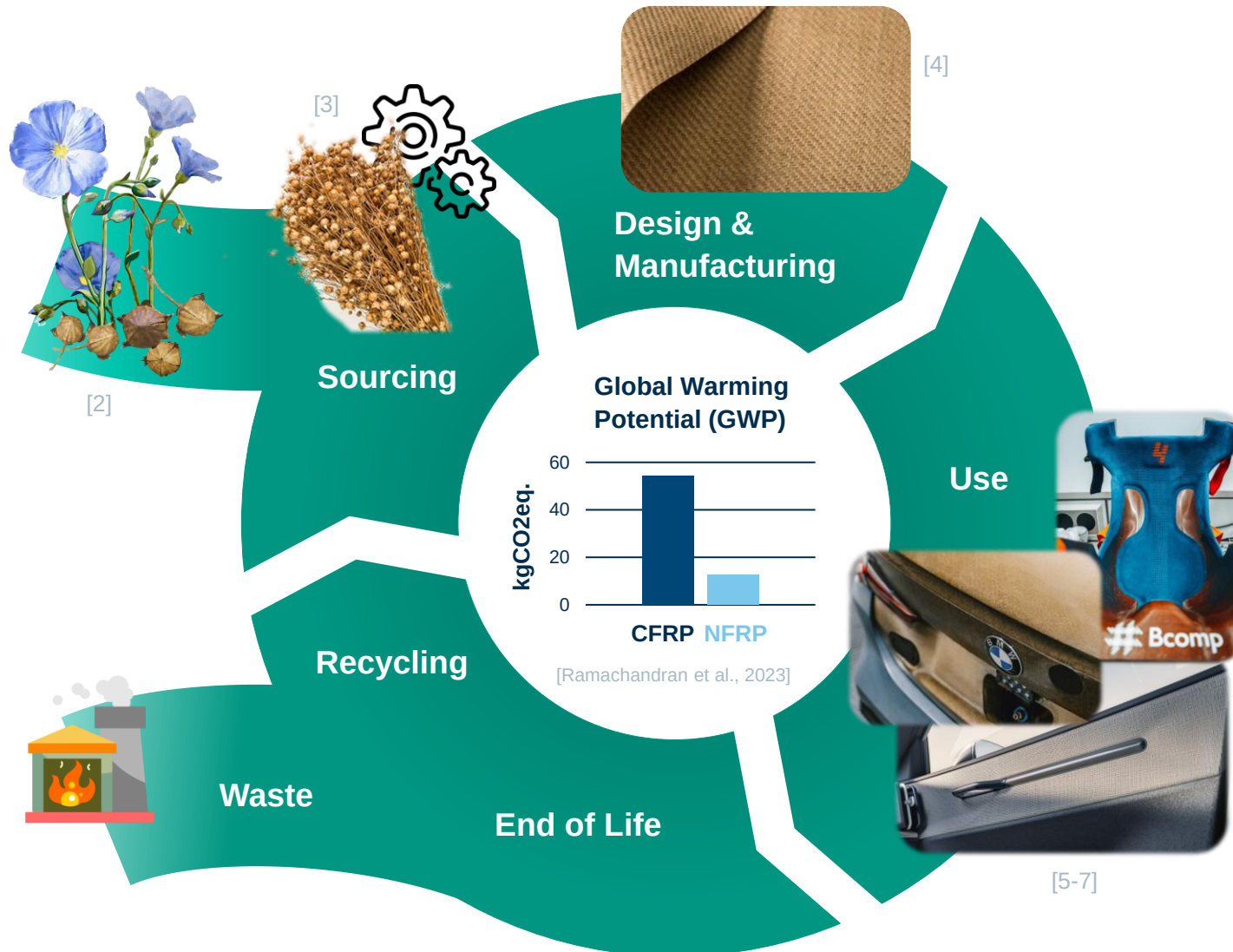


Multi-Objective Optimization of Natural Fiber-Reinforced Composites with Tailored Carbon Fiber Reinforcements

Niklas Frank, Simon Voltz and Tobias Düser

[1]

Natural Fiber Reinforced Polymers



Natural Fiber Reinforced Polymers (NFRP)

Advantages

- Regional, renewable resource
- Low GWP, density & costs
- Good energy absorption (crash)

Disadvantages

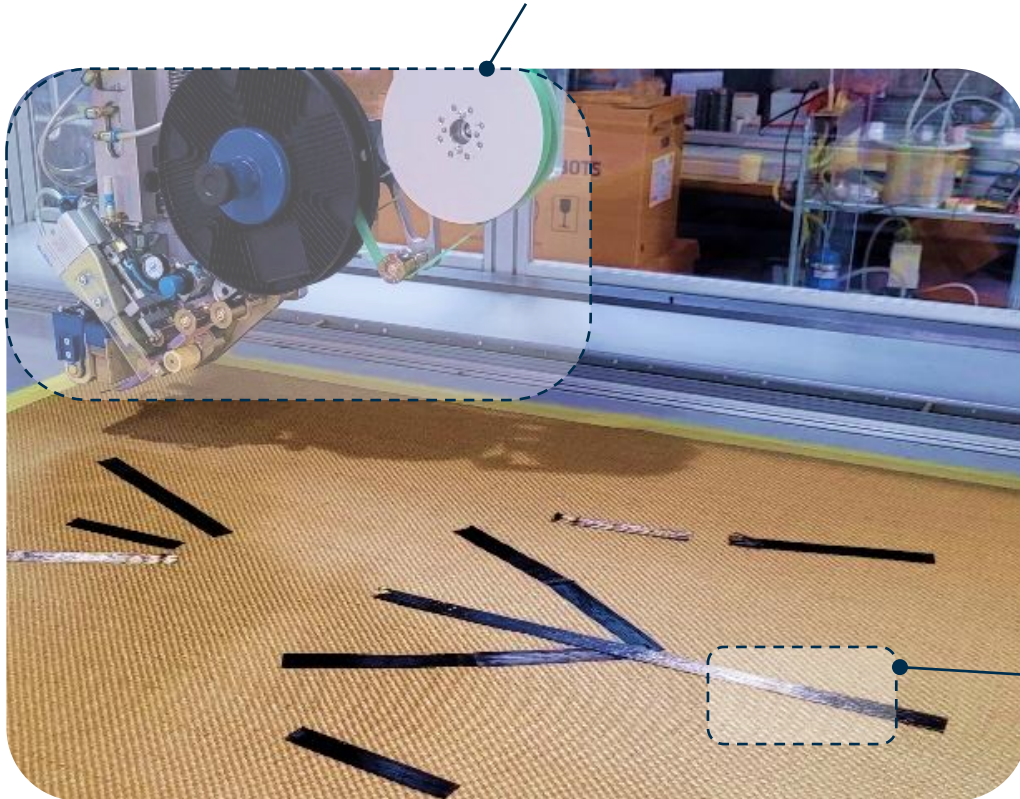
- Low mechanical properties
- Poor matrix-fiber bond
- Water absorption

➔ Mostly used for **non- and semi-structural parts**, e.g. panels

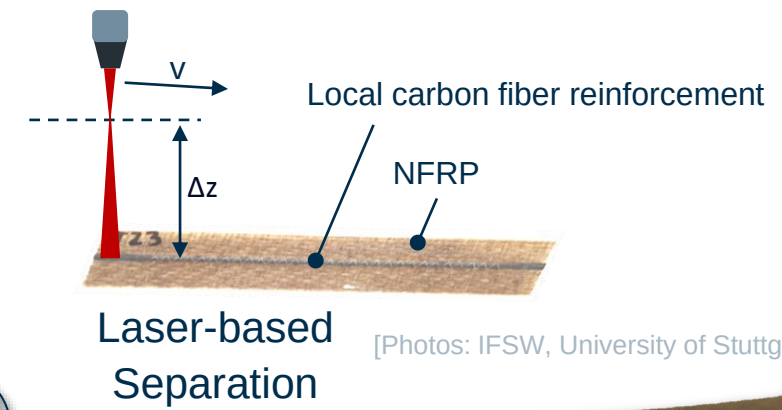
Research Object

NFRP with Tailored Carbon Fiber Reinforcements

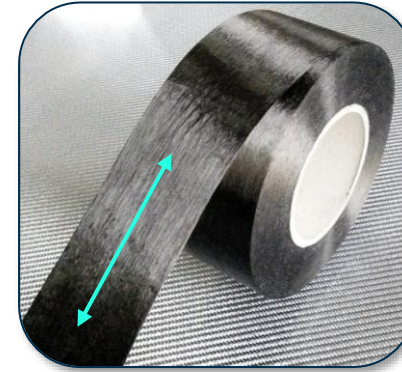
Dry Fiber Placement (DFP)



