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Function Integrative Structures II

Warsaw, June 26th -27th 2023

Introduction – function-integration - Evaluation

Integration of functional elements

Advantages

- Functionality of the part surface remains
- Combination of several single components in one part
- Part protects elements against external disturbances and media
- Improved data collection quality, consistency and repeatability

Disadvantages

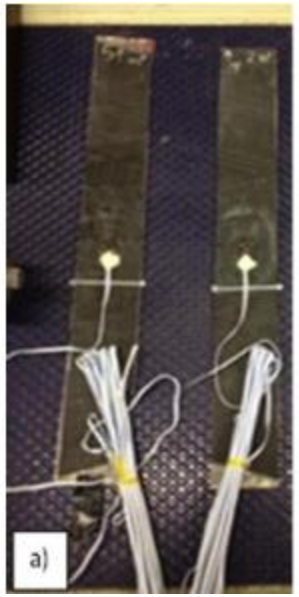
- More complex components/ manufacturing
- Limited repair possibilities
- Possible failure of the active function
- Functional elements represent mechanical disturbances

Challenges

- Positioning and fixing of the functional elements
- Implementation of more complex tool concepts and manufacturing processes
- Functional elements have to withstand process parameters during the manufacturing process
- Contacting the functional elements
- Electrical insulation of the functional elements is required for integration into electrically conductive composite structures (e.g. CFRP structures).

Function Integration without any Consequences?

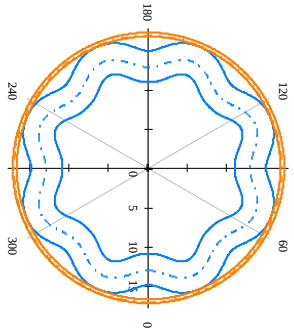
"Effect of embedded electric sensor on the structural strength of filament wound hybrid composite"

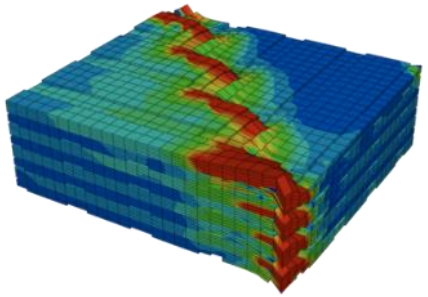


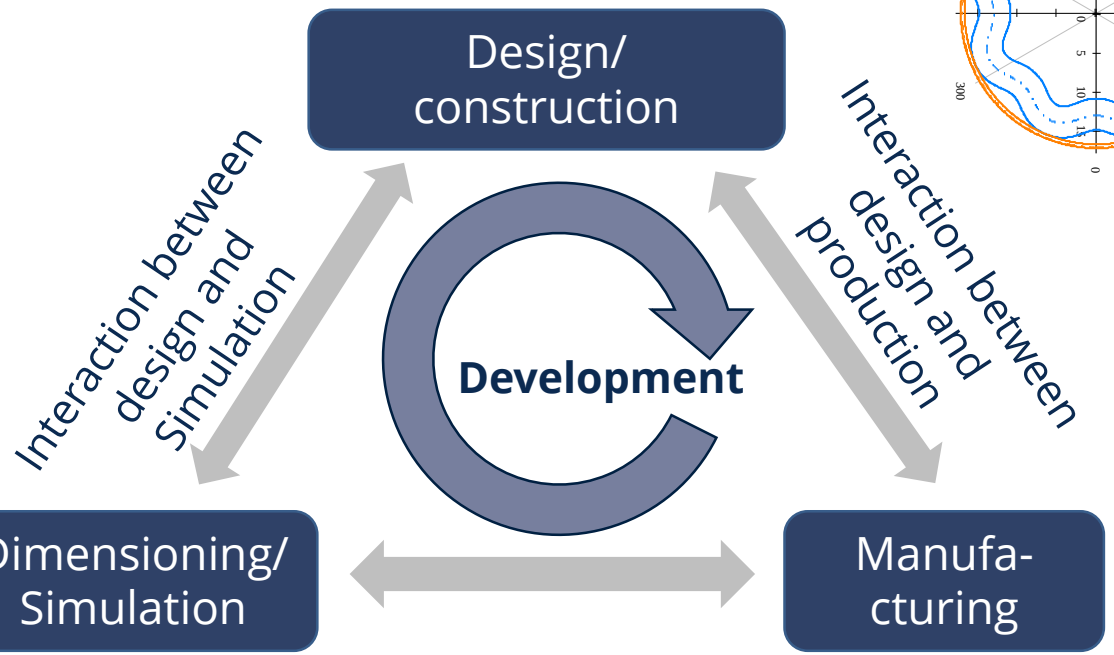
[Sianaki et al., 2014]

- Mechanical property loss
  - Elastic modulus **-15%**
  - Ultimate strength **-3%**
- Damage initiation: At the location of embedded circuit

Interactive development process





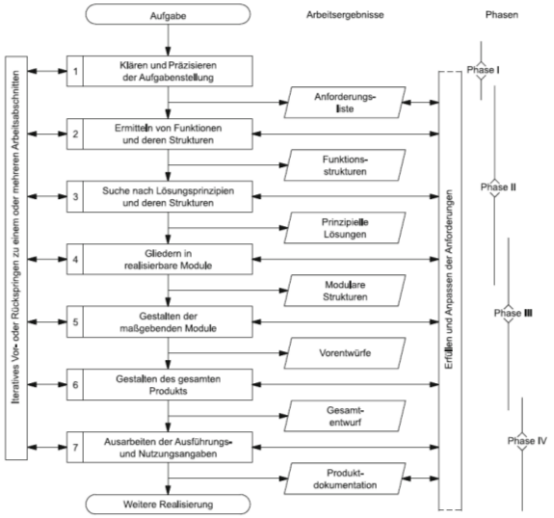


- Integration of individual disciplines
- Interaction of design, layout, manufacturing and material
- Numerous aspects must be taken into account in the development of lightweight structures

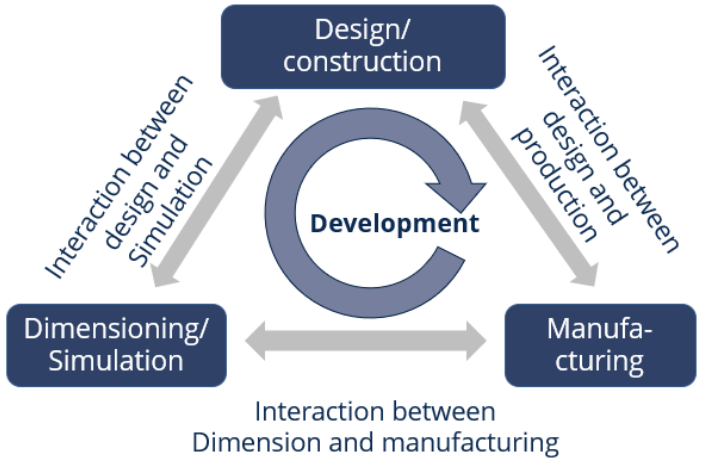
@MB-LB-08, Spitzer Sebastian

Main focus of Function-oriented Design

Classic development process (*VDI 2221*)
Method-oriented



Interactive development process
System-oriented



Spiral development process
Function-oriented

Key aspects of spiral development process

- Focus on **functions**
- Broad **material portfolio**
- **Synthesis and analysis** of different concepts and their grading

Spiral development process @ Function-oriented Design

Verification

- Verify results to the original requirements
- Possibly adjust the results

Abstraction

- Represent the structure as abstract functions

Synthesis

- Include other "secondary" functions
- Discard dependent or irrelevant functions
- Create a synthesis

Main functions

- Identification of main functions in contradiction to each other

Proposed solution

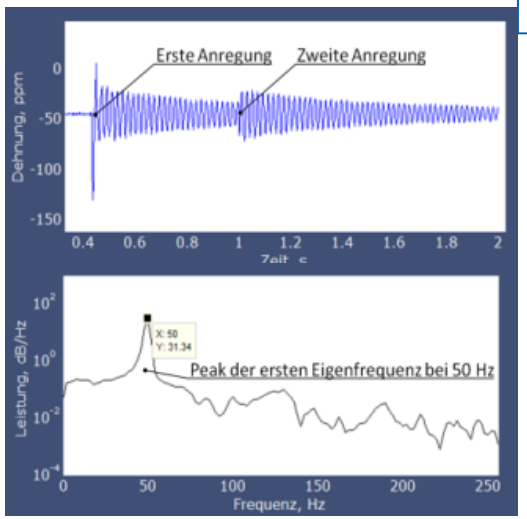
- Determination of the global optimum
- Consideration of boundary conditions

Interactions

- Describe the main internal interactions, e.g. analytical, simulation, semantic, weighting
- How do they relate to each other?

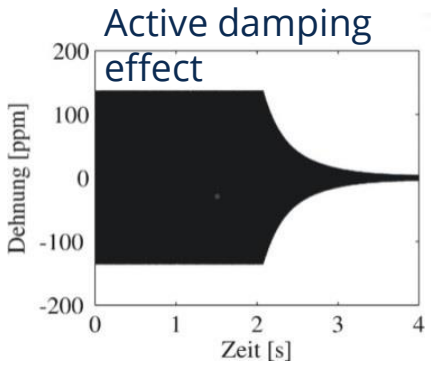
Self-diagnostic fan blade

- **Active thermosetting composite fan blade**
- **Material immanent sensor-actuator-network**
- **Embedded control und communication modules**
- **Wireless energy and data transfer**



Wireless transmitted vibration response

Eigenmode-adapted sensors and actuators



Embedded electronic components

Micro-controller

Communication module

Measurement electronics

Energy supply

Actuator supply

Spiral Development Process @ Function-Oriented Design

List of requirements → **Draft solution**

Verification

- Verify results to the original requirements
- Possibly adjust the results

Abstraction

- Represent the structure as abstract functions

Synthesis

- Include other "secondary" functions
- Discard dependent or irrelevant functions
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Main functions

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Proposed solution

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Interactions

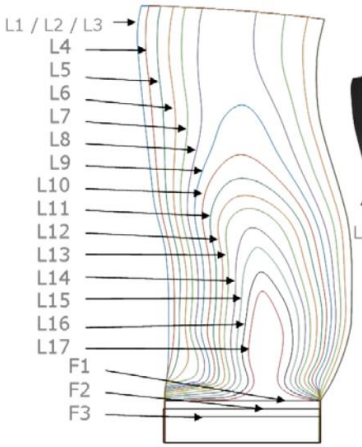
- Describe the main internal interactions, e.g. analytical, simulation, semantic, weighting
- How do they relate to each other?

I. Structural Functions

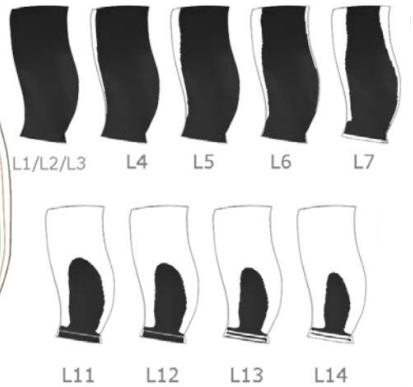
Requirements

Validation
- Stress and dynamic tests
- Rotor run-up
- Structural integrity assessment

Synthesis



Draft Solution

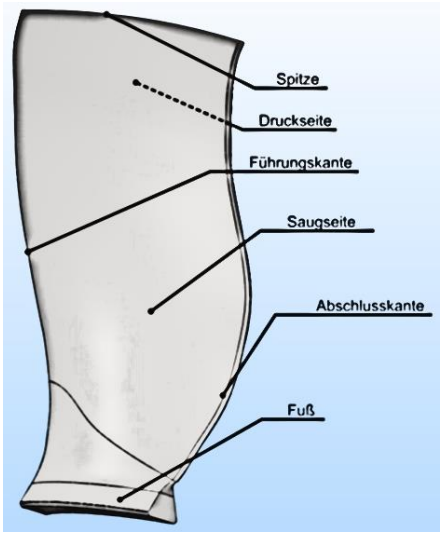


Designed blade

Abstraction
- Provides thrust
- Dynamic stability

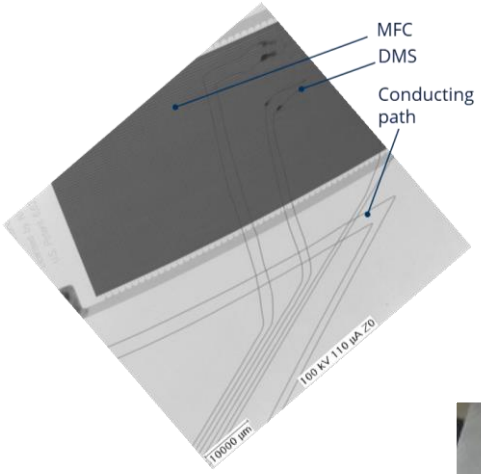
Interdependencies
- Power & Mass
- Stiffness & Stress

