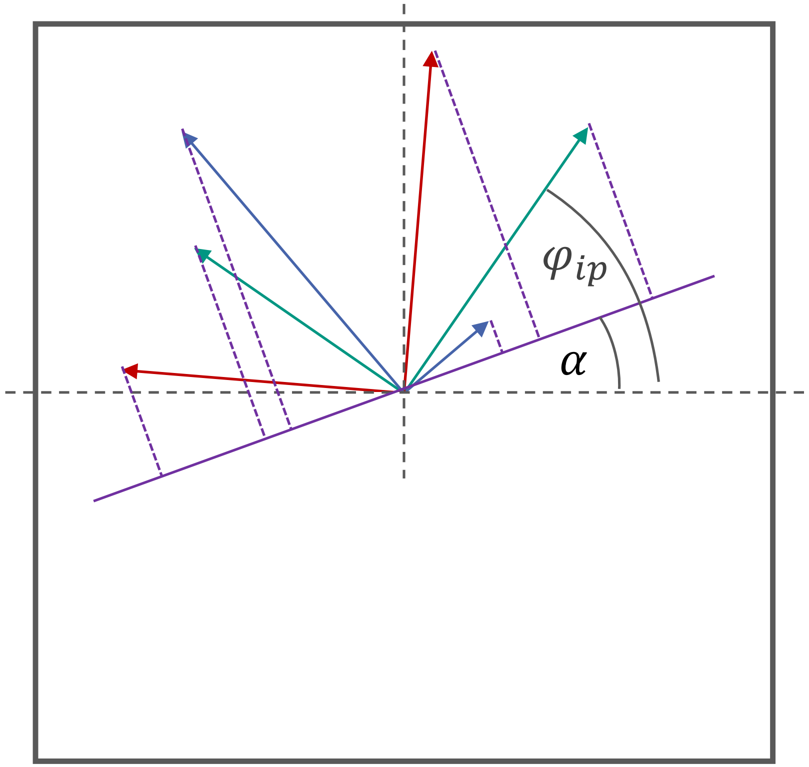
Element-wise analysis of principal stresses

1. Determination of material orientations
   for UD and BD (QI has no material orientation)
   - Sum projection of principal stress vectors
     on candidate material orientation
   - Maximum projection yields material orientation
     $\alpha^*_{UD} = \arg\max\big(P(\alpha)\big)$
   - Separate consideration of BD
2. Assessment of *Reserve Factor* R
3. Comparison and selection of best-fit material





$$P(\alpha) = \sum_i \sum_p \left| \sigma_{P\,i\,p} \cdot \cos(\varphi_{ip} - \alpha) \right|$$

Approach

Optimality criterion | Formal evaluation example

Element-wise analysis of principal stresses

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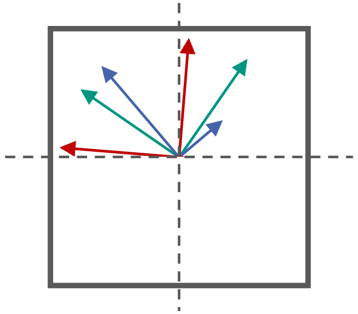
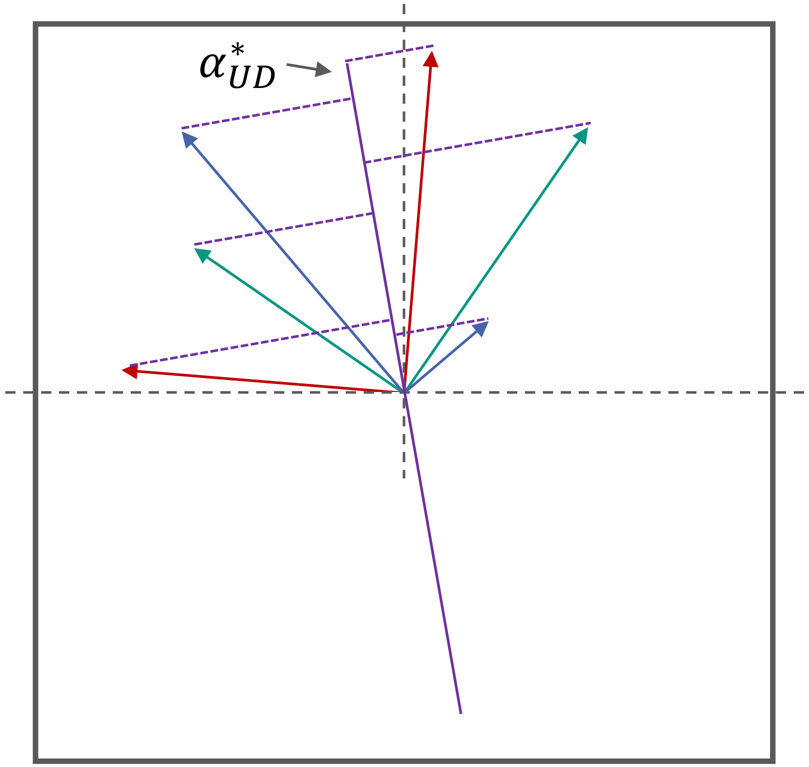




$$P(\alpha) = \sum_i \sum_p \left|\sigma_{\mathrm{P}\,i\,p} \cdot \cos(\varphi_{ip} - \alpha)\right|$$