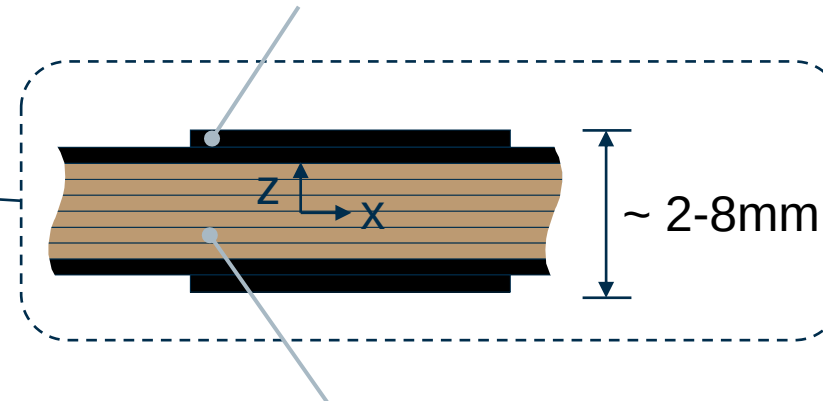
[Photo: IFB, University of Stuttgart]



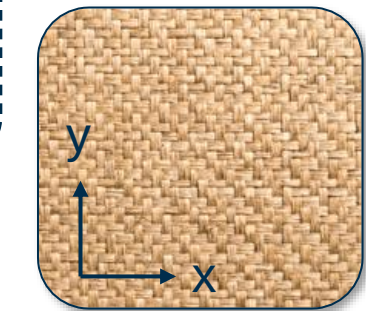
[Photos: IFSW, University of Stuttgart]



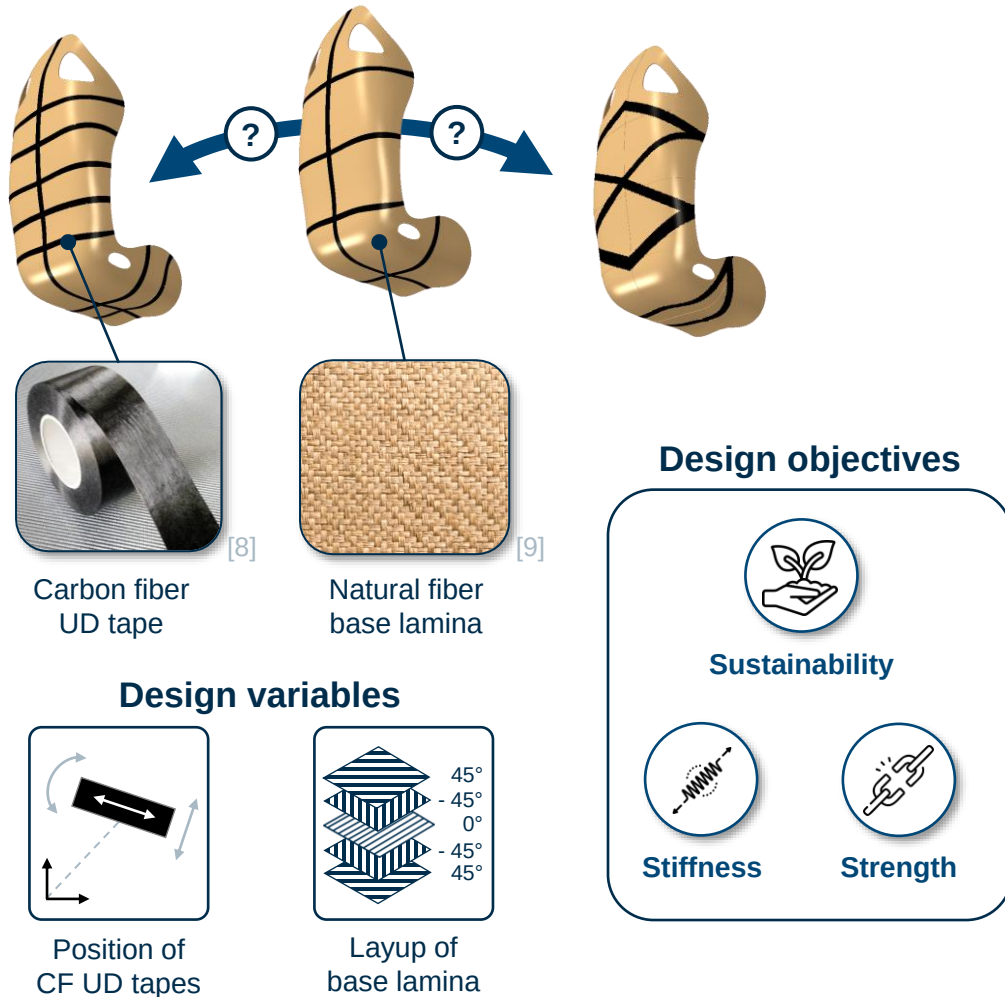
Unidirectional **Carbon Fiber** Tapes



Natural Fiber Woven Fabric Layers



Design of NFRP with Tailored Carbon Fiber Reinforcements



Challenge

- Large design space with **many variables**
- Trade-off** between **low amount of CF** and **mechanical performance**



Solution

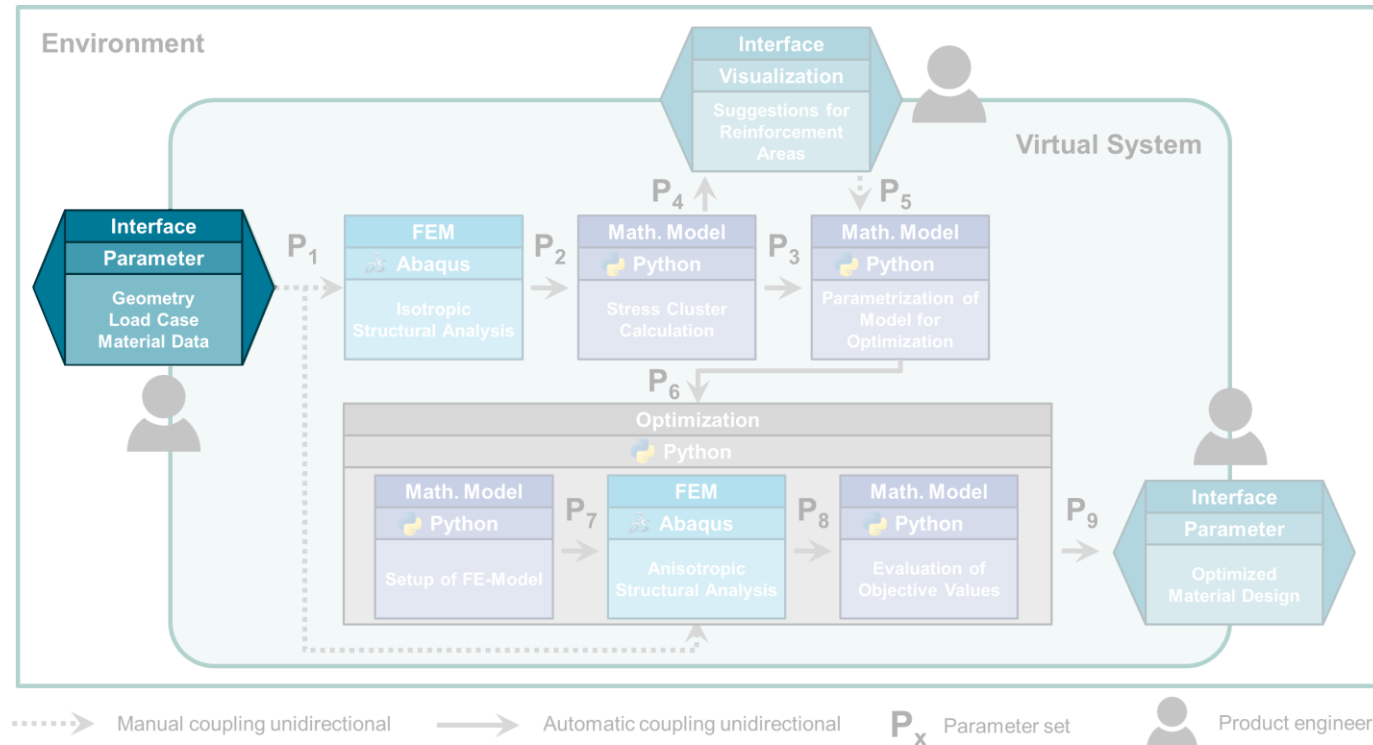
- Optimization** methods can be used to **explore the design space**