Main Function Analysis



II. Sensory & Actuator Functions

Requirements

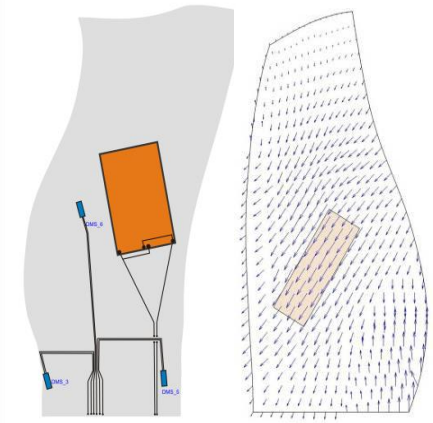


Validation

- CT & Ultrasonic scans
- Electrical tests

Synthesis

Draft Solution

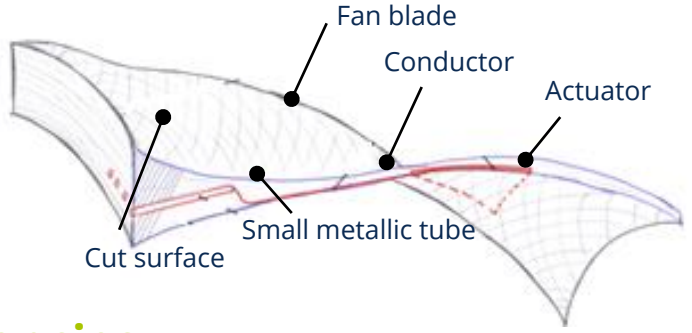


Sensor-integrated blade

Abstraction

- Dynamic strain measurement

Main Function Analysis



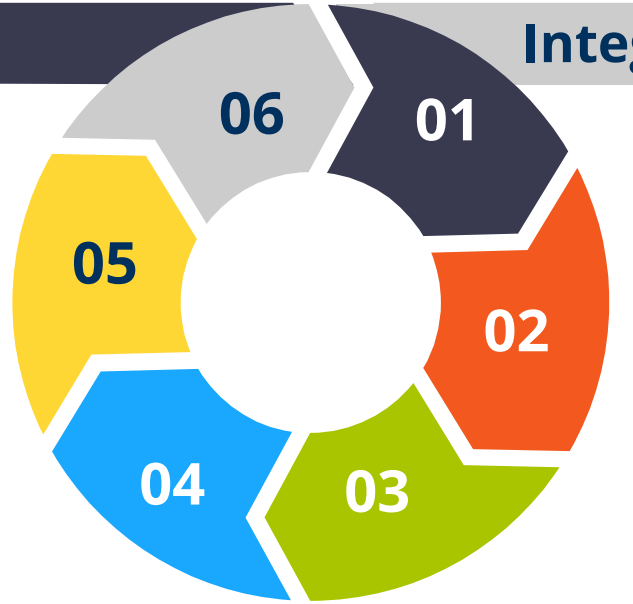
Interdependencies

- Number of sensors & Critical stress
- Structural rigidity & Information loss
- Impact resistant & Sensor integration

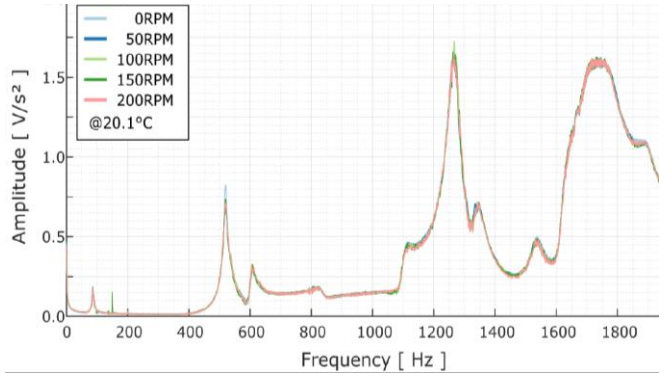
III. Data Acquisition - Electronic Functions

Requirements

Integrated signal acquisition system



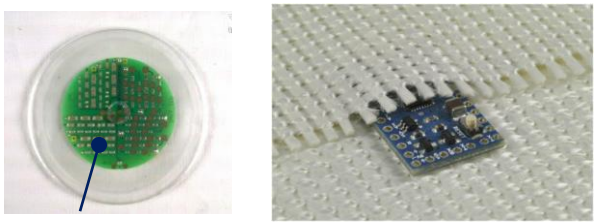
Validation



Abstraction

- In-situ signal acquisition
- Edge data analysis

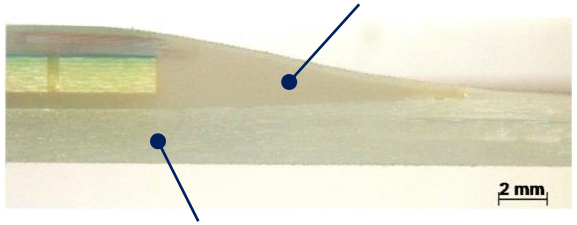
Main Function Analysis



Electronic components

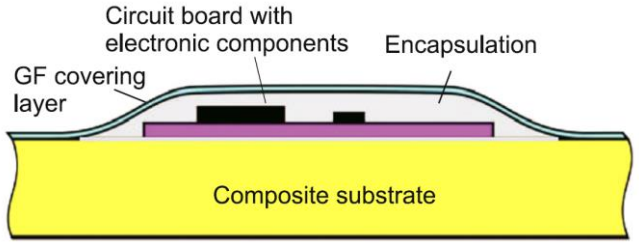
Synthesis

Appropriate integration of electronic components



Glass fibre-reinforced thermoset

Draft Solution



Interdependencies

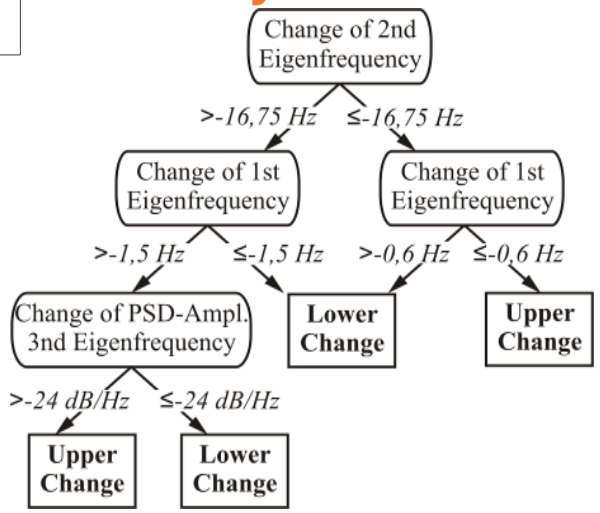
- Topology of electronics & Standardization
- Encapsulation & Stiffness
- Condition monitoring & Information of damage