Approach

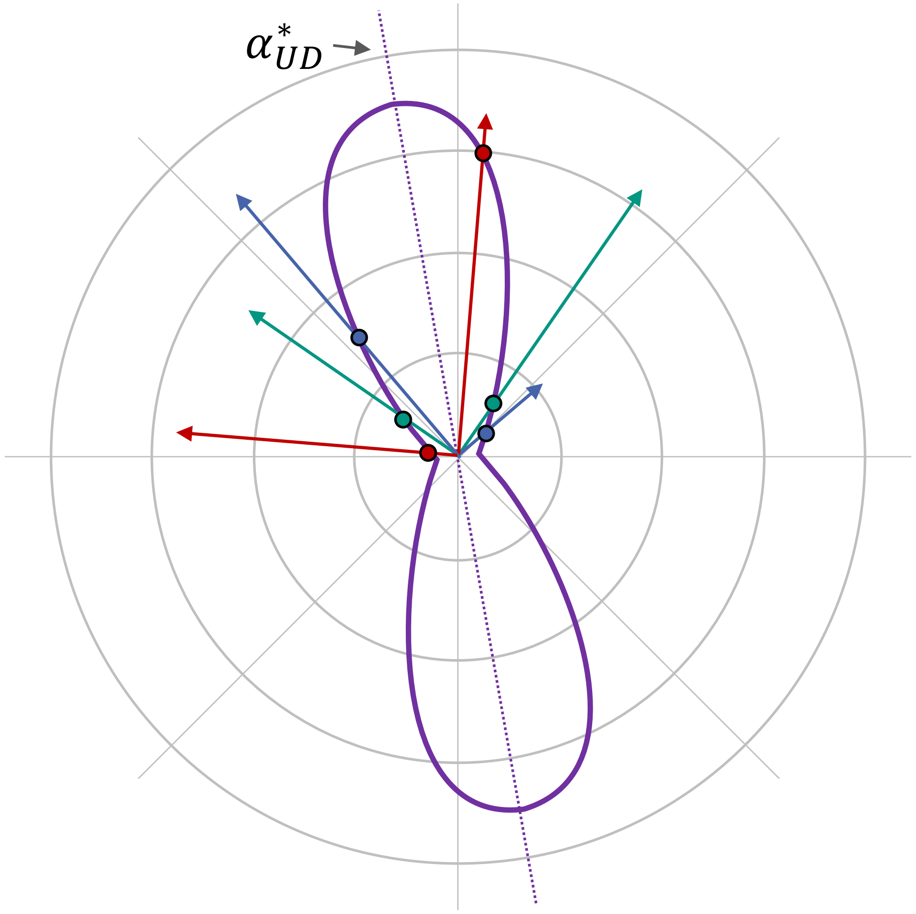
Optimality criterion | Formal approach

Element-wise analysis of principal stresses

1. Determination of material orientations
   for UD and BD (QI has no material orientation)

2. Assessment of reserve factor $R^{p}_{i\ \mathrm{UD}}$
   - Rotate stiffness matrix by material orientation, e.g. α^{*}_{UD}
   - Determine *Reserve Factor* for each principal stress p… $R^{p}_{i\ \mathrm{MAT}} = \max\left(\frac{\sigma_{P\ ip}}{E(\alpha^{*}_{\mathrm{UD}})}\right)$
   - …and load case i
   - Repeat for BD and QI

3. Comparison and selection of best-fit material



Approach
Optimality criterion | Formal approach

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Element-wise analysis of principal stresses

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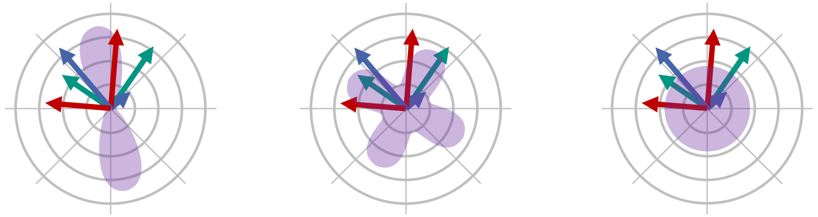


2. Assessment of reserve factor R

3. Comparison and selection of best-fit material
   - Determine most critical load case for each material

     $$R_{mat\ \mathrm{crit}} = \max(R_{i\ mat})$$

   - Determine best-fit material by

     $$M = \arg\min(R_{mat\ \mathrm{crit}})$$

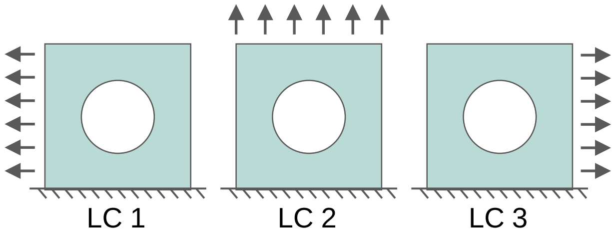
LC	UD	BD	QI
R_1^p	0.0040	0.0013	0.0018
R_2^p	0.0080	0.0014	0.0024
R_3^p	0.0060	**0.0018**	0.0023