However – High computational effort

- Evaluating** a large number of **design variants** requires **many simulations!**

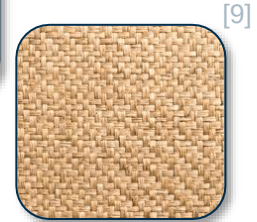
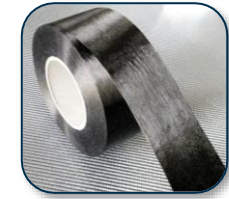
Optimization Method



Material Properties

- Linear elastic
- Orthotropic
- Plane stress

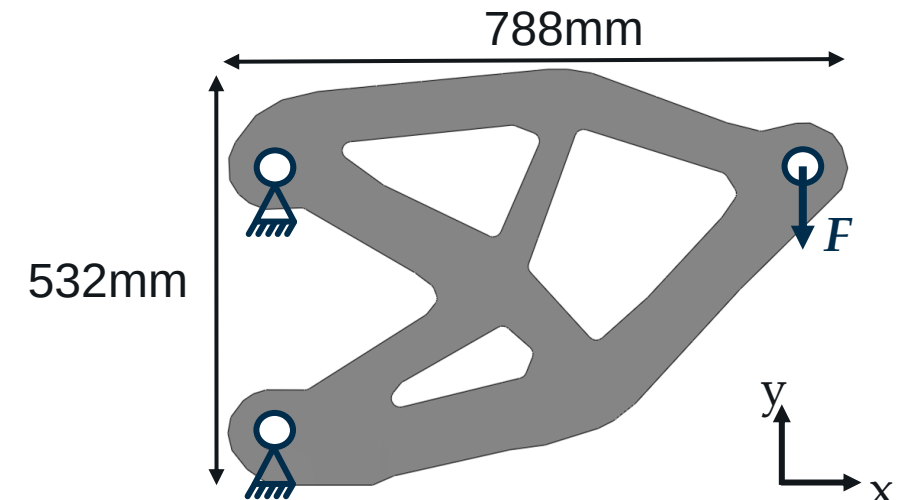
$$\rightarrow E_{||}, E_{\perp}, \nu_{||}, G_{||}, G_{\perp}$$



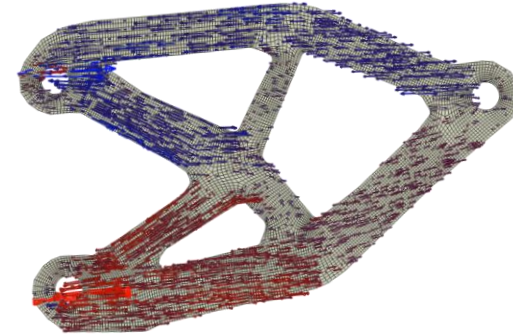
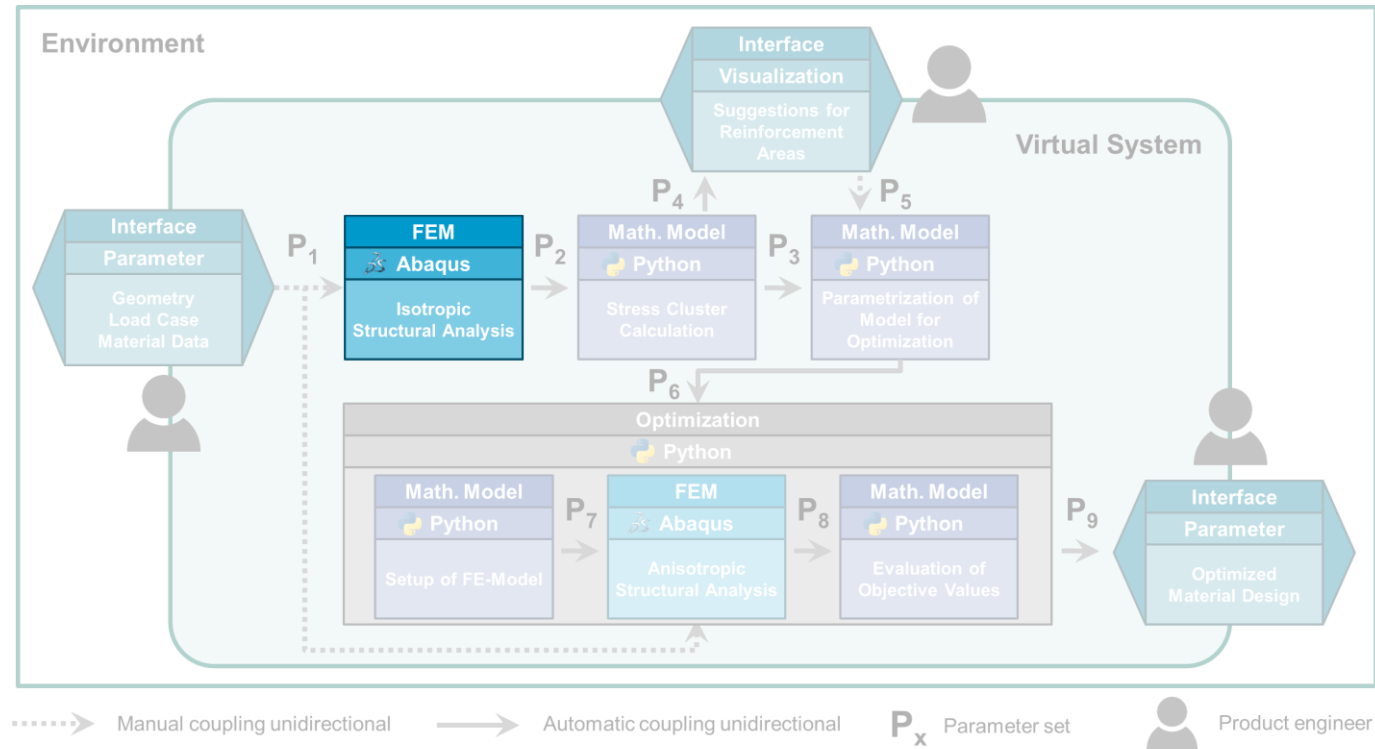
- Damage initiation criteria, e.g. Hashin

$$\rightarrow \bar{\sigma}_{||}^T, \bar{\sigma}_{||}^C, \bar{\sigma}_{\perp}^T, \bar{\sigma}_{\perp}^C, \bar{\tau}_{\perp}^L, \bar{\tau}_{\perp}^T$$