IV. Complex Functions – Damage diagnosis

Requirements

Validation
- Accuracy
- Cross validation
- ROC curves

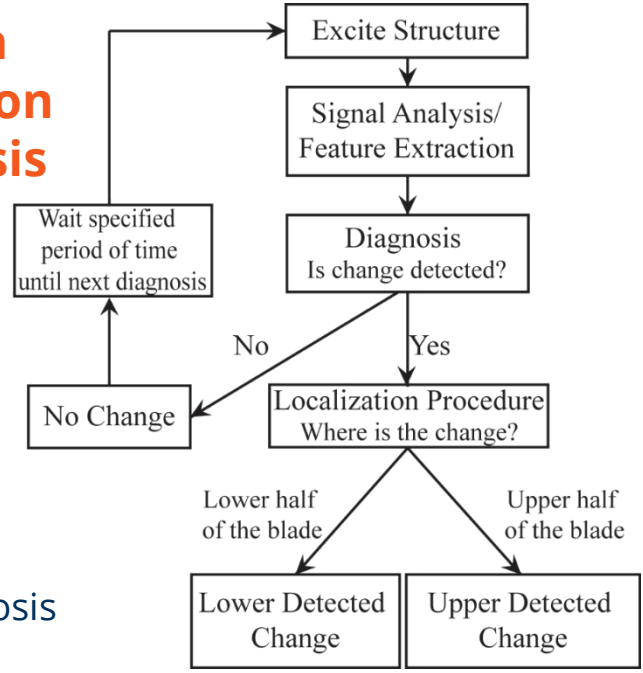
Synthesis



Blade with diagnostic function

Abstraction
- Damage Detection – Null hypothesis
- Damage localization

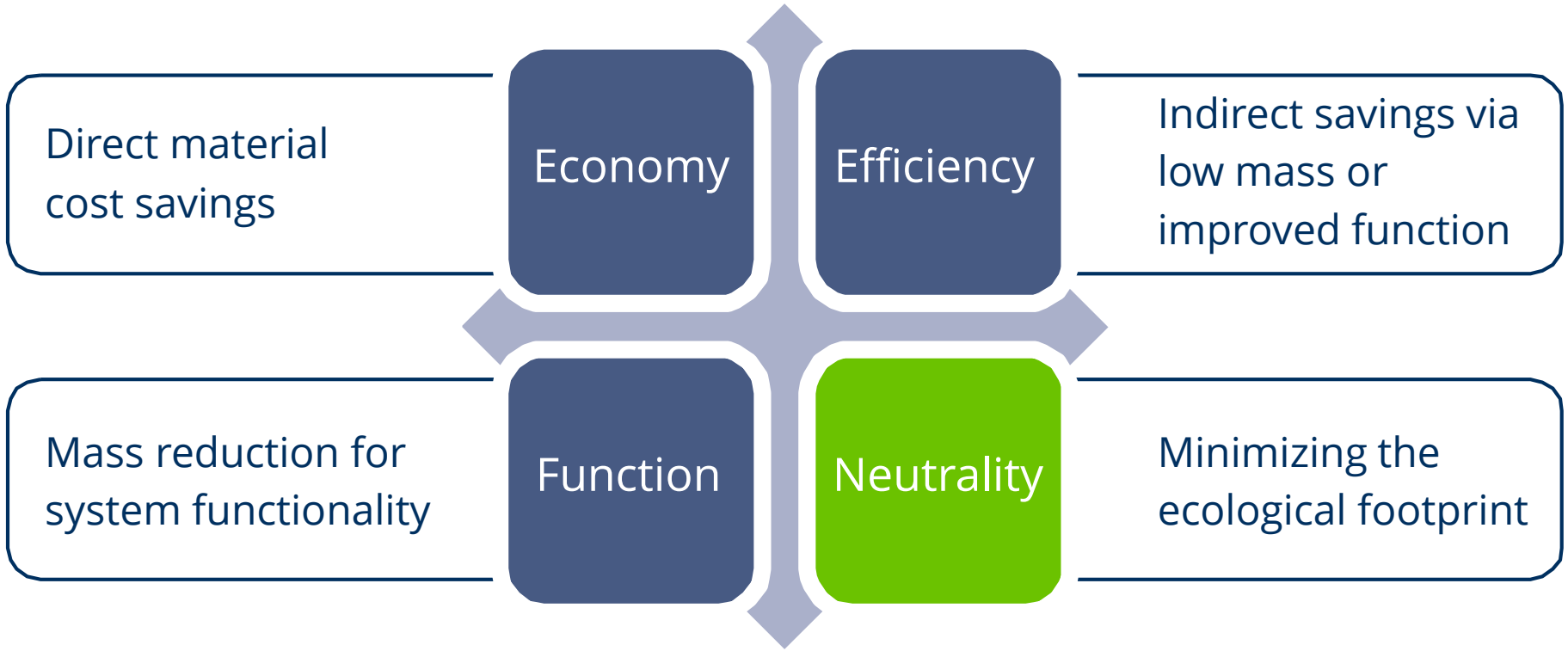
Main Function Analysis



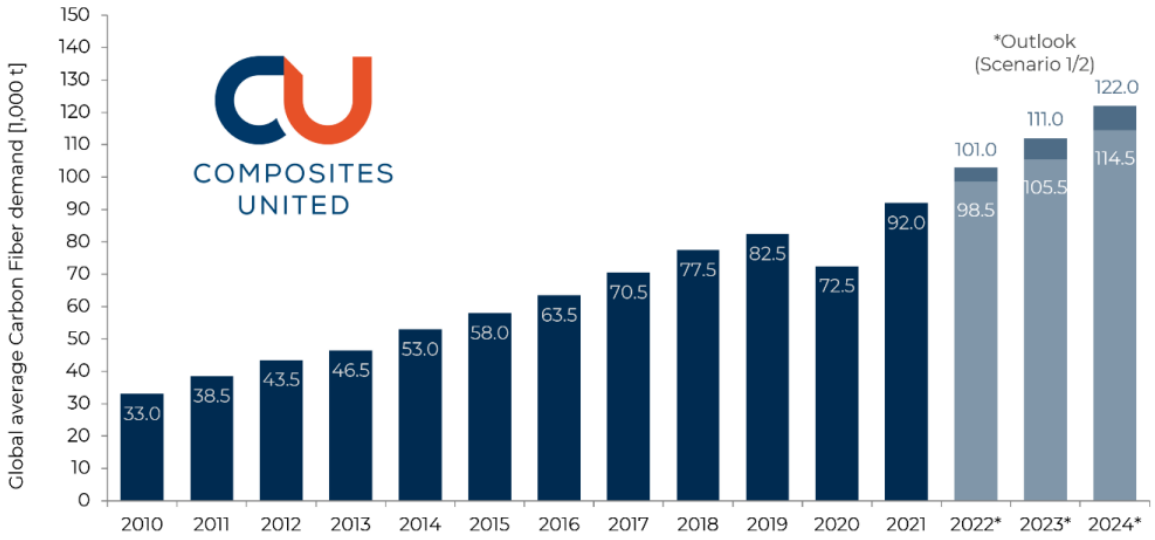
Draft Solution

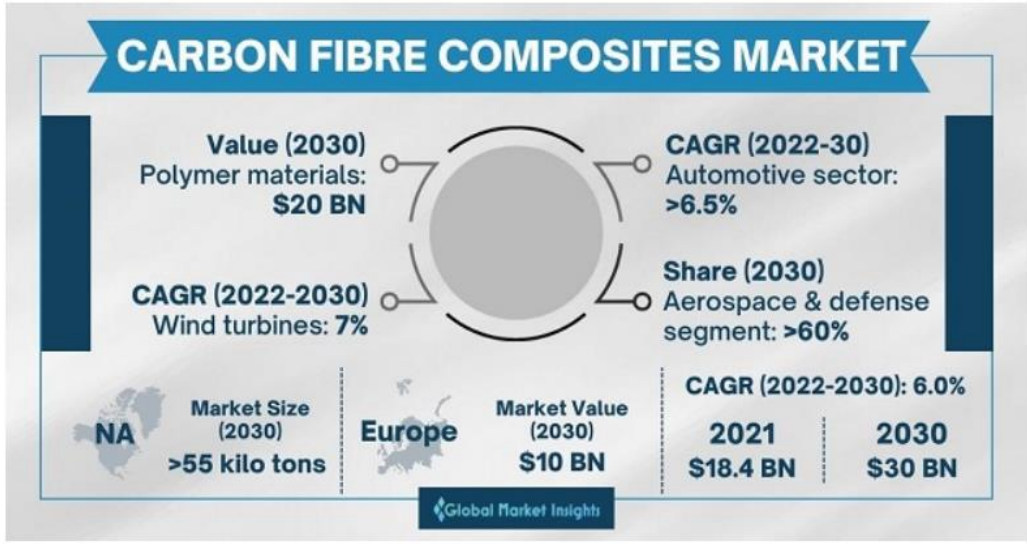
Interdependencies
- Sensitivity & Specificity
- Robust & Detailed prognosis
- Bias & Variance

Lightweight design classes



The Recyclability Function





- Annual growth rate of +9.77%
- Aerospace share (est.) by 2030: 60%
- Climate neutrality by 2050

Is it possible to integrate recyclability at the design phase of structural components?

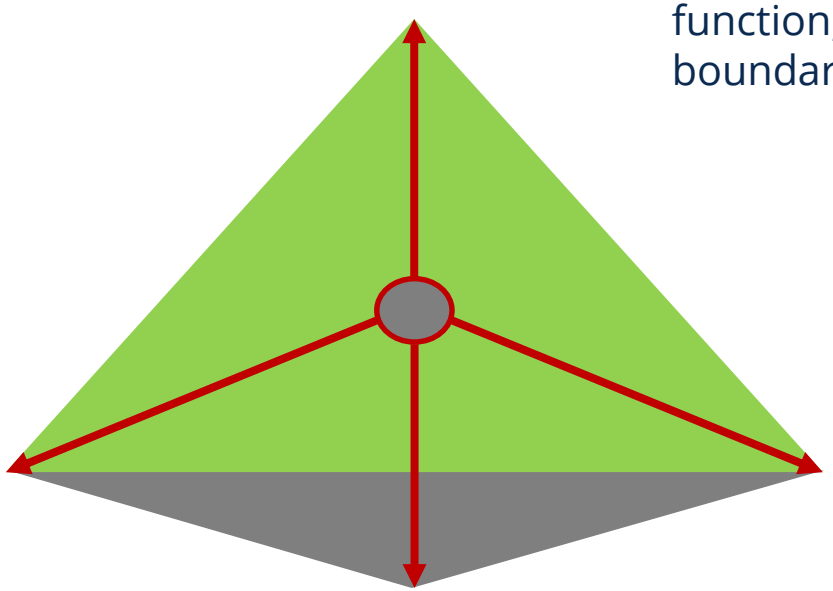
Function as an Inherent Contradiction of the System

Design in an **iterative process** to **solving contradicting goals** and taking into account
— **Contradictions** of mechanical and functional properties
— **Boundary Conditions**, e.g. geometry, mass
— **Constraints**, e.g. costs

Mass - Materials

Dependent on fulfilment of primary function, compliance with acceptable boundary conditions

Trade-off between contradictions

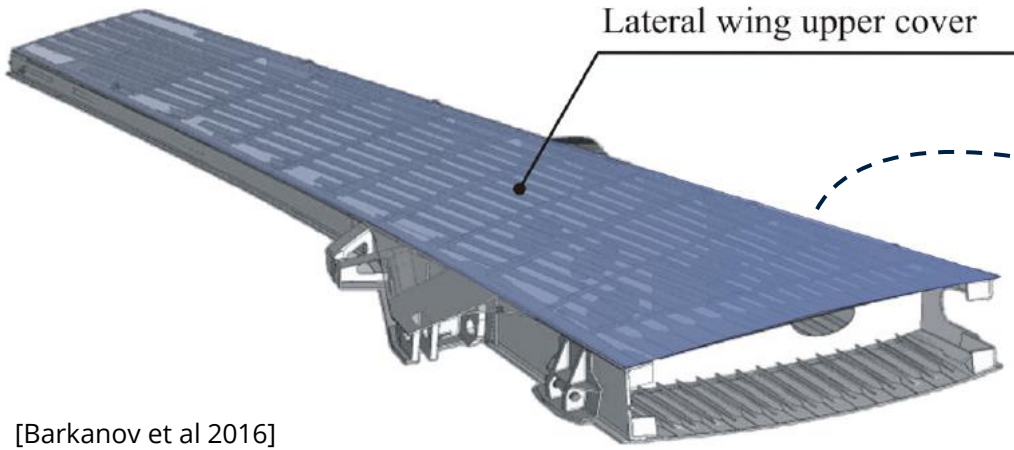


Functional properties
No significant reduction in mechanical properties & primary component function

Costs - Resources

Recycling

Structural Components with Recycled Fibers



[Barkanov et al 2016]

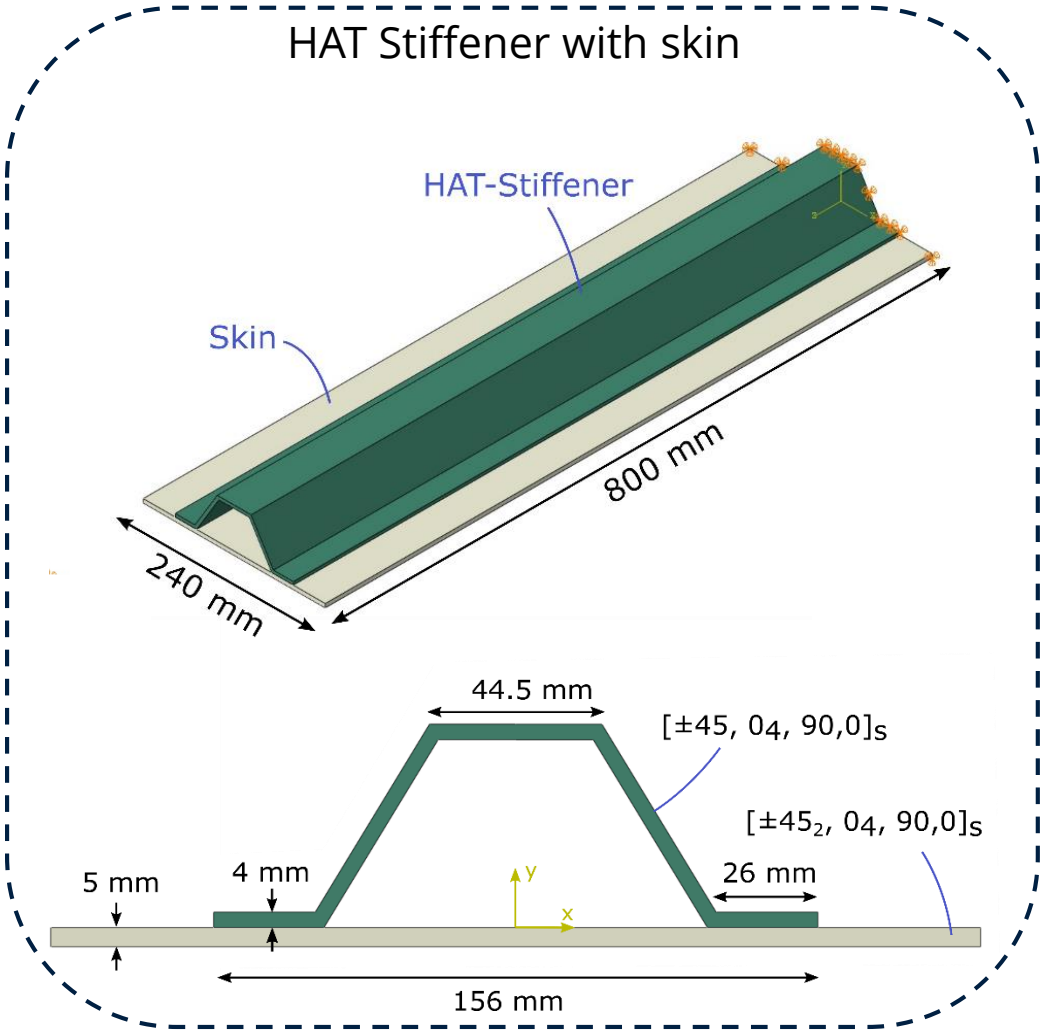
Fibers reclaiming methods

- Mechanical treatment
- Thermal (fluidized bed, pyrolysis)
- Chemical (solvolysis)

- Property loss
- Material loss

Fabrication methods for hybrid textiles

- Tailored fibre-placement (TFP)
- Automated tape placement
- Filament winding method



Structural Components with Recycled Fibers

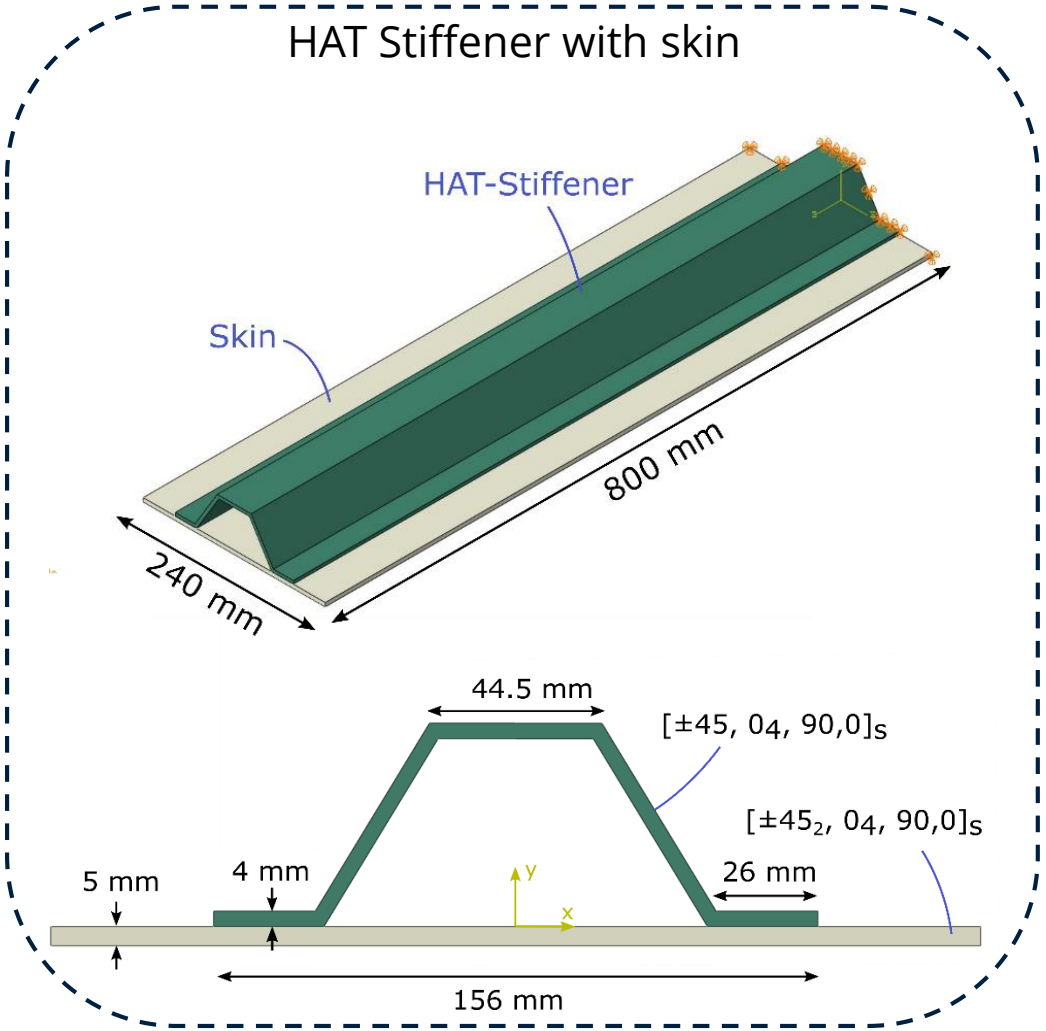
Material Properties

	Pristine CFRP (GPa)	Recycled CFRP (GPa)	Reduction
E_{11}	194	155	-20%
E_{22}	8	8	-
G_{12}	4,5	3,6	-20%