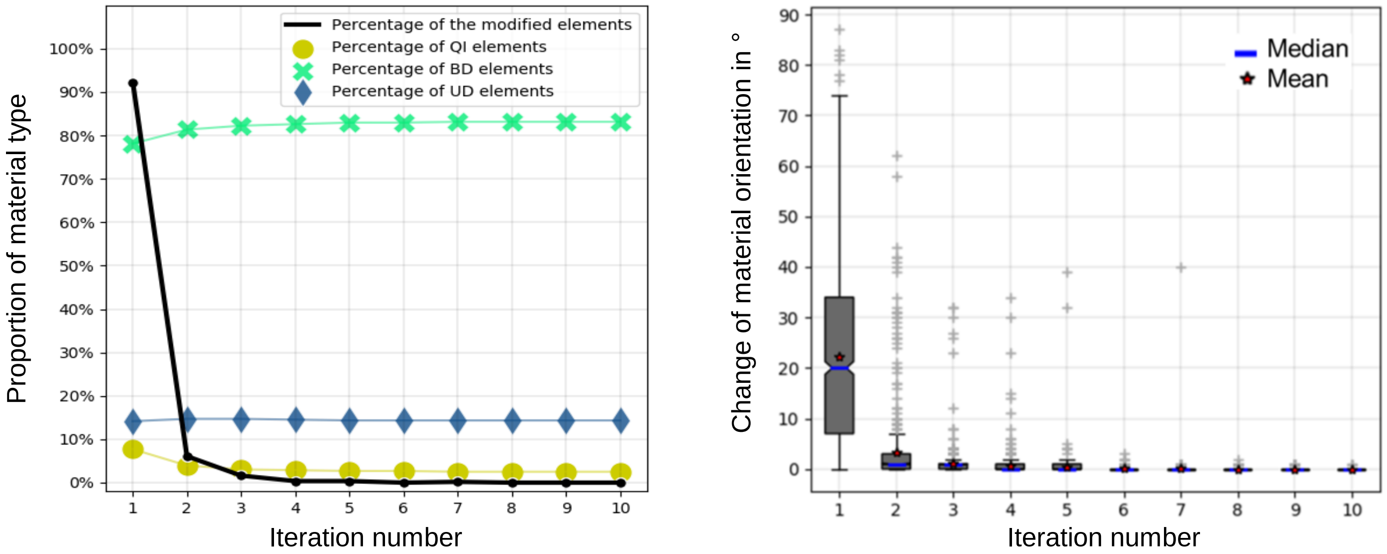
Example 1

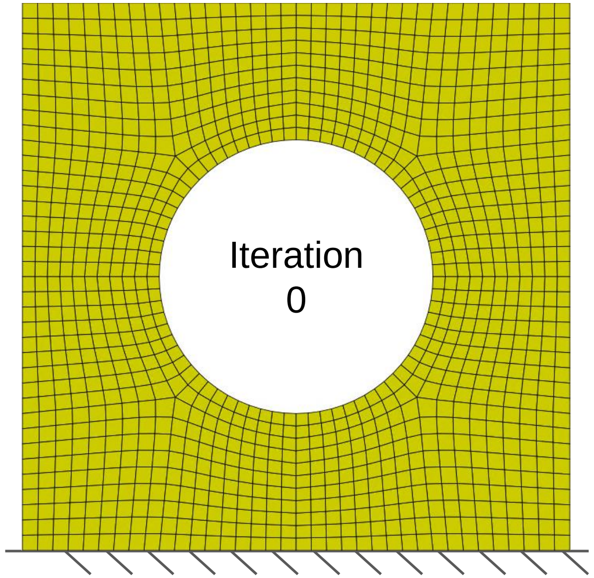
Generic Plate

Generic Plate

- Quadratic plate with central hole, line load applied to edges
- Convergence within 6 iterations







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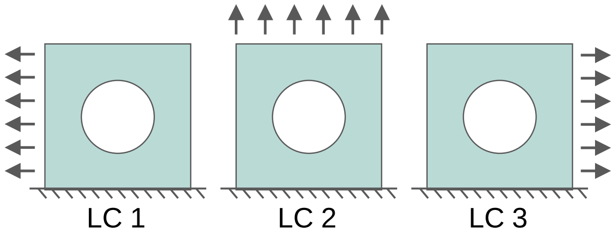

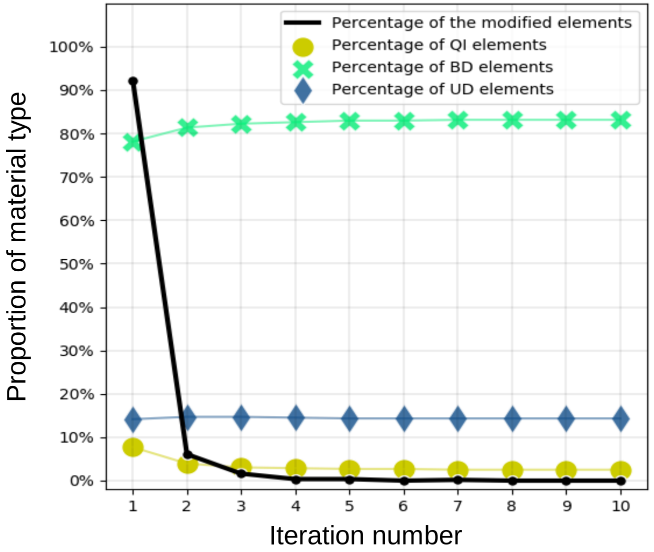

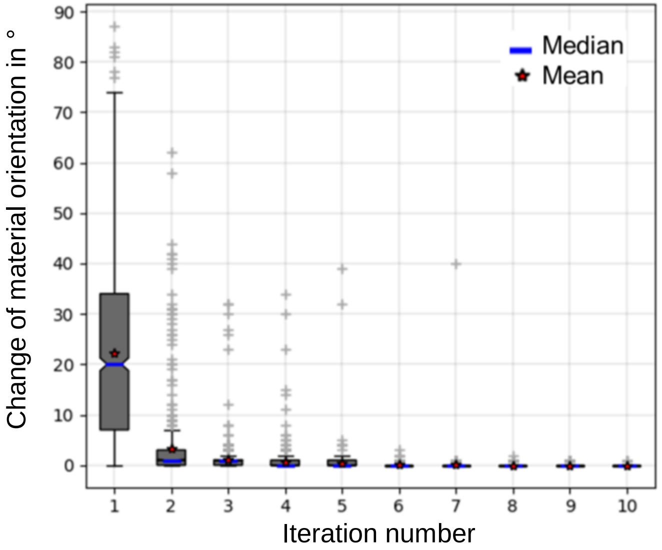

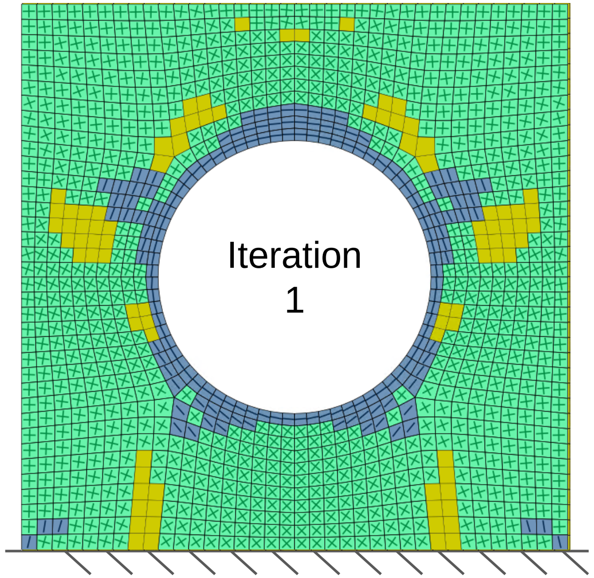

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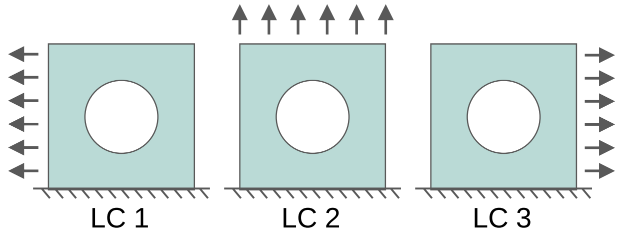