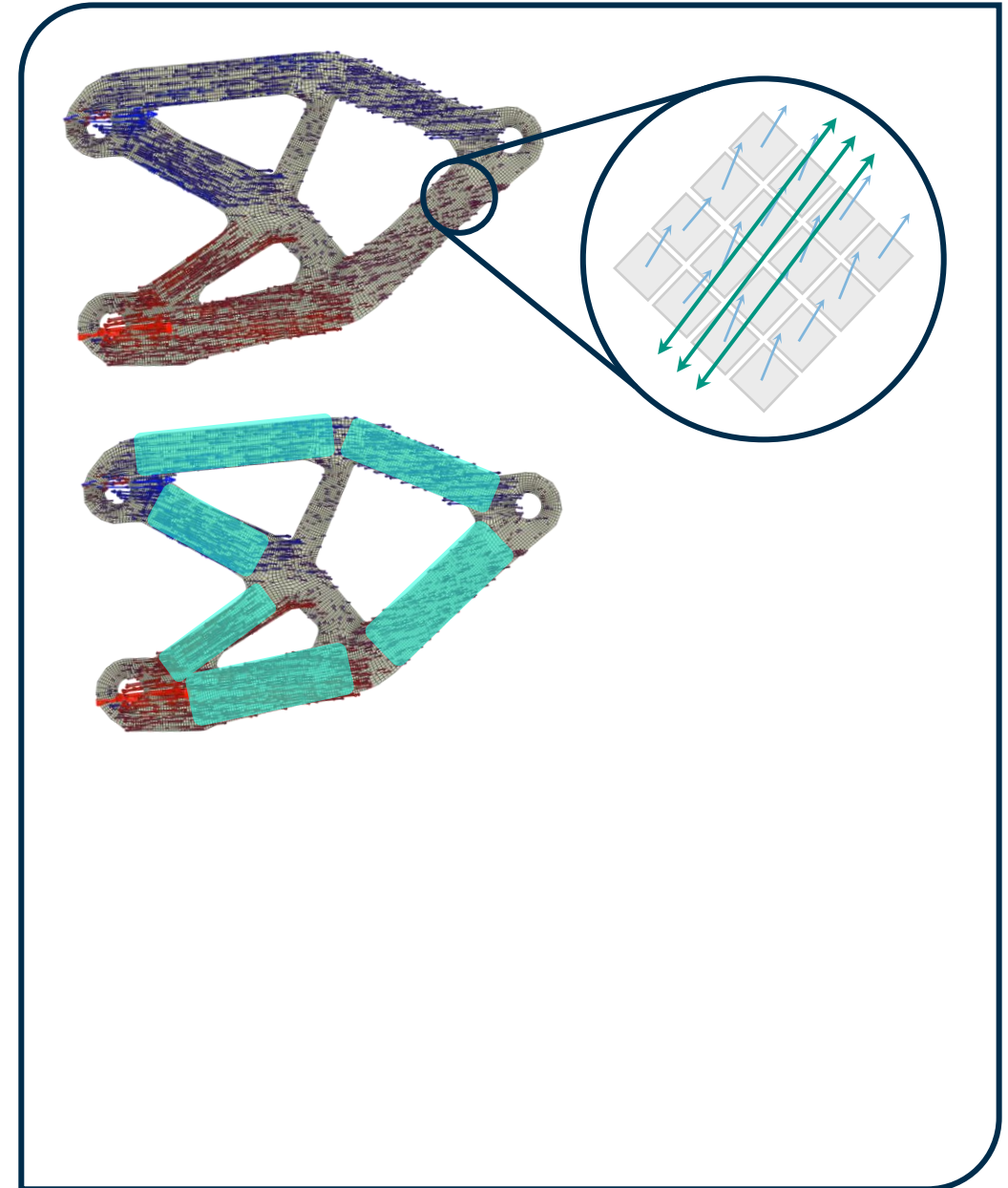
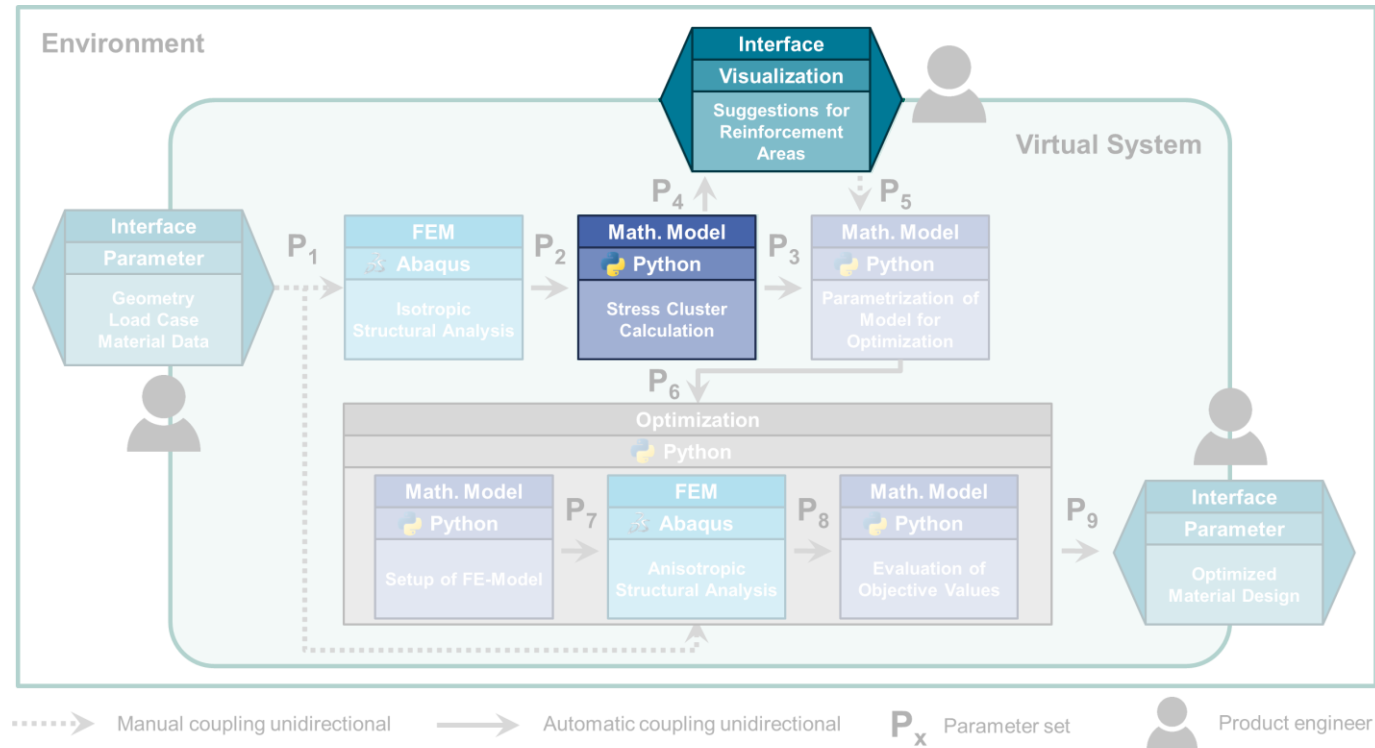
Geometry & Load Case