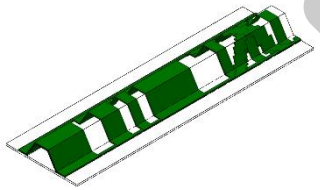
Requirements List

Requirements	Target State
Structural	• Stiffness loss in specific range • No damage should occur • Identical outer geometrical dimensions
Recycling	• Recycled proportion: 10% to 50% • Identify relationship between stiffness loss, efforts to recycled proportion

HAT Stiffener with skin

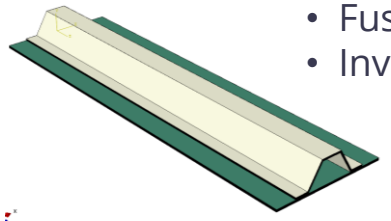


Spiral Development Process @ Function-Oriented Design



Verification

- Verify results to the original requirements
- Adjust the results



Synthesis

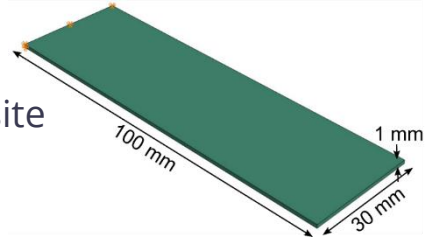
- Fuse informationn from plate
- Investigation of the HAT-stiffener

List of requirements

Draft solution

Abstraction

- Examine a composite plate



Main functions

- Structural integrity
- Recyclability

$$RI = \frac{Recycled\ material}{Total\ material} \quad \epsilon\ [0,1]$$

Proposed solution

- Finite element analysis

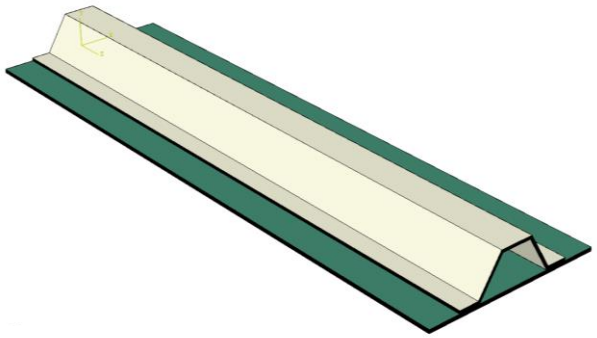
Interactions

- Structural optimization problem

Abstraction & Functions

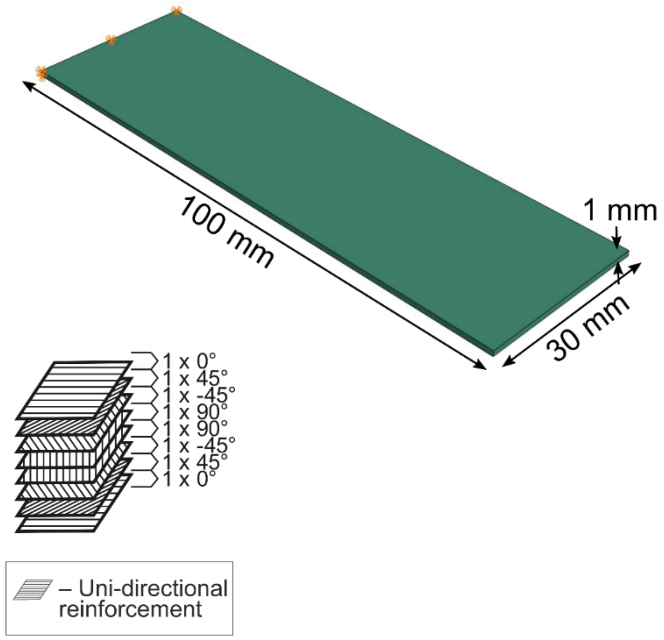
Abstraction

HAT-Stiffener



Plate

- Typical lay-up
- Similar length to width ratio



Functions

Structural integrity **(Main)**

- *Effort significant below damage initiation*

$$Eff_{ij} = \frac{\sigma_{ij}}{R_{ij}} \qquad i,j = \{12\}$$

- *Minimize stiffness loss*

$$f_i = \frac{|\, ef_{i,ref} - ef_{i,rec} \,|}{ef_{i,ref}} \times 100$$

- *Typical loading conditions and Safety Factor (SF) of 2.0*

Recyclability **(Secondary)**

- *Recycling Index*

$$RI = \frac{Recycled\ material}{Total\ material} \ \epsilon\ [0,1]$$

Interactions – Optimization Problem

- **Objective Function**:

$$\begin{cases} \text{Minimize } \mathbf{Structural\ Performance\ Loss}\ \ \mathbf{SP_{loss}} \\ \text{Subject to, } \zeta_{min} < \ \mathrm{RI}^{\mathrm{target}} \ < \zeta_{max} \end{cases}$$

- **Errors**
  - Eigenfrequency error:

$$\mathcal{F}^{err} = \left|\left|\bar{\mathcal{F}}\right|\right| = \sqrt{\sum_{i=1}^{5} |\mathcal{F}_i|^2}$$

  - Recycling error:

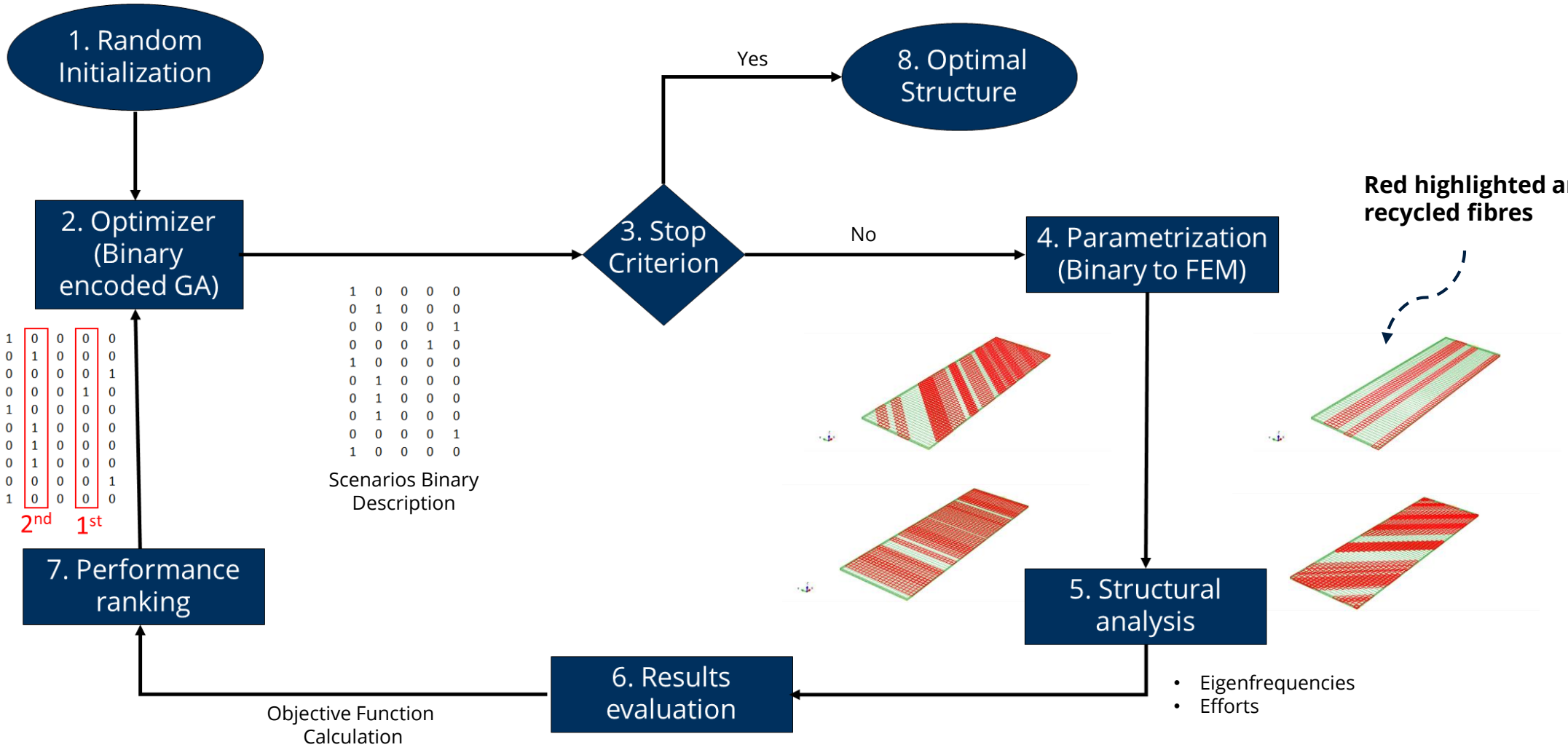
$$Rec^{err} = \max\{\,\overline{RI}\,, 0\,\} \quad \text{where} \quad \overline{RI} = \frac{RI^{target} - RI}{RI^{target}} \times 100$$

- **Constrains**: Effort Penalty

$$Eff^{p}{}_{ij} = \frac{100}{1 + e^{\left(-1000 \times (Eff_{ij} - 0.49)\right)}} \qquad i,j = \{1,2\}$$

Longitudinal, transverse & shear direction

Interactions – Optimization Problem



Proposed Solution – Finite Element Model

Mesh discretization

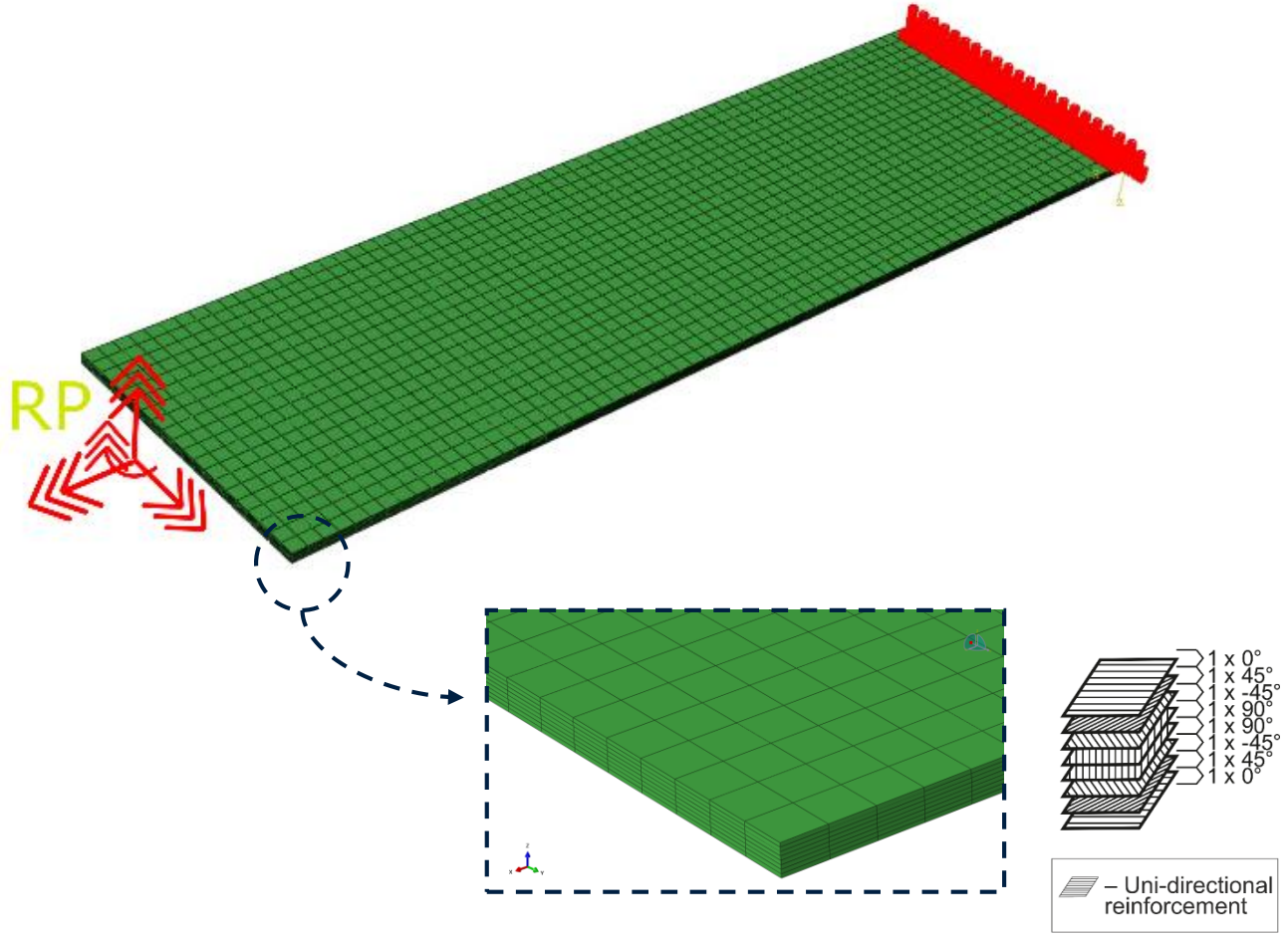
- 10720 SC8R shell elements
- Element size = 1.4925