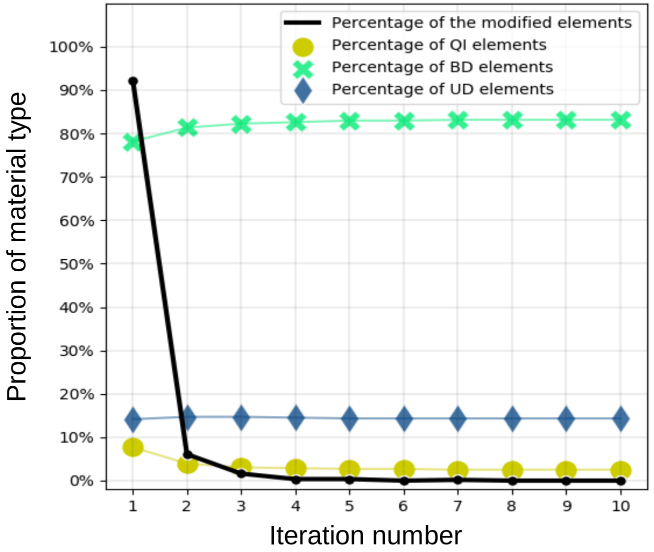

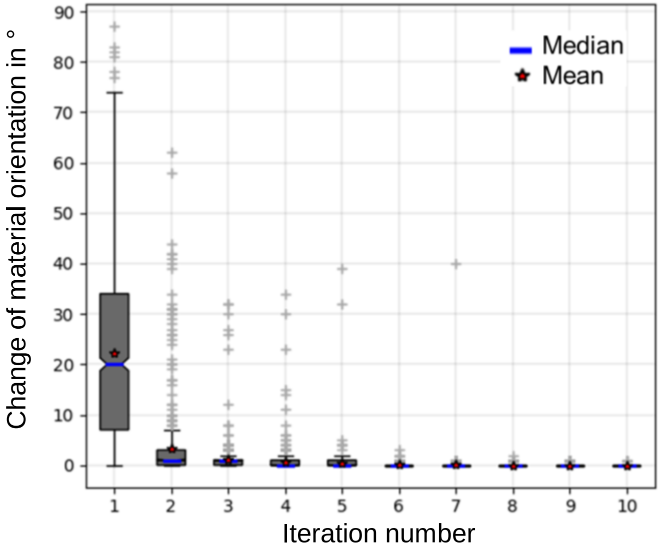

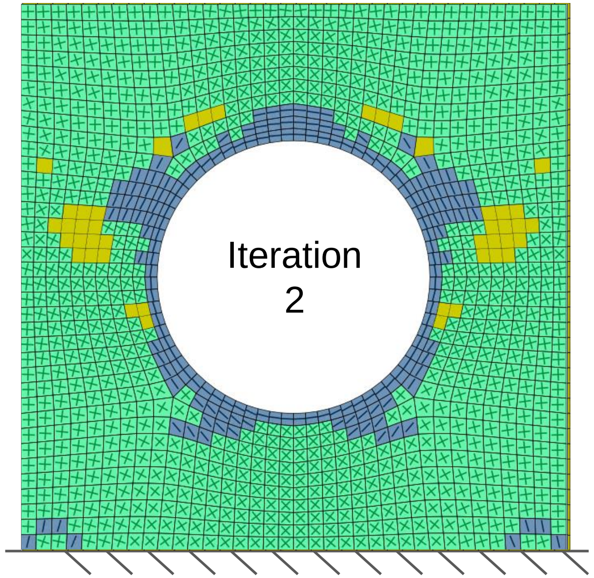

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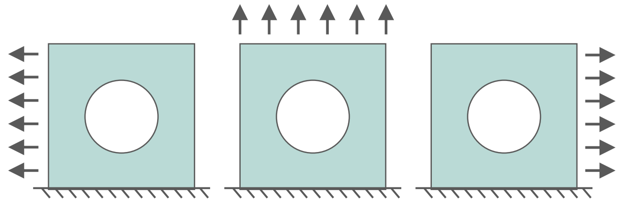