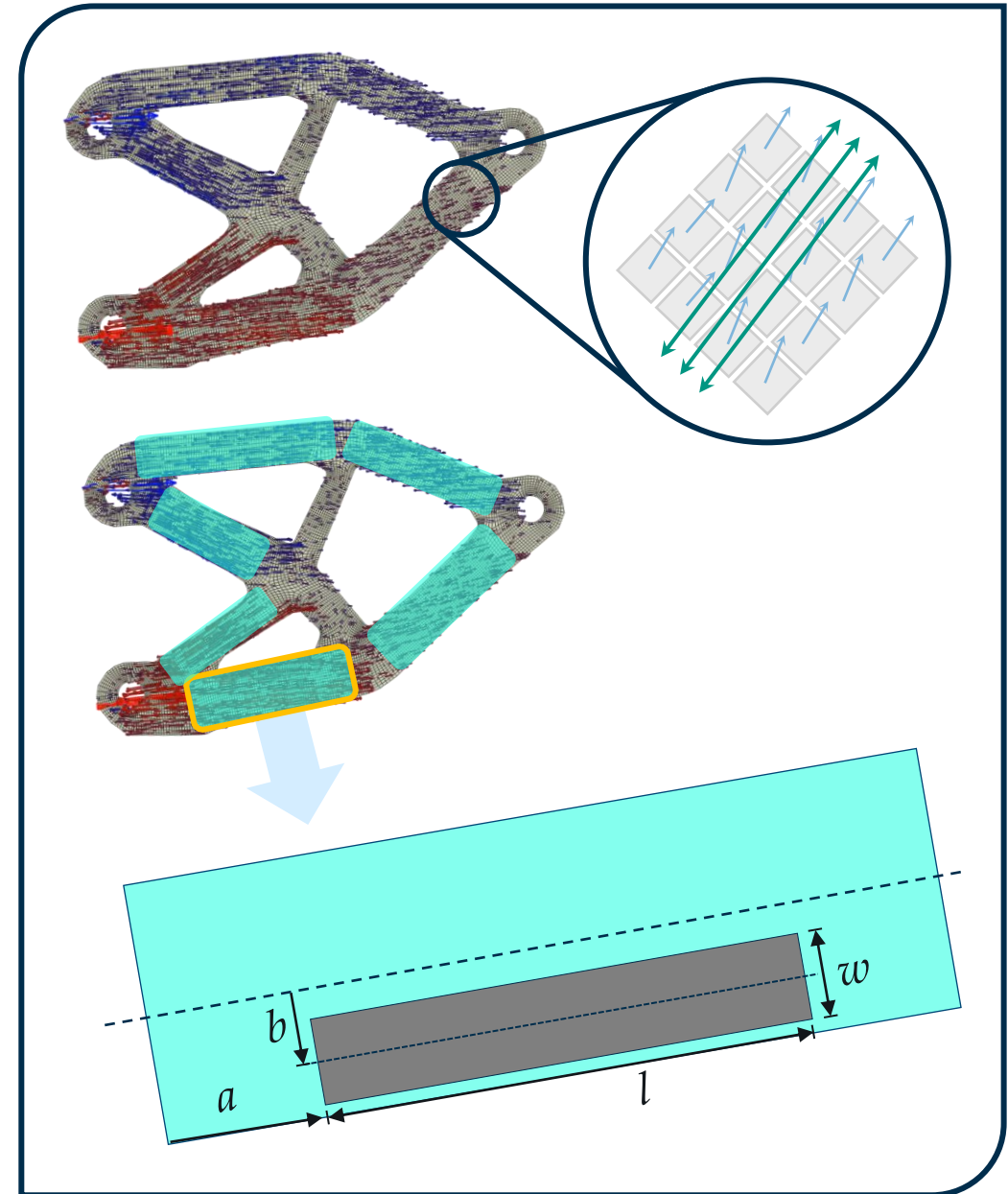
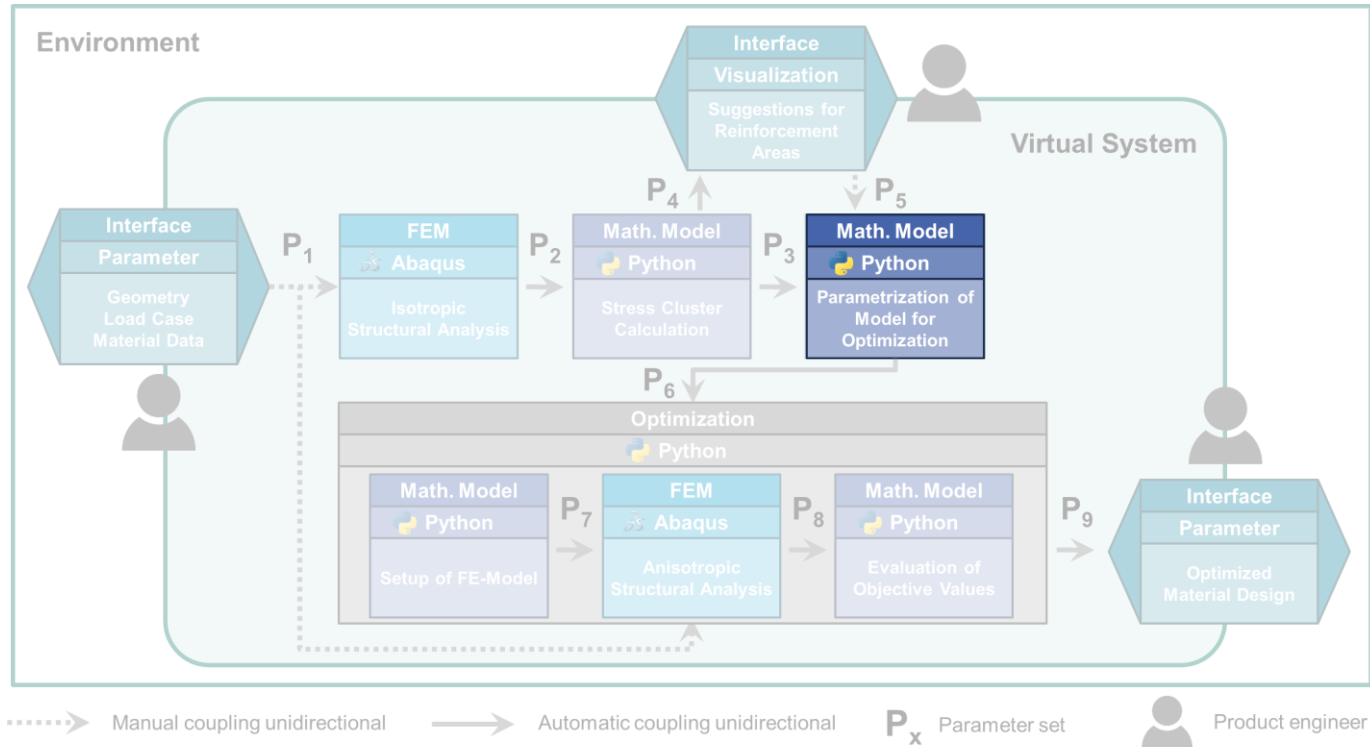
Optimization Method