Plies description

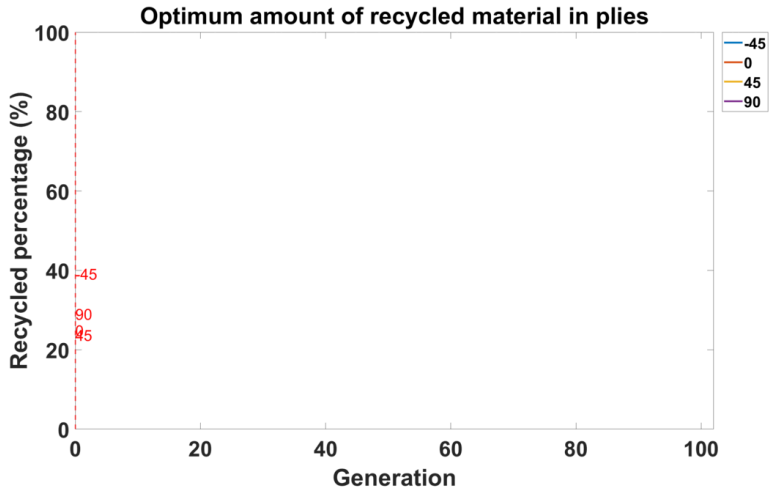
- 1 element per ply along thickness

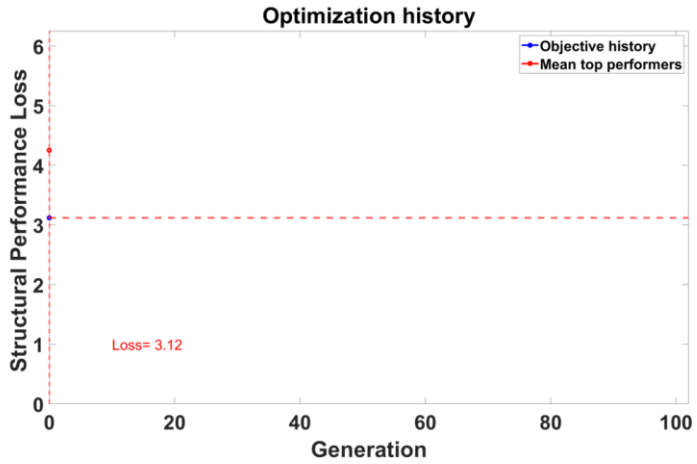
Boundary & Loading Conditions

- Free end: RP for load applications
- Fixed End: Restricted translational & rotational DOF
- Applied load: Concentrated force for
  - Tension
  - Bending
  - Shear
  - Torsion



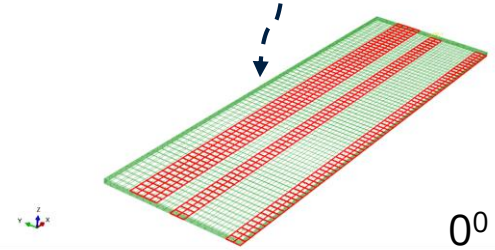
Proposed Solution – Results for RI = 30%



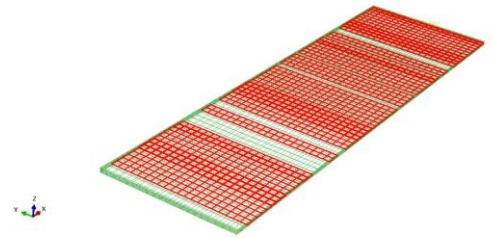


Red highlighted areas: recycled fibres

45^0

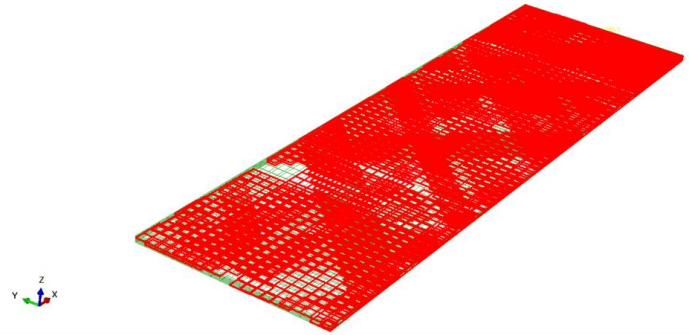


0^0

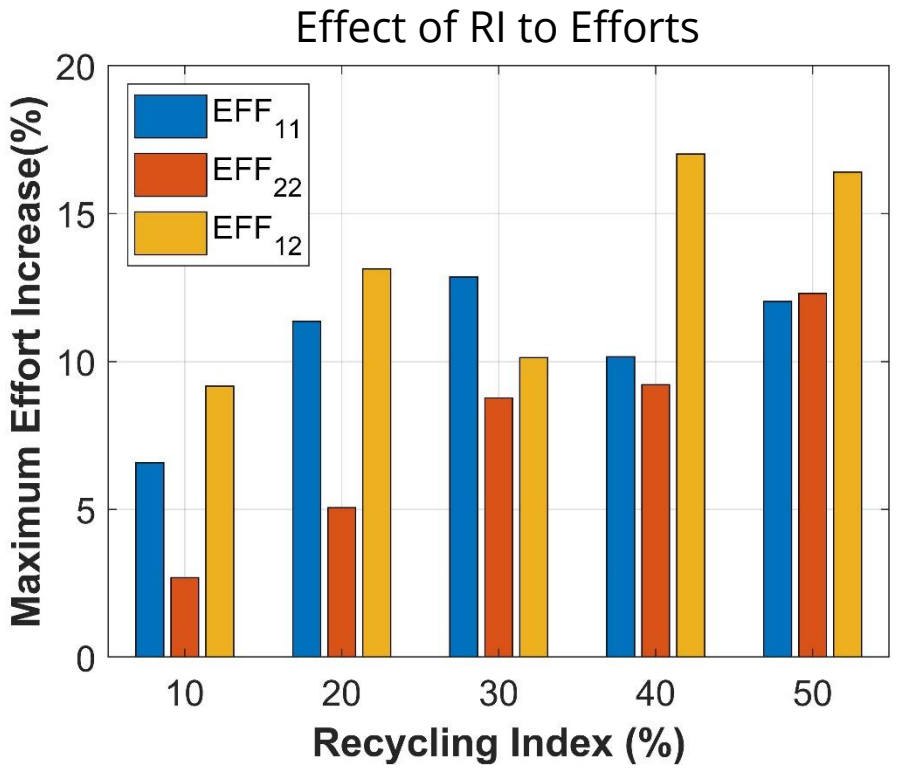


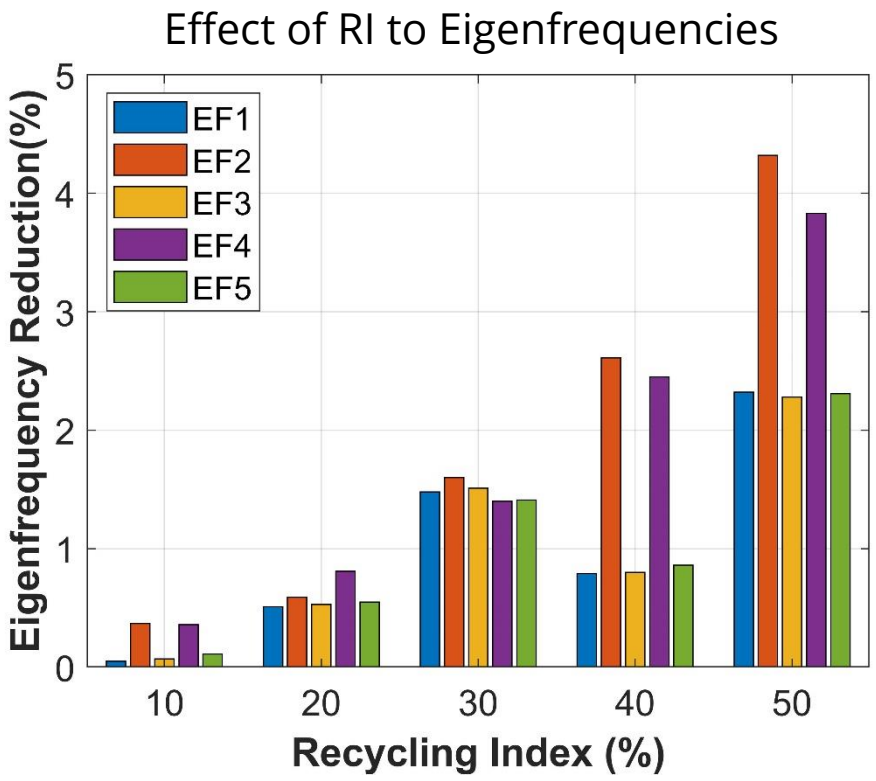
90^0

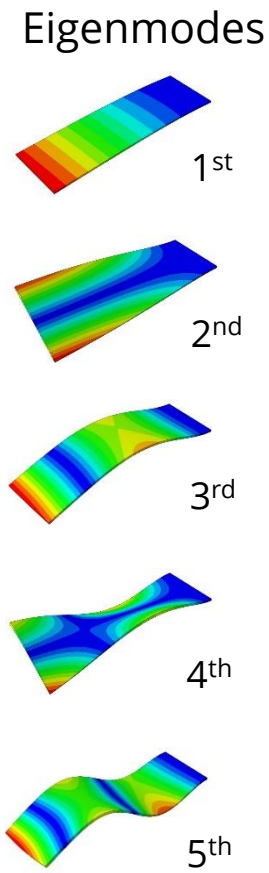
-45^0



Proposed Solution – Results







- Increase in effort for increasing RI
- Up to 50% RI for only 2-5% change of EFs