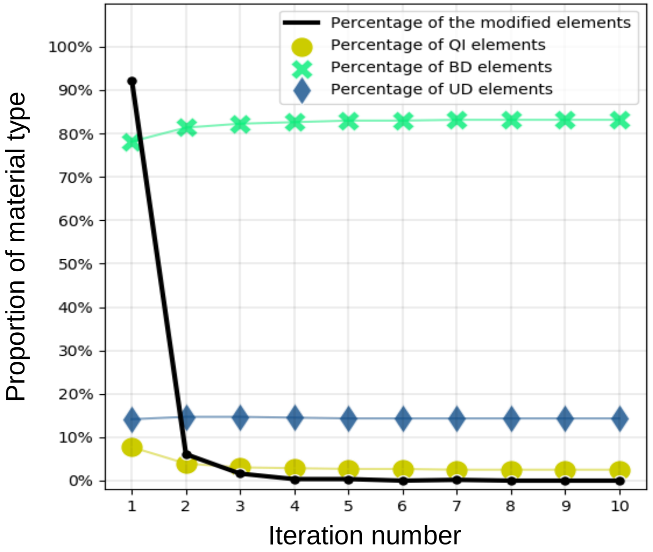

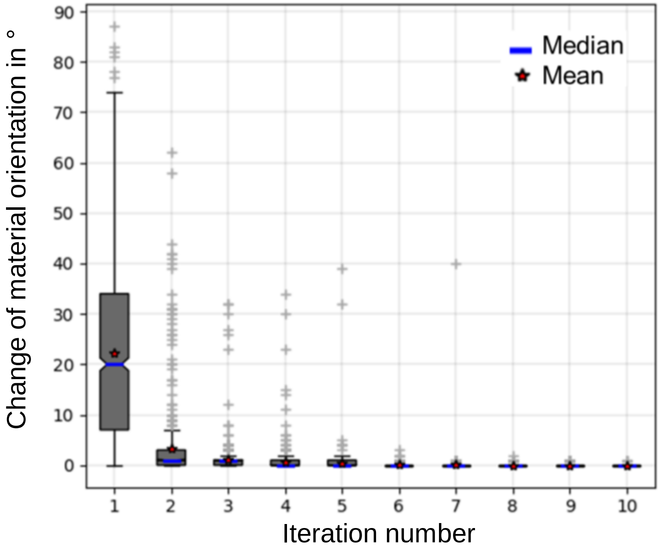

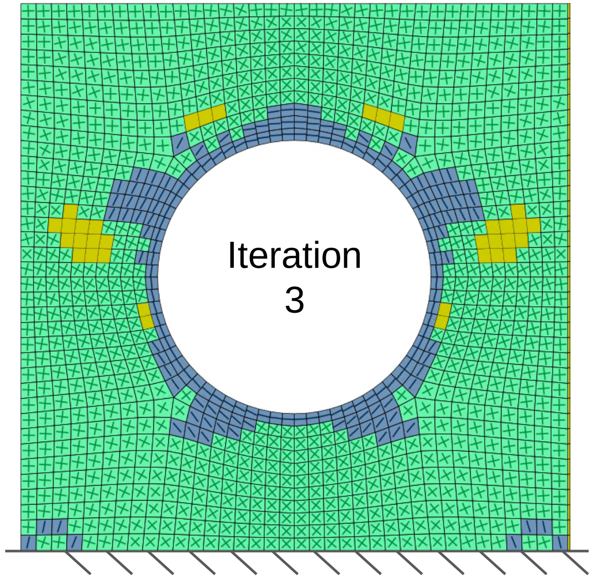

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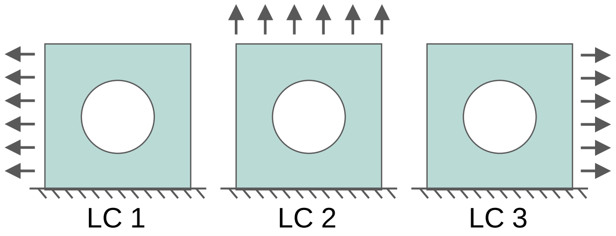