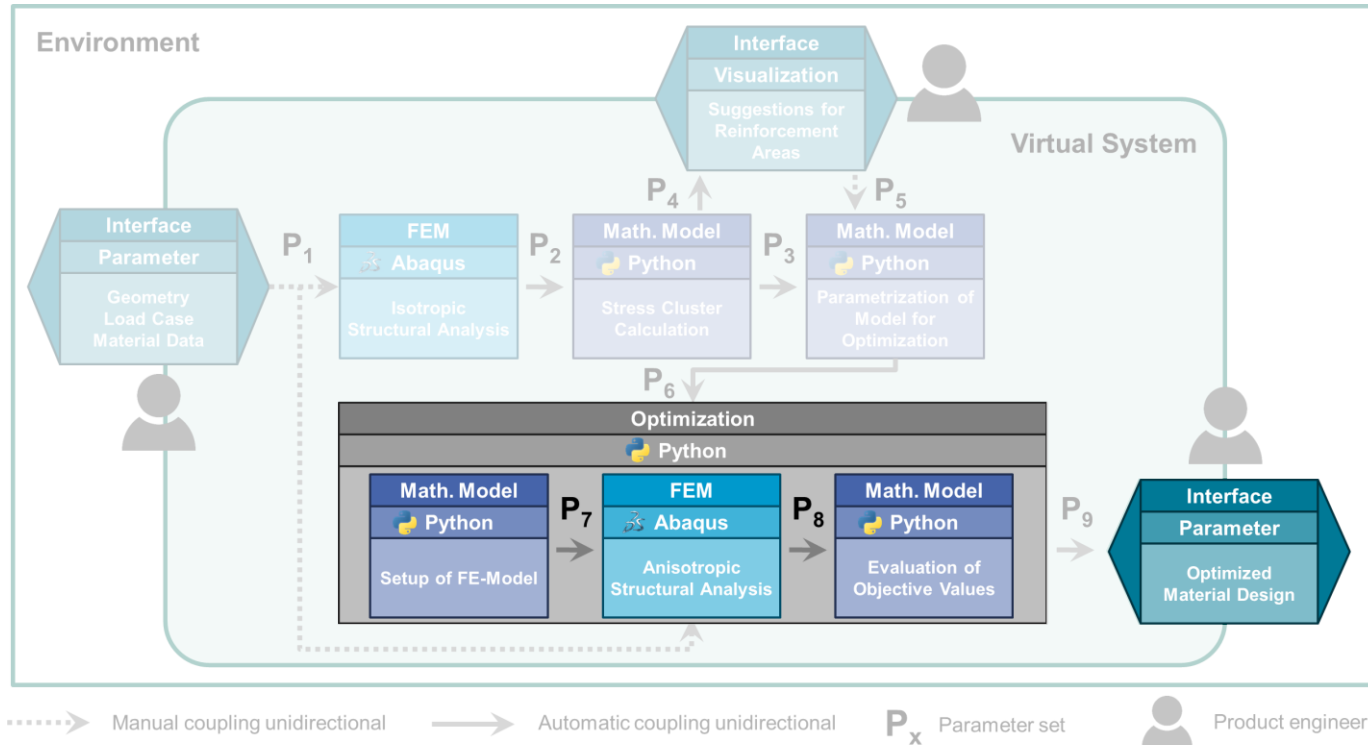
Optimization Method



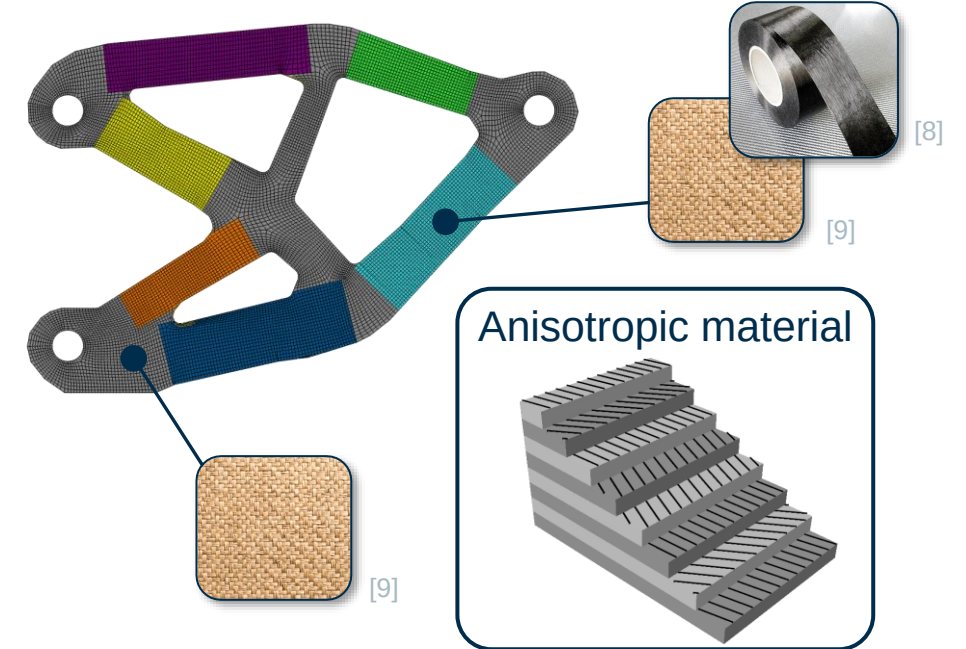
Optimization Method



Optimization Method



Optimization of Material Design



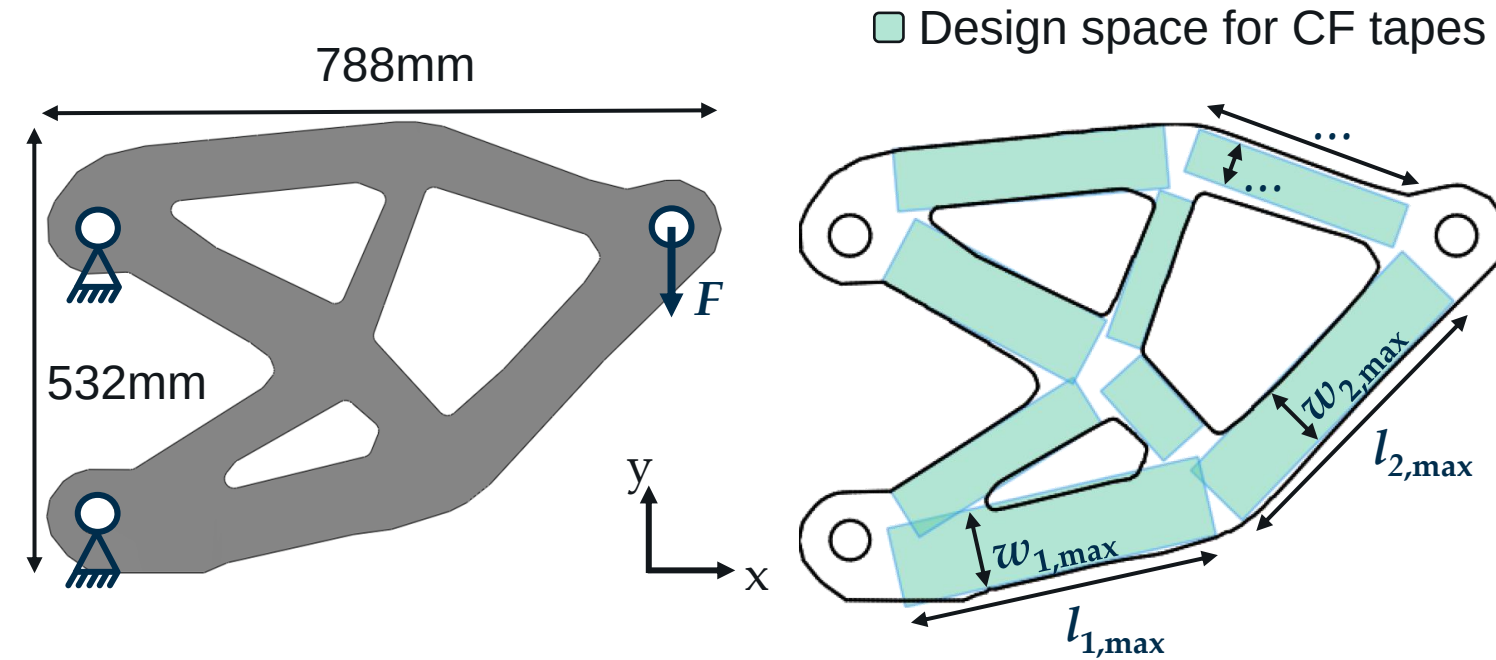
J_1 : Strain energy
 J_3 : Hashin values
 J_2 : Sustainability

FE simulation
Based on design variables

Objective Function: $\min J = \alpha_1 J_1 + \alpha_2 J_2$

Constraint: $J_3 < 1$

Numerical Example



Objective Function: $\min J = \alpha_1 J_1 + \alpha_2 J_2$

Constraint: $J_3 < 1$

[Frank et al., 2026]

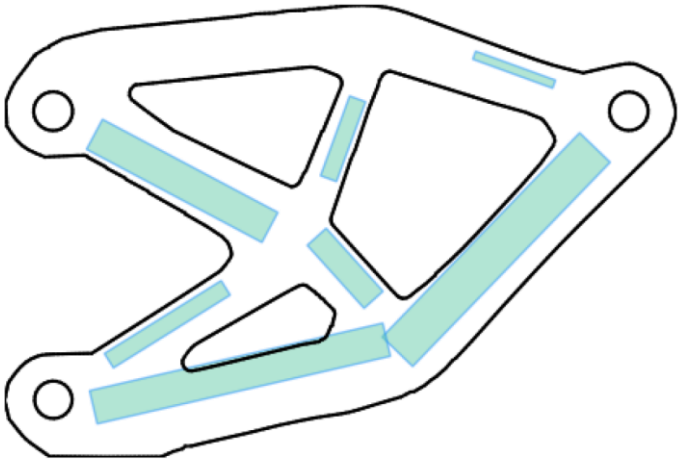
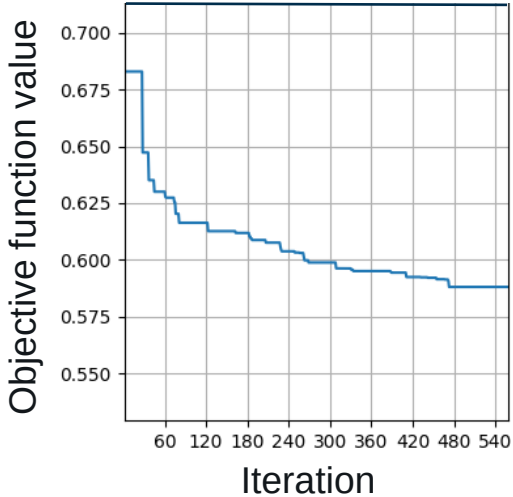
Setup

- Approx. 10300 elements
- 6 NFRP layers (constant)
- Symmetric layup
- Min. tape width: 10mm
- Differential evolution algorithm
- Population size: 100
- Max. iterations: 600

Numerical Example

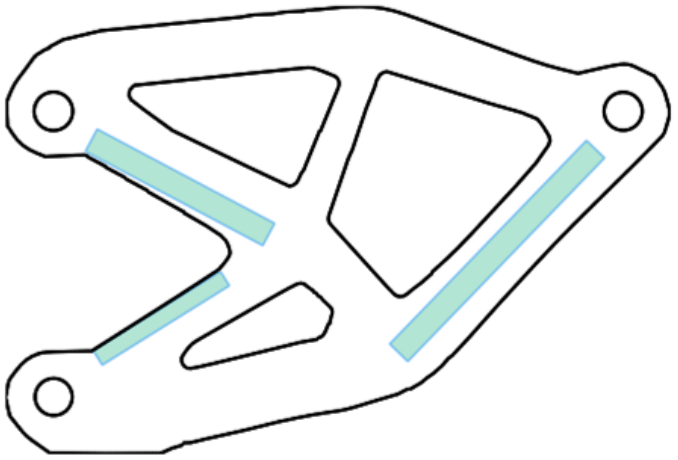
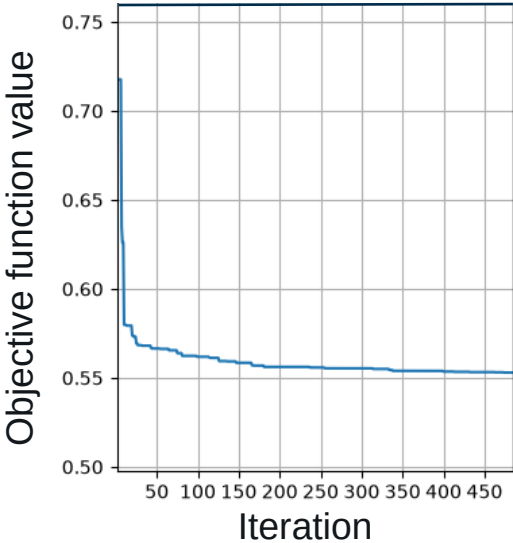
Optimized CF tapes