Synthesis – Hat-Stiffener with Skin

Mesh discretization

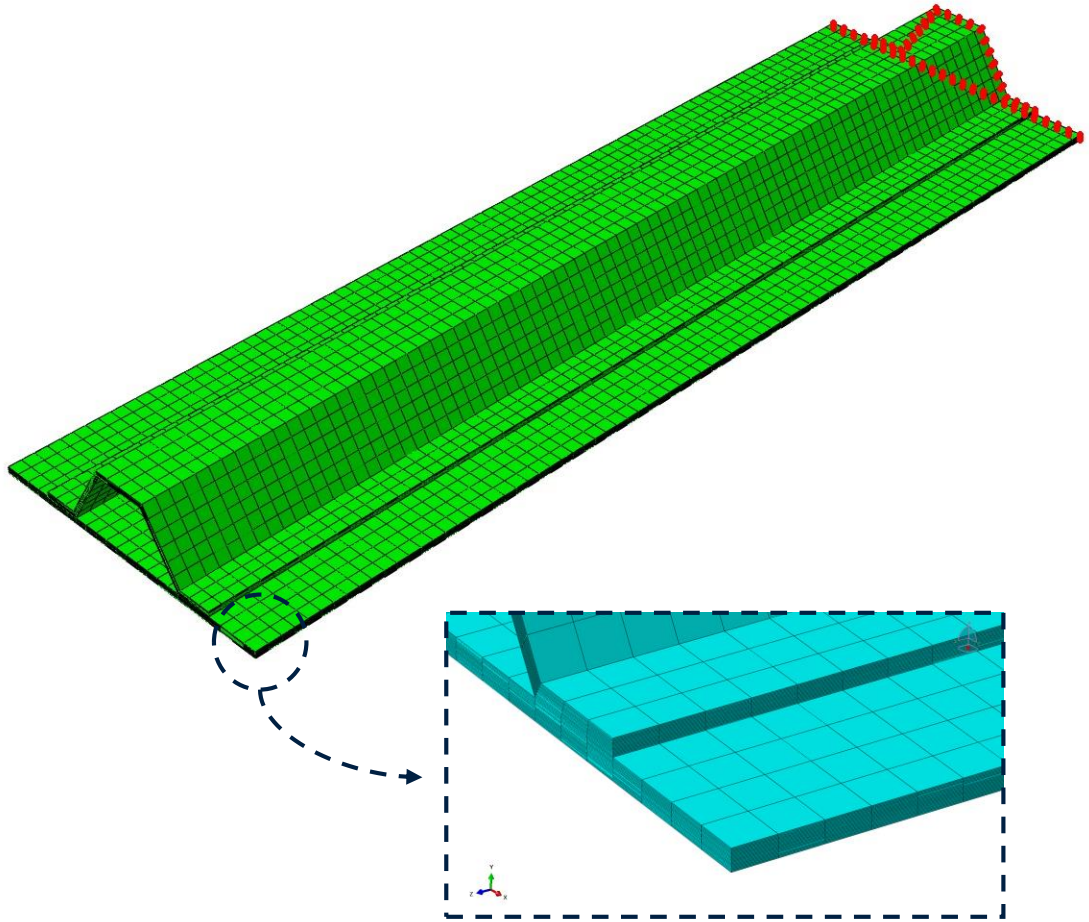
- 66560 SC8R shell elements
- Element size – stiffener = 10
- Element size –skin = 10

Plies description

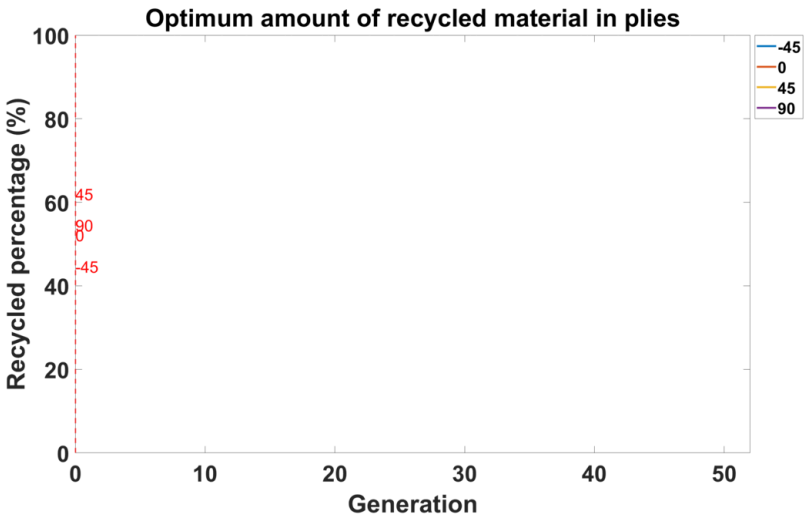
- 1 element per ply along thickness

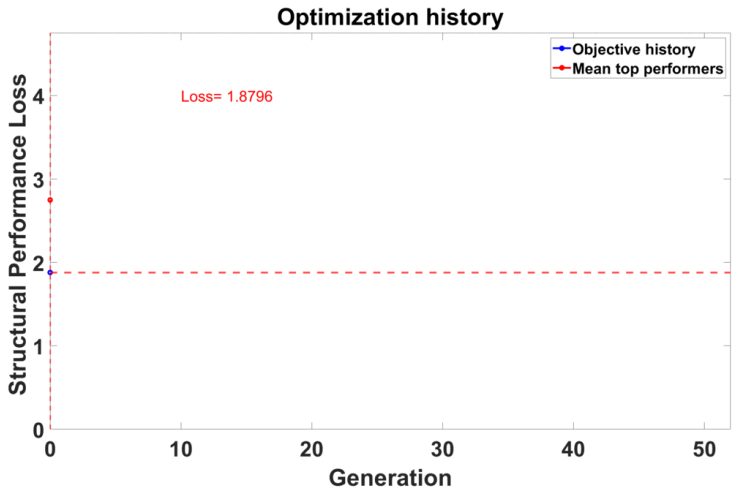
Boundary & Loading Conditions

- Free end: RP for load applications
- Fixed End: Restricted translational & rotational DOF
- Applied load: Concentrated force for
  - Tension
  - Bending
  - Shear
  - Torsion

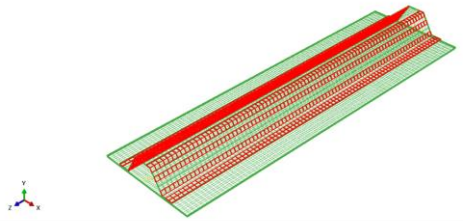


Synthesis – Hat-stiffener with skin, RI = 40%

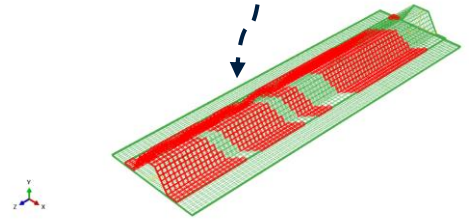




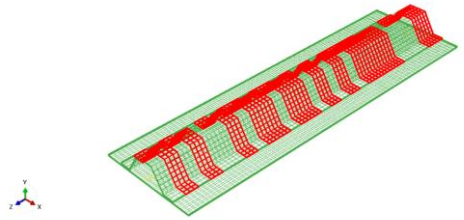
Red highlighted areas: recycled fibres



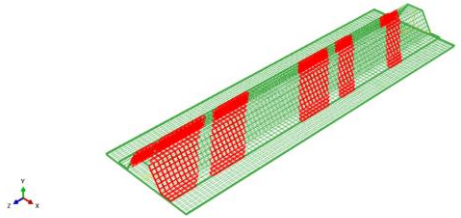
90^0



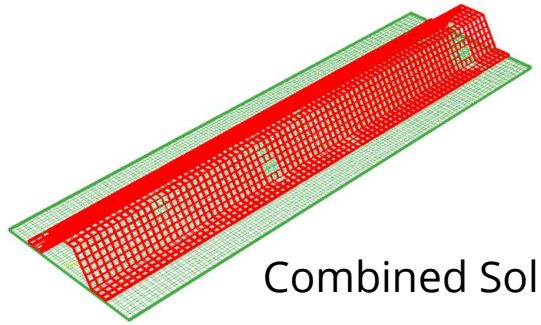
45^0



0^0



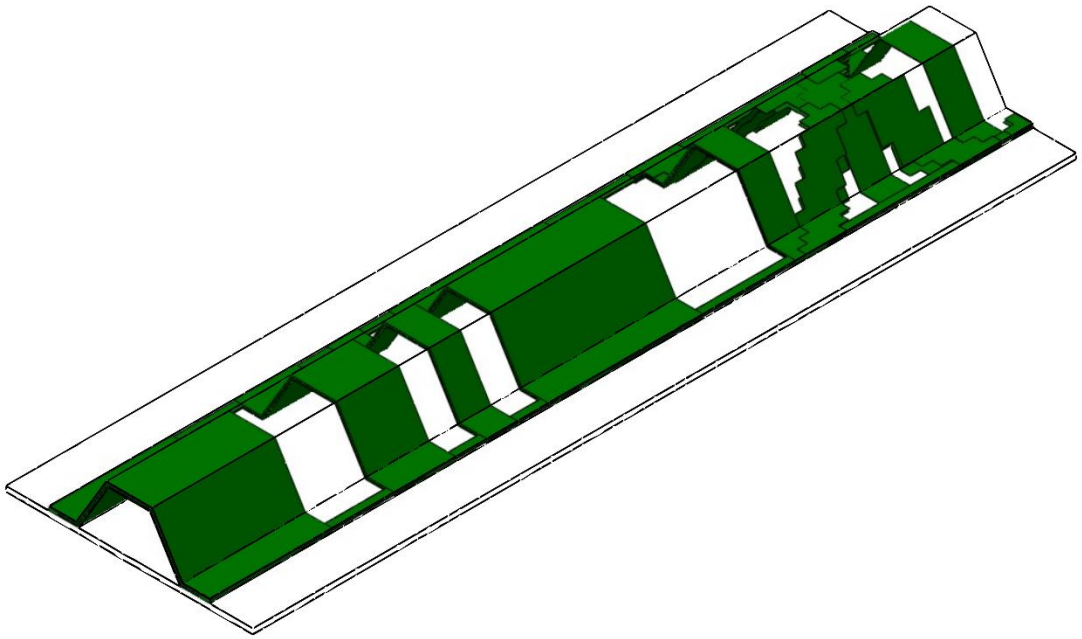
-45^0



Combined Solution

Verification

Requirements	Target State
Structural	• Eigenfrequency value reduction in the range of 2 % - 5 % • Effort below damage initiation • Identical outer geometrical dimensions
Recycling	• Recycled proportion: 10% to 50% • Non linear relationship between stiffness loss, efforts to recycled proportion



RI = 30%

Compliant mechanisms

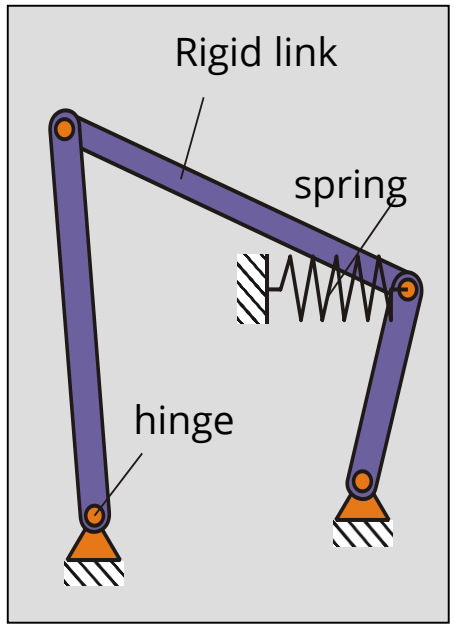
FESTO FinGripper

Compliance is the deformation due to an impressed force.

Gears (mechanisms) are used for the transmission and transformation (transmission) of movements, energy and/or forces. (VDI 2127)

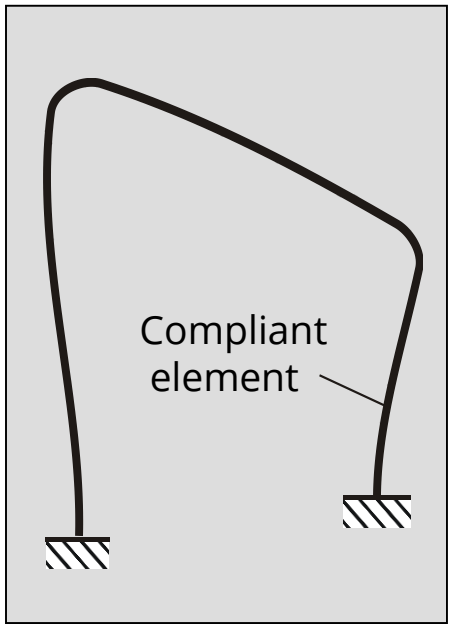
Comparison - conventional against compliant mechanisms

Conventional mechanism



- ⊖ High part variability
- ⊖ Weight intensive
- ⊖ frictional
- ⊖ clearance afflicted
- ⊖ high installation costs

Compliant mechanism

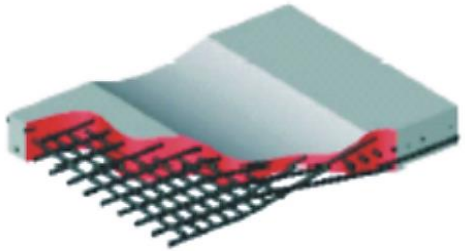


- ⊕ reduction of part variability
- ⊕ light-weight design
- ⊕ low-maintenance
- ⊕ Precise movements without clearance
- ⊕ miniaturisable