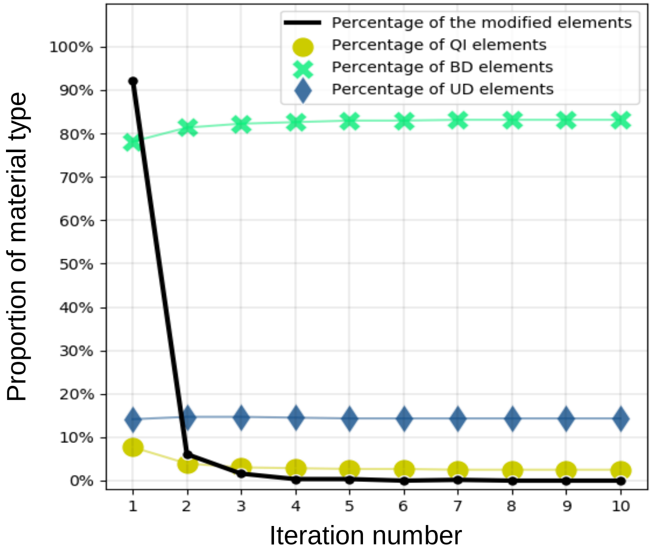

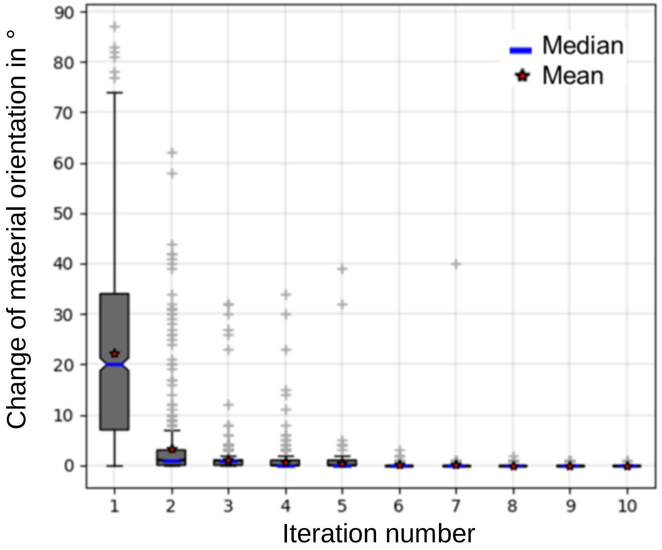

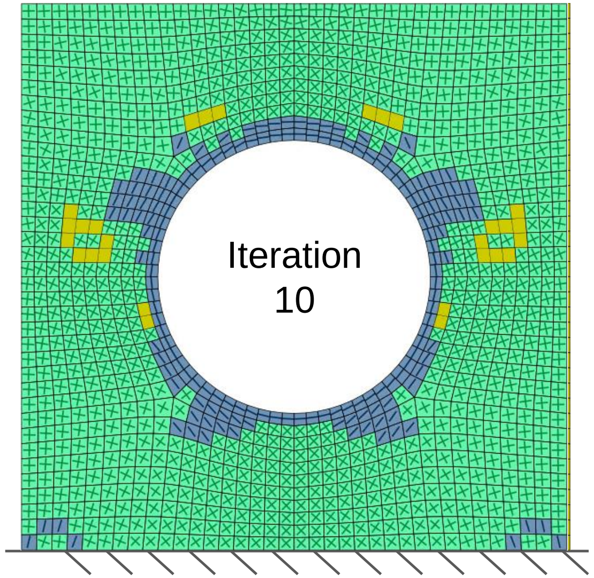

Example 2

Real-world example | Load Cases

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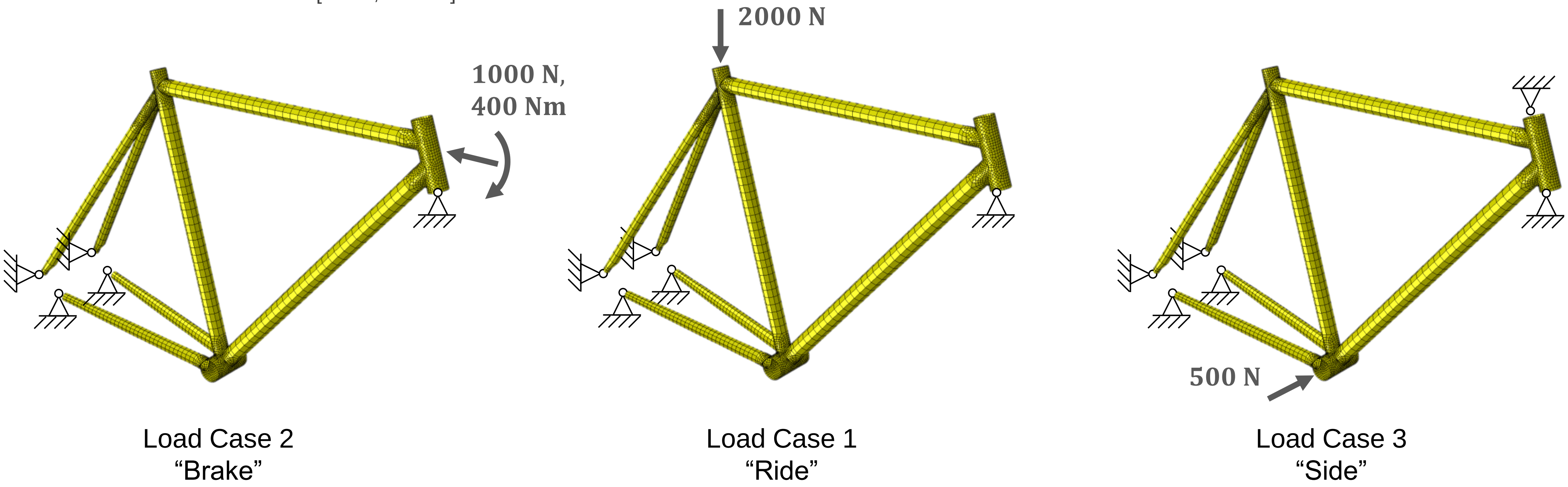
Bicycle frame

- Real-world application on a 3D bicycle frame [NLR20]
- 3 load cases considered [Liu10, NLR20]