$\alpha_1 = 0.75$
 $\alpha_2 = 0.25$



Layer	Orientation
1	35°
2	4°
3	-25°
4	-25°
5	4°
6	35°

$\alpha_1 = 0.60$
 $\alpha_2 = 0.40$



Layer	Orientation
1	8°
2	30°
3	-24°
4	-24°
5	30°
6	8°

[Frank et al., 2026]

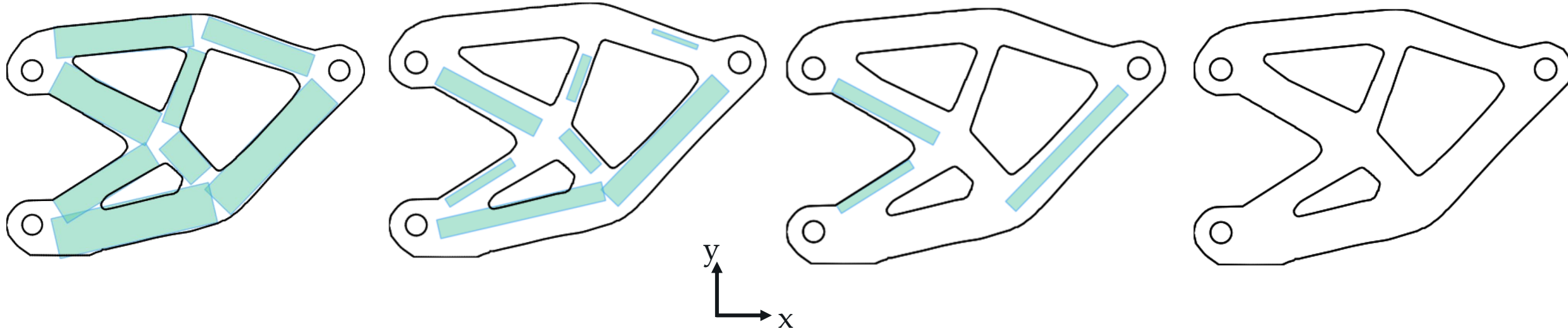
Numerical Example

Reference: All tapes

$\alpha_1 = 0.75, \alpha_2 = 0.25$

$\alpha_1 = 0.60, \alpha_2 = 0.40$

Reference: No tapes



Parameter	J_1 [Nmm]	J_2 [cm ²]	u_y [mm]	H_{fiber}^T [-]	H_{fiber}^C [-]	H_{matrix}^T [-]	H_{matrix}^C [-]
All tapes	4.295	1403.1	-0.09	5.1e-4	1.2e-3	1.4e-2	1.1e-2
$\alpha = [0.75, 0.25]$	6.456	541.5	-0.14	4.0e-4	9.3e-4	1.4e-2	1.4e-2
$\alpha = [0.6, 0.4]$	7.517	182.6	-0.16	4.2e-4	9.7e-4	1.9e-2	1.1e-2
No tapes	9.082	0.0	-0.20	6.7e-4	1.4e-3	1.8e-2	1.9e-2

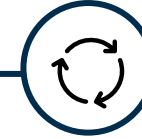
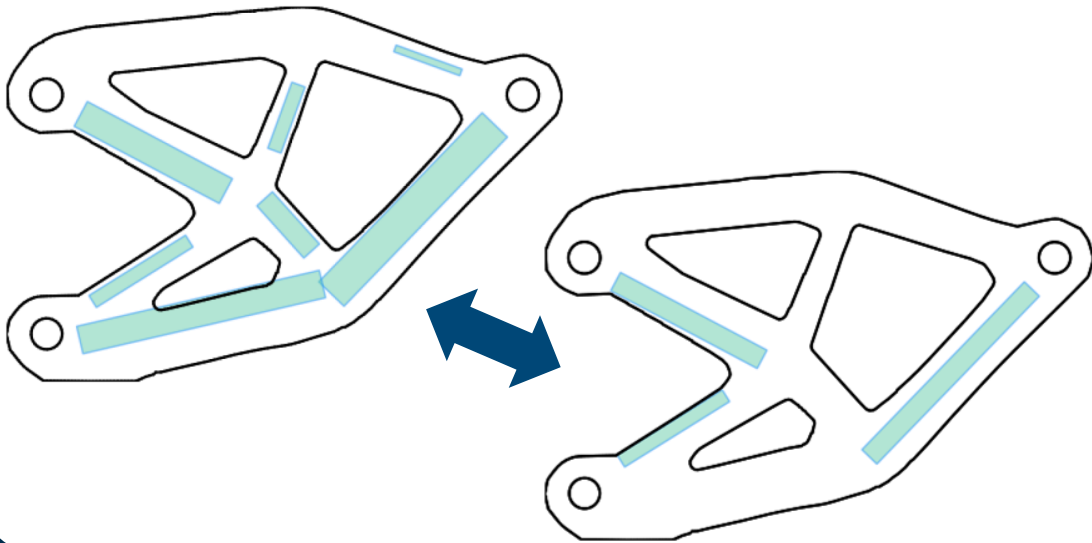


[Frank et al., 2026]

Conclusion & Outlook



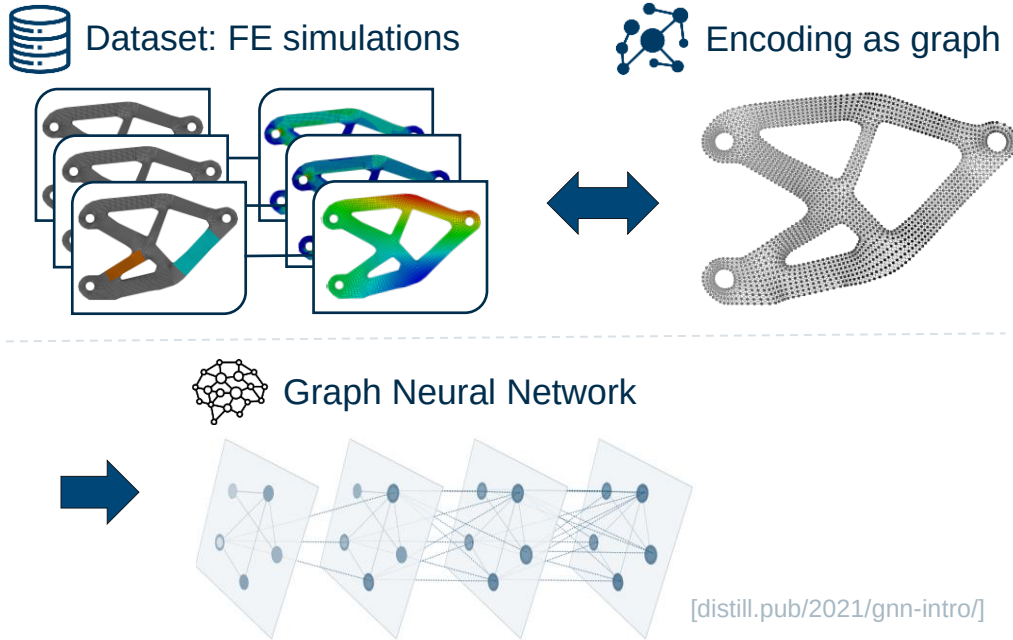
- Method for the **simultaneous optimization** of **NFRP layup orientations** and **configuration of CF tapes**
- Supporting product developers in finding **trade-offs** between **part stiffness** and the **use of CF**