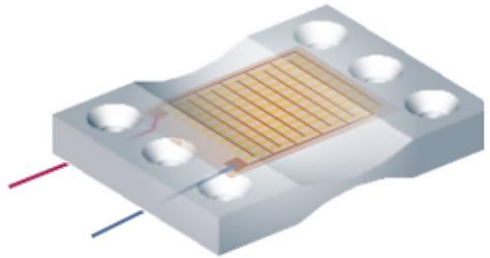
Compliant mechanisms – Development of hinge designs

classic friction- and slackness afflicted joint

deformable solid state joint (state of the art)



textile solid-state joint with direction-dependent stiffness



textile-reinforced flexible joint with integrated actuator

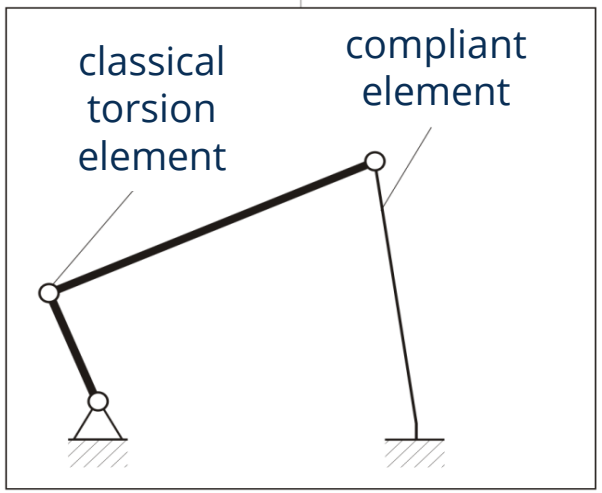
Classification of compliant mechanisms

hybrid
compliant mechanisms

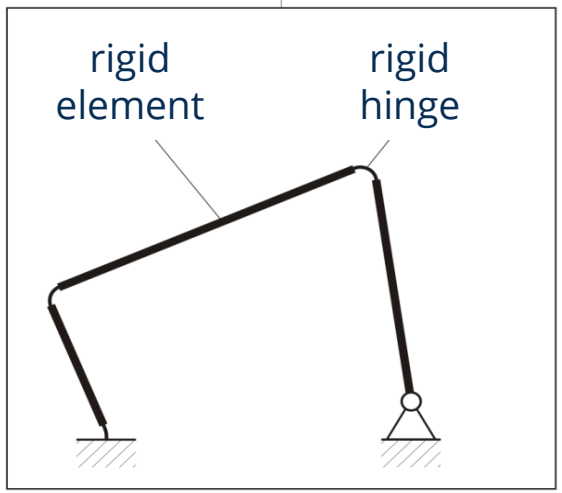
monolitic
Compliant mechanisms

concentrated
compliances

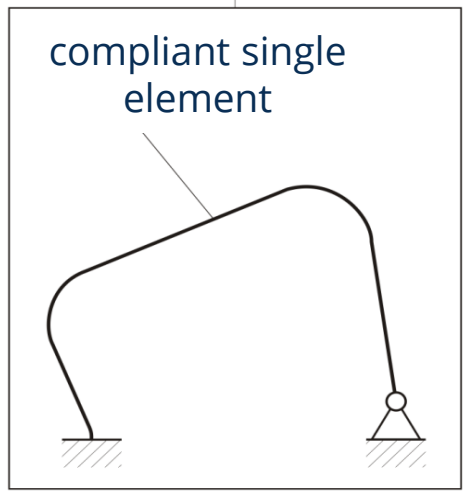
distributed
compliances



differential
design



integrated
design



integral
design

Classification of compliant mechanisms

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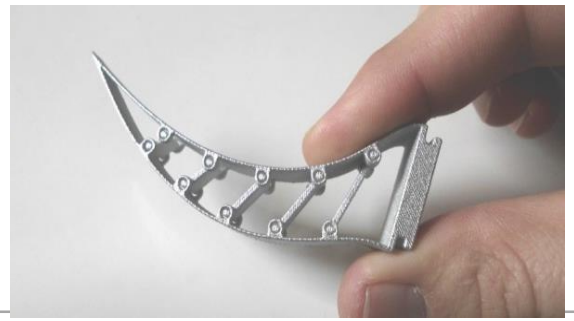
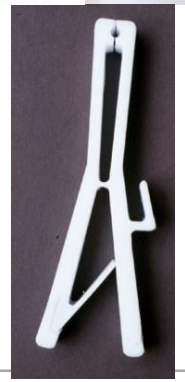
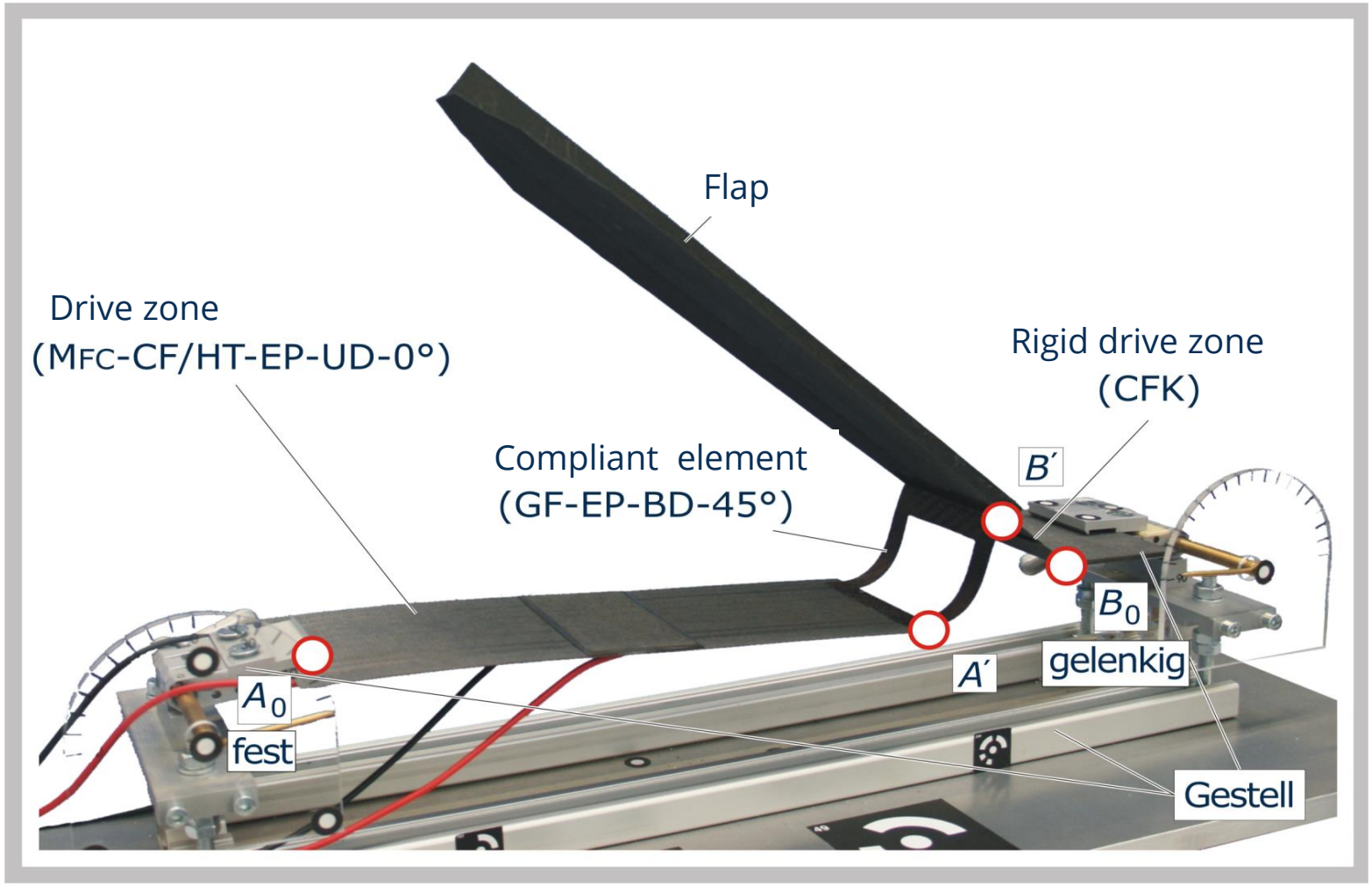


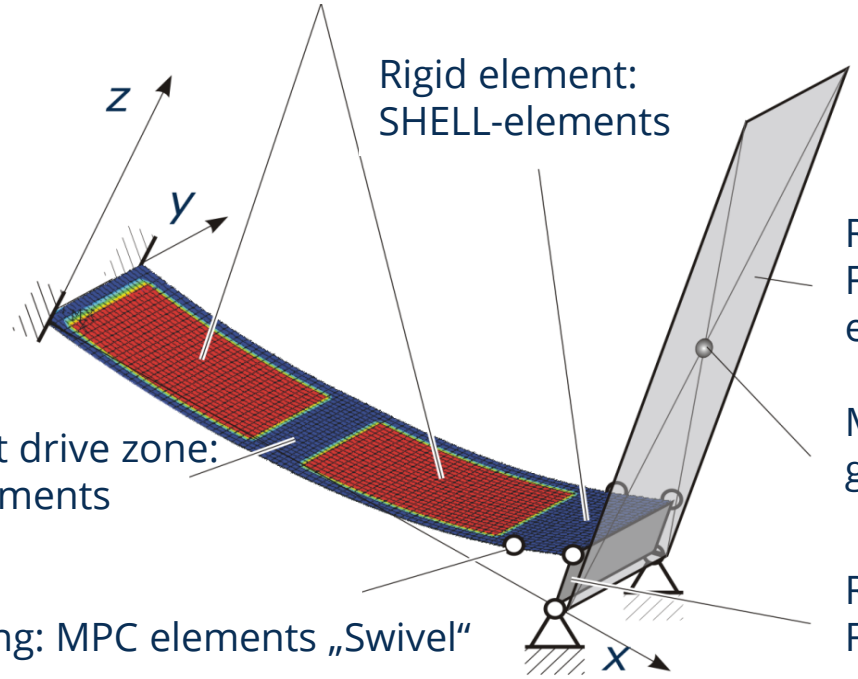


Example for an active compliant mechanism - demonstrator



Example for an active compliant mechanism - simulation

Piezo actuator: SHELL-elements with thermo mechanical coupling



Rigid element:
SHELL-elements

Rigid flap:
Frame – multipoint-constraint-(MPC) elements „rigid beam“

Mass element in flap centre of gravity

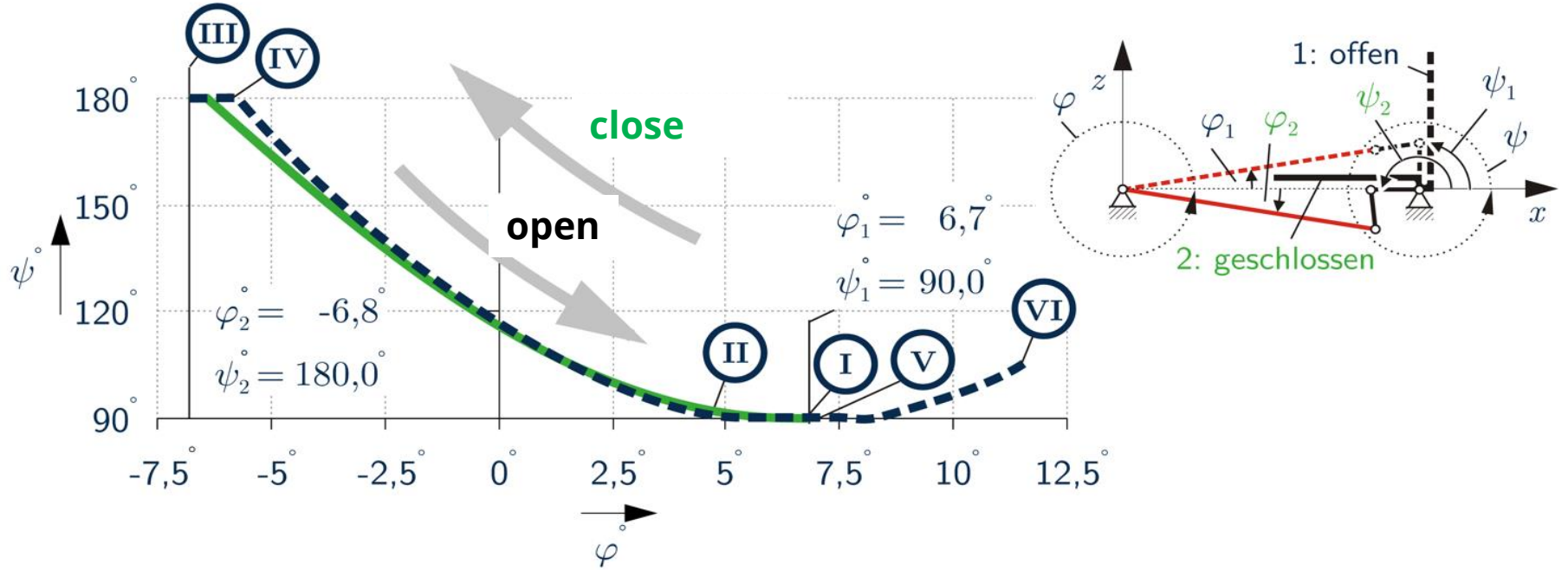
Compliant drive zone:
SHELL elements

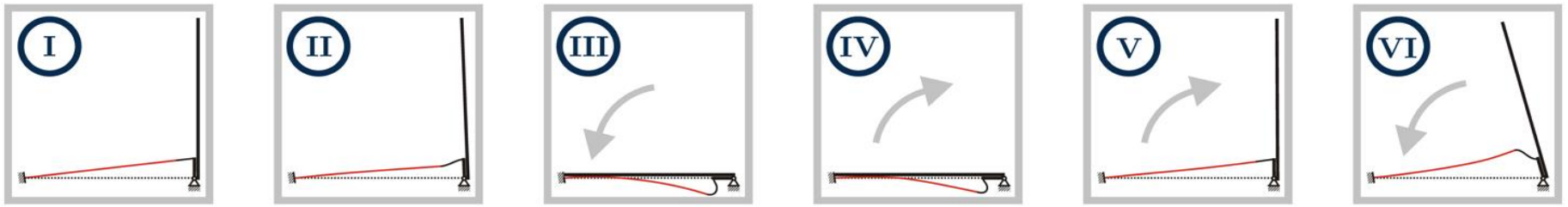
Rigid drive zone
Frame: beam-MPC-elements