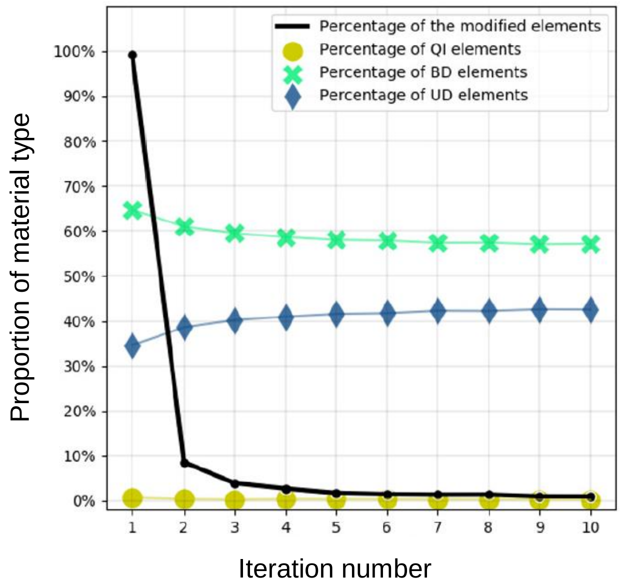


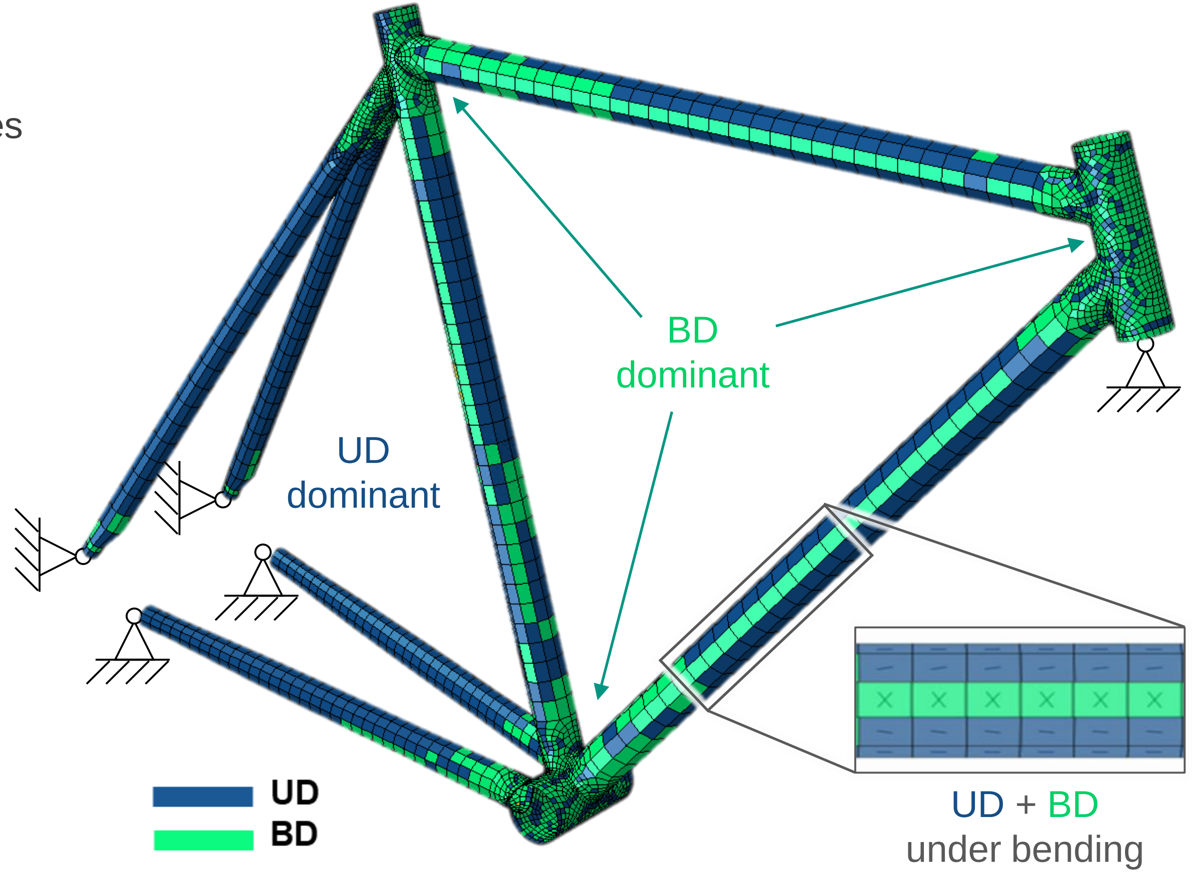
Example 2

Real-world example | Results

Bicycle frame

- Convergence after 9 iterations
- Optimisation results support classical engineering strategies
  - UD-dominated truss-tubes, UD+BD in bent tubes

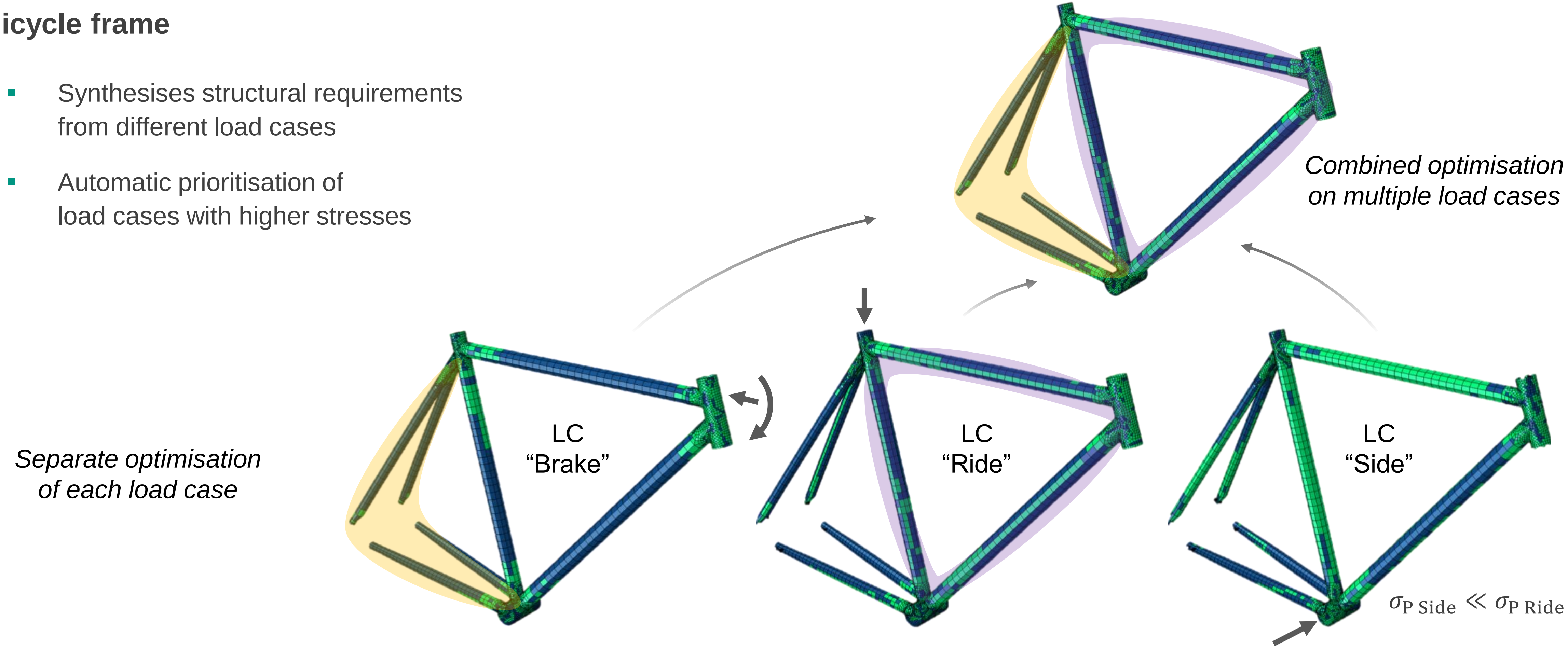




Example 2
Real-world example | Multiple loads vs single load

Bicycle frame

- Synthesises structural requirements from different load cases
- Automatic prioritisation of load cases with higher stresses