- Many FE simulations for one iteration
 - → **High computational effort**
- Investigation of other **optimization algorithms**
 - Bayesian optimization
 - Response surface
- **Machine Learning** approaches
 - Graph Neural Networks
 - Predict stiffness of reinforcement configuration
- **3d shell structures** and **multiple load cases**

Outlook – Graph Neural Networks (GNN) for Simulation

General Concept



Prediction Tasks

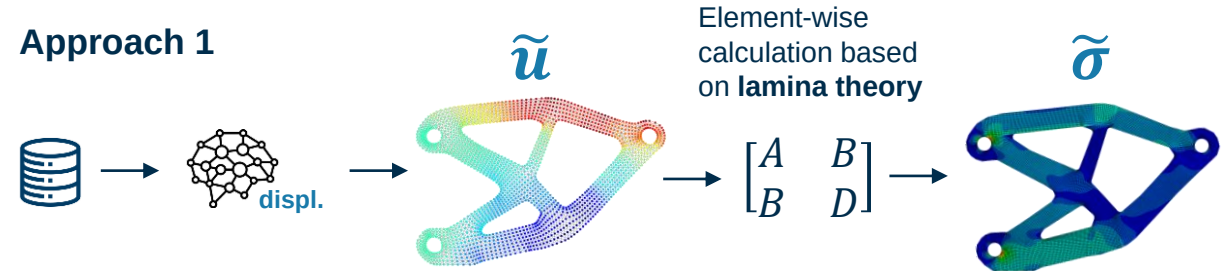
Input: Graph

Graph-level prediction
(e.g. mechanical compliance)

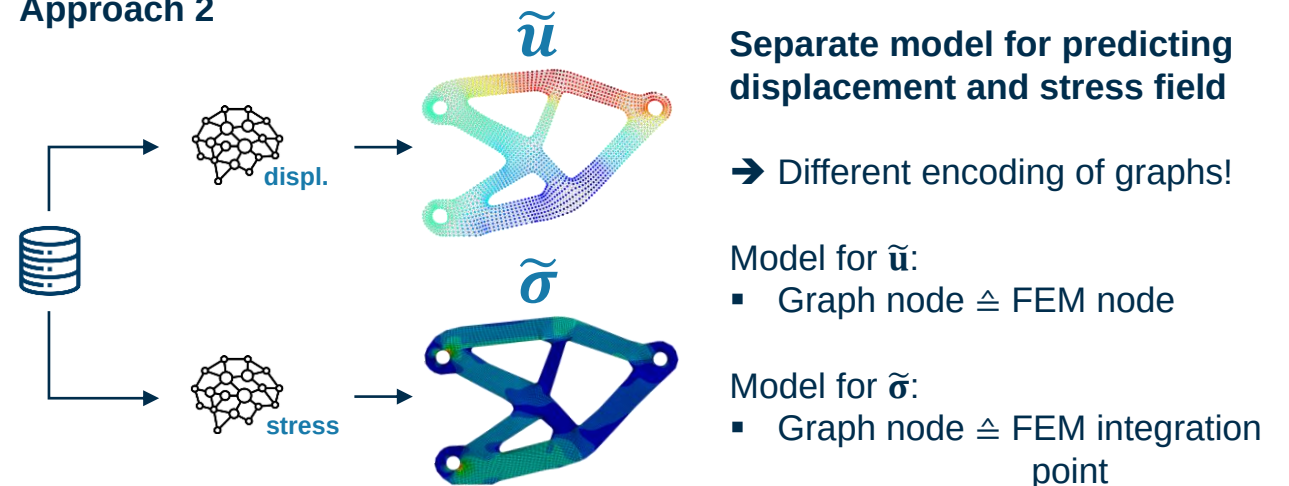
Node-level prediction
(e.g. displacement or stress values)

Application to Case Study

Approach 1

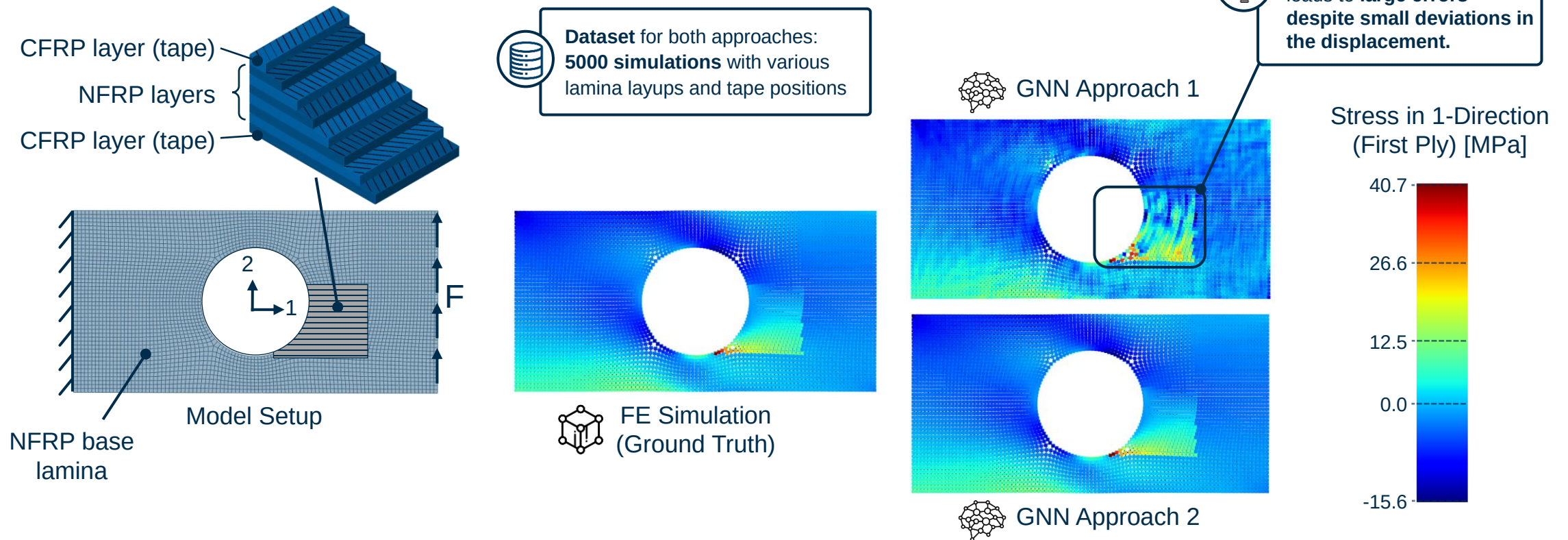


Approach 2



 **PyG** Implemented with PyTorch Geometric

Outlook – Comparison of Approaches



Using **separate models** for **solution variables** (displacement) and their **derivatives** (stress) leads to **more accurate results**.

However, **more computational effort** is required (training of multiple models).

References

Images

- [1] <https://www.bcomp.com/wp-content/uploads/2020/03/rectangle-3@3x.jpg>
- [2] https://www.pflanzenforschung.de/download_file/68
- [3] <https://fleurbelle.de/wp-content/uploads/2022/12/Flachs-getrocknet.jpeg>
- [4] <https://www.bcomp.com/wp-content/uploads/2023/12/DSC8473-scaled.jpg>
- [5] https://www.tuningblog.eu/tipps_tuev-dekra-u-co/bmw-naturfasern-405023/
- [6] <https://www.bcomp.com/wp-content/uploads/2021/01/SeatPhoto-4-1024x683.jpg>
- [7] https://www.bcomp.com/wp-content/uploads/2023/12/Full-version-vin10111_paneldoor_mist-scaled-1.jpg
- [8] https://www.fibermax.eu/image/cache/catalog/tapes/ct80u06_3-01-800x600w.webp
- [9] <https://www.bcomp.com/wp-content/uploads/2021/06/5040d-232x300.png>

Literature

- Ramachandran, K., Gnanasagaran, C. L., Vekariya, A. (2023) *Life cycle assessment of carbon fiber and bio-fiber composites prepared via vacuum bagging technique*. Journal of Manufacturing Processes, 89:124-131, doi.org/10.1016/j.jmapro.2023.01.068
- Frank, N., Voltz, S., Düser, T. (2026) *Optimization of Hybrid Natural Fiber-Reinforced Polymers With Selective Reinforcements*. Presentation at the 14th ASMO UK / 3rd ASMO-EUROPE / ISSMO conference on Engineering Design Optimization, 06.07.2026 - 07.07.2027, Imperial College, London.