Coupling: MPC elements „Swivel“

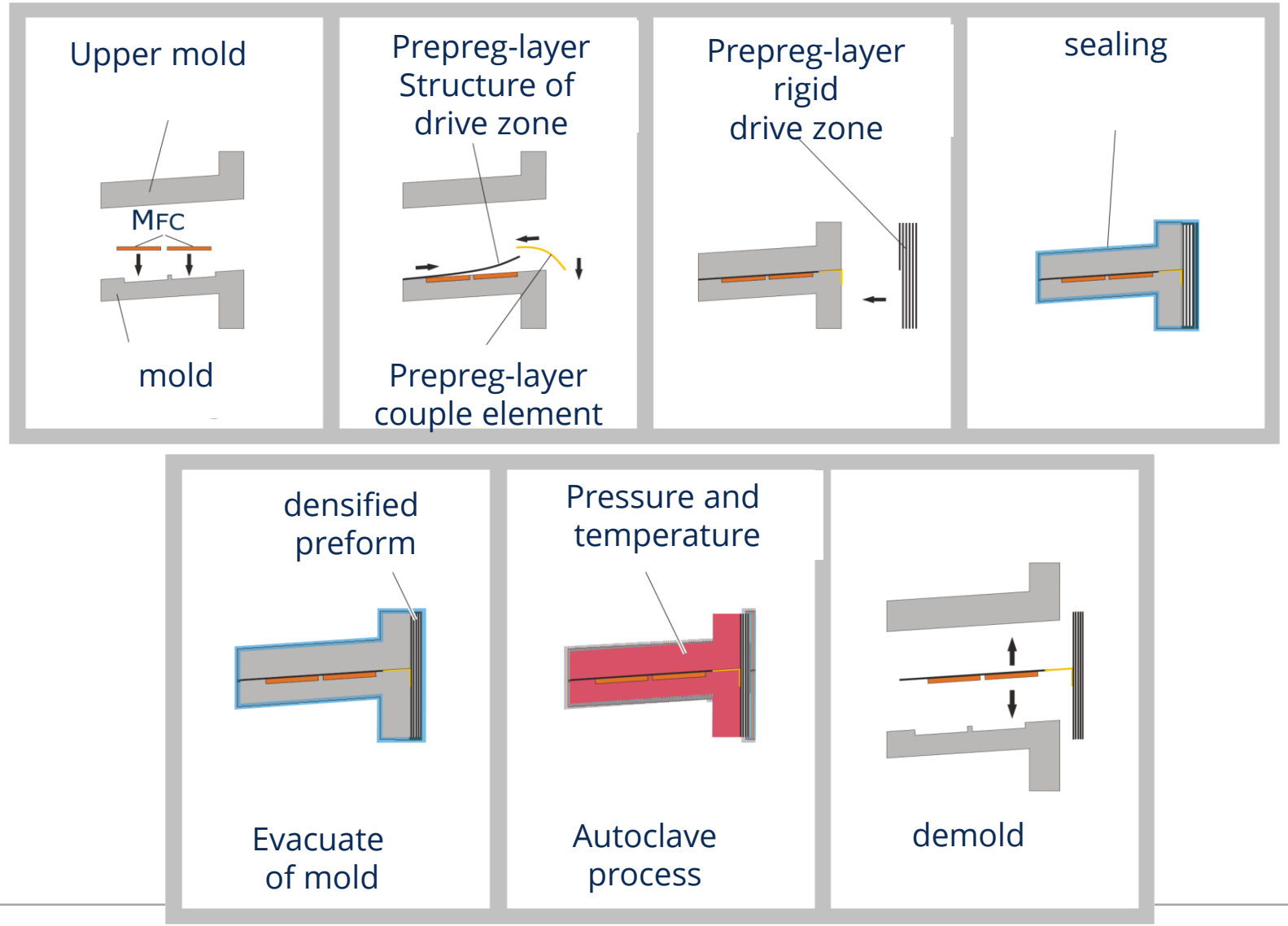
Example for an active compliant mechanism - simulation

Determination of transfer function

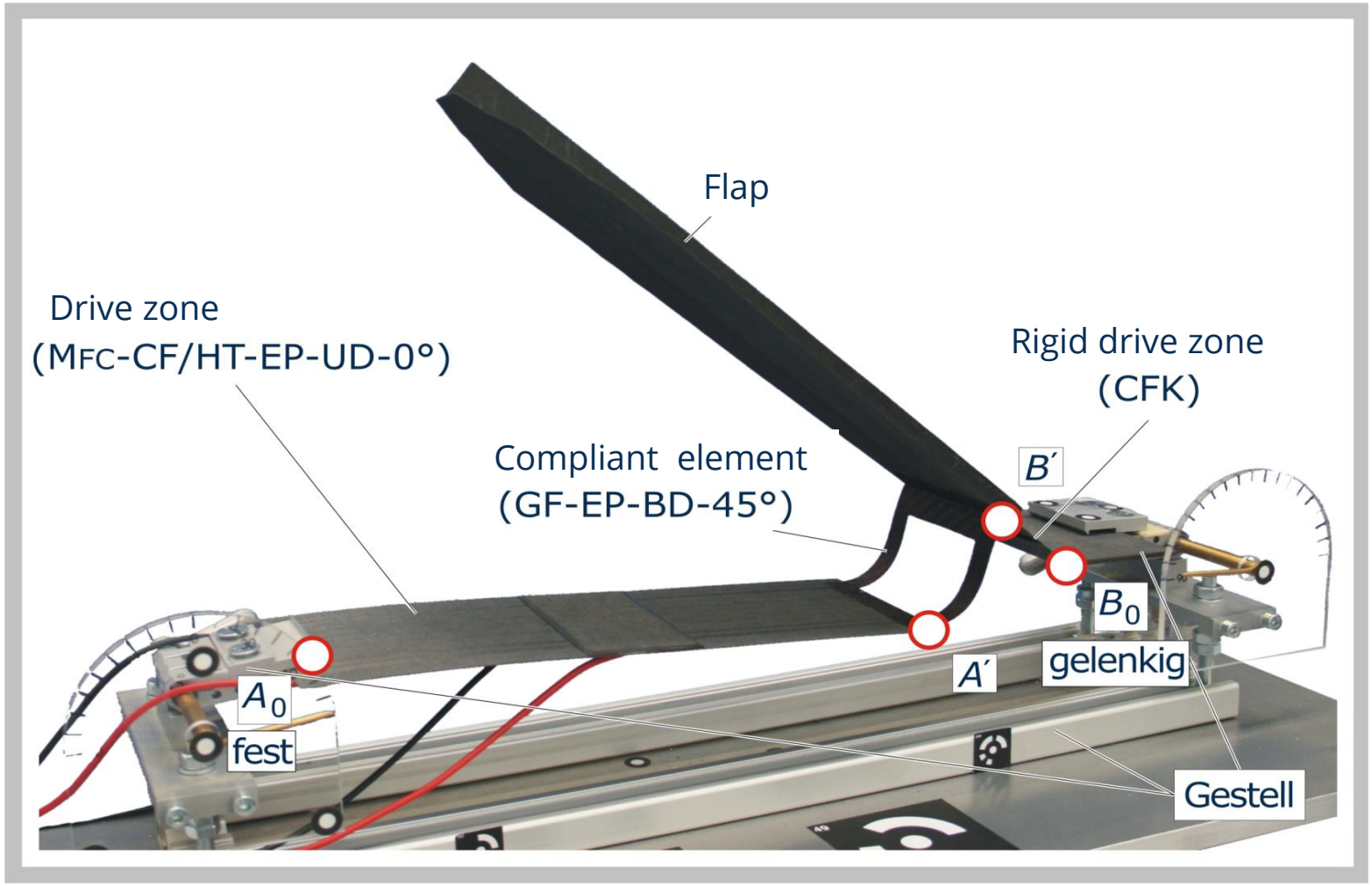




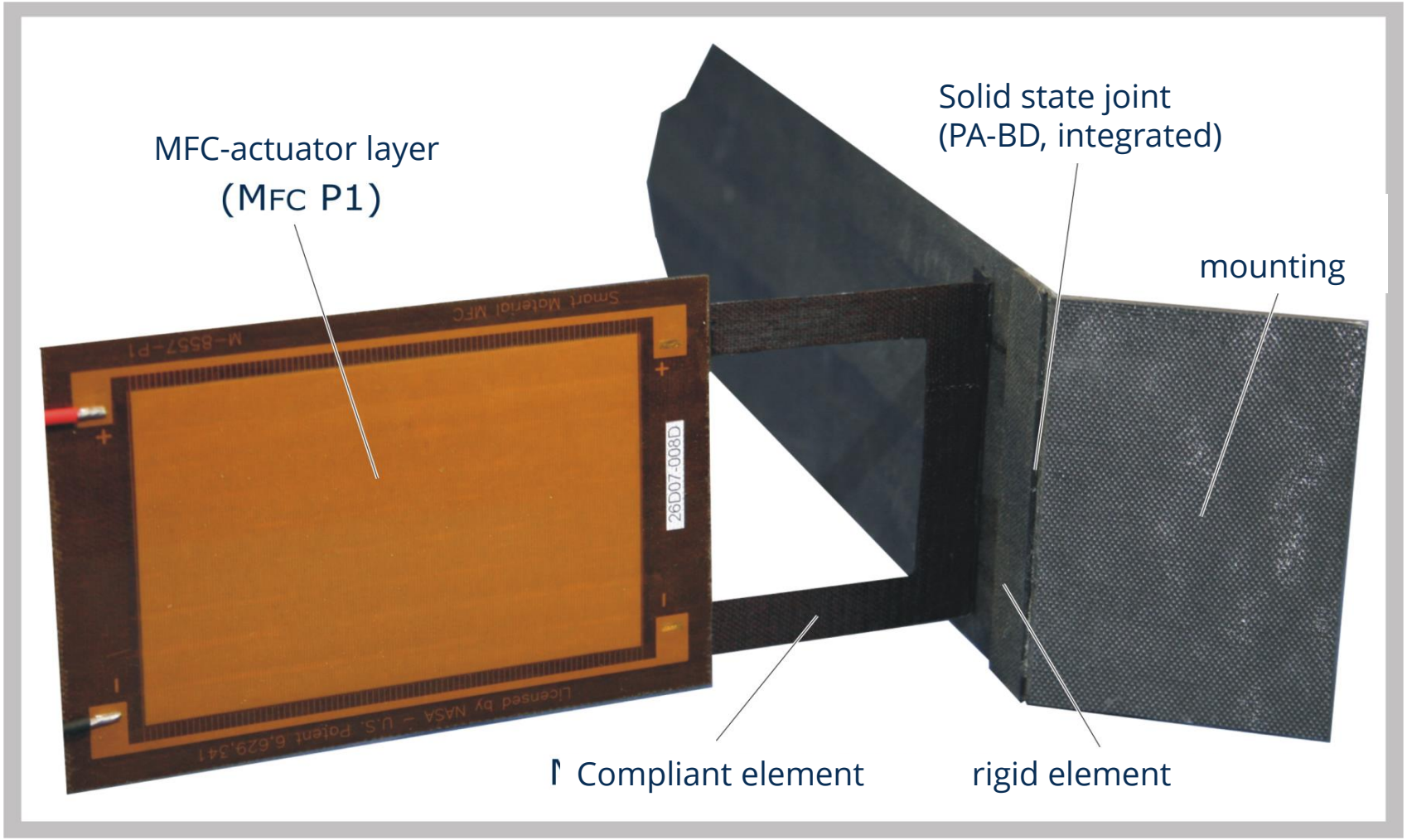
Example for an active compliant mechanism - manufacturing



Example for an active compliant mechanism - demonstrator



Example for an active compliant mechanism - demonstrator



Example for an active compliant mechanism - testing