Example 2

Real-world example | Multiple loads vs single load

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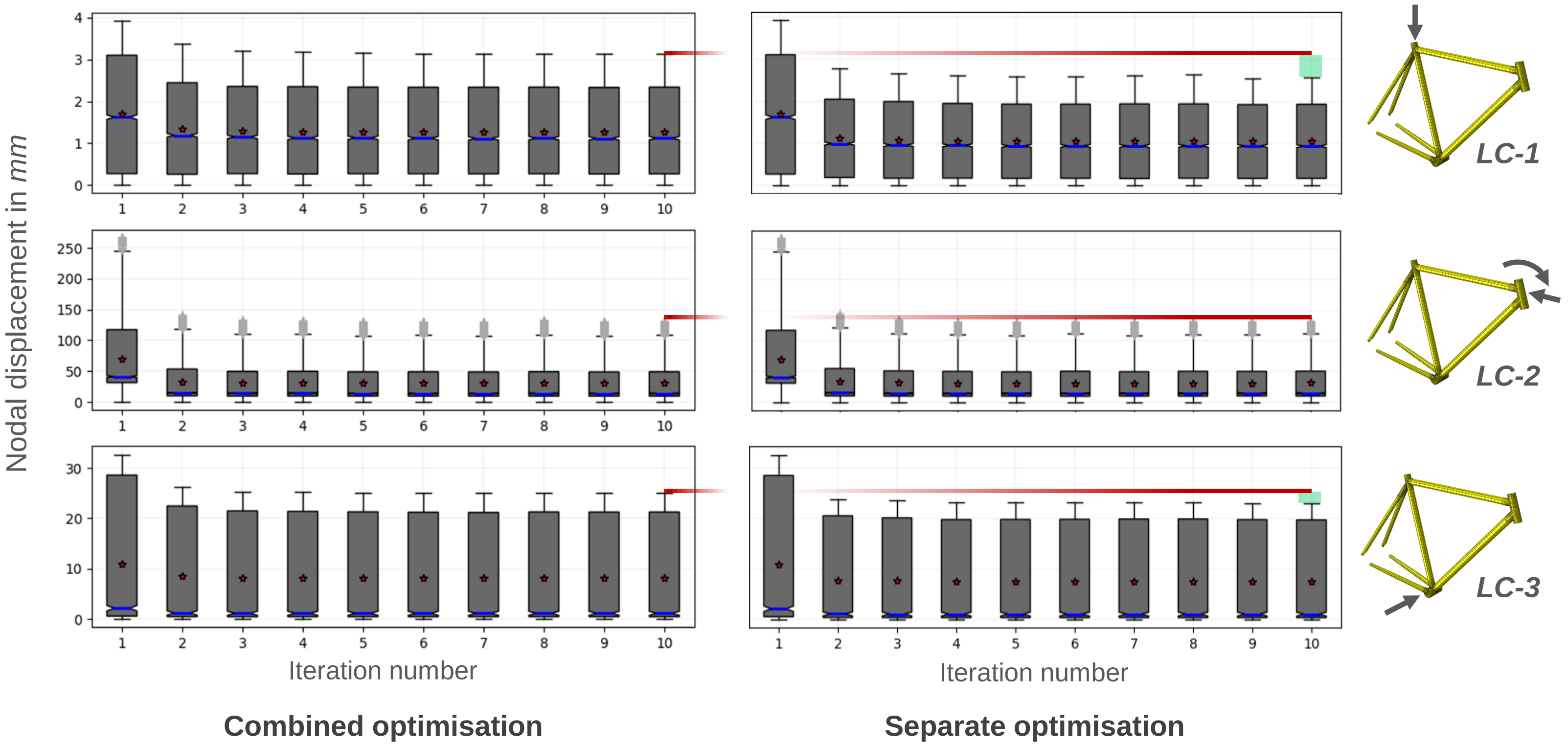
Bicycle frame

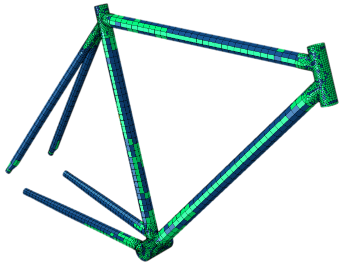
- Synthesises of structural requirements from different load cases
- Automatic prioritisation of load cases with higher stresses
  - Displacement reduces in all cases
  - Highest stresses in LC-2: Combined optimisation approaches separate optimisation
  - LC-1 and LC-3 show further potential in separate optimisation
    - Potential unexploited since LC-2 dominates component

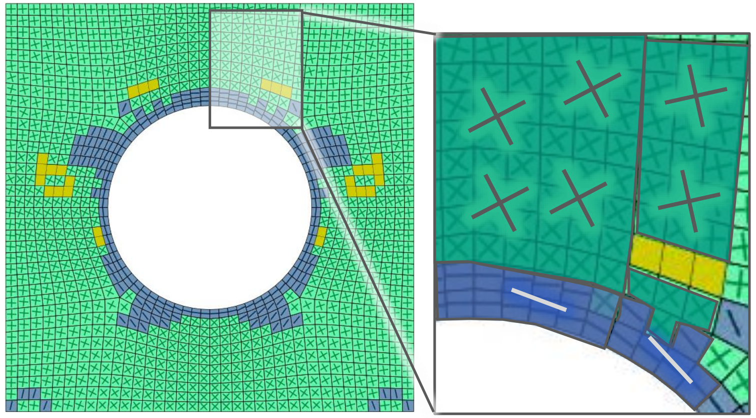


Summary
Rapid Determination of Reinforcement Type

Summary

- Early recommendation of reinforcement type (UD, BD or QI) and respective orientation for multiple load-cases
- Extension of an existing, optimality-criterion-based approach [Zin16]
  - Rapid convergence when iterating recommendations
- Comparison of multi- and single-load-case optimisation
  - Automatic prioritisation of critical load cases observed





Outlook

- Automatically combine similar regions to coherent patches for manufacturability
- Handling of (near) hydrostatic stress states

Clemens Zimmerling
Institute of Vehicle System Technology (KIT)

Thank you.

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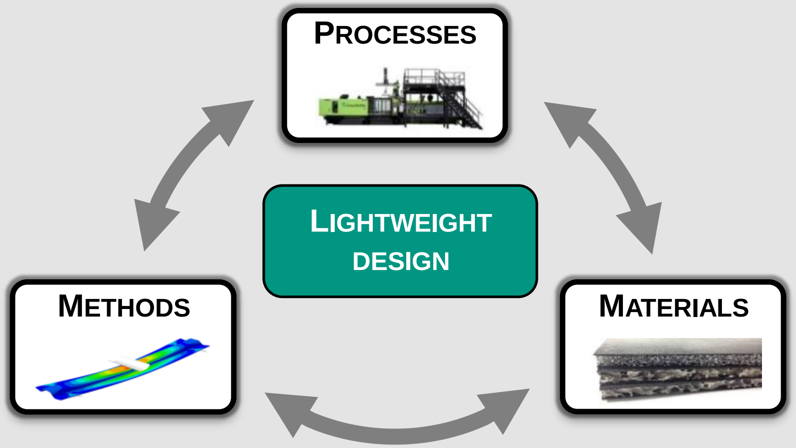
KIT - Lightweight Design Network

www.leichtbau.kit.edu



Contact

FAST Institute of Vehicle System Technology

Karlsruhe Institute of Technology (KIT)
Institute of Vehicle System Technology
Lightweight Design
Rintheimer-Querallee 2,
76131 Karlsruhe, Germany

Dipl.-Ing. **Clemens Zimmerling**
clemens.zimmerling@kit.edu

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